Program
Asteroid Science in the Age of Hayabusa2 and OSIRIS-REx
November 5–7, 2019

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Lunar and Planetary Institute   3600 Bay Area Boulevard   Houston TX 77058-1113

LPI Contribution No. 2189
Asteroid Science in the Age of Hayabusa2 and OSIRIS-REx
November 5–7, 2019

Guide to Sessions

Monday, November 4, 2019
5:00 p.m. Pima Room Reception

Tuesday, November 5, 2019
8:30 a.m. Grand Ballroom Tuesday Keynotes
10:00 a.m. Grand Ballroom Regolith-Rich and Regolith-Poor Asteroids
1:30 p.m. Grand Ballroom Cratered Asteroids
3:30 p.m. Grand Ballroom Active Asteroids
5:00 p.m. Poster Area Poster Session: Astronomical Observations
5:00 p.m. Poster Area Poster Session: Bennu and Ryugu Comparative Science
5:00 p.m. Poster Area Poster Session: Comets, Meteors, and Meteorites
5:00 p.m. Poster Area Poster Session: Lab Experiments
5:00 p.m. Poster Area Poster Session: OSIRIS-REx Data Analysis
5:00 p.m. Poster Area Poster Session: Upcoming Missions and Future Concepts
5:00 p.m. Poster Area Poster Session: Other Bodies
5:00 p.m. Poster Area Poster Session: Hayabusa2 Data Analysis
5:00 p.m. Poster Area Poster Session: Sample Analysis

Wednesday, November 6, 2019
8:30 a.m. Grand Ballroom Wednesday Keynotes
9:10 a.m. Grand Ballroom Hydrated and Dehydrated Asteroids I
10:40 a.m. Grand Ballroom Hydrated and Dehydrated Asteroids II
1:30 p.m. Grand Ballroom Dark Asteroids
3:30 p.m. Grand Ballroom Trash-Pile Asteroids
5:00 p.m. Poster Area Poster Session: Other Bodies
6:30 p.m. Kuiper Space Science Atrium/Basement Lab Tour

Thursday, November 7, 2019
8:30 a.m. Grand Ballroom Rubble-Pile Asteroids
10:30 a.m. Grand Ballroom Altered Asteroids
1:30 p.m. Grand Ballroom Primitive Asteroids
3:30 p.m. Grand Ballroom Sample Analysis
7:00 p.m. Grand Ballroom Banquet
## Program

**Tuesday, November 5, 2019**

**TUESDAY KEYNOTE**

*8:30 a.m.  Grand Ballroom*

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<tr>
<th>Times</th>
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<tr>
<td>8:30 a.m.</td>
<td>Lauretta D. * Cantwell E. *</td>
<td>Welcome and Introductions</td>
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<tr>
<td>8:50 a.m.</td>
<td>Fujimoto M. *</td>
<td>Keynote Speaker</td>
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<tr>
<td>9:10 a.m.</td>
<td>Ulamec S. *</td>
<td>Keynote Speaker</td>
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<td>9:30 a.m.</td>
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**Tuesday, November 5, 2019**

**REGOLITH-RICH AND REGOLITH-POOR ASTEROIDS**

*10:00 a.m.  Grand Ballroom*

**Chairs:** Andrew Ryan and Katharina Otto

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<tr>
<th>Times</th>
<th>Authors (*Denotes Presenter)</th>
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<tr>
<td>10:00 a.m.</td>
<td>Rozitis B. * Emery J. P. Ryan A. Christensen P. R. Hamilton V. E. Simon A. A. Reuter D. C. Clarke B. E. Delbo M. Howell E. S. Lim L. F. Nolan M. C. Susorney H. C. M. Walsh K. J. Lauretta D. S.</td>
<td>Thermal Inertia and Surface Roughness Maps of (101955) Bennu from OSIRIS-REx Infrared Observations [#2055] OSIRIS-REx has obtained spatially-resolved infrared observations of asteroid Bennu from the mission's Detailed Survey phase. We analysed these observations with a thermophysical model to produce thermal inertia and surface roughness maps of Bennu.</td>
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<td>12:00 p.m.</td>
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<td>LUNCH</td>
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<td>2:40 p.m.</td>
<td>Daly R. T. * Bierhaus E. B. Barnouin O. S. Perry M. E. Ernst C. M. Palmer E. E. Gaskell R. W. Weirich J. R. Susorney H. C. M. Johnson C. L. Daly M. G. Walsh K. J. Nolan M. C. Lauretta D. S.</td>
<td>The Variable Depth-to-Diameter Ratios of Candidate Impact Craters on Bennu: Inferences and Implications [#2030] Impact craters on Bennu exhibit striking variation in depth-to-diameter ratio. We explore the implications of this observation.</td>
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<td>3:00 p.m.</td>
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| 3:30 p.m. | Jewitt D. *                  | **Active Asteroids [#2001]**  
The purpose of this talk is to provide an up-to-date overview of our knowledge concerning the active asteroids. This is a new subject of particular relevance to the meeting given the reported ejection of particulate solids from asteroid Bennu.                                                                    |
We report on our efforts to fit trajectories to particles observed by the OSIRIS-REx spacecraft in Bennu’s environment.                                                                                                                                       |
We will present observations of boulder morphologies on Bennu consistent with exfoliation via thermal fatigue and use models to quantify the expected crack spacing and speed at which particles may be ejected from the surface due this process.                                         |
| 4:40 p.m. | Bottke W. F. * Moorhead A. Hergenrother C. W. Michel P. Schwartz S. Vokrouhlický D. Walsh K. Lauretta D.                                          | **Meteoroid Impacts as the Source of Bennu’s Particle Ejection Events [#2064]**  
We explored micrometeorite impacts onto Bennu using NASA’s Meteoroid Engineering Model. Their kinetic energies (7000 J every two weeks near perihelion) and timing (most hit late afternoon) can explain Bennu’s most energetic particle ejection events.                                                                 |
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<td>McGraw L. E. Emery J. P. Thomas C. A. Rivkin A. R. Wigton N. R.</td>
<td><strong>OH/H\textsubscript{2}O on Near-Earth Asteroids [#2150]</strong>&lt;br&gt;Most near-Earth asteroids (NEAs) are not expected to contain OH/H\textsubscript{2}O on their surfaces. However, evidence for OH/H\textsubscript{2}O has now been found on several S-complex NEAs, which has implications for the delivery and retention of OH/H\textsubscript{2}O in near-Earth space.</td>
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<td>Nolan M. C. Al Asad M. M. Barnouin O. S. Benner L. A. M. Daly M. G. Drouet d’Aubigny C. Y. Emery J. P. Rozitis B. Gaskell R. W. Giorgini J. D. Hergenrother C. W. Howell E. S. Magri C. Margot J. L. Palmer E. E. Pajola M. Perry M. E. Rizk B. Susorney H. Weirich J. R. Lauretta D. S.</td>
<td><strong>Comparing the Radar Shape Model of (101955) Bennu with Ground Truth from OSIRIS-REx [#2033]</strong>&lt;br&gt;We use the measured properties of Bennu to understand the accuracy of radar models.</td>
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<tr>
<td>Popescu M. de León J. Campins H. Tatsumi E. Licandro J. Rizos J. L. Lauretta D. S.</td>
<td><strong>Basaltic Interlopers in the C-Complex Asteroid Families: Possible Sources for Exogenous Material on (101955) Bennu and (162173) Ryugu [#2096]</strong>&lt;br&gt;We searched for V-type asteroids with orbital proper elements similar to those of the B/C-complex inner-main belt families. The findings are in favor of the presence of basaltic material at the surface of (101955) Bennu.</td>
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<tr>
<td>Hendrix A. R. Vilas F.</td>
<td><strong>C-Complex Asteroids: UV-Visible Characteristics and Implications for Space Weathering Effects [#2147]</strong>&lt;br&gt;We present a study of space- and ground-based UV-vis observations of a suite of C-complex asteroids. We compare with lab measurements of candidate materials and meteorites to understand space weathering effects, with implications for Bennu and Ryugu.</td>
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<tr>
<td>Brucker M. J. McMillan R. S. Bressi T. H. Larsen J. A. Mastaler R. A. Read M. T. Scotti J. V. Tubbiolo A. F.</td>
<td><strong>SPACEWATCH(R) Observations of High Priority Near-Earth Asteroids [#2005]</strong>&lt;br&gt;It is essential to monitor Near-Earth Objects (NEOs) that might hit Earth. We present details and results from our Target-of-Opportunity program to recover faint virtual impactors using non-classically scheduled time on larger telescopes.</td>
</tr>
<tr>
<td>Hendler N. H. Malhotra R. M.</td>
<td><strong>Observational Completion Limit of Minor Planets from the Asteroid Belt to Jupiter Trojans [#2145]</strong>&lt;br&gt;We present an easily implemented method of estimating the limiting magnitude of objects as a function of semi-major axis which requires less assumptions in its application, making results more transportable and comparable between works that apply it.</td>
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<td>Cheng B. Yu Y. Baoyin H.</td>
<td>The Boulder Dynamics During YORP Spin-Up of Asteroids [2112] Based on SSDEM simulations, the creep evolution of the boulders on granular regolith during YORP induced spin-up is investigate. Results show the geologic features of boulders on Ryugu and Bennu are consistent with a surface landslide history.</td>
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<tr>
<td>Sugiura K. Watanabe S. Kobayashi H. Genda H. Hyodo R. Inutsuka S.</td>
<td>Numerical Simulations of the Deformation of Rapid-Rotating Asteroids and the Formation of Spinning Top Shapes [2012] We conduct numerical simulations of the spin-up of asteroids using a smoothed particle hydrodynamics code. Our simulations show that the spin-up of rubble piles with the friction angle of 80 degrees result in the formation of spinning top shapes.</td>
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<tr>
<td>Bottke W. F. Vokrouhlicky D. Ballouz R. L. Barnouin O. S. Connolly H. C. Jr Elder C. McCoy T. J. Michel P. Nolan M. C. Rizk B. Scheeres D. J. Schwartz S. R. Walsh K. J. Lauretta D. S.</td>
<td>Interpreting the Cratering History of Bennu, Ryugu, and Other Spacecraft-Explored Asteroids [2042] By comparing the main belt size distribution to craters found on spacecraft-observed asteroids, we can calculate crater scaling laws. Applying our results to large craters on Bennu/Ryugu suggests they may have ancient surfaces (~1 Gyr).</td>
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<tr>
<td>Hsu H.-W. Wang X. Horanyi M.</td>
<td>Regolith Budget of Asteroids [2053] Recent missions to asteroids showed the lack of regolith. Our model to simulate asteroids’ regolith budget provides an explanation about the (non)-presence of regolith and could inform future science and exploration activities.</td>
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<tr>
<td>Genda H. Kurosawa K. Wakita S. Davison T. M.</td>
<td>Impact Heating Due to Friction and Plastic Deformation [2048] Impacts cause significant heating. Effective conversion from kinetic to internal energy in the colliding bodies with strength occurs. We discuss the fates of hydrous materials in parent bodies of asteroids during disruptive collisions.</td>
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| Szutu B. Jenniskens P.       | **Modelling the Particle and Physical Makeup of Meteoroids** [#2034]  
Every night, the SETI CAMS project detects hundreds of meteors. Starting with a predecessor’s meteoroid model written in MATLAB, we developed a numerical model in Python that obtains the physical parameters of each detected meteor. |
| Campins H. Nolau J. O. Swindle T. D. Connolly H. C. Jr | **Ordinary Chondrites in the Allende Strewn Field: Relevance to Asteroids Bennu and Ryugu** [#2063]  
Six strewn fields of low-albedo meteorite falls were studied in search of high albedo xenoliths, as in Almahata Sitta. Eight ordinary chondrite finds were identified within the Allende strewn field; weathering and exposure ages studies are pending. |
| Melikyan R. E. Hergenrother C. W. Clark B. E. Ye Q. Chesley S. R. Lauretta D. S. | **Bennu’s Natural Sample Delivery Mechanism: Estimating the Flux of Bennu Particle Meteors at Earth** [#2102]  
The OSIRIS-REx mission has observed the ejection of particles off the surface of Bennu. While some particles return to its surface, others escape Bennu’s gravity. We model these meteoroids in an attempt to estimate Bennu meteor flux at Earth. |
| Eschrig J. Bonal L. Beck P. Prestgard T. J. | **Investigating the Link Between Chondrites and Their Asteroidal Parent Bodies** [#2024]  
Reflectance spectroscopy is currently the main measuring method for the remote characterization of asteroidal bodies. To better our understanding of these spectra we analyze the reflectance spectra acquired for different chondrites in the laboratory. |
| Russell S. S. Almeida N. V. King A. J. | **The Fall and Terrestrial Alteration of the Ivuna (CI1) Meteorite: Underlining the Importance of Well-Curated Sample Return** [#2099]  
We show that since the Ivuna meteorite fell in 1938 it has been significantly altered, despite attempts to curate it according to best practise. We make recommendations for curation of carbonaceous sample return material. |
| Jenniskens P. Lauretta D. S. Towner M. C. Bland P. A. Heathcote S. Jehin E. Hanke T. Cooper T. Baggaley J. | **First Results from an Observing Campaign to Detect the Meteoroids of Bennu at Earth** [#2017]  
First results are presented from an international observing campaign to detect the meteoroids of Bennu at Earth using 200 low-light video cameras spread over 5 networks in Australia, Chile, southern Africa, and New Zealand during September of 2019. |
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<td>Fornasier S.</td>
<td>Primitive Bodies: Highlights of the 67P/CG Nucleus as Observed by ESA Rosetta Mission [#2006]</td>
<td>We will present an overview of the main results achieved by the Rosetta mission on the surface, activity, and evolution of comet 67P. These results, coupled with those obtained on Bennu and Ryugu, will cast light on the solar system interpretation.</td>
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<tr>
<td>Ramprasad T.</td>
<td>Coordinated Analysis of a Compact Type-A Calcium-Aluminum-Rich Inclusion in the Northwest Africa (NWA) 5028 CR2 Chondrite: Implications for Refractory Inclusions to be Returned by the Hayabusa2 and OSIRIS-REx Missions? [#2134]</td>
<td>We probe high-temperature phases from a compact type-A CAI using electron microscopy, to understand their origin and histories. We expect to find CAIs in the mission return samples and their study will aid in understanding the early solar system.</td>
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<td>Frere N. A. H.</td>
<td>The Blue Edge Problem and Red Edge Problem for HED Asteroid Analogs [#2003]</td>
<td>Vesta-like asteroids have been convincingly linked, through spectral analysis, to HEDs. Incomplete asteroid spectra motivate the derivation of new calibration equations for ferrosilite, enstatite and wollastonite using a 0.8 µm blue edge.</td>
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<tr>
<td>Nuth J. A. III</td>
<td>Volatile-Rich Asteroids in the Inner Solar System [#2126]</td>
<td>We show that there are two mechanisms that can place volatile-rich bodies, formed well beyond the snow line, into long-term residence in the inner solar system. This leads to predictions for the composition of samples returned from Bennu and Ryugu.</td>
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<td>Wang X. Hood N. Carroll A. Hsu H.-W. Horanyi M.</td>
<td><em>The Role of Electrostatic Dust Lofting in Shaping the Surface Properties of Asteroids [#2022]</em>&lt;br&gt;Here we present recent advancement on understanding electrostatic dust lofting and its implications on shaping the surface properties observed by previous and new asteroid missions including Hayabusa2 and OSIRIS-REx.</td>
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<td>Avdellidou C. Schultz C. Price M. Cole M. DiDonna A. Harthong B. Delbo M. Britt D. Peyroux R.</td>
<td><em>Mechanical Properties of Very Weak Carbonaceous Asteroid Analogues and Response to Hypervelocity Impacts [#2023]</em>&lt;br&gt;We report the production of a weak material, analogue to carbonaceous meteorites with a CM-like composition, following the preliminary compositional results for Bennu and Ryugu. We present results of hypervelocity impact experiments.</td>
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<td>Brucato J. R. Poggiali G. Dotto E. Barucci M. A. Pajola M. Hamilton V. E. Christensen P. R. Simon A. A. Reuter D. C. Clark B. Lauretta D. S.</td>
<td><em>Laboratory Spectroscopic Properties of Carbonaceous Chondrites and Minerals at Cryogenic Temperatures in Support of OSIRIS-REx [#2019]</em>&lt;br&gt;We acquired in laboratory spectra in vacuum, at various cryogenic temperatures and with variable particle sizes of minerals and meteorites for simulating space environmental conditions experienced by Bennu.</td>
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<td>Breitenfeld L. B. Rogers A. D. Glotch T. D. Hamilton V. E. Christensen P. R. Lauretta D. S.</td>
<td><em>Evaluating Bennu Surface Compositions Using MIR Spectra of Fine-Particulate Albedo-Constrained Mineral Mixtures and Multivariate Analysis [#2045]</em>&lt;br&gt;We have prepared a fine-particulate (&lt;50 microns) albedo-constrained training set and MIR spectral library for compositional abundance predictions using multivariate analysis with application to OSIRIS-REx OTES spectra.</td>
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<td>Maturilli A. Alemanno G. Helbert J.</td>
<td><em>Laboratory Studies on the 3 µm Spectral Features of Mg-Rich Phyllosilicates and Insights for the Interpretation of Asteroid Ryugu Surface Spectra [#2089]</em>&lt;br&gt;We investigated the Ryugu absorption features in the 3 µm region detected by the Hayabusa2 NIRS3 spectrometer by performing laboratory experiments at PSL on two Mg-rich phyllosilicates (serpentine and saponite).</td>
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<td>Keller L. P., Christoffersen R.</td>
<td>Space Weathering of Primitive Asteroids: Iron Oxidation State Changes in Ion Irradiated Murchison CM2 Chondrite Matrix [#2131]</td>
<td>Ion irradiation experiments on Murchison matrix phyllosilicates to simulate solar wind interactions during space weathering results in an increase in the Fe²⁺/Fe³⁺ ratio, but no production of nanophase Fe metal is observed.</td>
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<td>Bramble M. S., Milliken R. E.</td>
<td>Thermal Emission Spectroscopy of Ordinary Chondrites at Simulated Asteroid Conditions with Implications for Asteroid Thermophysical and Compositional Interpretations [#2139]</td>
<td>We report on a broad suite of environmental chamber measurements of anhydrous silicates, mixtures of silicates and metal, and ordinary chondrites, and we discuss how their emission properties vary between ambient and simulated asteroid conditions.</td>
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<tr>
<td>Potin S., Beck P., Schmitt B.</td>
<td>The Strong Influence of Viewing Geometry and Surface Texture on the Reflectance Spectra of Small Bodies and Meteorites [#2036]</td>
<td>We analyzed the effect of geometry and surface texture on the reflectance spectra of carbonaceous chondrites and terrestrial analogues. We showed that geometry affects all the whole spectra and must be of great importance in data analyses.</td>
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<tr>
<td>Bates H. C., Donaldson Hanna K. L., King A. J., Bowles N. E., Russell S. S.</td>
<td>TIR Spectral Signature of Aqueously and Thermally Metamorphosed CM and CY Chondrites [#2041]</td>
<td>We present thermal infrared spectra collected under simulated asteroid conditions for a number of CM chondrites, some of which have experienced thermal metamorphism, as well as some newly identified CY chondrites.</td>
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<tr>
<td>Haenecour P., Zega T. J., Howe J. Y., Sunaoshi T.</td>
<td>Simulations of Thermal Processing in Carbonaceous Asteroids with In-Situ Heating of Meteoritic Materials [#2046]</td>
<td>To better understand the response of fine-grained materials (e.g., compositions and microstructures) to thermal processing on airless bodies, we carried out in-situ heating experiments of matrix materials from carbonaceous chondrites inside a TEM.</td>
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<td>Kikuchi S., Shibuya T.</td>
<td>Experimental and Thermodynamic Approach to Study Aqueous Alteration of Chondrite at Low Temperature [#2049]</td>
<td>We present 7-month experiment simulating reactions between synthetic chondrite and NH₃-containing solutions at 25 and 80 °C. Our results provide important insights into the understanding of the earliest alteration process of chondritic rock.</td>
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<td>Otto K. A., Schröder S., Stephan S., Trauthan F., Elgner S., Matz K.-D., Preusker F., Scholten F., Jaumann R.</td>
<td>Comparison of Inclusion Size Frequency Distributions of Rocks on Ryugu and Carbonaceous Chondrites [#2058]</td>
<td>We imaged a number of carbonaceous chondrites with the MasCam qualification model to compare inclusion characteristics of rocks on Ryugu with meteorites.</td>
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Ricochets and Impulses on Asteroids [2007]

Laboratory impact experiments into polydisperse material show that a single pulse leaves buried boulders on the surface. Non-normal projectiles matching the Froude number for 10m boulders on Bennu usually roll or ricochet away from their impact site.

Investigation of the Evolution of Hydration in Carbonaceous Asteroid Regolith Simulant [2142]

We measured the 3 µm absorption band of a carbonaceous asteroid regolith simulant while exposing it to a series of heating and cooling profiles while under ambient and hard-vacuum conditions to simulate asteroid-like conditions.

The Specific Heat of Regolith Material [2157]

Specific heat $c_p(T)$ is one of the parameters which determine a surface’s temperature response to heating.

A Search for the Near-Infrared Spectral Signature of Bright Boulders on OSIRIS-REx Target Asteroid (101955) Bennu [2004]

Presenting three approaches for isolating the spectral signal of high and low albedo boulders on Bennu.

From Point Source to Particle: A GIS to Map a Sample to an Object Millions of Kilometers from Earth [2027]

The OSIRIS-Rex mission will yield an unprecedented comprehensive dataset of asteroid Bennu from point source through a global dataset at a variety of resolutions and ultimately sample analysis results, all of which will be linked in a single GIS.

Results from Spectral Clustering Analysis Applied to OSIRIS-REx Color Images of (101955) Bennu [2059]

We show the results from our clustering analysis of the color images of (101955) Bennu obtained with MapCam by the NASA’s OSIRIS-REx spacecraft. We have analyzed both the latest global mosaic and the final four candidate sites for sample collection.

Space Weathering Maps of (101955) Bennu Using a Radiative Transfer Model [2069]

We produced nine space weathering maps of Bennu’s surface using a radiative transfer model.
Impact Features on (101955) Bennu’s Boulders: Implications for its Dynamical Evolution and Surface History

There are boulders on the surface of Bennu that have impact features. We present the size frequency distribution of these features, and demonstrate how these boulders can be used to infer the relative ages of different parts of Bennu’s surface.

An Impact-Crater Ejecta Deposit on Bennu

We present data on the ejecta field associated with the 70m crater at 45S 325E, including the range of impact conditions that could emplace an ejecta deposit on Bennu and the mass flow that created the extensive field.

Linear Structural Features on Bennu

We review these linear structures on Bennu, assess their orientations, and discuss their relevance to our emerging understanding of Bennu’s internal structure.

OSIRIS-REx Gravity Field Estimates for Bennu Using Spacecraft and Natural Particle Tracking Data

Estimates of the Bennu gravitational field are presented, based on spacecraft tracking and on particle observations.

Shape, Spin, Strength, and Stability of Bennu

Ridges and rubble / In the face of YORP spin-up / shape may reveal strength.

Bennu’s Global Digital Terrain Model from the OSIRIS-REx Laser Altimeter

In a roughly five-week campaign starting on July 1, 2019, the OSIRIS-REx spacecraft started its global mapping phase. This dataset will result in the highest fidelity shape and topography of the asteroid from OSIRIS-REx.

A Global Color Map of Asteroid Bennu

The surface of Bennu displays significant albedo and color diversity. We present color and normal reflectance mosaics of Bennu created from the OSIRIS-REx Camera Suite images.

The Orientations of Boulders on (101955) Bennu’s Surface

The orientations of boulders on Bennu can point to signs of surface migration and give information about the mechanical properties of surface material, but careful analysis can also lead to insights into the energetics of events that induce motion.
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<tr>
<td>Neumann G. A. Barker M. K. Mazarico E. Daly M. G. Barnouin O. S. Lauretta D. S.</td>
<td>Exploring the Origins of Terrace Formation on Bennu</td>
<td>We present evidence for latitudinal scarps or terraces across the northern and southern hemispheres of the asteroid Bennu at mid-to-high (40–70°) latitudes, and explore their geological origins.</td>
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<td>Rizk B. Pajola M. Walsh K. J. Bierhaus E. B. DellaGiustina D. N. Drouet d’Aubigny C. Y. Golish D. R. Jawin E. R. Delbo M. Ballouz R.-L. Molaro J. L. Bennett C. A. Burke K. N. Michel P. Lim L. Dworkin J. P. Campins H. Connolly H. C. Jr. McCoy T. J. Daly M. G. Nolan M. C. Lauretta D. S.</td>
<td>The Frequency of Putative Fallback Particles Atop Bennu’s Fields of Brecciated Boulders</td>
<td>We classify pebbles perched on boulder surfaces exhibiting orientations and albedos divergent from the underlying boulder texture as either native inclusions or particulate fallback. We analyze them in light of Bennu’s status as an active asteroid.</td>
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<td>Pelgrift J. Y. Lessac-Chenen E. J. Adam C. D. Leonard J. M. Nelson D. S. McCarthy L. Sahr E. M. Liounis A. Moreau M. C. Bos B. J. Hergenrother C. W. Lauretta D. S.</td>
<td>Reconstruction of Bennu Particle Events from Sparse Data</td>
<td>We show how Bennu’s particle ejection events can be reconstructed using only two observations. We apply this newly developed technique to estimate particle velocities and ejection locations for 11 ejection events observed by OSIRIS-REx.</td>
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<td>Delbo M. Walsh K. J. Molaro J. L. Al Asad M. DellaGiustina D. N. Pajola M. Bennett C. A. Jawin R. Ballouz R. L. Schwartz S. R. Rizk B. Lauretta D. S.</td>
<td>Fractures in Boulders on Asteroid (101955) Bennu: Searching for Evidence of Thermal Cracking</td>
<td>OSIRIS-REx images of Bennu revealed a surface covered by boulders, many of which present fractures and exfoliation features potentially due to thermal cracking processes. We present our mapping of fractures on boulders across the surface of Bennu.</td>
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<tr>
<td>Marshall J. Beddingfield C. B. Lauretta D.</td>
<td>Regolith Surface Creep on Asteroid Bennu: Preliminary Results from Image Analysis, Soil-Stress Modeling, and Laboratory Experiments</td>
<td>Measurements of boulder orientations on Bennu show a N-S alignment in mid-latitudes, consistent with soil stress modeling and lab experiments and are thought to result from surface creep of material toward the equator, driven by rotational forces.</td>
</tr>
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<td>Cambioni S. Delbo M. Deshapriya J. D. P. Poggiali G. Ryan A. Emery J. P. Hamilton V. E. Christensen P. R. Lauretta D. S.</td>
<td>Machine Learning–Based Thermophysical Analysis of OSIRIS-REx Sample Site Candidates</td>
<td>We perform a 2-component thermophysical modelling of OSIRIS-REx/OTES infrared radiances concerning the final four sample site candidates. We find that the sites are distinguishable in terms of their thermophysical properties.</td>
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</table>
Asteroid Regolith Thermophysical Properties: Porosity and Skin-Depth Effects [2070]
We investigate the mechanisms of heat transfer in regolith as a function of porosity and particle size, particularly when the particles are large. Emphasis is placed on comparing apparent (observed) thermal inertia to actual thermal inertia.

The Bennu Ephemeris Based on OSIRIS-REx Data Through Orbital B [2111]
We present an updated estimate of the trajectory of Bennu based on OSIRIS-REx data through the Orbital B phase of the mission. We refine the Yarkovsky effect modeling and revise the impact hazard assessment in the second half of the 22nd century.

Overview of OSIRIS-REx Thermal Observations [2113]
We provide an overview of OSIRIS-REx thermal observations along with some results.

Reflective Surface Texture Through OCAMS and OVIRS On-Board OSIRIS-REx: What Single-Scattering Processes can Tell Us About the Surface of Dark Asteroids like (101955) Bennu? [2149]
OCAM images and OVIRS spectra were used to compose Bennu’s RADF distribution. Single-scattering processes were modeled through a radiative transfer model formulated by Van Ginneken et al. (1998). Results show specular reflection is not negligible.

Calibration of REXIS CCD Performance Efficiency [2067]
This presentation will show the methods of REXIS CCD performance calibration using observations of the Crab Nebula taken in March 2019.

The REXIS Data Analysis Pipeline [2127]
A description of the REXIS data analysis pipeline and calibration tools for extraction of elemental abundances on the surface of Bennu is given in detail.

Tracking REXIS Performance with Fe-55 Onboard Radioactive Sources and Calibration Operations [2008]
The Regolith X-ray Imaging Spectrometer (REXIS) on OSIRIS-REx is a coded-aperture imaging soft X-ray telescope. We will present the analysis results of the onboard Fe-55 radioactive sources and calibration operations.

REXIS measures and maps global elemental abundances using surface X-ray fluorescence spectroscopy on the asteroid Bennu: here we describe and present the X-ray and space environment model used for the derivation of Bennu’s elemental composition.
**Spectral Fitting with the REXIS Solar X-Ray Monitor (SXM) [#2057]**

Here we describe calibration steps for the Solar X-ray Monitor (SXM) of the student-built Regolith X-ray Imaging Spectrometer (REXIS) instrument aboard OSIRIS-Rex.

**REXIS First Results: Regolith X-ray Imaging Spectrometer Aboard OSIRIS-Rex [#2075]**

REXIS is the student-built flight experiment designed to complement the science payload by determining elemental abundances through measurements of fluoresced x-rays from the asteroid surface stimulated by solar x-ray flux.

**Computational Predictions of Electrostatic Levitation About Asteroid Bennu [#2065]**

We numerically model the trajectories of electrostatically levitating particles in a fully 2D plasma model. The fate of levitating particles has significance for understanding the particle sizes observed on Bennu’s surface.

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**Tuesday, November 5, 2019**

**POSTER SESSION:** UPCOMING MISSIONS AND FUTURE CONCEPTS

5:00–7:00 p.m. Poster Area

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<th>Authors (*Denotes Presenter)</th>
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<tr>
<td>Thangavelautham J. T. Asphaug E. A.</td>
<td>Advancing Asteroid Science and Technology Using Student Built CubeSat Centrifuge Laboratories [#2152]</td>
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<td>UA is planning to develop a research and education center called ASTEROID ( Asteroid Science, Technology and Exploration Research Organized by Inclusive eDucation) funded by NASA.</td>
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<td>We present the Multi-Asteroid eNcounter Tour with Imaging and Spectroscopy (MANTIS), proposed to the most recent Discovery competition. MANTIS visits 14 unexplored asteroids, with a payload optimized for flybys.</td>
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<td>This paper presents the expected characteristics of the returned samples from Phobos and the prospective scientific outcomes from their laboratory analyses.</td>
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<td>In light of recent asteroid landing missions, design considerations for future asteroid missions can follow several variables used in an existing model for Mars missions. However, there are limitations for its use in smaller planetary bodies.</td>
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On 2019 July 29, a 7th-mag star in Auriga was recorded from 52 mobile stations in a path across the s.w. USA. Six of them recorded its occultation by Phaethon, the first successful occultation with a small NEO, to help JAXA’s DESTINY+ flyby in 2025. |
| Yumoto K. Cho Y. Sugita S. | *Volatile-Driven Cryovolcanic Eruption on Asteroid Ceres as a Probe to its Interior [#2052]*  
Conduit ascent of cryovolcanism with volatile exsolution was modeled under Ceres conditions. Our model calculations show that exsolution of volatile species may have facilitated the ascent process of cryovolcanism on Ceres for a wide time range. |
| Zhang Y. Michel P. Richardson D. C. | *Formation of Extremely Elongated Bodies by Tides: Application to the Interstellar Object 1I/`Oumuamua [#2072]*  
There is a considerable amount of extremely elongated small bodies in the solar system and exoplanet system, as indicated by 1I/`Oumuamua. Our study shows that tidal disruption events can account for the formation of such elongated shape. |

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<th>Authors (*Denotes Presenter)</th>
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We performed thermal simulation using different resolution of DEM, and compared with TIR observation data. The finest DEM model was drastically different from other shape model and well matches to the observation data. |
With the availability of a 3D shape model of the boulder observed on Ryugu’s surface by the MARA instrument, the data analysis is revisited, resulting in more precise estimates of the boulder’s thermal inertia, roughness and emissivity. |
We estimated the mass density of the boulders from the dynamic motion of boulder near the sampling site on Ryugu. We used ONC-W1 image to measure the velocity and volume of the boulder, and estimated the mass density. |
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<tr>
<td>Kitazato K. et al.</td>
<td>Near-Infrared Spectral Variability on Asteroid Ryugu</td>
<td>We present near-infrared spectral results of asteroid Ryugu from Hayabusa2 spacecraft. Ryugu spectra exhibit a weak, narrow OH feature and small variations on specific regions.</td>
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<tr>
<td>Ikeda H. et al.</td>
<td>Hayabusa2 Radio Science Investigation Around Asteroid Ryugu</td>
<td>The gravity field of Ryugu is evaluated by using radiometric, optical, and altimetric measurements acquired in the low altitude region. In order to improve the estimation accuracy, the target marker orbiting experiment is planned.</td>
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<tr>
<td>Palomba E. et al.</td>
<td>Spectral Investigation of Dark and Bright Areas on the Surface of Ryugu</td>
<td>By using the data obtained by the NIRS3 spectrometer onboard Hayabusa2 spacecraft, the intent of this work is to detect dark and bright areas on Ryugu surface and to study their characteristics.</td>
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<tr>
<td>Matsuoka M. et al.</td>
<td>Whitened Data-Based Cluster Analysis of Infrared Spectra of Ryugu</td>
<td>This study performs cluster analysis using a new statistical method and indicates the NIR spectral heterogeneity possibly reflecting mineralogical and/or physical properties at the Ryugu surface.</td>
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<td>Yokota Y. et al.</td>
<td>Normal Albedo Map of Ryugu at Visible Wavelength</td>
<td>We report on the derivation of the normal albedo map of Ryugu from the opposition observations by the Optical Navigation Camera (ONC) onboard Hayabusa2.</td>
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<td>Morota T. et al.</td>
<td>Surface Reddening of Ryugu Revealed from Global Mapping and Touchdown Operation of Hayabusa2</td>
<td>Based on these proximity observations and global observations, we infer the nature of stratigraphy expressed in color and albedo of Ryugu.</td>
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<td>Color and Spectral Slope Maps of Asteroid Ryugu from Hayabusa2 Optical Navigation Camera Images [2076]</td>
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<td>We will present our latest image mosaics and color analysis of Ryugu using the data from the Optical Navigation Camera. We studied the correlations between color/spectral slope units identified in our maps and geologic features on Ryugu.</td>
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<td>Resurfacing Process on Ryugu Constrained by Crater Distribution [2077]</td>
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<td>We compared resurfacing processes on Ryugu, Itokawa, Eros, and Bennu by using crater production function and R-plot. The results suggest that similar resurfacing process is acting on four asteroids.</td>
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<td>An Overview of Hayabusa2 Mission and Asteroid 162173 Ryugu [2086]</td>
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<td>The Hayabusa2 mission reveals the nature of a carbonaceous asteroid through a combination of remote-sensing observations, in situ surface measurements by rovers and a lander, an active impact experiment, and analyses of samples returned to Earth.</td>
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<td>Space Impact Experiment on Ryugu: Artificial Crater [2090]</td>
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<td>An artificial impact crater with a diameter larger than 10 meters was successfully formed in the SCI impact of Hayabusa2.</td>
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<td>Hayabusa2 Sample Collection at Ryugu [2146]</td>
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<td>Hayabusa2 successfully landed on asteroid Ryugu twice to collect samples at two different surface locations.</td>
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<td>Thermal Physical Properties of Asteroid 162173 Ryugu Revealed by High-Resolved Thermal Imaging — A Link to Porous Asteroid Formation [2092]</td>
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<td>Global, local and close-up thermal images by TIR on Hayabusa2 unveiled the highly porous surface of C-type asteroid Ryugu and also the existence of some dense boulders, hypothesizing a formation history of Ryugu and a link to porous planetesimal.</td>
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<td>Ryugu Spectral Surface Regions via Unsupervised Machine Learning Classification of NIRS3 Data [2016]</td>
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<td>Hayabusa2 reach 162173 Ryugu in June 2018 and found a very dark and boulder rich asteroid with very homogenous NIR spectral reflectance. Machine learning tools on NIRS3 found regions with correlate to geomorphology and distinctive spectra.</td>
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<td>Geometric Correction and Data Archives of Thermal Infrared Imager Onboard Hayabusa2 [2080]</td>
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<td>This study performs a geometric correction of the thermal infrared imager (TIR) observation for the detailed temperature observation of Ryugu and determines the local temperature of the characteristic body on the surface.</td>
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<td>Summary of Results from LIDAR On Board Hayabusa2 [2082]</td>
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<td>We summarize the instrumental specifications, data processing strategy, and scientific results of the LIDAR on board Hayabusa2. The LIDAR is a powerful tool to reevaluate the satellite’s orbit and the vertical structure of surface morphology.</td>
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### Distribution of NIR Spectral Slope on Ryugu Surface [2084]

NIRS3 data revealed a dark surface of Ryugu with a positive spectral slope. Areas with different spectral slopes have been analyzed, to detect physical/chemical properties of the Ryugu surface, likely related to space weathering processes.

### Shape Reconstruction of the Asteroid Ryugu in Hayabusa2 Mission [2093]

We successfully reconstructed the shape models of Ryugu with images taken by the optical navigation camera (ONC) with SPC and SfM methods.

### Porous Boulders on (162173) Ryugu: Compaction Modeling and Implications for Parent Body’s Radius, Accretion Time, and Interior Porosity Distribution [2105]

We calculated the evolution of temperature and porosity for planetesimals in order to identify potential parent bodies for Ryugu’s material and likely burial depths for the boulders observed at the surface.

### New Features of AiGIS for Hayabusa2 Mission: A 3D-GIS for Visualization of Map and Shape of Irregular-Shaped Small Bodies [2087]

AiGIS is a GIS-oriented tool to visualize geographic information of irregular-shaped small bodies developed by the research group ARC-Space at the University of Aizu under collaborations with JLPEDA/ISAS/JAXA and Aizu Lab. Inc.

### The Shape Distribution of Small Boulders on Asteroid Ryugu [2079]

We report the shape distribution of boulders with 0.2–2.1m on the surface of Ryugu based on close-up images near the TD2 site. The result shows that is similar to laboratory impact fragments in catastrophic disruption.
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<th>Authors (*Denotes Presenter)</th>
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<tr>
<td>Weber J. Ramprasad T. Domanik K. Zega T. J.</td>
<td><strong>FIB Tomography of Wark-Lovering Rims in the Allende Meteorite [#2114]</strong>&lt;br&gt;Here, we demonstrate successful FIB tomography of wark-lovering rims in the Kuiper Imaging facility. The method development demonstrated will enable the 3D FIB-tomography of samples to be returned from the Hayabusa 2 and OSIRIS-REx missions.</td>
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<tr>
<td>Fukushi K. Takeichi Y. Suga H. Kebukawa Y. Wakabayashi D. Yamashita S. Kimura K. Takahashi Y.</td>
<td><strong>Photon Factory BL-19: A New STXM Beamline with Wide Energy Range for Aquaplanetology [#2148]</strong>&lt;br&gt;This paper introduces a beamline BL-19 in a SR facility in Japan (Photon Factory) built for studying our project Aquaplanetology and Ryugu samples with a wide energy range to measure various elements to study water-rock interactions.</td>
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<tr>
<td>Davidson J. Alexander C. M. O’D. King A. J. Bates H. C. Foustoukos D. I. Schrader D. L. Bullock E. S. Busemann H. Riebe M. E. I. Schönbächler M. Clay P.</td>
<td><strong>Samples Relevant for Carbonaceous Asteroid Sample Return: Coordinated Studies of CM Chondrites Meteorite Hills 00639 and Aguas Zarcas [#2115]</strong>&lt;br&gt;We report the preliminary results of coordinated studies of the recent CM2 fall Aguas Zarcas and the shock-heated CM2 Antarctic find Meteorite Hills 00639, which may be petrologically similar to material returned from asteroids Bennu and Ryugu.</td>
</tr>
<tr>
<td>Busemann H. Riebe M. E. I.</td>
<td><strong>Noble Gases as Important Tracers for Processes on Small Planetary Bodies – A Detailed Look at the Carbonaceous Chondrites [#2073]</strong>&lt;br&gt;Noble gases are important to characterize asteroidal material and decipher the processes that this material has experienced, which is here demonstrated with a comparative study of carbonaceous chondrites illustrating the effects of aqueous alteration.</td>
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<td>Schrader D. L. Davidson J. Zega T. J. McCoy T. J.</td>
<td><em>The Fe/S Ratio of Pyrrhotite in Chondrites: A Universal Relationship with the Degree of Parent Asteroid Aqueous and Thermal Alteration?</em> [#2118]</td>
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<tr>
<td>Seifert L. B. Haenecour P. Zega T. J.</td>
<td><em>Analysis of a Supernova Olivine Aggregate in the CO Chondrite Dominion Range 08006: Implications for the Measurement of Presolar Grains in Samples of Asteroids Bennu and Ryugu</em> [#2135]</td>
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<tr>
<td>Glotch T. D. Young J. M. Yao Z. Bechtel H. A. Hamilton V. E. Christensen P. R. Lauretta D. S.</td>
<td><em>Near-Field Infrared Spectroscopy as a Tool for Analysis of Chondritic Returned Samples</em> [#2061]</td>
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<td>Helbert J. Maturilli A. de Vera J. P.</td>
<td><em>Planetary Sample Analysis Laboratory (SAL) at DLR</em> [#2088]</td>
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<tr>
<td>Zega T. J. Lauretta D. S. Barnes J. J. Haenecour P. Swindle T. D. Chang Y. J. Domanik K. Weber J.</td>
<td><em>The Kuiper Materials Imaging and Characterization Facility at the University of Arizona: A New Laboratory for the Coordinated Analysis of Planetary Materials and Samples to be Returned by Hayabusa 2 and OSIRIS-REx</em> [#2117]</td>
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### Wednesday, November 6, 2019
#### WEDNESDAY KEYNOTES

**8:30 a.m.**  Grand Ballroom

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<td>8:30 a.m.</td>
<td>Stansbery E. *</td>
<td>Keynote Speaker</td>
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<td>8:50 a.m.</td>
<td>Wijeyeratne S. *</td>
<td>Keynote Speaker</td>
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### Wednesday, November 6, 2019
#### HYDRATED AND DEHYDRATED ASTEROIDS I

**9:10 a.m.**  Grand Ballroom

**Chairs:** Maria Antonieta Barucci and Ralph Milliken

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<tr>
<td>9:10 a.m.</td>
<td>Milliken R. E. *</td>
<td>A Global View of the Near-Infrared Reflectance Properties of Ryugu as Seen by the NIRS3 Spectrometer on Hayabusa2 [#2132] Results of the global spectral properties of Ryugu as seen by the NIRS3 instrument and implications for alteration.</td>
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<td>Kitazato K.</td>
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<td>9:40 a.m.</td>
<td>Hamilton V. E. *</td>
<td>The Global Mineralogy of (101955) Bennu from VNIR and TIR Observations During the Detailed Survey Phase of the OSIRIS-REx Mission [#2044] The surface of Bennu is volumetrically dominated by hydrated silicates similar to those in highly altered CI/CM chondrites. VNIR and TIR spectra display heterogeneity in Detailed Survey mapping data that is not entirely understood at this time.</td>
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<td>Lauretta D. S.</td>
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<td>11:00 a.m.</td>
<td>Usui F. * Hasegawa S. Ootsubo T. Amano K. Nakamura T.</td>
<td>Dehydration Process of C-Complex Asteroids Revealed Through Near-Infrared Spectroscopy [#2100] In this talk, we will discuss a comparative study of spectral characteristics of asteroids and meteorites in the 2.7-micron band based on telescopic observations, in-situ spacecraft explorations, and sample analyses in laboratories.</td>
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<td>11:20 a.m.</td>
<td>Hanna R. D. * Hamilton V. E. Haberle C. W. Kaplan H. H. Howell E. S. Takir D. Zolensky M. E. Lauretta D. S.</td>
<td>What is the Hydrated Phase on Bennu’s Surface? [#2029] We are investigating select CMs and ungrouped C2s Essebi and Tagish Lake to determine the hydrous phase(s) present on Bennu. We are searching for phases within these meteorites that are spectrally consistent with both OVIRS and OTES data.</td>
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<td>11:40 a.m.</td>
<td>Kurokawa H. * Shibuya T. Sekine Y. Ehlmann B. L.</td>
<td>Modeling of Infrared Reflectance Spectra of Volatile-Rich Asteroids [#2083] We computed the model infrared reflectance spectra of asteroids using the results of chemical equilibrium calculations for water-rock reactions. We constrained the aqueous environments experienced by Ryugu, Bennu, Ceres, and the main-belt asteroids.</td>
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<td>1:30 p.m.</td>
<td>Lim L. F. * Kaplan H. H. Hamilton V. E. Christensen P. R. Simon A. A. Reuter D. C. Emery J. P. Rozitis B. Barucci M. A. Campins H. Clark B. E. Delbo M. Licandro J. Hanna R. D. Howell E. S. Lauretta D. S.</td>
<td><strong>Main-Belt Infrared Spectral Analogues for (101955) Bennu: AKARI and Spitzer IRS Asteroid Spectra [#2121]</strong>&lt;br&gt;Bennu’s near-IR and thermal IR spectra are compared with larger asteroid data sets from AKARI and Spitzer.</td>
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<td>2:00 p.m.</td>
<td>Domingue D. * Kitazato K. Matsuoka M. Tatsumi E. Sugita S. Yokota Y. Honda R. Iwata T. Abe M. Ohtake M. Vilas F.</td>
<td><strong>Photometric Properties of Ryugu’s Surface from Both the Hayabusa2 NIRS3 and ONC-T Instruments [#2104]</strong>&lt;br&gt;Dark, rough, and rocky / Mysteries revealed by light / Captured or scattered.</td>
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<td>2:20 p.m.</td>
<td>Schroeder S. E. * Otto K. Schmitz N. Scharf H. Greshake A. Scholten F. Trauthan F. Jaumann R.</td>
<td><strong>Imaging Inclusion Spectral Diversity in Carbonaceous Chondrites with MASCam [#2078]</strong>&lt;br&gt;We imaged 15 carbonaceous chondrites with a model of the camera of MASCOT, the lander onboard Hayabusa2. By comparing the results with actual MASCam data, concentrating on spectral properties, we hope to identify the closest analog to Ryugu.</td>
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<td>2:40 p.m.</td>
<td>Potin S. * Beck P. Bonal L. Usui F. Vernazza P. Schmitt B.</td>
<td><strong>The Shape of the 3 µm Absorption Band Linked to the Alteration History? Laboratory Investigations on Carbonaceous Chondrites and Applications to AKARI, Hayabusa2 and OSIRIS-REx Spectra [#2035]</strong>&lt;br&gt;We conducted reflectance spectroscopy on carbonaceous chondrites under asteroid-like environment. Comparing our results to asteroidal observations, we show that the 3µm band of Ryugu and Bennu point out different alteration histories.</td>
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<td>3:00 p.m.</td>
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### Wednesday, November 6, 2019

**TRASH-PILE ASTEROIDS**

**3:30 p.m.  Grand Ballroom**

**Chairs:** Cyrena Goodrich and Lucie Riu

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<td>4:00 p.m.</td>
<td>Kaplan H. H. * DellaGiustina D. N. Simon A. A. Hamilton V. E. Poggiali G. Barucci M. A. Reuter D. C. Lauretta D. S.</td>
<td>Detection of Pyroxenes on Bennu with the OSIRIS-REx Visible and InfraRed Spectrometer [#2056] The OSIRIS-REx Visible and InfraRed Spectrometer detected regions on the surface of Bennu with spectral properties consistent with pyroxene minerals. We describe the context, composition, and implications of this detection.</td>
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<td>4:20 p.m.</td>
<td>Sugimoto C. * Tatsumi E. Sugita S. Riu L. Nakamura T. Morota S. Matsuoka M. Kitazato K. ONC team NIRS3 Team</td>
<td>Bright Spots on Ryugu Observed by ONC-T [#2051] Asteroid Ryugu has small distinctly bright spots on its surface. We examined the spectra of 21 bright spots ranging ~0.5–2 m in diameter and found that they can be classified into two groups (S- and C- complexes).</td>
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<td>4:40 p.m.</td>
<td>Riu L. * Nakamura T. Tatsumi E. Sugimoto C. Sugita S. Kitazato K.</td>
<td>Analyses of Bright Clusters Detected at the Surface of Ryugu [#2018] We present here an analysis of the bright clusters at the surface of Ryugu as detected by NIRS3. The aim of this study is to characterize those large brighter areas with both NIR and VIS spectroscopy with the NIRS3 and ONC instruments respectively.</td>
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**Wednesday, November 6, 2019**

**POSTER SESSION:**  **POSTER HOUR**

**5:00-6:00 p.m.  Poster Area**

*Posters from Tuesday will be Available for Additional Viewing*
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<td>9:00 a.m.</td>
<td>Grott M. * Biele J. Michel P. Sugita S. Schröder S. Sakatani N. Neumann W. Kameda S. Michikami T. Honda C.</td>
<td>Macro-Porosity and Grain Density of C-Type Asteroid (162173) Ryugu [#2038] We use Ryugu’s observed boulder size-frequency distribution to estimate porosity and grain density. Macro-porosity (porosity in-between boulders) is found to be 15+/−2.5 %, while grain density is consistent with CM and CI chondrites.</td>
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<td>9:20 a.m.</td>
<td>Hirabayashi M. * Cho Y. Morota T. Tatsumi E. Walsh K. J. Barnouin O. S. Ballouz R.-L. Michel P. Scheeres D. J. Watanabe S. Sugita S.</td>
<td>Spin-Driven Evolution of Top-Shaped Asteroids at Fast and Slow Spins Seen from (101955) Bennu and (162173) Ryugu [#2047] A top-shaped asteroid may evolve its shape due to global deformation at a fast spin and surface mass movements at a slow spin.</td>
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<td>9:40 a.m.</td>
<td>Michel P. * Ballouz R.-L. Barnouin O. S. Walsh K. J. Jutzi M. May B. H. Manzoni C. Richardson D. C. Schwartz S. R. Sugita S. Watanabe S. Miyamoto H. Hirabayashi M. Bottke W. F. Jr. Connolly H. C. Jr. Lauretta D. S.</td>
<td>Disruption and Reaccumulation: Forming the Top-Shaped Asteroids Ryugu and Bennu and Explaining Their Different Levels of Hydration [#2010] Disruption simulations show that top-shape asteroids and more or less hydrated aggregates with similar porosities, like Ryugu and Bennu, can be formed in a single parent body disruption.</td>
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<td>10:30 a.m.</td>
<td>Lantz C. * Brunetto R. Baklouti D. Hénault E. Nakamura T. Le Pivert-Jolivet T. Kobayashi S. Borondics F.</td>
<td><em>Decoding Space Weathering on Carbonaceous Objects Using Infrared Spectroscopy [#2002]</em> We will present the results of ion irradiations of carbonaceous chondrites from different petrologic groups. Reflectance spectra in VISNIR, MIR and FIR are acquired to monitor space weathering effects of dark asteroids.</td>
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<td>11:00 a.m.</td>
<td>Clark B. E. * Ferrone S. M. Kaplan H. H. Zou X. -D. Trang D. DellaGiustina D. N. LeCorre L. Golish D. R. Li J.-Y. Ballouz R.-L. Hergenrother C. W. Rizk B. Burke K. N. Bennett C. A. Keller L. Howell E. S. Lantz C. Barucci M. A. Fornasier S. Thompson M. Michel P. Molaro J. Jawin E. R. Delbo M. Simon A. Reuter D. Pajola M. Lauretta D. S.</td>
<td><em>Overview of the Search for Space Weathering Signals on the Surface of Bennu: One Rock Type, or Two? [#2125]</em> We provide an overview of the evidence for space weathering on asteroid (101955) Bennu, and summarize relevant findings from several ongoing parallel studies of surface processes and surface properties.</td>
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<td>11:20 a.m.</td>
<td>Tatsumi E. * Sakagani N. Kameda S. Kitazato K. Kourama T. Yokota Y. Honda R. Yamada M. Morota T. Cho Y. Honda C. Matsuoka M. Hayakawa M. Suzuki H. Tanaka S. Takita J. Nakamura T. Yabuta H. Hiroi T. Vilas F. Domingue D. de León J. Sawada H. Ogawa K. Hirata N. Hirata N. Yamamoto Y. Hiramabashi M. Michel P. Sugita S. Watanabe S.</td>
<td><em>Pole Region Observation Campaign on Ryugu [#2091]</em> We performed the pole region observations with ONC-T and NIRS3. Possible 0.7-µm band absorption is found on both poles. These 0.7-µm band absorption might be related to the space weathering or the thermal metamorphism due to the solar irradiation.</td>
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<td>11:40 a.m.</td>
<td>Thompson M. S. * Laczniaik D. L. Morris R. V. Clemett S. J. Loeffler M. J. Dukes C. A. Trang D. Keller L. P. Christoffersen R. Agresti D. G.</td>
<td><em>The Effects of Space Weathering on the Organic and Inorganic Components of a Carbonaceous Chondrite: Implications for Returned Samples from Hayabusa2 and OSIRIS-Rex [#2103]</em> We performed laboratory experiments to simulate micrometeorite impacts and solar wind irradiation of a carbonaceous chondrite. We present results of coordinated analyses to determine the spectral, microstructure, and chemical changes in the samples.</td>
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### Thursday, November 7, 2019
**PRIMITIVE ASTEROIDS**
1:30 p.m.  Grand Ballroom
**Chairs:** Michael Zolensky and Maitrayee Bose

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| 1:30 p.m.| Zolensky M. E.*              | *Physical Regolith Processes Revealed by CM and CI Chondrites*<sup>[#2026]</sup>  
Petrographic evidence of impact shock melting and brecciation has been presented for CM and CI chondrites, which we review here as a reminder of what we expect in the returned Ryugu and Bennu samples. |
| 2:00 p.m.| Bose M. * Jin Z.             | *Minerals from Asteroid Regolith and Meteorites Reveal Early-Stage Processes in Solar System History*<sup>[#2144]</sup>  
Olivine and pyroxene in Itokawa and thermally metamorphosed ordinary chondrites have the same hydrogen isotopic compositions as Earth’s mantle and contain abundant water. |
Thermodynamic modeling of water-chondrite reactions under various conditions suggests that a large redox gradient in the parent body could generate various secondary mineral assemblages and organic contents. |
| 2:40 p.m.| Manga V. R. * Zega T. J. Muralidharan K. Lauretta D. S. | *Deduction the Thermodynamic Origins of Planetary Materials: Implications for the Histories of Materials to be Returned by Hayabusa2 and OSIRIS-Rex*<sup>[#2143]</sup>  
We describe thermodynamic modeling of planetary materials within a predictive framework of first-principles quantum-mechanics starting from electronic structure calculations to support the laboratory analysis of the returned samples. |
| 3:00 p.m. | **BREAK** | |

### Thursday, November 7, 2019
**SAMPLE ANALYSIS**
3:30 p.m.  Grand Ballroom
**Chairs:** Shogo Tachibana and Dante Lauretta

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| 3:30 p.m.| Righter K. * Lauretta D. S.   | *Overview of CM Chondrites in the US Antarctic Meteorite Collection: Implications for Understanding Bennu and Ryugu*<sup>[#2032]</sup>  
Utilization of CM chondrites in the US Antarctic meteorite collection in understanding Bennu and Ryugu is hindered by uncertain pairing relations, general lack of knowledge of brecciation, and sample friability. |
The discovery of extraterrestrial amino acids and L-excesses of non-terrestrial origin in the Aguas Zarcas meteorite provides additional evidence of an early solar system formation bias toward L-amino acids prior to the origin of life. |
| 4:20 p.m.| Yabuta H. *  
Heading towards the initial sample analysis of Hayabusa2, significance of investigating organic macromolecules in solar system small bodies as well as the expected insights from Asteroid Ryugu will be presented. |
| 4:40 p.m. | **Closing Remarks** | |
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Geometric Correction and Data Archives of Thermal Infrared Imager Onboard Hayabusa2  

Mechanical Properties of Very Weak Carbonaceous Asteroid Analogues and Response to Hypervelocity Impacts  

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* R.-L. Ballouz, K. J. Walsh, D. N. DellaGiustina, M. Al-Asad, P. Michel, C. Avdellidou, M. Delbo, E. R. Jawin, O. S. Barnouin, C. A. Bennett, E. B. Bierhaus, W. F. Bottke, H. C. Connolly, M. G. Daly, R. T. Daly, J. L. Molaro, B. Rizk, S. R. Schwartz, D. Trang, and D. S. Lauretta ........................................ 2123

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MODELING OF THE BENNU X-RAY SPECTRUM AND RESPONSE OF REXIS FOR THE RECONSTRUCTION OF ELEMENTAL ABUNDANCES AND CHARACTERIZATION OF THE SPACE ENVIRONMENT. Branden Allen1, Daniel Hoak1, Jaesub Hong1, David Guevel1, Jonathan Grindlay1, Richard P. Binzel2, Rebecca Masterson2, Mark Chodas2, Carolyn Thayer2, Madeline Lambert2, Elena Romashkova2, Max Yu2, Andrew Cummings2, Lucy F. Lim3, Beth E. Clark4, Timothy J. McCoy5, Dante S. Lauretta6.

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The Regolith X-ray Imaging Spectrometer (REXIS) [1] is the student collaboration instrument for the OSIRIS-REx mission. REXIS is designed to measure and map global elemental abundances through solar induced X-ray fluorescence on the surface of the target asteroid Bennu.

An extensive instrument and asteroid modeling framework for the estimation of instrument performance and interpretation of the measured X-ray spectra, had initially been created during the design phase of the REXIS instrument for performance estimation, has been updated for the the extraction of surface elemental abundances for the identification of meteorite analogs, cf. [2] and [3]. The updated model takes into account updates in instrument performance using measurements from flight, additional higher fidelity models of our CCD response using the Suzaku XIS model, the skyback model for modeling of the cosmic X-ray background (CXB), an utilizes new shape model information for Bennu via VTK to appropriately account for the response of the REXIS instrument optics on Bennu as well as solar X-ray exposure. Additionally the framework has been extended to accept XRF response matrices generated using GEANT4 for both the characterization of X-ray emission from the asteroid surface induced by both incident X-ray as well as particles.

The simulation framework is discussed in detail as well as a comparison of the predicted and observed performance of the REXIS instrument. Finally we describe the use of the model for the classification of Bennu and discuss applicability to future planetary X-ray fluorescence spectrometers / imagers.

Fig. 1- Instantaneous REXIS instrument response on Bennu.


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Introduction: The thermal infrared imager (TIR) onboard the Hayabusa2 spacecraft has observed the surface temperature of the asteroid 162173 Ryugu from June 27, 2018, to late 2019 [1]. To make global maps of the surface thermal properties for the asteroid is the primary goal of the TIR. Thermal inertia is especially the main target, which is written as the thermophysical amount of thermal conductivity, specific heat, and density. Also, a surface roughness [2], caused by surface shadows of light and multiple radiations, apparently changes the local temperature of the surface. Both thermal inertia and surface roughness affects the peak shift of diurnal time at the maximum temperature of the asteroid surface and probably cause orbital changes of the asteroid as studied as the Yarkovsky effect [3]. TIR reveals the evolational history, such as the physical properties of the coalesced bodies, orbital changes due to the Yarkovsky effect, and the thermal changes.

This study performs a geometric correction of TIR observation for the detailed temperature observation of Ryugu and determines the local temperature of the characteristic body on the surface.

Geometric Correction: After the Earth swing-by of the Hayabusa2 spacecraft, TIR observed the planet and its moon from December 5 to December 22, 2015 [4]. We extracted positions of both the Earth and the Moon from the observed images of TIR and compared the positions and predicted coordinates (J2000) using the SPICE toolkit [5]. We adjusted the Euler angles of TIR for the Hayabusa2 body flame (FK) by the least-squares fitting. The resulting positional accuracy was less than 100 km from 340000–350000 km observation for the Earth and moon positions.

In the rendezvous phase of Ryugu, we performed the detail alignment correction of TIR using a shape model of Ryugu [6]. We adjusted 87 images observed from the mid-altitude of 5 km (2018-08-01) to the shape model for one rotation cycle. These observed images (Fig. 1a) were fitted to the numerical images made from the shape model of Ryugu (Fig 1b). The projection method was ray projection to a focal plane of images [7]. The best-fit Euler angles were,

\[
\begin{align*}
Z & \approx -1.052 \pm 0.010 \text{ (degree)} \\
Y & \approx -1.80.007 \pm 0.033 \text{ (degree)} \\
X & \approx 0.115 \pm 0.017 \text{ (degree)}
\end{align*}
\]

This result implies that the positioning accuracy of the surface resolution achieved to the one sigma error of 2–3 m at an altitude of 5 km observation. Also, the results indicate that the spatial resolution of TIR is within the error of one pixel because the specific resolution of TIR is 0.051 degrees/pixel.

Figure 1. Geometric correction using the shape model of Ryugu (SHAPE_SPC_800k) [6]. (a) upper: example of an observed image (Level-2:2018-08-01T18:22:56). (b) lower: residual of the observed image and the projected temperature onto the TIR image plane from the shape model using SPICE tool kit.

Data Products: The observed data are automatically converted from raw digital data to temperature images using a Linux computer at ISAS/JAXA and the calibration database HEAT at the University of Aizu [8]. The raw data and part of the Level-1 data are currently available on JAXA’s website [9]. Here, the outlines of Level-1~4 products are schematically shown in Figure 2 and described as follows:
**Level-1. Raw Image** - the raw image includes observed pixel coordinates connect to the planetocentric coordinates in the header - the coordinates generated by the SPICE kernels. The file format is Fits [10].

**Level-2. Brightness Temperature Image** - the brightness temperature converted from raw digital number images. The HEAT DB extracts near condition data from the pre-launch experiment DB, concerned with the temperature of the sensor and find best-calibrated data. **Level-3. Temperature Map on Shape Model** - the observed brightness temperature is projected onto the shape model of Ryugu. The file format is CSV text tables. **Level-4. Thermal inertia map** - the global thermal inertiies are projected on a planetocentric map. The effects of surface roughness are corrected by simulation of the heat balance model of the Ryugu surface [11].

![Figure 2. Data Production flow of TIR.](image)

**Results and Discussions:** The accuracy of the geometric correction is less than 3 m at an altitude of 5 km observation using projection on the shape model. This result satisfies the scientific objective of TIR mentioned in the introduction.

The observed images include distortion in image corners. The distortion correction [7] was performed the same as the geometric correction using a least-squares fitting with a polynomial function. However, the fitting was not converged because the distortion was less than one-pixel. Therefore, we neglected the corner distortion of observed images.

Figure 3a shows the example of map projection data of TIR (Level-3). For comparison, numerical simulation data [12] is shown in Figure 3b. These temperature and thermal inertia (350 Jm²s⁻⁰.⁵K⁻¹) was adjusted to the maximum temperature area (Ejima Saxum) of the observed image. The data simulated secondary-radiation and multiple-reflection, but the data did not include a surface roughness. These data imply that the surface geometry affects the surface temperature, such as hot areas. On the other hand, a global flatten-feature concerned with temperature is shown in the observed image, but such features are not shown in the simulated data. Therefore, surface roughness affects the global temperature of the surface.

TIR observed many close-up images with the spatial resolution of centimeters. The MARA radiometer onboard MASCOT lander also observed local surface temperatures [13]. We can compare these data for deriving of the local thermal properties and reveal the amazing characteristic body on the surface of Ryugu.


![Figure 3. Example data of temperature map on the shape model.](image)
Mechanical properties of very weak carbonaceous asteroid analogues and response to hypervelocity impacts.
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Introduction: Two on-going sample return space missions, Hayabusa2 and OSIRIS-REx are orbiting and characterising two near-Earth asteroids, (162173) Ryugu and (101955) Bennu respectively. Initial ground-based observations and preliminary mission data indicate that the composition of these small objects is similar to the CM or CI meteorites [1-4]. However, their mechanical properties appear to be different [5,6]. How does this weak materials respond to impacts? What type of regolith is produced during micrometeoroid bombardment? Will we expect to find exogenous materials embedded on the weak surfaces of Bennu and Ryugu?

Materials: In our work we used as targets to hypervelocity impact experiments, asteroid analogue materials with mineralogy similar to the CM meteorites. Specifically, the CM2 regolith simulant is a close mineralogical match to the Murchison CM2 carbonaceous chondrite meteorite. Since one of the aims of the project was to examine qualitatively the produced regolith after impact events, we used as inclusions glass beads for an easier examination. The samples were produced and casted at the Exolith Lab of the University of central Florida. Samples were also mechanically tested at the 3SR Lab in Grenoble, where the compressive stress and tensile strength were measured.

Experiments: In order to study the response of the CM-like asteroid analogue material to collisions with small projectiles, at typical impact speeds occurring in the asteroid Main Belt, we performed a series of laboratory hypervelocity impact experiments. We used the facilities of the Impact Lab of the University of Kent in the UK. The main instrument used here is a 2-stage light-gas gun (LGG), which can achieve speeds up to 7.5 km/s. Targets were the squared blocks of CM analogues with dimensions 9.5 cm x 9.5 cm and 4.4 cm thickness, while as projectile we used stainless steel of different diameters. In these experiments we measured the depth and diameter of the craters, the quality of the ejecta and the state of the inclusions. In particular we wanted to test a part of the hypothesis that on materials with inclusions, impacts produce mainly multimineralic fragments, whereas thermal cracking, as a slower process produces monomineralic.

Conclusions & Implications: We created in the laboratory a material mineralogically analogue to the CM carbonaceous meteorites but with mechanical and thermal properties intermediate between those of the CM meteorites, that we receive on Earth, and those measured by space missions for the boulders on the C-complex NEAs Ryugu and Bennu. We find that the material fragmented and ejected by an impact at those speeds contains both multi- and monomineralic fragments, which include single glass spherules – that we embedded in the analogues to mimic chondrules – and metallic phases that were easily separated from the matrix. The results from this study indicate that it could be more difficult than predicted to distinguish grains produced from thermal fragmentation from those created by the impact of micro-meteorites in the regoliths of asteroids that have CM like composition with mechanically weak surface boulders. Ongoing work investigates the impact effects on CI-like materials and also the effect of thermal cracking on both CM- and CI-like materials.

Figure 1: Impact crater on a CM2 asteroid analogue sample.
Figure 2: Ejecta of a CM2 asteroid analogue sample.


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IMPACT FEATURES ON (101955) BENNU’S BOULDERS: IMPLICATIONS FOR ITS DYNAMICAL EVOLUTION AND SURFACE HISTORY. R-L. Ballouz1, K.J. Walsh2, D.N. DellaGiustina1, M. Al Asad3, P. Michel4, C. Avdellidou4, M. Delbo4, E.R. Jaddin5, O.S. Barnouin6, C.A. Bennett7, E.B. Bierhaus8, W.F. Bottke2, H. C. Connolly Jr.8,1, M.G. Daly9, R.T. Daly9, J.L. Molaro10, B. Rizk1, S.R. Schwartz1, D. Trang11, D.S. Lauretta1.

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Introduction:

OSIRIS-REx’s Detailed Survey imaging campaign using the PolyCam instrument, part of the OSIRIS-REx Camera Suite (OCAMS) [1], has returned images of the surface of (101955) Bennu with pixel scales down to 1 cm/pixel. The unprecedented resolution of these images have revealed clearly-resolved cavities on Bennu’s smoothest boulders. These cavities are near-circular in shape and have diameters that range from 6 cm to 1 m. We have begun to catalog these cavities in orbital images, and have found more than 100 boulders that exhibit at least 1 of these features on their surface.

Signatures of Bennu’s impact history:

The likely mechanism for the creation of these cavities is impacts on Bennu by a population of small impactors. We find that the number of cavities per unit area varies by boulder. It may indicate a variable surface exposure age for the boulders, different strengths against impacts for the boulders, or an alternative process for their creation.

Assuming these cavities are created by impacts, they represent miniature craters (mini-craters) generated by the impactor population located at Bennu’s current location near Earth and its past orbit, possibly including Bennu’s past residence in the main asteroid belt. By measuring the size frequency distribution (SFD) of these mini-craters, we will have a new assessment of Bennu’s dynamical history through direct comparison to the inter-planetary micro-meteorite population near Earth, which has been determined from the Apollo lunar rock samples (see [2]), lunar impact monitoring [3,4], and the Long-Duration Exposure Facility [5] and to the modeled main-belt impactor flux [6].

The preliminary counting of mini-craters on Bennu’s boulders has been limited to smooth boulders that have flat surfaces, where these features are the most apparent. Detections of candidate impact features on Bennu’s hummocky boulder population are ambiguous as the scales of the mini-craters (10’s of cm) appear similar to this population’s surface roughness. Therefore, we limit our analysis to mini-craters found on smooth brighter boulders.

For the same impactor population (similar impactor densities and collision speeds), the size and shape of craters on boulders are controlled by the size of the impactor and the target boulder’s material properties such as density, yield strength, and porosity [7,8]. Therefore, limiting our analysis to boulders with similar morphologies allows us to better constrain the properties of the impactor population.

We measured the diameters of cavities ranging from 3 cm (3x the pixel scale) up to 30 cm, and the surface areas of the individual boulders by outlining the exposed surface with polygons. Our preliminary measurements of the diameters of the mini-craters on boulders suggests that the cumulative SFD exponent of these mini-craters is -2.36 (Fig. 1), which is very similar to the SFD exponent of lunar impact flashes reported in [4], -2.28.

![Fig. 1. Cumulative size frequency distribution (SFD) of mapped cavity diameters on flat smooth boulders on Bennu. The best-fit power law exponent of the SFD is similar to that of lunar impact flashes [4].](image-url)
Clocks on Bennu’s surface:

The detailed comparison of the surface density of mini-craters on these boulders with their location on Bennu may provide us with a new way to provide relative ages of different regions of the surface. This can be used as a basis of comparison or calibration point to alternative approaches, such as an assessment of the small crater population, [9] or space-weathering on Bennu’s surface [10]. Our findings may eventually be validated by analyzing the cosmic ray exposure ages of the returned sample.

References:


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EXPLORING THE ORIGINS OF TERRACE FORMATION ON BENNU


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Summary: We present evidence for latitudinal scars or terraces across the northern and southern hemispheres of the asteroid Bennu at mid-to-high (40–70°) latitudes, and explore their geological characteristics. These features may be the result of surface creep due to YORP spin-up that leads to localized regional surface failure. Geotechnical analyses indicate that the latitude bands where the terraces are located are the most prone to failure. Simple laboratory experiments that attempt to simulate quasi-static slope failure of a blocky surface indicate that regional terracing as observed on Bennu is likely. Similarly, numerical simulations of this slope failure at gravitational acceleration commensurate with Bennu’s show a similar failure pattern. Evidence for some infilling of larger mid-to-low latitude craters by surface flow could be evidence that the creeping surface failure displacement creating terraces may be recent.

Introduction: The Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft arrived at (101955) Bennu in December 2018 [1]. A global digital terrain model (GDTM) of Bennu was derived from imaging and laser altimetry observations [2]. Initial assessment of the surface slope and elevation relative to gravity [3,4] indicates that Bennu possesses some interior stiffness, with significant evidence for surface mass-wasting.

Here, we explore manifestations of surface mass-wasting that result in terrace formation on Bennu. As in our earlier assessment [2], we use slope and elevation relative to gravity along with a slope stability analysis to gain insights into the possible origin of these features. We supplement these geotechnical assessments with simple laboratory and numerical investigations.

Methods: The slope and elevation of Bennu are computed using a recent GDTM developed from all OSIRIS-REx Camera Suite (OCAMS) images [5] collected between late November 2018 and April 2019, that is conditioned with OSIRIS-REx Laser Altimeter (OLA) [6] data collected through April 2019. We also use the asteroid mass reported in [3]. The RMS error of the global model is <0.7 m. Individual Orbital Phase B OLA scans (data collected <7cm intervals between returns), OCAMS images and global imaging mosaics all provide context for the slope and elevation results.

The slope stability analysis uses the “factor of safety” model for infinite slope [6], FS, that compares the ratio of resisting frictional and cohesive stresses to gravity

\[ FS = \frac{\tan \phi \tan \theta}{\tan \theta} \frac{c}{\gamma_s T \sin \theta} \]

where \( \theta \) is the slope angle, \( \phi \) is the frictional angle of the surface material, \( c \) is the cohesion, \( \gamma_s \) is the depth-averaged total unit weight, and \( T \) is the thickness of the regolith/boulders that could fail. Values of \( FS < 1 \) imply the slope is prone to failure. We used the lowest-resolution shape model available for our analysis (average facet size of 12.5 m) to reduce local slope biases in our assessment. We set \( \phi = 40^\circ \) for highly angular granular materials, and used \( c = 1 \) Pa based on the minimum cohesion necessary to form the equatorial ridge of Bennu [3].

As a complement to the FS calculations, we performed both a series of simple laboratory experiments and numerical investigations to form terraces in granular material. In the laboratory investigation, we make use of a gravel mixture composed of particles with three distinct colors with diameters near ~0.2 cm, ~0.5 cm, and ~1 cm. The coarse-grained material employed was intended as a proxy for the boulder-rich surface of Bennu. We placed the gravel in a clear-sided box, and slowly lifted one of its sides to mimic slope increases on Bennu due to YORP spin-up. We used a high speed (100 frames/s) camera to observe the displacement of the surface material.

In the case of the numerical study, we used pkdgrav [7], with a soft-sphere model that includes four components in the normal, tangential, rolling, and twisting directions to compute inter-particle contact forces [8,9]. These simulations evaluated the consequences of slowly steepening a slope composed of near equal-sized spherical particles whose friction mimic that of coarse granular sand with friction angles near 40 deg in the Bennu
gravitational environment. Cohesion effects were ignored. The results could be compared both to the observations on Bennu, and the simple laboratory experiments.

**Results:** Terraces are evident in polar and latitudinal assessments of the slope and elevation of Bennu (Figure 1). They are most prevalent near latitudes of ±60° but span 30°–80°. The OCAMS data indicate that many of the terraces are steep scarps, with an accompanied downslope ledge. The longest scarp spans over 120° of longitude. Although a statistical assessment is needed, the steep scarps appear to lack discernible boulders (except when a scarp itself is a boulder face). Some of the terraces are composed of rows of large step-faced boulders, with smaller rocks accumulating both above and below these rock faces as the surface material slowly creeps along and sometime precipitously fails to form the terraces.

This formation scenario is supported by our stability analysis. For the case where $c=0$, the slopes are the least stable at the current spin rates in the latitude bands where terraces are observed. Reducing $\phi$ to 32°, a more plausible friction angle for Bennu surface material, or continuing to increase the spin rate, we find regions that are at risk of slope failure today near where terraces are located. A cohesion of $c=1$ Pa completely hinders any surface failure at current spin rates, which is inconsistent with observations; the failure would be deep-seated for such cohesion conditions.

At Earth gravity, the laboratory experiments provide some useful insights in understanding what to expect at Bennu. The experiments reveal that initially, as the slope steepens, individual boulders are the most likely to topple over. As the slope increases further, regional failures occur to produce many of the characteristic of the terraces seen on Bennu. The low $g$-numerical simulation show a similar set of events; these do not show a need for an instability to cause surface failure. In the laboratory, additional presence of smaller grain sizes in certain areas enhances the likelihood of surface mass-wasting, which may explain why some scarps on Bennu often lack coarse grains.

**Discussion and Conclusion:** We show that the formation of terraces on Bennu could be the result of slope instabilities generated by YORP spin-up. Their morphology and slope characteristic are consistent with laboratory-based assessments of regional slope failure, and the location of the observed terracing is consistent with expectations from slope stability analyses using the current spin-rates. A possible concern, however, for such an origin of these terraces is that YORP spin-up on Bennu occurs very slowly [10], causing minute increases in slope with time. For such conditions, several studies [e.g., 11,12] indicate that slope failure should be global and catastrophic. Our numerical studies at low-$g$ show creeping flows as seen in the laboratory can occur on Bennu even when slopes increase very slowly. The slope distribution in Figure 1 shows that on Bennu, large craters are long-lived, especially at the equator, but are slowly being obscured in the mid-latitudes where the slopes are steepest and the terraces are forming/present [4]. The wide-spread evidence for small craters in many of the regions where the terraces are visible indicate these features are probably fairly recent [13]; these impacts can help instigate surface failure to further build terraces and cause surface flows.

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RYUGU AND BENNU: MULTIVARIATE STATISTICAL ANALYSIS OF SPECTRAL DATA OBTAINED BY THE HAYABUSA2 AND OSIRIS-REx MISSIONS. M. A. Barucci1, P. H. Hasselmann1, M. Fulchignoni1, A. Praet1, J. D. P. Deshapriya1, S. Formasier1, R. Honda2, Y. Yokota3,4, S. Sugita4,5, S. Kitazato6, M. Yoshikawa3, A. A. Simon7, V. E. Hamilton8, B. E. Clark6, J. P. Emery9, D. C. Reuter7, S. Watanabe11,3, D. S. Lauretta12, and Hayabusa2 & OSIRIS-REx Teams, 1LESIA, Observatoire de Paris, PSL Research University, CNRS, Univ. Paris Diderot, Sorbonne Paris Cité, UPMC Univ. Paris 06, Sorbonne Universités, 92195 Meudon, France (antonella.barucci@obspm.fr). 2Kochi University, Kochi 780-8520, Japan. 3ISAS, JAXA, Sagamihara 252-5210, Japan. 4The University of Tokyo, Tokyo 113-0033, Japan. 5Chiba Institute of Technology, Narashino 275-0016, Japan. 6The University of Aizu, Aizu-Wakamatsu 965-8580, Japan. 7NASA Goddard Space Flight Center, Greenbelt, MD, USA. 8Southwest Research Institute, Boulder, CO. 9Department of Physics, Ithaca College, Ithaca, NY, USA. 10Department of Astronomy and Planetary Science, Northern Arizona University, AZ, USA. 11Nagoya University, Nagoya464-8601, Japan. 12Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA.

Introduction: We studied the visible and near-infrared spectral behaviour of the Ryugu and Bennu surfaces, as observed by the Hayabusa2 and OSIRIS-REx missions, using the G-mode multivariate statistical method, aiming to distinguish spectrally homogeneous groups. The objective of the statistical analysis is to identify any possible small surface compositional variation on both asteroids.

The two asteroids Ryugu and Bennu seem similar with very dark albedo (4.5% and 4.4% respectively) [1, 2], but with very different surface properties and spectral behaviour [3, 4]. The spectra of Bennu show negative, bluish slopes and large band depths at 2740 nm whereas the spectra of Ryugu show a red slope with a weak narrow absorption band at 2720 nm.

Method: The G-mode multivariate statistical analysis [5] has been widely used in the planetary field to classify asteroids [6, 7] and transneptunian objects [8, 9] in homogeneous compositional groups, and to search for compositional differences on the surface of the comet 67P/Churyumov-Gerasimenko [10]. The method allows the user to obtain an automatic statistical clustering of a sample containing N objects (in this work the pixels) described by M variables (the normalized reflectance of each filter for the camera data and of a selected set of wavelength channels for the spectral data) in terms of homogeneous groups without any a priori criteria and taking into account the instrumental errors in measuring each variable. The user selects the confidence level that corresponds to a given critical value q1: the larger the q1, the less detailed the classification. If the user wants to classify the whole sample with a 99.7% probability of making the right decision in inserting a sample in a group, the critical value of q1 has to be 3.00, which is the value corresponding to the 3σ level of a standardized normal distribution (i.e. a probability of 0.3% of misclassifying an object). Allowing a lower confidence level increases the probability of making a wrong decision, but it is possible to have a more detailed grouping. The method gives metrics for the relative importance of the variables in separating the groups. For a detailed description of the method, we refer the reader to the aforementioned literature [6].

Data: For Ryugu, we used the ONC-T camera and NIR3 spectral data obtained by Hayabusa2 in July 2018. For the camera the normalized reflectance measured in the seven band filters spanning from 400 to 950 nm with their errors have been used. The data have been co-registered and photometrically corrected as described by [1]. For the NIR3 data, we used the spectra thermally and photometrically corrected as described by [3] selecting 24 variables among those most significant in the spectral range 1900 and 2900 nm.

For Bennu we used the spectral data from the OVIRS instrument [11, 4] onboard OSIRIS-REx. The data we used are thermally and photometrically corrected [4] and we selected 24 variables among those most significant in the spectral range 500 - 3400 nm avoiding wavelengths that could have residual instrument artefacts and imperfect thermal tail removal. For this preliminary analysis, we used data from the 12:30 pm Equatorial Station (acquired in May 2019), which are at similar spatial resolution as those of Ryugu (20 m/spectrum and a small phase angle (7.6° - 9.5°).

Results: The analysis of both data for Ryugu and Bennu allows us to characterize spectral properties of the major morphological surface features. From the results of the multivariate statistical analysis on Ryugu and Bennu spectral (visible and near-infrared) data, we confirm small spectral variations characterized by the detection of different groups, increasing at the decrease of confidence levels.
The statistical analysis of the spectrophotometry by ONC-T and NIRIS3 spectral data for Ryugu at 3σ confidence level clearly highlights a very homogeneous surface with slightly different small areas containing about 3% of the analyzed data. Decreasing the confidence level at 2σ, a few small groups are detected with different average spectral slopes. The different groups obtained from NIRIS3 spectral data show also differences in the area of the 2720 nm band that could be associated to different abundance of hydrated phyllosilicates, nevertheless particle size and porosity are also important parameters that could change not only the spectral slopes but also the band depth.

The small detected variations characteristic of the various groups obtained for Ryugu confirm it is a homogeneous object with possible i) slight differences in the abundance of hydrated phyllosilicates, ii) presence of fresh material, less altered by space weathering, and iii) different particle sizes. Some younger surfaces appeared around the equatorial ridge and on Otohime Saxum [1]. We suggest that the groups having redder spectral slopes are referring to surface zones with small particle size regolith. The obtained results show a clear spectral dichotomy both between the eastern and western hemispheres and between northern and southern hemispheres [12].

The preliminary statistical analysis of the OVIRS spectral data for Bennu shows also a general homogeneous surface with different small areas. Also for Bennu a very homogeneous surface is highlighted with slightly different small areas containing about 3% of the analyzed data at 3-2.5σ confident level. Decreasing the confidence level to 2.1σ, a few small groups are detected with different average spectral slopes, different depth of the absorption band at 2740 nm and different spectral behavior beyond 3000 nm. The depth of the band at 2740 nm is connected to the presence of phyllosilicates [10] and can be interpreted as different abundance of phyllosilicate and/or variation in particle size [13] whereas the variation of the spectra beyond 3000 nm is associated with different abundance of organic material. The groups having relatively redder spectra are concentrated at the big, dark boulder (24°, 28°) and near the equatorial ridge. Some of them are also located on more rough terrains. Decreasing the confidence level at 1.8σ, more small groups characterized by the presence of small specific variations are detected.

From the results obtained by the multivariate analysis on both asteroids, we confirm small spectral variations characterized by the detection of different groups. A spectral dichotomy has been detected both between eastern and western and northern and southern hemispheres on Ryugu. In this talk we will explore the range of spectral dichotomy that may also be present on Bennu in the region centered at latitude 0°. The detected spectral variations can give information on the formation phase of the two bodies.

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TIR SPECTRAL SIGNATURE OF AQUEOUSLY AND THERMALLY METMORPHOSED CM AND CY CHONDRITES. H. C. Bates1,2, K. L. Donaldson Hanna3, A. J. King1, N. E. Bowles2 and S. S. Russell1, 2Dept. of Earth Sciences, Natural History Museum, London, UK, SW7 5BD (h.bates@nhm.ac.uk), 2Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford, UK, OX1 3PU. 3Department of Physics, University of Central Florida, Orlando, Florida, USA, 32816.

Introduction: JAXA’s Hayabusa2 will return samples from the C-type asteroid Ryugu in 2020 [1] and NASA’s OSIRIS-REx will return samples from the B-type asteroid Bennu in 2023 [2]. Preliminary observations suggest a complex alteration history on both bodies: Hayabusa2 identified hydrated minerals on the surface of Ryugu, but also found evidence for dehydration [3]. Observations by OSIRIS-REx found hydrated minerals similar to highly aqueously altered CM and CI chondrites on Bennu [4].

In order to interpret the results from Hayabusa2 and OSIRIS-REx we need to analyse appropriate meteorite analogues. To that end we have collected thermal infrared (TIR) spectra for a suite of aqueously and thermally altered CM and CI chondrites. There have been few spectral measurements for meteorites under appropriate near-surface asteroid conditions, which are known to cause changes in spectral signature [5,6]. It is therefore critical to perform measurements under simulated asteroid environment conditions (SAE) in order to accurately compare between laboratory measurements and remote observations of asteroids. Here we present TIR emissivity measurements collected under SAE conditions, for a number of aqueously and thermally metamorphosed CM, CY and C2-ung chondrites.

Samples: We investigated three unheated CM chondrites: Alan Hills (ALH) 83100 (CM1/2), ALH 83102 (CM1/2) and Lonewolf Nunataks (LON) 94101 (CM2). We also analysed the heated chondrites (heating stages after [7]) Elephant Moraine (EET) 92069 (CM2, Stage II, 300 – 500 °C), Wisconsin Range (WIS) 91600 (CM-an, Stage II), Yamato (Y-) 793321 (CM2, Stage II) [9,10,11], Pecora Escarpment (PCA) 02010 and PCA 02012 (paired CM2s, Stage IV, >750 °C) [12], and the CY chondrites Yamato (Y-) 980115 (Stage III, 500 – 750 °C), Y-86789, Y-86789, and Belgica (B-) 7904 (all Stage IV) [13].

Experimental: Samples were ground to a powder with a particle size of <35 μm. TIR emissivity measurements were collected in the Planetary Analogue Surface Chamber for Asteroid and Lunar Environments (PASCALE) at University of Oxford. The near-surface environment of Bennu was simulated by removing atmospheric gases (<10⁻⁴ mbar), cooling the interior of the chamber to <-150°C and heating samples from above and below until the maximum brightness temperature of the sample is ~75°C. This induces a thermal gradient in the upper hundreds of microns of the sample, which is what we would expect on the surface of Bennu near local midday [14]. Spectra were collected using a Bruker VERTEX 70v Fourier Transform Infrared (FTIR) spectrometer from 1800 – 200 cm⁻¹ (5.5–50 μm) using a wide range beam splitter at a resolution of 4 cm⁻¹.

Spectral features in thermally metamorphosed CM chondrites: Figure 1 shows the TIR spectra for representative unheated (blue), Stage II (green) and Stage IV (red) CM chondrites. PCA 02010 and ALH 83102 show very similar spectral signatures to PCA 20102 and ALH 83100 respectively, and so are not included in the figure. In the unheated sample spectra we see vibrational features caused by -OH and H₂O in the phyllosilicates between 1800–1300 cm⁻¹. These spectra also show a sharp emissivity peak (also known as a Christensen Feature or CF) near 1100 cm⁻¹, a transparency feature (TF) near 870 cm⁻¹ and reststrahlen bands (RB) near 1015 cm⁻¹, 430 cm⁻¹ and 275 cm⁻¹. These features are consistent with those observed in phyllosilicate spectra [5,14].

The Stage II sample spectra show a decrease in spectral slope between 1800–1300 cm⁻¹, and smaller –OH/H₂O vibrational features relative to those seen in the unheated CM spectra. These spectra have a broader emissivity plateau between 1300–900 cm⁻¹, and a TF at shorter wavenumbers compared to the unheated CM spectra near 800 cm⁻¹. The spectra show RB near 920 cm⁻¹ and between 600–200 cm⁻¹ that correspond with Mg-rich forsteritic olivine [16]. This is consistent with EET 96029 and Y-793321 containing ~12 vol% primary Mg-rich olivine having experienced a low degree of aqueous alteration prior to thermal metamorphism [10,11]. The abundance of primary olivine seems to be the main control on the observed TIR spectral features. The Stage II sample spectra also show a feature at 850–870 cm⁻¹, which is consistent with these meteorites containing ~14 vol% pyroxene [17].

The Stage IV PCA 02012 and PCA 02010 spectra show some similarities with the Stage II spectra including a TF at ~800 cm⁻¹, RB near 920 cm⁻¹ and 870 cm⁻¹ (both contain ~14 vol% pyroxene), and the same features between 600–200 cm⁻¹. They do, however, have much steeper spectral slopes between 1800–1300 cm⁻¹, overtone Si-O vibrational features near 1765 cm⁻¹ and 1645 cm⁻¹, and a RB at 1060 cm⁻¹, which can all be

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attributed to olivine. Spectral contrast for all features is stronger than in the Stage II spectra. These differences are consistent with PCA 02012 and PCA 02010 containing a higher abundance (~20 vol%) of primary Mg-rich olivine. In contrast, the presence (~30 vol%) of secondary, poorly crystalline Fe-rich olivine in the Stage IV CM samples (61 vol% [19]) also shows a strong effect on the spectra.

Spectral features in the CY and CM-an chondrites: Figure 1 also shows the TIR spectra for WIS 91600, Y-980115, B-7904 and Y-86789. The Y-86720 spectrum is similar to that of Y-86789 and is not shown. The WIS 91600 spectrum shows a broad emissivity peak between 1800–1300 cm\(^{-1}\), which could be a result of its poorly crystalline, dehydrated phyllosilicate component (~70 vol%) [9,18]. The spectrum also shows an emissivity peak near 1080 cm\(^{-1}\), a RB near 870 cm\(^{-1}\), a TF near 800 cm\(^{-1}\), plus features near 410 cm\(^{-1}\) and 285 cm\(^{-1}\) that are likely due to Mg-rich olivine (~11 vol%), although the spectral contrast in this region is low. The WIS 91600 spectrum also has a RB feature at 340 cm\(^{-1}\), which can be attributed to its unusually high magnetite abundance of ~10 vol% [19]. This feature has been identified in Bennu spectra suggesting magnetite is present on its surface [4].

Y-980115 has a similar spectral signature to WIS 91600, which could be because of its high ratio of poorly crystalline/crystalline silicates [13]. The Stage IV Y-86789 spectrum shows Si-O overtone features between 1800–1300 cm\(^{-1}\), a complex emissivity plateau between 1250–850 cm\(^{-1}\), a TF at 800 cm\(^{-1}\), and RB between 600–200 cm\(^{-1}\). The spectral signature of Y-86789 is likely a result of its high olivine content (63 vol% [13]). The difference in shape compared to the Stage IV CM spectra in the 1250–850 cm\(^{-1}\) and 600–200 cm\(^{-1}\) ranges may be related to the Stage IV CYs containing only secondary, poorly crystalline Fe-rich olivine and no primary Mg-rich olivine. B-7904 does contain some primary Mg-rich olivine, potentially explaining the subtle differences between its spectrum and the other CY spectra, and its similarity to the PCA 02010 and PCA 02012 spectra between 600–200 cm\(^{-1}\). Differences between B-7904’s spectrum, and the CM chondrite spectra in other spectral ranges may be due to its recrystallized olivine content being much higher than the Stage IV CM samples (61 vol% [13] compared to ~27 vol%).

Conclusions: The TIR spectral signature in CM chondrites is controlled by the primary, Mg-rich olivine content, which in turn is determined by the degree of aqueous alteration. Samples which have experienced less aqueous alteration show overtone and vibrational bands associated with forsteritic olivine throughout the whole spectral range. Due to the absence of this primar

![Fig. 1: TIR spectra for representative unheated (blue), Stage II (green) and Stage IV (red) CM, CT and C2-ung chondrites. Lines represent vibrational features for olivine and pyroxene relative to PCA 02012, phyllosilicate vibrational bands relative to the unheated CM chondrites, and the magnetite vibrational band in WIS 91600.](image-url)
THE SPECIFIC HEAT OF REGOLITH MATERIAL. Jens Biele¹, Matthias Grott², Michael E. Zolensky³, Artur Benisek⁴, Edgar Dachs⁴, (1) DLR – German Aerospace Center, RB-MUSC, 51147 Cologne, Germany, Jens.Biele@dlr.de, (2) DLR – German Aerospace Center, Institute for Planetary Research, Berlin, Germany, matthias.grott@dlr.de, (3) NASA Johnson Space Center (Houston, United States), michael.e.zolensky@nasa.gov, (4) Materialforschung und Physik, Universität Salzburg, Austria, Artur.Benisek@sbg.ac.at, edgar.dachs@sbg.ac.at.

Introduction: Specific heat \( c_p(T) \) is one of the parameters which determine a surface’s temperature response to heating. Remote sensing in the mid-infrared is often used to estimate a parameter termed the thermal inertia of the surface material, which is defined as

\[
\Gamma = \sqrt{\rho k(T)c_p(T)},
\]

where \( T \) is absolute temperature in K, \( k \) is thermal conductivity in W m\(^{-1}\) K\(^{-1}\), \( \rho \) is bulk density in kg m\(^{-3}\), and \( c_p \) is specific heat at constant pressure in units of J kg\(^{-1}\) K\(^{-1}\). Knowledge or an estimate of \( c_p(T) \) is required to extract information on, e.g., thermal conductivity \( k \) from the data, which in turn allows for an estimation of important surface properties like grain size [1-4] and porosity [5]. Furthermore, knowledge of thermophysical surface properties is essential to model the Yarkovsky [6-8] and YORP [8, 9] effects as well as the response of planetary surfaces to impact cratering.

Only a handful of meteorite heat capacities have been published, virtually all of them measured at temperatures at or above 300 K or at a ~175 K (Consolmagno et al., 2013). The only other extraterrestrial material with known \( c_p \) over a limited temperature range is lunar samples from the Apollo missions, and many studies have used these values as a “standard” \( c_p(T) \) curve. Heat capacity, however, strongly depends not only on temperature but also on composition, thus the use of lunar data for, e.g., C- or M-class asteroids or objects containing frozen volatiles may give rise to large systematic errors. Missing \( c_p(T) \) data for rocks (in general, “regolith material”, any solid material found on the surface of solar system bodies) can be calculated from the contributions of the constituent minerals (and mineraloids, i.e. amorphous substances): linear mixing model, neglecting (except for olivine Fo-Fa) the non-ideal “excess heat capacity”. Except at very low temperatures, the model specific heat is accurate to ~1% in general.

Review in progress: We report here on a comprehensive review we are undertaking at present. We review the available data on lunar samples and meteorites as well as the specific heat capacities of the most abundant endmember minerals (the most common and important mineral groups that occur in solar system materials and which are part of the \( c_p \) database) including iron-nickel metal. Furthermore, organic materials found in meteorites and the specific heat of frozen volatiles thought to exist on outer solar system bodies are considered. From these data, we built up a computerized database to calculate the specific heat of approximately 90 minerals and compounds for temperatures between absolute zero and close to melting (or decomposition) by use of tables and correlation equations apt for convenient but accurate interpolation. We also review reference (mineralogical) compositions for common ordinary and carbonaceous chondritic meteorites as well as lunar surface material to prepare the construction of the reference specific heat models.

Results are, besides the \( c_p \) database, reference \( c_p(T) \) for lunar regolith, common meteorite classes and some (mostly commercial) laboratory regolith simulants. Where lunar and meteorite data were available, we fit those to composition models, enabling meaningful extrapolation to very low and very high temperatures. The effect of metal (Fe-Ni) and organic material content will be discussed quantitatively. Finally, we will look at models for very cold, icy regolith, including an educated guess on the specific heat of the enigmatic tholins. Using the database, anyone can construct his/her own \( c_p(T) \) curves from the mineralogical composition.

We present some exemplary results.

![Fig. 1: New Lunar average \( c_p(T) \). All raw data points with fitted and extrapolated \( c_p \) (combination of lunar minerals)](image-url)
Fig. 2: $c_p(T)$ of phyllosilicates, compared to average lunar

Fig. 3: $c_p(T)$ of Iron-Nickel

Fig. 4: Calculated $c_p(T)$ of analogue materials (DSI, “Hirdy”=U Tokyo UTPS)

**Key points**
- „Cologne $c_p$ database“ ~90 pure endmember minerals literature review, low-T (~5K) to melting point or decomposition, typically 1% accuracy
- $c_p$ at low T: ices, tholin analogs, minerals.. (TNOs!)
- Inversion of lunar $c_p$ data with raw data points shown and uncertainties of synthetic curve, convenient fit equation 5-1400K see [10]
- Construct reasonable reference curves (or models) for the isobaric heat capacity $c_p$ of small body surface material over a wide temperature range, typically (0) 10-1000K.
- Review paper in preparation
- We have a DSC (differential scanning calorimeter) in the laboratory, LN2 cooling, temperature range ca. 93-1023K, required sample mass 20-30 mg, realistic accuracy ~1%; plan is to measure $c_p(T)$ of our lab analogue materials and other interesting minerals, meteorites… ideas are welcome

**References**

**Impact Craters on Bennu: Their Morphology, Size-Frequency Distribution, and Correlation with Other Data Sets.** E.B. Bierhaus\(^1\), D. Trang\(^2\), O.S. Barnouin\(^3\), K.J. Walsh\(^4\), R.T. Daly\(^5\), M. Pajola\(^6\), E.R. Jawin\(^7\), T.J. McCoy\(^8\), H.C. Connolly, Jr.\(^9\), V.E. Hamilton\(^10\), D.N. DellaGiustina\(^10\), B. Rizk\(^3\), M.G. Daly\(^9\), A. Hildebrand\(^8\), B.C. Clark\(^11\), P. Michel\(^12\), C.L. Johnson\(^13\), D. Reuter\(^14\), A.A. Simon\(^15\), M. C. Nolan\(^8\), and D.S. Lauretta\(^8\). \(^1\)Lockheed Martin Space, Littleton, CO, USA; \(^2\)University of Hawaii, Honolulu, HI, USA; \(^3\)Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA; \(^4\)Southwest Research Institute, Boulder, CO, USA; \(^5\)INAF-Astronomical Observatory of Padova, Vic. Osservatorio 5, 35122 Padova, Italy; \(^6\)Smithsonian Institution, National Museum of Natural History, Washington, DC, USA; \(^7\)Rowan University, Glassboro, NJ, USA; \(^8\)Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA; \(^9\)York Univ., Toronto, CA; \(^10\)Univ. of Calgary, Calgary, CA; \(^11\)Space Science Institute, Boulder, CO, USA; \(^12\)Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Laboratoire Lagrange, Nice, France; \(^13\)Univ. of British Columbia, Vancouver, CA; \(^14\)NASA Goddard Space Flight Center, Greenbelt, MD.

**Overview:** We present new observations of Bennu’s candidate crater population, derived from images, lidar data, and spectrometers acquired during the spring and summer of 2019. In addition to an updated size-frequency distribution, these data demonstrate a spectrum of crater morphologies, and a potential correlation of spectral features as a function of size. We provide preliminary analysis to explain the appearance of the candidate craters, with implications for Bennu’s physical properties and age.

**Introduction:** The OSIRIS-REx spacecraft approached asteroid (101955) Bennu in the late summer and fall of 2018, and began its initial survey of the asteroid in December 2018 [1]. During the spring and summer of 2019, the spacecraft collected a series of observations with its sophisticated suite of remote sensing instruments, including images taken by the OCAMS visible imagers [2] that achieve pixel scales as fine as 2 cm/pix, lidar scans by the OLA laser altimeter [3] that provide direct topographic measurements of the surface, and near-global coverage with OVIRS and OTES, which provide spectral measurements from the visible to the far IR [4,5,6].

These increasing-fidelity data sets provide a rigorous means to investigate the distribution of surface features on Bennu, as well as their relationship to one another and to the overall asteroid shape. Bennu’s candidate impact craters have several compelling characteristics that constrain Bennu’s surface age [7], as well as its surface and sub-surface properties.

**Observations:** To date, observations of craters include:

(i) The candidate craters are distributed across the surface, though with an apparent concentration of more distinct craters along the equator or at low latitudes. Because the equator is a region of near equipotential, compared with the mid-latitudes, this may indicate that classical crater features are better preserved in regions (such as the equator) with lower average slope and geopotential. The spatial distribution of undegraded craters may be an important signature of regolith mobility on Bennu and a measure of the conditions that lead to mobility.

(ii) Some candidate craters are expressed in elevation (which is related to gravity and rotation) and geometric 3D space (i.e., depressions in the asteroid shape), whereas others are expressed only in 3D space (Figure 1). One candidate crater is expressed only as an annular ring of boulders. This diversity, and characteristics such as depth-to-diameter ratios [8], are crucial to understanding the formation and evolution of craters in the rubble-pile structure of Bennu, as well as Bennu’s structure in terms of porosity and impact strength.

![Figure 1](image.png)

Figure 1. (A) Image of a ~150 m diameter crater candidate centered at about 53.7° N latitude and 72.1° longitude. (B) The same image as in (A), projected on Bennu’s shape model, which is colorized by facet radius. (C) An approximately circular depression in facet radius, with the same diameter as the feature observed in the visible image. (D) The same view of Bennu as in (B) and (C), here colored according to elevation. No obvious circular feature appears in elevation at this location.

(iii) The candidate crater population may reach spatial saturation at the largest diameters [9], indicat-
ing that the global shape of Bennu is old [1,7,9], and may date to Bennu’s accretion as a rubble pile.

(iv) Extrapolation of the large crater population to smaller diameters predicts many more craters than seen at small sizes, i.e. small craters are underabundant. This could be due to erosional effects [e.g. 10], formation effects [11], or both.

(v) There is a fascinating transition in crater morphology at approximately 20 m diameter. The floors of craters greater than 20 m diameter have similar, or even enhanced, boulder abundance relative to the surrounding terrain. In contrast, the floor of craters less than 20 m diameter often are generally rock-free and appear to have a greater abundance of finer-grained material (Figure 2). A hypothesis to explain the correlation between the abundance of finer particles and smaller crater sizes is the presence of a near-subsurface layer, perhaps up to a few meters deep, of finer-grained material. Because finer-grained material is more easily lost to space, or recirculated into the subsurface, these regions could be younger than other parts of the surface.

(vi) There may be relationships between spectral properties (e.g. reflectivities, band-depths or spectral slope) and crater diameter. Figure 3 plots the 550 nm reflectance derived from OVIRS observations. The reflectance has larger scatter at small diameters, and less scatter at larger diameters. This could represent excavation into heterogeneous regions that remain distinct at small scales (small diameters), and mixing to a more consistent average at larger scales (larger diameters).

Summary: Collectively, these observations suggest complex interplays among the crater formation process and Bennu’s rubble-pile structure [12], the evolution of material on the surface, and the re-accumulation of slow-speed ejecta from a primary impact or other ejection mechanism. These observations will inform scaling law development for crater formation on rubble-pile surfaces, with direct consequences for deriving relative and absolute surface age values for rubble-pile asteroids.


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REXIS FIRST RESULTS: REGOLITH X-RAY IMAGING SPECTROMETER ABOARD OSIRIS-REX.

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Introduction: The Regolith X-ray Imaging Spectrometer (REXIS) is the student collaboration experiment flying aboard OSIRIS-REx. REXIS measures x-ray fluorescence stimulated by solar x-rays impinging on the surface of asteroid Bennu. We will present REXIS’s first results in measuring elemental abundances in the regolith of Bennu and discuss how these results complement the other payload instruments.

REXIS is an x-ray spectrometer designed to take advantage of the incident solar x-ray flux that generates a diagnostic fluorescence signature from the asteroid’s surface. REXIS joins a lineage of x-ray fluorescence experiments flown in space dating back to the Apollo era and previously demonstrated for asteroid science [1]. REXIS [2] consists of two components: a main imaging spectrometer with a coded aperture mask and a separate solar X-ray monitor to account for the Sun’s variability. The REXIS main spectrometer employs a detector array consisting of four MIT Lincoln Laboratory CCID-41 charge-coupled devices (CCDs) in a 2×2 array allowing measurement of the x-ray spectrum over the range of 0.4 to 8 keV with an energy resolution (FWHM) of <220 eV at 5.9 keV. REXIS seeks to measure fluoresced lines in the Fe-L, Al-K, Mg-K, S-K, and Si-K complexes. The detector array was protected from background radiation during the cruise by a front cover that was successfully opened in response to commands sent from the ground in September 2018, two years into flight.

Characterization of the X-ray fluorescence measured from Bennu requires knowledge of the incoming solar x-ray flux. REXIS's second component is a solar X-ray monitor (SXM) designed to measure the variable incoming solar flux and its energy distribution. The SXM utilizes an Amptek XR-100SDD silicon drift diode (SDD) with a collimated effective area of about 0.8 mm2, providing spectral coverage over the range of 1 to 20 keV.

REXIS Operation: REXIS utilizes measurements of astrophysical x-ray sources (Crab Nebula, Sco X-1) to measure the boresight offset of the instrument and calibrate the quantum efficiency of the CCDs. Internal sources of Fe-55 enabled performance monitoring during the cruise phase and continue to provide an ongoing measure of the detector charge transfer efficiency. In flight at Bennu, six nodes of 256 x 1024 pixels each are delivering low noise and a stable energy resolution signal for acquisition of science data.

REXIS asteroid science measurement operations at Bennu were executed in July 2019 during the Orbital B phase of the OSIRIS-REx mission. The first science results to be produced are "spectral mode" characterization of the elemental abundance ratios (relative to Si) of Bennu's regolith. Laboratory reference measurements for meteorite elemental abundance ratios [3] form the foundation for interpreting the REXIS results. Key ratios to be examined in the REXIS data include Mg/Si and Fe/Si to independently determine whether the asteroid's composition closely resembles that of carbonaceous chondrites, as interpreted from the main payload suite.

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MINERALS FROM ASTEROID REGOLITH AND METEORITES REVEAL EARLY-STAGE PROCESSES IN SOLAR SYSTEM HISTORY. Maitrayee Bose and Ziliang Jin, Arizona State University, School of Earth and Space Exploration, 550 E. Tyler Mall, Building PSF, Room 686, Tempe, AZ 85287 (Maitrayee.bose@asu.edu).

Introduction: Proto-Earth formed quickly in the first few million years in a hot and dry environment, close to Sun. It’s surface was possibly molten owing to planetesimal impacts, and therefore must have naturally lost its water and destroyed labile organic biomolecules. It has been proposed that proto-Earth received additional water, later in its accretionary history, via accretion of hydrous carbonaceous asteroids [e.g., 1, 2]. These carbonaceous asteroids are proposed to have been introduced into the inner solar system chaotically, during formation and migration of giant planets, and delivered materials rich in water and other organic materials including amino acids. Alternative models have been suggested where Earth could have acquired its water directly from the solar nebula [e.g. 3–6]. We explored a combination of these scenarios to understand how water was incorporated into the Earth–Moon system both during planetary accretion and impacts from chondritic asteroids. Impacts are particularly important for deep delivery of hydrogen into the magma. We tested this scenario by studying samples never investigated before, namely regolith grains from asteroid 25143 Itokawa and meteorite analogs belonging to the L/LL class of ordinary chondrites.

Results and Discussion:
Itokawa. The hydrogen isotopic composition (δD) of the measured pyroxene grains from Itokawa is −79 to −53‰, strikingly similar to Earth’s mantle water [7]. These minerals contain water contents of 698 to 988 parts per million (ppm) weight, which corresponds to a water content of 160 to 510 ppm for Bulk Silicate Itokawa parent body [7]. We also estimated that asteroids like Itokawa that formed interior to the snow line could have provided up to 0.5 Earth’s oceans during the formation of Earth and other terrestrial planets. This implies that migration from the outer solar system may not be required to explain the high water on Earth and other terrestrial planets. Incorporation of the water into mineral structure in the solar nebula and accretion of ordinary chondrite parent bodies should be able to explain the water in our oceans.

The striking similarity of the D/H ratio of the Itokawa grains to that of Earth’s mantle provides corroborating evidence for a common liquid heritage for Inner solar system bodies. Itokawa had a complex history of thermal metamorphism and collision, reaching temperatures at least as high as 900°C. But our thermal-diffusion models predict that less than 10% of the water in the grains would be lost, as a result of these processes.

Meteorite analogs. The water contents and D/H ratios in pyroxenes from several metamorphosed ordinary chondrites were measured [8]. The δD values vary from -123 to 106‰ similar to Itokawa pyroxenes, while the water contents in the grains are between 458 and 1807 ppm. We had chosen meteorites belonging to both L and LL class, and petrologic types 4–6 in order to look for correlations between petrologic type and volatile contents or D/H ratios but no relationships were ascertained. The most surprising component of these studies is the high water contents on these nominally anhydrous phases.

Mechanism of hydrogen incorporation into microscopic particles in the early solar nebula. We revisited the issue of incorporation of hydrogen into the minerals in the low-pressure environment in the early solar system. A process of incorporating water from the nebula directly into the mineral structure of early-formed solids is chemi-adsorption [9], which is not efficient in the hot, rarified environment in the inner solar system.

We have identified and modeled a more dominant process - implantation of H⁺ that operated in the early sun’s history and is capable of introducing vast amounts of hydrogen into the freshly formed minerals [10]. The dusty ionized plasma, rich in H⁺ moving at keV energies can be efficiently implanted into the top surface of the grains, which then diffuses inward to saturate the bulk of small 50-500 μm particles. A density of ionized hydrogen of about 2×10⁵ cm⁻³ results in an estimated flux to be ~2×10¹⁵ cm⁻² s⁻¹. This flux is considerably larger than the proton flux attributed to the solar wind and galactic cosmic rays. Assuming a high-retention coefficient (>10%) of the implanted hydrogen, up to 1000 ppm of water can be produced in particles of enstatite composition within a year. Thus, we propose that this process of H⁺ implantation, followed by diffusion is the driver for incorporating water into the first-formed solids in our solar system.

Preparing for Bennu and Ryugu samples. C-type asteroids Bennu and Ryugu are expected to contain abundant organic or hydrated minerals, compared to Itokawa, that need to be investigated for their volatile contents and D/H ratios to constrain the chemistry occurring in these bodies. Our lab at Arizona State University (ASU) is preparing for analyses on Bennu and
Ryugu samples. Measurements of tiny amounts of hydrogen and deuterium have become possible because of the ASU NanoSIMS that can achieve small beam sizes, relevant for studying small particles and its high sensitivity for measuring trace amounts (<15 ppm) of hydrogen. We have developed the protocols that will allow us to measure the tiny regolith minerals at high lateral resolution and desired precision.

Because olivine is the largest mineral component in the Itokawa collection, we estimate that it will be for Bennu and Ryugu as well. Hence, we are synthesizing matrix-matched olivine standards for hydrogen isotope analyses to share with the community. We have also measured metal in a few Fe-Ni meteorites for volatiles (unpublished work), which becomes particularly important considering that magnetite was found on Bennu [11]. Finally, the thermal-diffusion models used on Itokawa, can be used to predict how Bennu and Ryugu may have lost volatiles as a result of nebular and parent body processes.

Conclusions: Through our work, we have shown how cosmochemical constraints on water contents and D/H ratios in small bodies can provide important input to dynamical models attempting to explain the provenance of water in planets. Our investigations have augmented an understanding of processes that produce water loss (via impacts, thermal metamorphism) and can inform models about water delivery to the terrestrial planets by hydrated planetesimals and water partitioning into the core of planets during differentiation.

I will talk about our work on Itokawa and ordinary chondrites in the meeting, including the consequences of high- vs low-velocity collisions of planetesimals and the impact of fast cooling rates of materials post-impact that drive volatile losses on small bodies.

METEOROID IMPACTS AS THE SOURCE OF BENNU’S PARTICLE EJECTION EVENTS. W. F. Bottke¹, A. Mooreshead², C. W. Hergenrother³, P. Michel¹, S. Schwartz³, D. Vokrouhlicky³, K. Walsh¹, D. S. Lauretta³, ¹Southwest Research Institute, Boulder, CO, USA (bottke@boulder.swri.edu), ²NASA Meteoroid Environment Office, Marshall Space Flight Center EV44, Alabama, 35812, ³Lunar & Planetary Laboratory, University of Arizona, Tucson, AZ, USA. ⁴Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Laboratoire Lagrange, Nice, France. ⁵Institute of Astronomy, Charles University, Prague, Czech Republic.

Introduction. (101995) Bennu is the target of the NASA’s OSIRIS-REx sample return mission [1]. It is a 490 m NEO with a spectral signature consistent with primitive carbonaceous chondrites. An unexpected attribute of Bennu, however, is that it is currently ejecting small particles to space in distinct events [2].

Multiple particle ejection events were observed starting in January 2019, the time when OSIRIS-REx entered into Bennu orbit, and February 2019. Bennu reached perihelion in early January, so there may be an association between these events and Bennu’s orbital location at that time. The three most energetic events occurred at 6 January, 19 January, and 11 February. This corresponds to a roughly bi-weekly cadence.

Here we investigate the possibility that these largest events can be caused by meteoroid impacts. Meteoroids, mostly derived from comet particles, collide with the Earth, Moon, and presumably Bennu at very high speeds. We hypothesize that some of these events are substantial enough to eject material off of Bennu and into trajectories where they can be observed by OSIRIS-REx. To test this scenario, we have simulated the primary meteoroid flux onto Bennu using NASA’s Meteoroid Engineering Model (MEM) [3].

More Particle Ejection Constraints. All three large events took place in the late afternoon, between 15:22 and 18:05 local Bennu time (i.e., about 3.5-6 hours after local noon) [2]. They also took place within days to weeks of Bennu reaching perihelion. Each energetic particle event produced hundreds of observed particles, though all observed fragment were < 10 cm in diameter and had ejection velocities < 3.2 m/s. The kinetic energies of the observed particles were collectively < 200 mJ. The locations of all events observed to date, big and small, are fairly ubiquitous, ranging from 75°S to 20°N, though the small events have a preference for low latitudes.

Model Runs. MEM describes the mass-limited flux, directionality, velocity, and density distribution of meteoroids impacting a chosen target body orbiting between Mercury and the main belt (e.g., [3]). A common application of MEM is to evaluate impact risk and potential damage to Earth-orbiting satellites (e.g., International Space Station) and spacecraft traveling in the inner solar system. MEM builds on several studies of the interplanetary dust population and the nature of the near-Earth environment [4].

An ephemeris for Bennu was obtained from JPL HORIZONS; we downloaded state vectors at one-day intervals between 10 Jan 2019 and 22 March 2020. We consider one orbital period, starting with its 2019 perihelion passage. MEM generates a mass-limited flux for a given target; the code also divides the total flux into bins by the angle and speed with which they encounter the target. We scaled the flux on our bins to kinetic energy and summed the results to find the overall kinetic-energy-limited flux of meteoroids onto Bennu. We convert this flux to a cratering rate assuming that Bennu’s surface area is 0.782 km² [1].

We find that impacts with kinetic energies of 7000 J take place every two weeks near perihelion, the same cadence as the most energetic particle ejection events. We use this value as our metric in the figures below.

![Impact velocity distribution of sporadic meteoroids on Bennu with limiting kinetic energies of 7 kJ. The average speed is 42.8 km/s.](image1)

![Impactor mass distribution for meteoroids striking Bennu at the limiting kinetic energy of 7 kJ. The mean velocity of 42.75 km/s corresponds to a mass of 0.00766 g, whose log10 value is -2.12.](image2)

The impact velocity and mass distributions are shown in Figs. 1 and 2. The highest speeds and lowest masses mainly come from meteoroids derived from long period comet particles on retrograde orbits.
lowest speeds and most massive particles are mainly coming from Jupiter-family comets. Bennu’s impact rates are also higher that by more than a factor of 5 near perihelion than near aphelion.

In Fig. 3, we show the impact flux on Bennu’s surface at perihelion for a limiting kinetic energy of 7 kJ is shown in Fig. 3. Bennu is a retrograde rotator with an obliquity of nearly 180 deg, and so the vertical dashed line in the middle of the plot corresponds to the evening terminator and is labeled “6pm”.

We find that the majority of impacts should occur in the late afternoon near the terminator.

Fig. 3. The directionality of the meteoroid impact flux across the surface of Bennu at perihelion for a limiting kinetic energy of 7 kJ. Most impacts should occur in the late afternoon near the terminator.

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Introduction. Asteroid crater retention ages are poorly understood because no one knows which crater scaling laws are applicable to different bodies. By comparing results from a main belt collisional evolution model to asteroid cratering records, however, it is now possible to derive crater scaling laws that provide a good statistical match. We find that fits to craters on Vesta, Lutetia, Mathilde, Ida, Eros, and Gaspra yield crater to projectile ratios near 10. Assuming this scaling law also applies to the largest craters on smaller asteroids (e.g., Toutatis, Itokawa, Ryugu, and Bennu), we obtain crater retention ages that match the likely ages of their source families. Intriguingly, these ages are longer than the expected collisional lifetimes of these bodies. This may suggest (i) most bodies escaping the main belt are ancient survivors, (ii) the timescales of asteroid disruption events need to be reassessed, or (iii) our model/data match a fluke.

Craters on Large Asteroids. All asteroids imaged to date have craters, but the interpretation of these records is still debated. The problem is that we have limited understanding of (i) the main belt size frequency distribution (SFD) for sub-km bodies and (ii) asteroid crater scaling laws. Concerning the latter, laboratory shot experiments and numerical hydrocode results yield crater to projectile ratios \( f = D_{\text{crater}}/D_{\text{asteroid}} \) that can vary from ~5 to 100 [e.g., 1]. This means crater retention ages on an asteroid could be young or ancient, depending on the choices made for (i) and (ii).

Here we deal with this issue by means of a new approach. Using a collisional evolution model [2], we created several different main belt SFDs by varying the asteroid disruption law (Fig. 1). All our results reproduce the observed main belt SFD, the distribution of main belt asteroid families from \( D_{\text{orb}} > 100 \) km parent bodies, and results from cm-scale laboratory shot experiments. For reference, SFD #1 is from [2]. By fitting main belt SFDs #1-#8 to asteroid crater SFDs using a range of candidate scaling laws \( f \) and crater retention ages \( T \), we obtain results that can be tested against additional constraints (e.g., family forming event ages, sample ages, etc.).

In Fig. 2, we show how our best fit model SFD and scaling law combinations compare with craters on Vesta’s Rhea silvia basin. The \( f \) values are in the inset figure. Overall, the best results come from \( f \sim 10 \), SFDs

Fig. 1. Our model of the main belt SFD, numbered #1-#8. Our results from #1 match previous work from [2].

Fig. 2. Rhea silvia’s craters vs. model fits for various scaling laws. SFDs from Fig. 1. The inset shows \( f \) values for various projectile diameters.

#5-#7, and \( T = 0.9-1.4 \) Ga. These \( T \) values are the same as the dynamical age of the Vesta family [3] and \( ^{40}\text{Ar}/^{39}\text{Ar} \) ages from HED feltska grains [4].

We applied this method to craters on Lutetia, Mathilde, Ida, Eros, and Gaspra [e.g., 5]. In these cases, we also found main belt SFDs #5-#8 and \( f \sim 10 \) provide the best matches. Our results also yield crater retention ages for Ida (2.5 Ga) and Gaspra (1.4 Ga) that
match their family’s dynamical age [e.g., 6].

**Craters on Small Asteroids.** Craters on $D_{\text{at}} < 3$ km asteroids like Toutatis, Itokawa, Ryugu, and Bennu [5,7,8] are challenging to model, partly because their low gravities prevent impact codes from directly computing their final crater sizes but also because erasure mechanisms have removed many $D_{\text{crate}} < 0.1$ km craters. Still, fits to the largest craters on these asteroids yield surprising results.

![Fig. 3](image)

Fig. 3. Model fits for craters on Gaspra and Itokawa. We argue both were once part of Flora family.

Consider Itokawa, a $D_{\text{at}} \approx 0.3$ km NEO sampled by Hayabusa [e.g., 6]. All indications are that Itokawa is an escaped member of the Flora family. If we compare Itokawa’s largest craters with those of Gaspra, a Flora family member, we find both are aligned (Fig. 3). Moreover, $T$ for both matches the $^{40}\text{Ar}/^{39}\text{Ar}$ ages of Itokawa’s samples and the Flora family’s dynamical age (i.e., $1.4 \pm 0.3$ Ga [5, 9]). Though it is small number statistics, it could imply Itokawa’s largest craters have never been erased.

Model results suggest that the ages of the Bennu/Ryugu source families are $\approx 0.8$–$1.4$ Ga [10], similar to that of the Flora family. To provide context, we superpose their craters on Gaspra’s, while normalizing for their different collision probabilities (i.e., higher for Bennu/Ryugu). We again find an excellent match to the $D_{\text{crate}} > 0.1$ km craters (Fig. 4).

Finally, Toutatis’ craters (not shown) are a good match for the dynamical age of the Koronis family and the $T$ value for family member Ida ($\approx 2.5$ Ga).

**Discussion.** At face value, Itokawa, Toutatis, Ryugu, and Bennu have ancient surfaces for $D_{\text{crater}} > 0.1$ km if $f \sim 10$. Their predicted collisional lifetimes, however, are shorter by a factor of $\sim 5$. This contradiction could mean that our matches are flukes. The other possibilities are that (i) the most likely main belt asteroids to escape are long-lived family survivors and/or (ii) we do not yet understand small body disruption. Bennu-Ryugu samples will help us glean insights into this mystery.

![Fig. 4](image)

Fig. 4. Bennu craters superposed on Gaspra’s craters, with results scaled for collision probability. Gaspra’s craters are $\approx 1.3$ Ga, yet Bennu’s craters line up.

![Fig. 5](image)

Fig. 5. Ryugu craters superposed on Gaspra’s craters.

**References.**

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THERMAL EMISSION SPECTROSCOPY OF ORDINARY CHONDRITES AT SIMULATED ASTEROID CONDITIONS WITH IMPLICATIONS FOR ASTEROID THERMOPHYSICAL AND COMPOSITIONAL INTERPRETATIONS. M. S. Bramble1 and R. E. Milliken 1, 1Department of Earth, Environmental, and Planetary Sciences, Brown University, Providence, RI, USA (michael_bramble@brown.edu).

Introduction: Thermal infrared spectroscopic measurements record not only compositional information about the properties of a target but also about the environmental conditions in which the measurement was acquired. Spectral variations resulting from different environmental conditions are less apparent when measurements are acquired at terrestrial or martian conditions [1–4]. However, spectral variations resulting from the cold and vacuum environment of airless planetary surfaces can be significant and can greatly influence interpretations of physical and chemical properties of those surfaces when using emissivity spectra [e.g., 1, 2, 4–7]. The absence of interstitial gasses at vacuum conditions can lead to the formation of intense near-surface thermal gradients in particulate (regolith) materials that result in changes in emission spectral features [e.g., 1, 2, 4–7]. Once such category of airless planetary surfaces that is of great interest to the asteroid and planetary defense communities is S-type asteroids, a group that represents the most abundant objects in the inner main belt and near-Earth object populations [e.g., 8]. Through their paring with the ordinary chondrite (OC) meteorites, we can measure the latter under controlled asteroid-like conditions to probe how thermal and emissivity properties respond due to a cold and vacuum environment to better understand the compositional and thermophysical properties of OC parent bodies and other S-type objects.

We report here on a broad suite of environmental chamber measurements focused on anhydrous silicates, mixtures of silicates and metal, and ordinary chondrite samples, and we discuss how their thermal/emissivity properties vary between ambient and simulated asteroid environment (SAE) conditions. Understanding how thermal emission characteristics of relevant planetary materials are altered in an airless environment is important to advance our quantification of thermal radiation forces such as the Yarkovsky effect, and an improved understanding of the thermal properties of OCs under asteroid-like conditions can lead to better estimates of the forces that govern how objects move from the main belt to the near-Earth population.

Methods: A suite of OCs spanning the three groups (H, L, and LL) and at each thermally metamorphosed petrologic type (4–6) was acquired through the US Antarctic Meteorite Collection, and single mineral phases and mixtures chosen to mimic OC mineralogy were also measured for comparison. These samples were crushed, ground, and sieved into <25, 25–125, and 125–250 μm aliquots and thermal emission measurements were acquired at (1) ambient and (2) cold, vacuum conditions. Measurements were made with the Asteroid and Lunar Environment Chamber (ALEC) at Brown University [9]. The SAE conditions were produced in a vacuum (<10^-4 mbar) with samples heated from below in sample cups and irradiated from above by a 200 W quartz-halogen lamp. A liquid N2 cooled, rotary mounting platform holds heated sample holders each surrounded by an aluminum radiation shield that forms an enclosed ~85 K environment. Spectra were collected over a wavelength range of 2.5–25 μm (400–4000 cm⁻¹) through an emission port on a Thermo Nexus 870 FTIR spectrometer equipped with a DTGS detector. FTIR emission spectra were reduced to radiance, emissivity, and brightness temperature spectra using the absolute radiometry method developed for the ALEC system [9].

Results: Our emissivity spectra of OCs and mineral analogs display the expected spectral alterations due to the transition to SAE conditions based on results of previous studies of silicates in this environment [4–7, 10, 11]. Notably, the spectral contrast between the Christiansen feature (CF, an emissivity maximum) and the reststrahlen bands (RB) increases, and the CF position shifts towards higher wavenumbers for the SAE (Fig.1).

Using both the spectral contrast between the CF and RBs and variations in brightness temperature as a function of wavenumber, we confirm that the thermal gradients are less intense in both our analog OC mixtures and the suite of OCs compared with single mineral phases, and that gradients become less intense with increasing metal content (LL to H). Additionally, the shift in CF position is less intense in the meteorites and mixtures than the single phases. This confirms a hypothesis by
or simulated asteroid environment (SAE) conditions

[12] that the dark and opaque components in OCs would lead to less intense thermal gradients at SAE conditions. For a given petrologic type, we observe trends in spectral conditions as a function of group in our OC samples. RBs associated with olivine and pyroxene increase in band depth with the decreasing relative metal to silicate ratio from H to L to LL groups (Fig. 2), though the band depth differentiation between the L and LL groups is not strong. This trend is corroborated by the analog mixtures. We also observe a shift in RB position towards lower wavenumbers from H to L to LL for several silicate RB features. The clearest trend is in the olivine RB feature at ~1045 cm⁻¹ which is observed to shift by ~10 cm⁻¹ towards lower wavenumber from H to LL. This trend likely reflects the relative increase in Fe²⁺ content in the silicates towards the LL group. These trends occur at both ambient and SAE conditions.

We do not observe significant trends in spectral conditions within a group as a function of petrologic type, rather spectra within a group display remarkable similarity. Possible spectral differences within a group due to physical differences for different petrologic type, such as grain coarsening, would be lost in our samples due to our sorting into particle size aliquots. However, it is observed that brightness temperature systematically decreases at all wavenumbers as a function of petrologic type for all three particle sizes.

Discussion: We can investigate how environmental conditions will affect the interpretation of asteroid thermophysical properties by applying the results in spectroscopic variations to thermophysical methods and models. We find that the integrated radiance of our mineral mixtures and meteorite samples decreases with increasing particle size at ambient conditions. This is the result of the reduction in spectral contrast (i.e., higher emissivity values) with decreasing particle size. The transition to SAE conditions results in an increase in spectral contrast at all particle sizes due to the strong near-surface thermal gradient, but the contrast increase is particularly strong for the ~25 μm and 25–125 μm samples. As a result, the integrated radiance of these samples is further reduced in comparison with the ambient conditions (Fig. 3a). When applied to modeling temperatures of small bodies [e.g., 13], these trends in environmental conditions and radiance values could result in an underestimation of surface temperature if ambient lab data are used rather than SAE spectra, as lower emissivity values lead to less efficient thermal radiation and thus higher surface temperatures (Fig. 3b).

Conclusion: The thermal emission characteristics of OCs change under the cold and vacuum conditions that characterize airless planetary surfaces when compared with ambient lab conditions. While these variations are not as significant as observed for single silicate phases, presumably due to the role of opaque and metal components, the differences can still affect the interpretation of physical and chemical properties of asteroid surfaces when using remotely sensed thermal infrared data. We identify trends that vary as a function of OC group and petrologic type, though the OCs are remarkably similar in the thermal infrared and may trend toward being indistinguishable depending on the applied spectral sampling and radiance resolution. Ongoing work is further investigating the effect of varying environmental conditions on the modeling of asteroid thermophysical properties to further inform the evolution of asteroid orbits.


Figure 1: (a) Plot of integrated radiance across the thermal IR region as a function of temperature using emissivity data from an LL analog mineral mixture compared to the LLS LaPaz Ice Field 10009 sample (both with a particle size of <25 μm). These integrated radiance curves are compared to a blackbody and 75% greybody. All spectra were collected with heated cup temperature of 400 K and either at ambient (AMB) or simulated asteroid environment (SAE) conditions (b) Example subsolar temperatures recalculated using the data as in (a) as a function of heliocentric distance.

Figure 2: (a) Band depths of the ~945 cm⁻¹ spectral feature from a suite of mineral mixtures with a particle size of 125–250 μm that mimic the three OC groups. (b) Band depths of a ~880 cm⁻¹ feature in a suite of type 4 OCs spanning the H, L, LL groups (LaPaz Ice Field 10001, Wisconsin Range 91603, Grosvenor Mountains 95552). All spectra were collected with heated cup temperature of 400 K and either at ambient (AMB) or simulated asteroid environment (SAE) conditions.
EVALUATING BENNU SURFACE COMPOSITIONS USING MIR SPECTRA OF FINE-PARTICULATE ALBEDO-CONSTRAINED MINERAL MIXTURES AND MULTIVARIATE ANALYSIS. L. B. Breitenfeld1, A. D. Rogers1, T. D. Glotch1, V. E. Hamilton2, P. R. Christensen3, and D. S. Lauretta4, 1Dept. of Geosciences, Stony Brook University, Stony Brook, NY, laura.breitenfeld@stonybrook.edu, 2Dept. of Space Science, Southwest Research Institute, Boulder, CO, 3School of Earth and Space Exploration, Arizona State University, Tempe, AZ, 4Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ.

Introduction: Detailed assessment of the asteroid Bennu’s mineralogy and compositional variability is broadly applicable to the study of carbonaceous near-Earth asteroids and primitive material within our solar system. Among the chondrites, the spectral properties of Bennu are most analogous to those of a CI or CM chondrite [1-4]. The OSIRIS-REx spacecraft possesses the OSIRIS-REx Thermal Emission Spectrometer (OTES) instrument that observes Bennu in the mid-infrared (MIR) and can be utilized for further refining Bennu’s mineralogy [e.g. 4].

There are many factors including composition and particle size that impact MIR spectral properties. Currently available spectral and thermal data from OTES do not yet support a significant fine-particulate component (<60 microns) on Bennu. However, given that OTES spectra cannot be satisfactorily modeled by library spectra consisting entirely of coarse particulates (>90 microns) [5], a further investigation of the contribution of fines is worthwhile. Additionally, it is possible that small regions spectrally dominated by fine-particulate components might be observed using higher resolution data during the upcoming Reconnaissance phase of the mission.

Using linear mixing models [6,7], mineral abundance estimates from fine-particulate surfaces (<60 microns) generally have greatly reduced accuracy compared to coarse-particulate surfaces; however, significant improvements may be possible using multivariate analysis. This is because this alternative approach removes the assumption of linear mixing across all wavelengths. Multivariate analysis requires preparation of a training set covering the relevant compositions and particle sizes. This technique has proven as an effective tool for evaluating compositional abundances using several types of spectroscopy [8-10].

In the event that fine-particulate materials are detected in OTES data, we are preparing a fine-particulate (<50 microns) albedo-constrained library and training set for multivariate analysis. Here we present progress on the development of this training set, some initial assessments of expected model accuracy, and plans for future work. In addition, we note some preliminary spectral trends observed in fine-particulate mineral mixtures that might be relevant to OTES spectra.

Sample Preparation: The mineral species utilized in this work are commonly present within CI and CM chondrites [11-13]. These minerals include antigorite, clromeltite, saponite, magnetite, pyrrhotite, olivine (Fo40, Fo80, Fo95), calcite, dolomite, ferrihydrite, gypsum, and enstatite. Suitable samples were obtained from several museum collections and dealers or synthesized at Stony Brook. Natural samples were hand-picked for purity and in some cases were centrifuged, acid-washed, or magnetically separated to remove unwanted contaminants. Each was hand crushed or milled to create fine-particulate samples (<50 microns).

Mixtures: This work is ongoing and therefore mixtures are still being made. Clromeltite-bearing mixtures are not yet available. This precludes immediate application to OTES spectra at this time.

The suite of 13 minerals common in CI and CM chondrites was utilized as end-members within the multivariate analysis models. All samples were darkened using 11 volume% carbon powder [14] to constrain the albedo of the samples to more closely match Bennu albedo.

Using these samples, analog CI and CM meteorite mixtures were made using modal abundances that encompass literature values [4,11,12]. Binary and ternary mineral mixtures were also made. Using binary and ternary mixtures in this project is helpful in two ways.

1. Isolating complex mixing effects for the multivariate model and our understanding.
2. Ensuring every mineral in the model has several data points between 0 and 100 volume%.

This is important, because although narrower model ranges can allow for precise predictions, a restricted model could bias prediction results and would be unable to detect true outliers accurately.

Instrumentation: MIR spectra were acquired in a simulated asteroid environment (SAE). For these measurements, the Planetary and Asteroid Regolith Spectroscopy Environmental Chamber (PARSEC), a custom-built planetary environmental spectroscopy chamber at Stony Brook University, was utilized. PARSEC is coupled to a Nicolet 6700 FTIR spectrometer for emissivity measurements. Before SAE measurements, the chamber was pumped to ~10⁻⁹ mbar over several hours and subsequently cooled to ≤-125°C. Blackbody measurements were acquired at 70 and 100°C while samples were heated to 80°C.

Blackbody measurements were acquired at 70 and 100°C while samples were heated to 80°C.
Laboratory Spectral Trends: MIR spectra of antigorite, magnetite and binary mixtures of these two components combined are shown in Figure 1. As expected, binary mixtures with a higher proportion of antigorite have stronger antigorite features and vice versa. However, in mixtures, some spectral features become obscured by the presence of the other mineral. Regardless of the relative mineral abundances, the binary mixtures share more similarity to each other than to their pure end-members, showing significantly reduced spectral contrast and a change in slope relative to the pure mineral spectra.

![Figure 1](image_url)

**Figure 1.** MIR SAE emissivity spectra of antigorite and magnetite end-members with binary mixtures at various volume ratios. All samples were darkened with carbon. The abundance percentages have the carbon removed from the ratio calculations.

Unlike undarkened fine-particulate mineral spectra acquired under ambient conditions, these darkened SAE spectra of fine-grained silicates do not show the characteristic spectral “roll-off” (decrease in emissivity) at high wavenumbers. Ambient measurements of the identical samples similarly lack this spectral “roll-off” indicating the cause is primarily related to presence of the darkening agent. Amorphous carbon, which was used to darken the samples, has an imaginary index of refraction of ~1.5-5 throughout the MIR [15]. We hypothesize that at wavelengths shortward of the Christiansen feature, this high extinction coefficient results in a reduction in the emissivity “roll-off” typically associated with finely particulate silicates.

Multivariate Analysis: MIR spectra of the 13 darkened samples act as endmembers within the multivariate models. In addition to these data, spectra of mixtures were evaluated with partial least squares (PLS1 and PLS2) and least absolute shrinkage and selection operator (Lasso) multivariate analysis [16,17]. PLS1 evaluates one mineral abundance at a time while PLS2 evaluates multiple abundances collectively. Both PLS1 and PLS2 utilize all channels of the spectra while Lasso reduces the number of channels within the model [18].

The accuracy of each model was evaluated using the parameter leave-one-out cross-validated root mean square error (LOO RMSE-CV). This metric is calculated by removing one sample at a time, using a regression model based on the other n-1 samples to predict the n° sample. LOO RMSE-CV gives the best estimate of how the model will perform on unseen data since this error is calculated for predictions that do not rely on itself. LOO RMSE-CV range from 7.2-27.5 volume% for PLS1, 20.9-23.6 volume% for PLS2 and 3.4-26.8 volume% for Lasso models. Model accuracies depend on the type of model, parameters utilized and prediction mineral in question. The creation of these multivariate models is ongoing. As spectra are added to the multivariate models the errors will change.

Ongoing Work: These multivariate models will be applied to spectra of fine-grained CI and CM meteorite samples once the training set is completed. Testing models on ”unseen” data (spectra not part of the training set) is an important step to validate the accuracy of the model and for choosing the most appropriate model type (e.g. Lasso, PLS1/2). Last, these models will be applied to regions of Bennu including potential TAG sites.

In addition to the MIR library that has been outlined here, an equivalent VNIR library is also in progress. Comparable multivariate modeling will be applied to OVIRS data.

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LABORATORY SPECTROSCOPIC PROPERTIES OF CARBONACEOUS CHONDrites AND MINERALS AT CRYOGENIC TEMPERATURES IN SUPPORT OF OSIRIS-REx. J. R. Brucato1, G. Poggiali1,2, E. Dotto3, M. A. Barucci4, M. Pajola4, V. E. Hamilton5, P. R. Christensen7, A. A. Simon8, D. C. Reuter8, B. E. Clark9, D. S. Lauretta10, 1INAF Arcetri Astrophysical Observatory, Largo Enrico Fermi 5, 50125 Firenze, Italy (john.brucato@inaf.it), 2University of Firenze, Department of Physics and Astronomy Via Sansone 1, 50019 Sesto Fiorentino, Italy, 3INAF Astronomical Observatory of Roma, via Frascati 33, 00040 Roma, Italy, 4LESIA-Observatoire de Paris, CNRS, Universite Pierre et Marie Curie, 92195 Meudon Principal Cedex Paris, France, 5INAF-Astronomical Observatory of Padova, Vic. Osservatorio 5, 35122 Padova, Italy, 6Southwest Research Institute, Boulder, CO, USA, 7Arizona State University, Tempe, AZ, USA, 8NASA Goddard Space Flight Center, Greenbelt, MD, USA, 9Ithaca College, Ithaca, NY, USA, 10Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA.

Introduction: Interpretation of spectroscopic data from the OVIRS [1] and OTES [2] instruments onboard NASA’s OSIRIS-REx asteroid sample return mission [3] depends on the spectroscopic properties, particle size and temperature of materials present on Bennu’s surface [4, 5]. Spectral indices of silicates, carbonates, sulfates, oxides and chemicals available on public database are commonly obtained at room temperature and pressure. Up to now few studies [6] were performed analyzing the effects of space environment such as low pressure and temperature on spectroscopic features of minerals. In particular, whether temperature can affect spectral properties of minerals such as the peak emissivity position, band area and shape, was questioned decades ago, but today a systematic laboratory study on such effects is still missing. Other changes in spectral features are strictly related to particle size distribution. Thus, it’s important to acquire spectra in vacuum, at various temperatures and with variable particle sizes for better simulating space environmental conditions.

Laboratory methods: Our experimental apparatus at INAF-Astrophysical Observatory of Arcetri allows reflectance measurements in an extended spectral range from VIS to far IR and at temperatures from 64 K to 500 K with temperature stability ±0.1 K. The temperature range explored in the laboratory was chosen to be wider than that measured on Bennu’s surface during the OSIRIS-REx encounters (about 180-380 K). Interfacing an Oxford Instruments cryostat with a Bruker FT-IR interferometer we are able, with the proper mirror geometry, to acquire reflectance spectra of different powdered samples. The cold finger of the cryostat with its sample holder is placed inside a micro tail equipped with different windows transparent at each spectral range analysed. Inside the micro tail high vacuum with pressure <10⁻⁶ mbar is obtained with a turbo molecular pump.

Mineral phases of interest to OSIRIS-REx are pyroxene; olivine, crostetitid, chrysotile lizardite, antigorite, hematite, spinel, and magnetite, and meteorites analysed are Murchison (CM2.5), Mighei (CM2), Tagish Lake (Cl2), Ormns (CO), Allende (CV3), Rezzaz (CR). Samples are prepared with particle sizes ranging from 1 mm to less than 20 microns.

Results: Spectroscopic changes on reflectance spectra were observed in the VIS-NIR-MIR range at temperatures ranging from 64 to 500 K. Our results show that temperature induces peak position shifts of few cm⁻¹ every 100 K (see as an example Fig 1) and band areas of hydrated minerals from the group of phyllosilicates such as antigorite and lizardite increase with temperature reaching maximum values of 12% at about 350 K, then decrease at higher temperatures showing a bell shape profile.

At the current temperatures relevant for Bennu, peak position changes are not detectable at spectral resolution of both OTES and OVIRS. However, the band area changes are encouraging to infer physical and compositional properties of Bennu’ surface, especially comparing perihelion and aphelion observations when the temperature variation on Bennu are largest.

Figure 1 – Antigorite reflectance spectra (particles size <20 µm) in medium infrared range at different temperature in vacuum.

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SPACEWATCH® OBSERVATIONS of HIGH PRIORITY NEAR-EARTH ASTEROIDS. Melissa J. Brucker¹, R. S. McMillan¹, T. H. Bressi¹, J. A. Larsen², R. A. Mastaler¹, M. T. Read¹, J. V. Scotti¹, and A. F. Tubbiolo¹
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Introduction: It is essential to discover and monitor Near-Earth Objects (NEOs) that might hit Earth. We strive to reduce the uncertainty in orbital elements of NEOs and extend their spatial and temporal observation spans. We present details and results from our Target-of-Opportunity program to recover faint Virtual Impactors (VIs) using non-classically scheduled time on larger telescopes.

The Spacewatch Project: Spacewatch¹ conducts full-time follow-up astrometry of NEOs primarily with a 1.8-meter and a 0.9-meter telescope on Kitt Peak, Arizona. During bright time, we also utilize the Steward Observatory Bok 2.3m Telescope on Kitt Peak to capitalize on its aperture. We prioritize observing VIs², Potentially Hazardous Asteroids (PHAs³), objects on the Minor Planet Center's (MPC's) NEO Confirmation Page⁴, potential targets of radar⁵, NEOs with characterization data (especially targets of the NEOWISE spacecraft⁶), potential destinations of spacecraft⁷, and other objects of interest to the small bodies research community. Our first priority, VIs, have uncertainties in their orbital elements such that some possible orbit solutions predict an impact with Earth within the next 100 years. PHAs are NEOs with absolute magnitudes \(m \leq 22.0\) and Earth Minimum Orbit Intersection Distances (EMOID) \(\leq 0.05\) au. Spacewatch leads the world community of astrometrists in numbers of observations of PHAs that are fainter than \(V = 22.5\) and in extensions of calendar spans of observations of PHAs. Spacewatch's annual output of astrometry includes \(\sim 1,400\) NEOs including \(\sim 230\) PHAs, \(\sim 50\%\) of new VIs, \(\sim 110\) potential radar targets, \(\sim 150\) NEOs measured by NEOWISE, and \(\sim 60\) potential rendezvous destinations. We also target candidates for revealing the Yarkovsky effect⁸, which like (101955) Bennu⁹, may exhibit non-Keplerian orbits due to anisotropic infrared re-radiation of absorbed sunlight.

Target-of-Opportunity Program: In 2018, we began a Target-of-Opportunity (ToO) program to observe faint VIs on larger telescopes in order to rule out (or confirm) predicted impacts, extend the calendar span of observations, and prevent loss due to uncertainty. ToO time is a small amount of competitively awarded time that interrupts the schedule or queue instead of being classically scheduled ahead of time. When a target is selected that requires prompt observations, the ToO is triggered by contacting the observatory. For our ToO program, we focus on VIs since they have a potential to impact the Earth. If VIs accrue large positional uncertainties while they are too faint to be observed using normal NEO follow-up assets, their recovery, once they return and become brighter, can require extensive time and resources and may not be possible. To prevent the need for such extensive effort in the future, we extend the current temporal span of observations longer by days to weeks by using interrupt time on larger telescopes. These telescopes can detect fainter and/or faster-moving VIs than typical NEO astrometric follow-up assets in the one to two meter range. Longer spans of observations lead to lower orbital uncertainties, which in turn lead to more accurate impact predictions. In 2018, 209 new VIs were added to JPL's Sentry risk list and 91 (44\%) remain.

We want to improve the knowledge of VI orbits in order to eliminate orbit solutions containing high priority impact predictions and reduce the number of VIs.

ToO Target Selection: To select the best targets for our limited number of telescope interrupts, we give higher weight to VIs with first possible impacts that might occur before they become bright enough to be rediscovered. We calculate a “priority” factor using the cumulative impact probability from Sentry, the date of first possible impact (temporal urgency), and the reliability of the impact predictions (related to the observational arc length¹⁰). Object size and observability are considered separately. In addition to our prioritization scheme, we confer with JPL regarding impact priorities and with other follow-up observing groups. Figure 1 illustrates how a long list of VIs can be narrowed down to those most in need of prompt astrometry. The most urgent VIs lie in the upper part of Figure 1. If a VI has a priority value greater than -2, then it will be given highest consideration over other VIs.

Figure 1. Priority Factor for VIs Discovered in 2018. The set of VIs discovered in 2018 that were still listed by JPL on 2019 August 19 are plotted here. The blue circles are VIs that will become bright enough (\(V \leq 22\)) for serendipitous rediscovery by current all-sky surveys at least one synodic period before their first possible impact. The red diamonds are VIs that will not become bright enough and thus are given precedence. The priority is a logarithmic function of cumulative impact probability, temporal urgency, and reliability of
impact predictions. We did not trigger a ToO for the VI in the upper left of the plot due to its small size. An object with an estimated diameter of 2m will break up in Earth's atmosphere into pieces too small to cause serious damage.

**ToO Implementation:** Beginning with the 2018A observing semester, we have been awarded ToO time on the Victor Blanco 4-m Telescope and the Southern Astrophysical Research Telescope (SOAR) at Cerro Tololo Inter-American Observatory in Chile, the W. M. Keck Observatory in Hawai'i, the WIYN 3.5-m Observatory at Kitt Peak National Observatory in Arizona, the Large Binocular Telescope Observatory on Mt. Graham in Arizona, and the MMT on Mt. Hopkins in Arizona. We have been conservative about triggering ToOs in order to focus our efforts on objects with high potential hazard. We triggered ToO time in 2018A, 2018B, and 2019A at the Blanco Telescope and in 2018A at the WIYN Telescope. We successfully measured the target VI for each of our observations at the Blanco. Our 2018A observations contributed to the removal of the minor planet 2017 TA6 from the risk list. In 2019A, we observed 2019 GD4 on 2019 April 28. Table 1 shows the improvement in orbital elements as found in JPL’s Small-Body Database Browser before and after our observations (2019 April 27 and May 2).

**Table 1. Orbital Elements of 2019 GD4.**

<table>
<thead>
<tr>
<th>Element</th>
<th>Value Before</th>
<th>Value After</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>0.46660 ±0.00054</td>
<td>0.46651 ±0.00042</td>
</tr>
<tr>
<td>a (AU)</td>
<td>1.7995 ±0.0018</td>
<td>1.7993 ±0.0014</td>
</tr>
<tr>
<td>i (deg)</td>
<td>0.38104 ±0.00035</td>
<td>0.38098 ±0.00027</td>
</tr>
<tr>
<td>Ω</td>
<td>320.280 ±0.011</td>
<td>320.282 ±0.009</td>
</tr>
<tr>
<td>ω</td>
<td>197.813 ±0.011</td>
<td>197.812 ±0.009</td>
</tr>
<tr>
<td>M</td>
<td>21.454 ±0.034</td>
<td>21.460 ±0.026</td>
</tr>
</tbody>
</table>

**Conclusion:** Our ToO program with large telescopes, in conjunction with bright time observations on the Bok Telescope, strives to fill in the faint regime for priority NEO astrometry. The Spacewatch priority factor, by incorporating the arclength of observations as a measure of reliability, provides an analysis of the reliability and urgency of VI predictions which assists in making the best use of limited access to large telescopes.

**References:**


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Noble gases as important tracers for processes on small planetary bodies – A detailed look at the carbonaceous chondrites.

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Introduction: Noble gas analysis is essential to characterize and understand extraterrestrial materials. For two main groups of extraterrestrial materials noble gases play an important role in improving our understanding: (i) materials collected on/around the Earth (meteorites from the moon, Mars, asteroids and perhaps comets; asteroidal and cometary interplanetary dust particles and micrometeorites) and (ii) samples that have been, or are planned to be returned by space missions sampling asteroids (Hayabusa/II, OSIRIS-REx), the Moon (Apollo, Luna, Chang’e programs), Martian moons, the Sun (Genesis) and comets (Stardust).

By studying noble gases we can address a wide variety of essential scientific issues such as stellar nucleosynthesis and resulting primordial noble gas isotope anomalies, effects of the early active sun and accretion in the nebula, the timing of formation, impact and alteration events through gas retention ages, duration (and shielding) of exposure of materials on their parent bodies and in space, the alteration of primordially trapped noble gases during parent body alteration and the understanding of trapping mechanisms and carrier phases. Most of these processes are currently examined in our group. At the meeting, we will discuss processes that affected the primordially trapped noble gas contents in the various carbonaceous chondrite (CC) classes, which will be most relevant to the study and understanding of the C-rich asteroids Bennu and Ryugu.

Experimental methods: The noble gas laboratory at ETH Zurich examines extraterrestrial materials using a number of mass spectrometers and various extraction techniques. The latter cover all conventional techniques (IR laser stepwise heating [1,2], spatially resolved UV laser ablation, crushing and stepwise heating by fusion [3]) and the unique in-vacuum etching technique “CSSE” [4,5]. Mass spectrometers include the exceptional, custom built low-blank high-sensitivity instrument “Tom Dooley”, equipped with a compressor source that allows the detection of all He and Ne isotopes with significantly lower detection limits than commercial instruments [6], as well further single [3,5] and multi-collection instruments such as a new Nu instrument Noblesse with 5 Faraday/5 Multiplier configuration. The compressor source allows us to determine He and Ne concentrations and isotopic compositions even in small single grains. Recently we analyzed, e.g., hibonites bearing evidence for early solar activity [1], presolar grains showing their residence time in interstellar space [2] and single olivine grains returned by JAXA’s Hayabusa mission from LL type asteroid Itokawa to determine their exposure times to cosmic rays and solar wind [7,8] and fossil meteoritic chromite in sediments to reconstruct the fall of extraterrestrial material through time [9]. Online etching allowed us recently, e.g., to understand in detail the effects of aqueous alteration on presolar SiC and insoluble organic matter (IOM) and its noble gases on the Tagish Lake parent body [4], as well as the primordial noble gases in various acid soluble fractions of one of the least altered meteorites Miller Range (MIL) 090657 (CR) [10]. At the meeting we will mostly discuss data obtained by one temperature step (1700 °C) bulk extractions of carbonaceous chondrites. This data shows the effects of parent body aqueous alteration on potential carrier phases of a ubiquitous but poorly understood primordial noble gas component rich in Ar. In addition, we will combine this with recent results from the CSSE analysis of MIL 090657 [10], in which the Ar-rich component was analyzed directly.

Fig. 1. Trapped $^{36}$Ar and $^{132}$Xe concentrations in recently measured CCs (Y=Yamato, DOM=Dominion Range, QUE=Queen Alexandra Range [11], AS91A_14=CI-type material from Almahata Sitta [12]). The least altered CR chondrites show significantly more abundant Ar than the other CRs. Trends towards increased $^{132}$Xe in CYs and likely CRs are strongly affected by terrestrial Xe contamination (up to 50 %, [13]).
Results and Discussion: The data presented here is part of a detailed program to examine a large number of carbonaceous chondrites of various classes to characterize their primordially trapped noble gas contents. The data will serve as a baseline for (i) a better understanding of the original distribution of trapped noble gases and their carriers (presolar grains, phase Q and potentially other acid-soluble minerals) in the nebula, (ii) the examination of the effects to noble gas concentrations and compositions of both aqueous and thermal alteration on the parent bodies, and finally (iii) modeling noble gases accreted by the terrestrial planets. So far, various CR, CM [14], CI, CY [13,15], CO [11] and ungrouped carbonaceous chondrites have been measured as well as CI type material recently found in fragments of Almahata Sitta [12]. Various conclusions can be drawn already from these studies:

The concentration of trapped Ar and likely Xe (corrected for terrestrial Xe) in CR chondrites is decreasing with increasing aqueous alteration experienced on the parent body (Fig. 1). This has been suggested earlier for CMs [16] and partly confirmed in a recent, more detailed study on CMs [14]. However, CM chondrites are complex rocks that are often brecciated and consist of lithologies of different petrologic types [17] which complicates the picture. Mineralogical studies by XRD on aliquots of the same samples are on the way to determine the exact petrologic type of the material analyzed for noble gases [10].

The CIs, CYs, Sutter’s Mill and the most altered CR chondrites have significantly lower $^{36}\text{Ar}$ concentrations as well as lower element ratios than CR chondrites with low to intermediate alteration (both figures). This suggests that at least one carrier of trapped $^{36}\text{Ar}$-and perhaps trapped $^{20}\text{Ne}$ as well- is destroyed by aqueous alteration (CR3=>$\text{CR1}$). CR1s show concentrations and elemental ratios similar to the CIs and CYs which are also strongly aqueously altered. The Q (in IOM) / HL (in presolar diamond)-gas ratios remain largely unaltered in CRs. There is a tendency for Q and HL to be lost more readily than Ne-E during aqueous alteration of CR chondrites. The least altered CRs may contain 5x more Ar and 2x more Xe than CIs, and only ~20% of all CRs contain solar wind.

Our results suggest that all CR, CI, CY, and C chondrites started with a similar inventory of trapped noble gases as the least altered CRs. This inventory was later modified by parent body aqueous alteration. Etching with various agents gives some hint for separate, yet unknown Ne and Ar carriers differently susceptible to water, acetic acid, HNO$_3$, HF, and HCl [10]. These carrier(s) could be amorphous silicates, and/or metal / metal-sulphide or other phases that were formed during nebula condensation or possibly associated with chondrule formation. Vogel et al. [18] indeed found an enrichment of Ar relative to Ne in metal-sulphide chondrule coatings formed during metal-silicate separation in molten chondrules. Such enrichment of (carbonaceous) phase Q expelled into the metal phase could perhaps explain the presence of high Ar concentrations.

MACHINE LEARNING–BASED THERMOPHYSICAL ANALYSIS OF OSIRIS-REx SAMPLE SITE CANDIDATES. S. Cambioni1, M. Delbo2, J. D. P. Deshapriya3, G. Poggiali4, A. Ryan1, J. P. Emery5, V. E. Hamilton6, P. R. Christensen7, and D. S. Lauretta3. 1University of Arizona, Tucson AZ 85721 (cambioni@lpl.arizona.edu); 2Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Lab. Lagrange, Nice Cedex 06304, France; 3LESIA, Observatoire de Paris, PSL Research University, CNRS, Meudon Principal Cedex 92195, France; 4University of Florence, Department of Physics and Astronomy, Sesto Fiorentino (Florence), Italy / INAF-Osservatorio Astrofisico di Arcetri, Florence, Italy; 5Northern Arizona University, Flagstaff AZ, USA; 6Southwest Research Institute, Boulder CO, USA; 7Arizona State University, Tempe AZ, USA.

Overview. We use a new methodology [1] that combines machine learning and Bayesian statistics to constrain the surface properties of the OSIRIS-REx final four site candidates from measurements of the emitted infrared radiance. Our approach consists of: (1) training a neural network representation of the thermophysical behavior of the surface; and, (2) using the trained network as forward model in a Bayesian inversion of the observed infrared radiance. Terrains are modeled as composed by two units: rocks and fine particles (also called fines, with average particle size smaller than 2 cm). The surface properties of the sites – surface roughness, thermal inertia of the fines and rock units, and relative abundance – are retrieved; the contributions from the fine particle and rock unit and rock units are well separated. The sites differ in the thermal inertia of the rock component, relative abundance of the units and surface roughness. Conversely, the thermal inertia of the fines is found to be remarkably similar from site to site (equal to about 150 Js⁻¹/²K⁻¹m⁻²), suggesting a preferential size for the fine particles on the surface.

Introduction. The surfaces of airless planetary bodies are typically covered in regolith, a layer of fragmented and unconsolidated material that typically derives from the break-down of rocks and boulders on the surface of the asteroid. Large (hundreds of km diameter) asteroids are generally found to show more mature (finer) regolith than smaller asteroids [2]. The images obtained by NASA's OSIRIS-REx mission at asteroid (101955) Bennu [3] and JAXA's Hayabusa2 at asteroid (162173) Ryugu [4] seem to confirm this trend, as the target asteroids are covered in very coarse regolith, with predominance of boulders.

The rough morphology of small asteroids offers multiple challenges to near-surface, landing, and sampling operations of active space missions. NASA's OSIRIS-REx mission will collect a sample of the surface of Bennu and return it to Earth for laboratory analysis [3]. The sampling device of OSIRIS-REx, TAGSAM, is designed to collect and return at least 60g of the regolith, provided particles are smaller than about 2 cm in diameter. Accurate estimates of the availability of fine particles on the asteroid, including average particle size and abundance, are thus key to define the sampleability of the surface.

OTES data. The thermal and mechanical environment of the surface poses constraints on sampling operations. The thermal emission informs about the thermophysical properties of the surface. The OSIRIS-REx Thermal Emission Spectrometer is currently measuring infrared radiances emitted by the surface of the asteroid in the spectral range 5.71-100 µm (1750-100 cm⁻¹) with a spectral sample interval of 8.66 cm⁻¹ [5]. Under the hypothesis that the infrared radiance is contributed by the thermal emission of both fine particles and rocks, we use the methodology in [1] to estimate the thermal inertia of the fine particle and rock components, relative abundance of the units, and the surface roughness. The abundance of rocks and surface roughness inform us about the hazard associated with sampling a certain region. The thermal inertia of the fines can be converted in average particle size. As a guideline, particles on Bennu with thermal inertia less than 280 Js⁻¹/²K⁻¹m⁻² are predicted to have average size smaller than 2 cm in diameter, according to the model by [6].

Methodology. Our approach consists of approximating the thermophysical function y = F(x) (x: surface properties; y: infrared radiance) using neural networks trained on a dataset of thermal simulations of the type: {surface properties; infrared radiance}. The dataset has been generated using the TPM model [7] following the procedure described in [1]. Once trained, the networks can predict the infrared radiance at highly reduced computational time with respect to the “parent” model (running in less than a second versus minutes on a single processor 2.8 GHz Intel Core i7), thus enabling Markov Chain Monte Carlo (MCMC) Bayesian inference of surface properties from observed infrared radiances. MCMC requires thousands of runs of the forward model to sample the unknown posterior distributions – thus the need for a fast and accurate predictor, i.e., a trained neural network. We follow a two-step approach. We first fit the data with a single-component model (a neural network predicting the infrared radiance corresponding to the average thermal inertia and roughness). We then employ the trained 2-component model in the Bayesian inversion of the infrared radiance. In this case, the MCMC scheme is informed of the result of
the single-component fit, in order to guide the inversion towards convergence. For a more detailed explanation of the methodology, we refer the reader to [1].

Results. We focus on the analysis of the OTES data concerning the final four site candidates, which have been down-selected from a longer list of sites according to spacecraft safety (e.g. avoidance of high slopes and large boulders) and science criteria. For sites Nightingale, Osprey, and Kingfisher, we find that the goodness-of-fit (reduced $\chi^2$) of the 2-component model is more than 3-$\sigma$ better than that obtained by using the 1-component model. This means that the data are better fit if the thermal emission is modeled as contributed by two materials – which are here assumed to be fine particles (with size less than 2 cm in diameter) and rocks. The thermal emission from site Sandpiper is instead better fit using a 1-component model. The results of the Bayesian inversion using the 2-component model, in terms of the posterior probability distribution of the surface properties, are in Figure 1.

Discussion. The site candidates are distinguishable in terms of their thermophysical properties. The surface roughness (in terms of Hapke angle [8]) changes from site to site. The unit consistent with fine particles is present at every site, and it is the most abundant at the Osprey site (>50% at the scale of the diurnal skin depth). However, Osprey also shows the roughest surface. While the most probable thermal inertia of the rock component is different from site to site (but always below 600 Js$^{-1/2}$K$^{-1}$m$^{-2}$, bottom-left panel of Figure 1), the thermal inertia of the fine particles is found to be remarkably similar, with a most probable value of about 150 Js$^{-1/2}$K$^{-1}$m$^{-2}$ (top-right panel of Figure 1). Such value of thermal inertia is consistent with a particle size of about 3.6 mm – 5.3 mm for Cold Bokkeveld–like meteorite, or 9.5 mm – 1.5 cm assuming very low density and thermal conductivity (1400 kg/m$^2$ and 0.08 W/mK respectively, perhaps consistent with the values for the boulder on Ryugu analyzed by the MARA instrument [9]).

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Figure 1. Posterior probability distributions of the thermophysical properties of four sample site candidates on the surface of asteroid (101955) Bennu. The properties – surface roughness, thermal inertia of fine particles and rocks, and relative abundance of the units – are estimated by means of Bayesian inversion of infrared radiances collected by the OTES instrument. Among the sites, “Osprey” is found to have the highest abundance of material with thermal inertia lower than 280 Js$^{-1/2}$K$^{-1}$m$^{-2}$, which, following the method by [6], is here interpreted as fine particles with size less than 2 cm. The sites also differ in their roughness and thermal inertia of the rock component. Furthermore, the thermal inertia of the fine particles is remarkably similar among the different sites, which could indicate a preferential size for the particle material (see text).
ORDINARY CHONDRITES IN THE ALLENDE STREWN FIELD: RELEVANCE TO ASTEROIDS BENU AND RYUGU.
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Abstract: We analyzed six strewn fields of low-albedo meteorite falls in order to determine if there are xenoliths of high albedo material present among them, as is the case for Almahata Sitta. We determined the location and size of the six carbonaceous chondrite strewn fields listed in the Meteoritical Bulletin Database: Allende (CV3, fell in Mexico, 1969), Moss (CO3, Norway, 2006), Murchison (CM2, Australia, 1969), Sutter’s Mill (CM2, United States, 2012), Orgueil (CI1, France, 1864), and Tagish Lake (C2 ungrouped, Canada, 2000). The meteorite candidates were mapped and narrowed down by geographic location, placement relative to each strewn field, and year of fall to determine their likelihood of being a potential member of the original body. There are eight high albedo finds (ordinary chondrites, H and L) within the Allende strewn field that postdate the recorded fall. The finds have a placement that is supportive of being possible members of the Allende strewn field, although weathering of finds and exposure ages are still to be studied. No other recorded finds have been reported within the other strewn fields. Hence, further investigation of the exposure ages (both the cosmic-ray and the terrestrial) of the individual finds within the Allende strewn field would be diagnostic of a link with the Allende fall. If the high-albedo meteorites we have identified are indeed related to the Allende meteorite, the incorporation of foreign lithologies into carbon-rich meteoroids may not be as uncommon as previously thought. If the Allende parent body was composed of multiple lithologies, its formation process may have been similar to those of the Almahata Sitta parent body, Bennu and Ryugu.

Introduction: The albedo range on asteroids (101955) Bennu and (162173) Ryugu are the largest observed by in situ studies of asteroids. On Bennu The geometric albedo ranges from 3.5% to >15% and the surface features detected so far range from centimeters to decameters in diameter [8]. On Ryugu the albedo range is almost as large, although the high albedo features are not quite as large as on Bennu [9]. To date, similar albedo diversity among meteorites have been reported for Almahata Sitta and Kaidun; however, for Kaidun the different lithologies were within one meteorite with a sample size was too small to be used as an analog for the surfaces of Bennu and Ryugu [5]. Almahata Sitta was a large-scale fall event (in 2008) more relevant for comparison with Bennu. Almahata Sitta contained different lithologies within its strewn field including: ureilites, enstatite chondrites, two types of ordinary chondrites (H and L), and carbonaceous chondrites [2,4]; all these were linked to Almahata Sitta by their exposure histories. How rare are meteoritic falls like Almahata Sitta that contain different classifications within its strewn field? Here, we address this question and explore the relevance to the albedo and compositional diversity observed on the surfaces of Bennu and Ryugu [8,9,10]. This comparison is motivated in part by the likelihood that Bennu, Ryugu and Almahata Sitta originated from the same region of the asteroid belt and may have been affected by similar processes [1,3,11].

Summary and Conclusions: There are eight high albedo finds (ordinary chondrites, H and L) within the Allende strewn field that postdate the recorded fall. The finds have a placement that is consistent of being members of the Allende strewn field; however, weathering of finds and exposure ages have yet to be studied. No other recorded finds have been reported within the other strewn fields. This comparison is

The boulder dynamics during YORP spin-up of asteroids. Bin Cheng¹, Yang Yu² and Hexi Baoyin¹, ¹Tsinghua University, Beijing, China 100084, chengbin171@163.com, ²Beihang University, Beijing, China 100191.

Introduction: Hayabusa2 and OSIRIS-REx spacecrafts recently arrived at their target asteroids respectively, showing us the surface morphology of top-shaped asteroids in unprecedented detail [1, 2]. More surprisingly, there are numerous large boulders exposed on their surface. Boulder size measurements indicate that they are too large to be impact ejecta from observed craters, suggesting that they may be direct fragments from their parent bodies and record the geological evolution of the asteroid surface. Therefore, gleaning information about the way boulders have moved on the surface of these top-shaped asteroids over time will help us to understand these asteroid’s evolution histories and also to decipher the geologic clues recorded on these asteroids which might shape our Solar System in the past.

The asteroid’s evolution process during YORP spin-up has long been studied, and is being actively pursued at present in terms of finite element modeling and N-body simulations. Hirabayashi and Scheeres (2015) confirmed that a homogeneous spherical body should experience failure in its central region at high spin rates, while the surface-shedding failure behavior is possible for spherical bodies with heterogeneous internal structure. Based on Soft-Sphere Discrete Element Method (SSDEM), Zhang et al. (2018) found the asteroid body can disaggregate into similar-size fragments, which could be a plausible mechanism to form asteroid pairs. These studies, however, are all focus on the global structure failures. The motion dynamics of boulders during the surface regolith migration are still not fully understood.

In this study, we investigate the creep evolution of the boulders on granular regolith during the YORP-induced spin-up. A parallel code capable of simulating millions of particles, DEMBody, is implemented in order to track the boulder dynamics and regolith response in this process [3]. We systematically explore the effect of friction and cohesion on boulder dynamics, and we find different regolith properties would, to a significant degree, determine the motion behavior of boulders on regolith surface.

Simulations: The asteroid interior is represented as a rigid shell (about 400min radius) subjected to rotational acceleration, and a longitudinal slice of granular layer (about 30 m in thickness) consisting of 2,063,044 particles is used to simulate the surface unconsolidated regolith. Boulders of various sizes initially distribute on the surface of the regolith layer.

Results: The results show that the progenitor turns to an oblate shape as the spin rate approaches the critical limit, in parallel with landslide debris moving from the mid-latitude towards the equator. The boulders at mid-latitudes are transported downslope by creeping grains underneath, and at the same time sink into regolith layer and become tilted, consistent with the observation of partially buried boulders on Ryugu and Bennu. With the increasing of spin rate, the creep region expands towards high-latitudes, leading to the creeping down of boulders in high-latitudes; such a phenomenon resembles the scarp retreat in geology. However, the boulders near pole remain stable and not slipping away, which means that the creep region never reaches the pole. This result is consistent with the observation of the non-slipping polar boulder Otohime on Ryugu. The boulders at low-latitudes are totally buried by landslide deposition from mid-latitudes. Thus the deficiency of large boulders at the equator as observed on Ryugu and Bennu can be direct result of YORP-induced landslide.

The regolith properties also influence the creep dynamics of surface boulders. Higher friction and cohesion enhance the robustness of granular force networks, thus enlarge the stable region on pole. Interestingly, in cohesive case, a steep, rugged cliff emerges in the head of the landslide region, reminiscent of the scarps at mid-latitudes on Bennu.


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Introduction: Observations by the OSIRIS-Rex navigation camera NavCam 1 have revealed the presence of centimeter-scale, short-lived particles in the environment of Bennu [1]. In some cases these particles are clearly associated with large ejection events, with upwards of 100 detectable particles being released, while other ejection events appear to have only a few associated particles. In most cases the detections of a particle cannot be readily associated with a particular ejection event.

We are undertaking a major effort to fit trajectories to as many particles as possible. This effort is motivated by the goals of providing insight into the Bennu gravity field, the physical and dynamical properties of the particles, and the location of ejections and impacts.

Particle Trajectory Overview: Many observed particles are ejected directly onto hyperbolic escape orbits, while others return quickly to the surface on suborbital trajectories. A few particles persist in orbit about Bennu for a number of revolutions, in some cases upwards of a dozen revolutions.

The escape velocity from Bennu’s surface is in the range of 10–20 cm/s, depending on location [2], and particles ejected in excess of the escape velocity will tend to hyperbolic escape. The fastest observed particles have velocities up to a few m/s; however, there are strong selection effects against detection of faster objects. This is because particles have so far been detected only in long exposure (~5 s) images separated by varying intervals of 7 minutes up to a few hours.

Particle Data: The particle trajectory estimation relies on NavCam [3] detections of particles. The particle positions are referenced to stars present in the image, leading to right ascension-declination (RA-DEC) measurements at the image mid-exposure time. Position uncertainties range from ~0.25–2.0 pixels.

Force Model: Fitting orbits to Bennu’s particles requires particular attention to the forces governing the trajectory. The forces are dominated by the point-mass gravitational acceleration from Bennu, while the lower-order components of the gravity field and direct solar radiation pressure are also important. Because these forces are important to the trajectory, one can estimate the coefficients of a spherical harmonic expansion and the area-to-mass ratio of the particles. The former can give deeper insight into the nature and geophysics of Bennu, while the latter constrains the physical properties of the particle.

Objectives: The estimation and analysis of the particle trajectories can reveal important information about the principal cause of the particle ejection phenomenon, as well as the physical characteristics of both Bennu and the particles.
potential to reveal the gravity field of Bennu at much higher resolution than would have otherwise been possible by the OSIRIS-REx mission. A detailed gravity model can be used to constrain the density distribution and geophysical evolution of Bennu. Estimates of accelerations related to radiation pressure and mass loss will provide insight into the particle characteristics. Finally, a key objective of the trajectory estimation process is identification of ejection and impact locations. The distributions of the ejection events—spatially across the body, in terms of local solar time, or as a function of heliocentric distance—are key to understanding the underlying processes. Detailed analysis of high-resolution imagery of ejection sites can shed further light on the process at hand. Similar analysis of impact locations may provide insight as to the nature of the surface response to low-speed impacts.

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OVERTÝE OVER THE SEARCH FOR SPACE WEATHERING SIGNALS ON BENNU: ONE ROCK TYPE, OR TWO? B.E. Clark1, S.M. Ferrone1, H.H. Kaplan2, X.-D. Zou3, D. Trang4, D.N. DellaGiustina5, L. LeCorre6, D.R. Golish7, J.-Y. Li8, R.-L. Ballouz9, C.W. Hergenrother10, B. Rizk11, K.N. Burke12, C.A. Bennett13, L. Keller14, E.S. Howell15, C. Lantz16, M. A. Barucci17, S. Fornasier18, M. Thompson19, P. Michel20, J. Molaro21, E.R. Jawin22, M. Delbo23, A. Simon24, D. Reuter25, M. Pajola26, and D.S. Lauretta27. 1Ithaca College Dept. of Phys. and Astro., Ithaca, NY, USA, (bclark@ithaca.edu), 2Southwest Research Institute, Boulder, CO, 3Planetary Science Institute, Tucson, AZ, 4Hawai‘i Institute of Geophysics and Planetology, University of Hawai‘i, HI, 5Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 6ARES, NASA Johnson Space Center, TX, 7CNRS Université Paris Sud, France, 8LESIA, Paris Observatory, France, 9Purdue University, IN, 10Côte d’Azur Observatory, France, 11INAF, Observatory of Padova, Italy, 12NASA Goddard Space Flight Center, Greenbelt, MD.

Introduction: We report on progress in the search for signs of space weathering on Bennu. We provide an overview of the space weathering evidence to date, and summarize relevant findings from several ongoing parallel studies of surface processes and surface properties. We examine trends from these studies in the context of space weathering, and what is known about near-Earth asteroid surface maturation [1,2].

Because Bennu is covered with blocks, boulders, and rocks of various sizes, our search for space weathering signals has inevitably led to a study of the properties of Bennu’s rocks. Our research question is – do Bennu’s bright and dark rock populations form a maturity continuum due to space weathering, or alternatively, do the bright and dark rocks provide compelling evidence for two distinct rock populations on Bennu? In particular, we present our best estimate of the sub-field-of-view OVIRS (OSIRIS-REx Visible and Infrared Spectrometer) spectral properties of the largest bright boulders and compare them with the darker materials on Bennu’s surface to see if the observed spectral and albedo differences are consistent with space weathering effects, or not.

Space Weathering: We know that space weathering processes occur on asteroid surfaces and change the optical properties of a thin top layer over time [1, 2 and references therein]. Most airless bodies we’ve examined thus far have shown space weathering effects, so it is not likely that Bennu has escaped them. With some success, surface alteration processes have been simulated in the laboratory [3,4]. On many Solar System bodies, space weathering tends to darken and redden exposed material over time [1,2]. However on carbonaceous bodies rich in hydrated minerals, space weathering effects are more complicated [3,4]. In particular, the experiments reported by Thompson et al. [3] suggest that the high volatile and water content of carbonaceous materials produce vesiculated textures, both in the matrix of the substrate, and in the re-condensed phases.

Rocks on Bennu: Imaging data suggest that higher albedo rocks show relatively fresh surfaces as compared with the darker mottled background rocks on Bennu [5,6]. If these rocks are related on a maturity continuum, it is reasonable to suppose that the older rocks on Bennu are those with darker and more weathered appearance due to exposure to space environment surface alteration processes over time. It would then follow that the brighter, more angular rocks on Bennu are closer to fresh unweathered material. For example, we suggest that the large darker boulder in Figure 1 is an example of the highly space-weathered end-product boulder type on Bennu, and its perched guest (smaller brighter rock) is an example of a recently exposed fresh surface.

Figure 1: A 17m boulder on Bennu at approximately lon. 100E, lat. +20 shows an example of a smaller bright rock on top of a dark boulder [18].

Size-Frequency Distribution: DellaGiustina & Emery [5] showed that the rocks on Bennu can be divided into two populations with separate power-law size-frequency distributions: The higher-albedo
boulders on Bennu (those with radiance factor (I/F, RADF) at normal geometry greater than 6.8%), show a cumulative size-frequency distribution (CSFD) slope of $-4.4 \pm 0.07$, with a longest dimension of about 11 meters. The remaining boulders on Bennu show a CSFD of $-2.5 \pm 0.2$ with a longest dimension of about 60 meters. These data suggest that their formation scenarios differ [5,6,7,8]. Perhaps we're seeing a bimodal distribution of the rocks on Bennu, one that argues for two distinct rock types that may have come from two distinct precursor asteroids, or two distinct regions from one precursor asteroid.

However, the large boulders on Bennu seem to show a continuum in brightness from a low of 3% to highs of ~12-15%. A bi-modal distribution is not observed for these large boulders [5,9]. This suggests that many of the rocks on Bennu (bright and dark) could have the same original composition, but exhibit different amounts of total optical alteration due to space weathering [9,10].

**Other Surface Processes:** Thermal and mechanical weathering (cracking and disaggregation of rocks) are apparently active processes at Bennu’s surface [11,12], and these processes may serve to expose fresh unweathered material over time. This could explain why the brighter rocks found on Bennu tend to be smaller on average than darker rocks that occur with the same frequency [5].

There are several competing mechanisms for resurfacing processes on small bodies: a) impacts and crater erasure by subsequent seismic shaking [7]; b) mass movement created by rotational acceleration (and subsequent geoid) due to YORP [8], c) micrometeorite impacts, d) thermally induced surface degradation [13], d) solar wind ion implantation, and now f) particle ejection and re-impact [14]. All of these processes have the potential to create patterns in spectral/albedo properties on the surface of Bennu, and hence contribute to the story of space weathering on Bennu.

**Summary:** We will summarize evidence from the following lines of investigation and search for a consensus: does a preponderance of the evidence support one rock type or two rock types on Bennu?

(A) A search for transitional examples: due to active thermal and mechanical rock breakdown [11,12], there should be rocks showing both the advanced space-weathered texture on one side, and a brighter less weathered texture on the other side (i.e. on freshly exposed faces) [15].

(B) A census of the bright rocks [9,18]: Bright rocks should differ from dark rocks in placement, albedo and color patterns that are consistent with a maturity relationship, similar to what we observed at Eros and Itokawa, and/or similar to what we find with carbonaceous chondrites in the laboratory [10].

(C) Any spectral or albedo variations that correlate with active surface processes such as cratering, downslope movement, and/or seismic shaking. [5,16].

(D) An inventory of the compositionally distinct lithologies on Bennu [17]. If there are two distinct compositions among the rocks that correlate with morphological or textural properties, this would be good evidence for a two-rock-component model for Bennu.

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**References:**

Introduction: Albedo, spectral slope, and absorption band depth variations exist within and among C-class asteroids and carbonaceous chondrite (CC) meteorites [1, 2]. Spacecraft observations also show that small C-class asteroids (Bennu, Ryugu) can show variations across their surfaces and at depth in terms of albedo and spectral slope. Such spectral variations and differences may be attributable to non-compositional parameters such as differences in viewing geometry and physical properties (e.g., grain size, porosity). To disentangle the spectrum-altering effects of compositional variations from observing conditions and physical properties, we undertook a spectroscopic (0.35-2.5 µm) examination of the Murchison CM2 carbonaceous chondrite.

Experimental Procedure: A 10 gram piece from a ~1kg mass of Murchison was used for this study. Spectra were examined as a function of: (1) viewing geometry; (2) porosity; and (3) grain size. We also discuss previous laboratory space weathering experiments [3].

Results: Below, we first discuss changes or differences in albedo, spectral slope, and absorption band depths as a function of viewing geometry, followed by changes in the context of physical “evolution” of Murchison from an intact bedrock (slab spectra). Selected spectral results are shown on the following page.

(1) Viewing geometry. For a <150 µm powder, spectral changes are controlled by whether the sample is viewed in forward or backscattering geometry. In backscattered geometry, increasing phase angle (p) leads to an initial increase and then decrease in spectral slope, and a general decrease in visible region reflectance (albedo). In forward scatter geometry, increasing phase angle leads to small non-systematic changes in spectral slope, general decrease in albedo, and increase in band depth. For fixed incidence or emission angle and forward or backscattering geometry, albedo and band depth generally decrease and the spectra become more blue-sloped and concave-down.

(2) Slabs versus powders. Saw-cut rough faces of Murchison slabs are bluer-sloped and generally as dark or darker than powders; band depths are variable (regardless of powder grain size).

(3) Slabs with fine-grained powder coatings. As a slab is coated with increasing amounts of fine-grained dust (as may occur during physical weathering of an asteroid), band depths decrease, while albedo and spectral slope show no discernible trends.

(4) Decreasing maximum grain size of powders. As a powdered surface becomes progressively finer-grained, band depths increase slightly and the spectra become redder and brighter.

(5) Increasing fine-grained component. As the ratio of fine (<45 µm) to coarse (500-1000 µm) powder increases, band depths decrease, and the spectra become redder and brighter.

(6) Decreasing porosity. When a powdered sample is compressed (decreasing porosity), spectral variations seem to be sensitive to viewing geometry. At low phase angles (30°), decreasing porosity shows no systematic trends for band depth or spectral slope, but albedo increases. At higher phase angles (90°), band depths seem to increase, and the spectra get bluer and brighter.

(7) Heating. Laboratory heating experiments on Murchison result in significant spectral changes. Progressive heating leads to bluer slopes. Albedo initially decreases to ~600°C, and then increases to higher temperatures. Absorption band depths in the 0.7-1.2 µm region generally decrease, and their shapes and positions also change.

(8) Mineral fractionation. Murchison enriched in specific components show spectral variations. Enrichment of olivine may lead to a slight decrease in albedo and small changes in spectral slope; the most noticeable change is an increase in the depth of the 1 µm region olivine absorption band. For matrix-enriched samples, albedo decreases, spectra become bluer, and the 0.7 µm region absorption band becomes deeper.

(9) Space weathering. Laboratory space weathering of Murchison (pressed powder pellets) [3] showed that increasing space weathering leads to darker and bluer spectra that have reduced absorption band depths.

Summary: Changes in the physical state of CCs can lead to changes in all key spectral parameters (albedo, slope, band depths). However, some diagnostic spectral properties (absorption band position and shape) are unchanged, unless accompanied by changes in composition, such as preferential enrichment of phases, space weathering, and heating.

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Reflectance spectra of saw-cut faces of Murchison.

Reflectance spectra of Murchison with progressive decrease in maximum grain size of a single subsample.

Changes in slope and albedo for the above Murchison grain size series spectra.

Reflectance spectra of Murchison <45 µm powders versus saw-cut fines (>99% <5 µm grain size).

Reflectance spectra of Murchison powder with increasing content of fines (<45 µm) relative to coarse grains (500-1000 µm).

Increase in reflectance and slope with increasing proportion of fine grains (<45 µm) relative to coarse grains (500-1000 µm).
SPECTRAL FITTING WITH THE REXIS SOLAR X-RAY MONITOR (SXM). Andrew Cummings1, Branden Allen2, Jaesub Hong2, Daniel Hoak2, David Guevel2, Jonathan Grindlay2, Richard P. Binzel1, Rebecca Masterson1, Mark Chodas1, Carolyn Thayer1, Madelin Lambert1, Lucy F. Lim3, Dante S. Lauretta4.

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The Regolith X-ray Imaging Spectrometer (REXIS) instrument [1] aboard OSIRIS-REx performs its science objectives by measuring the X-ray fluorescence of Bennu’s surface that is stimulated by the incoming flux of solar x-rays. However the Sun’s variation over the course of minutes-to-hours requires simultaneous solar X-ray monitoring for correct interpretation of the flux received from Bennu. For this reason REXIS is equipped with a Solar X-ray Monitor (SXM) which consists of a silicon drift diode (SDD) and measures incident solar x-ray spectra (see Figure 1).

To model the SXM spectra we employ the Chianti Atomic Database [2], which is the premier resource for calculating the spectral energy distribution emitted by the Sun. The ChiantiPy python library is used in conjunction with the Chianti database to model solar spectra and to determine the best-fit (Figure 2) as a function of time on time scales down to 32 s.

This presentation will show the results for raw solar spectra generated over a range of temperatures between 0.5 to 100 MK and multiple abundances in order to properly characterize X-ray flares whose primary emission originates either in the photosphere or the corona of the sun. Fitting the solar temperature is accomplished by folding the simulate Chianti spectra with the SXM response to produce a series of simulated SXM observations as a function of Chianti input parameters (temperature, flux, solar composition) and then a minimization routine is carried out in order to produce the best fit.

The addition of abundances on the reconstruction of solar X-ray spectra is discussed as are the effects on the error budget of the reconstructed solar spectral parameters.

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Introduction: The shapes of asteroids are a product of their formation and evolution interplaying with their bulk properties. The OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer) [1] mission measured the shape of Bennu using stereophotoclinometry and laser altimetry. Bennu is found to be a highly porous rubble-pile with a top-like shape. Bennu’s surface is dominated by boulders and craters. It exhibits a non-circular equatorial ridge and high-standing longitudinal ridges that, in some instances, span all latitudes. These structures suggest interior strength through friction or cohesive forces. Long surface lineaments and mass-wasting suggest recent surface and, perhaps, interior processes [2,3]. This work focuses on the creation and analysis of the highest resolution global shape of Bennu as produced by the OSIRIS-REx Laser Altimeter (OLA) [4].

The Dataset: In a roughly five-week campaign starting on July 1, 2019, the OSIRIS-REx spacecraft started its global mapping phase. The spacecraft orbited Bennu in a near-terminator orbit with a distance above the surface of approximately 700m. The central goal in this phase was to collect high density topographic measurements of the surface and shape of Bennu using OLA. This dataset will result in the highest fidelity shape and topography of the asteroid from OSIRIS-REx.

OLA executed a series of overlapping scans of angular dimension 183 x 174 mrad, approximately 100 m on the surface, and a nominal point spacing of 100 µrad, approximately 7 cm on the surface. An example of a single scan is shown in Figure 1. These measurements were performed at a rate of 10kHz with a duration of 5.5 minutes. Over the total measurement campaign, 892 scans were collected resulting in almost 3 billion measurements of the surface of Bennu.

The resulting dataset covers the entirety of Bennu. As a result of the polar orbit, the poles have a greater measurement density than the lower latitudes (Figure 2). The average spot spacing is <2cm globally with all but a few outlier locations being covered to <4cm.

The Global Model: The global shape model is created by co-registering the individual scans through the identification and registration of unique surface features in the scan. The scans are rigidly transformed to globally minimize the residuals between the features. Details of this method can be found in Seabrook et al. [5].

Initial results of the registration process are shown in (Figure 3) in the form of RMS deviations in 0.03125 x 0.03125 degree bins Figure 3. This metric is a measure of asteroid surface roughness combined with registration errors.

We will present the final 5cm global model and update the shape parameters of the asteroid from the current parameters estimated from optical imagery listed in Table 1 [3]. We will also survey the morphology of a variety of Bennu’s significant features.

Table 1. Bennu’s main shape parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average radius</td>
<td>244 ± 0.09 m</td>
</tr>
<tr>
<td>Best fit ellipsoid (x)</td>
<td>252.78 ± 0.05</td>
</tr>
<tr>
<td>Best fit ellipsoid (y)</td>
<td>246.20 ± 0.09</td>
</tr>
<tr>
<td>Best fit ellipsoid (z)</td>
<td>228.69 ± 0.12 m</td>
</tr>
<tr>
<td>Volume</td>
<td>0.0615 ± 0.0001 km³</td>
</tr>
<tr>
<td>Surface area</td>
<td>0.782 ± 0.004 km²</td>
</tr>
<tr>
<td>Bulk density</td>
<td>1.190 ± 13 km⁻³</td>
</tr>
</tbody>
</table>
Figure 1: An example of a single OLA scan on the surface of Bennu. This raw point-cloud consists of over 3.3 million measurements and has an average spot spacing of about 7cm.

Figure 2: The spot spacing achieved by the OLA measurement campaign resulted in < 2cm average spot spacing with denser coverage near the poles and sparser coverage at lower latitudes.

Figure 3: A global map of the vertical deviations in 0.03125 x 0.03125 degree bins. (To be replaced with the latest with fewer registration errors.)

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Introduction: OSIRIS-REx revealed that the asteroid Bennu has hundreds of candidate impact craters [1], henceforth called “impact craters” for simplicity. Impact craters provide clues to the physical properties of Bennu’s surface, the age of the surface, and the processes that have shaped Bennu into its present state. They also yield insights into cratering mechanics. Cratering on Bennu occurs in a challenging regime: gravity is very weak [2, 3]; target strength is quite low [2,3], but poorly known, and could vary with depth; target porosity is high [3,4]; and the target surface is very coarse-grained and Boulder-rich [2,5]. Here we assess impact crater depth-to-diameter ratios, d/D, to characterize impact craters on Bennu and better understand impact processes on rubble-pile asteroids.

Methods: The OSIRIS-REx mission produces shape models and DTMs using two primary techniques: stereophotoclinometry (SPC) and the OSIRIS-REx Laser Altimeter (OLA) [4]. We produced regional DTMs of each impact crater using both methods. Two DTMs per crater were derived from SPC (the first based on a model from January 2019 called v20 and the second based on a mature, higher-resolution model from July 2019 called v34); a third DTM was made from individual OLA scans. The SPC DTMs have a ground-sample distance (GSD) of 44 cm (Jan. 2019) and 15 cm (June 2019), respectively. The OLA DTMs have a 10 cm GSD. We focus on craters >10 m in diameter to ensure that the craters are adequately represented in the v20 DTMs. 84 impact craters exceeded this size threshold; 71 were suitable for d/D analysis. Craters were excluded for reasons such as overlap with another depression.

From each regional DTM, we extracted topographic profiles across each crater at eight different azimuths. Rim-to-rim diameter and rim-to-floor depth were determined along each profile. At times, individual profiles were excluded because they passed through an irregularity (e.g. large boulder) on the rim. The remaining profiles were averaged to compute the rim-to-rim diameter, rim-to-floor depth, and d/D for each crater.

The irregular shapes and morphologies of impact craters on Bennu pose challenges to analysis. As a second assessment of crater diameter and depth, we mapped the crater rim in each DTM and determined the best-fit ellipse to the rim. The equivalent diameter of this ellipse provided a second estimate of rim-to-rim diameter. The difference between best-fit plane fit to the mapped crater rim and maximum depth within the ellipse provided a second estimate for rim-to-floor crater depth. The profile- and plane-based methods yield consistent results in most cases. However, given Bennu’s rubble-rich surface, the best-fit plane method more accurately captures the measurement uncertainties.

Results: Impact craters on Bennu have a range of d/D values (Fig. 1). With respect to elevation, d/D varies from 0.06 to 0.27. Craters of a given size can exhibit a range of depths. d/D is not strongly correlated with the latitude or longitude of the crater. The range of d/D in craters depends on crater size (Fig. 2).

![Figure 1. The diameters and depths of craters larger than 10 m on Bennu. As points of reference, dashed lines indicate the d/D ratios for typical terrestrial planets (d=0.2D), the asteroid Eros, and rubble pile Itokawa.](https://example.com/figure1.png)

The v20 and v34 crater DTMs yield similar trends. The additional detail afforded by the v34 topography improved the measurements of the craters smaller than ~20 m in diameter. OLA comparisons are ongoing; for the craters that have had OLA DTMs generated to date, the results from all three DTMs are consistent (Fig. 3).

Discussion: Many craters on Bennu are shallower than the d/D ~0.2 typical of fresh, simple craters on the terrestrial planets. These lower d/D ratios are more
consistent with results from Itokawa [6] and Eros [7]. The $d/D$ ratios of fresh, bowl-shaped impact craters on Ryugu range from 0.14 to 0.2 [8]. While many Bennu craters have $d/D$ within this range (Fig. 2), others, including the largest craters, fall outside this range.

Two fundamental questions emerge from the $d/D$ data. First, why do craters of a given size show such diverse $d/D$ ratios? Second, why do some craters appear to vary with crater size?

The range of $d/D$ ratios for a given crater size could reflect several factors. Variations in degradation are one possibility. Post-impact modification (e.g., infill) could reduce $d/D$; such a process would not explain why some craters are so deep. Future work will include a detailed analysis of $d/D$ on Bennu as a function of crater freshness attributes. That analysis will refine comparisons between the crater populations on Bennu and Ryugu. On Bennu, the steepest slopes are currently located at the midlatitudes [3], but no strong correlation is observed between latitude and $d/D$. A range of $d/D$ may be a natural outcome of impacts into coarse-grained targets, even if cratering efficiency is unaffected [9]. In this regime, changes in the geometry of the first contact between target and projectile, as well as the connectivity of target grains, can create a broad range of outcomes from similar initial impact conditions [10]. Variations in target properties such as porosity and strength affect impactor penetration and coupling [11] and could also lead to a range of $d/D$.

The change in $d/D$ as a function of crater size (Fig. 2) could reflect several factors. If the small, deep craters are the anomalous ones, then some of the factors described above may be at work. However, if the large, shallow craters are the anomalous ones, then the strength of Bennu may increase with depth. An interplay between strength and gravity as a function of crater size [e.g., 12] could also be at work. A more competent layer at depth can lead to crater flattening as seen on the Moon, thereby decreasing $d/D$ [e.g., 13]. Bennu’s shape and topography implies a stiffness [4] that could be consistent with increased strength at depth.

Figure 2. The $d/D$ of impact craters as a function of crater size. The range of $d/D$ values narrows as crater size increases from 10 to ~100 m. The smallest craters (less than ~30 m) are some of the deepest; the shallowest craters are also among the largest.

Figure 3. DTMs (left) and crater profiles (right) from a ~19 m crater at ~63° N 315.07° E. All three DTMs lead to the same $d/D$, within error.

Acknowledgements: This material is based on work supported by NASA under contract NNM10AA11C issued through the New Frontiers Program. We are grateful to the entire OSIRIS-REx Team for making the encounter with Bennu possible.

**Introduction:** With both NASA and JAXA due to return samples from carbonaceous asteroids within the next four years, studies of analogous carbonaceous chondrites are of critical importance to support the analysis of these future returned samples. JAXA’s Hayabusa2 will return samples from asteroid Ryugu, a C-type asteroid, in December 2020 while NASA’s OSIRIS-REx will return samples from asteroid Bennu, a B-type asteroid, in September 2023. Spectroscopic observations of Ryugu compared to laboratory measurements of meteorites suggest it is most consistent with heated CI and heated CM chondrites [1, 2]. In contrast, spectroscopic observations of Bennu indicate it is most consistent with CM chondrites, although a relationship to heated CM [3] or CI chondrites (e.g., [4]) is also possible.

Here we report the preliminary results of detailed coordinated studies of the recent fall Aguas Zarcas (CM2) and the Antarctic find Meteorite Hills (MET) 00639 (shock-heated CM2), which may be petrologically similar to material returned from asteroids Bennu and Ryugu. By studying analogous material prior to sample return we will increase the scientific value of returned samples and constrain the formation and alteration conditions of their parent asteroids.

**Samples:** The brecciated Antarctic find MET 00639 (13.4 g total mass) is part of a larger CM pairing that exhibits platy or shale-like matrix [5] and has been identified as a close spectral match to asteroid Ryugu [2]. Here we report preliminary data from MET 00639 split 7 (thin section) and split 19 (500 mg chip).

Aguas Zarcas fell in Costa Rica on the 23rd April 2019 and currently has a total known mass of 27 kg, providing ample material for many studies, including destructive analyses. Like many other CM chondrites Aguas Zarcas is brecciated [6]. Here we report preliminary data from four samples (both thin sections and powdered chips), two of which were collected prior to rain and two of which were collected after several days of rain.

**Analytical Methods:** Bulk samples of all five samples (one MET 00639, four Aguas Zarcas) were crushed to a grain size of <40 µm and well-homogenized. Aliquots of each powder were then allocated for bulk chemical (H-C-N), modal mineralogy, and other analyses. Aliquots were analyzed for bulk H, C and N according to the method of [7]. Bulk mineralogy was determined for each sample via position sensitive detector X-ray diffraction (PSD-XRD) at the Natural History Museum in London (e.g., [8, 9]).

Backscattered electron (BSE) images and X-ray element maps were obtained on thin sections using a Cameca SX-100 electron probe microanalyzer (EPMA) at the University of Arizona’s Lunar and Planetary Laboratory (LPL). Element maps were used to identify mineral phases for study. Phases identified for quantitative analysis were then imaged in high resolution using the JEOL JXA-8530F Hyperprobe field emission EPMA at Arizona State University (ASU) John M. Cowley Center for High Resolution Electron Microscopy (operating conditions: 20 kV and 15 nA). Quantitative compositional analyses (silicate and opaque phases) were subsequently performed on the LPL Cameca SX-100 EPMA using similar conditions to those reported in [10].

**MET 00639:** Preliminary results from this multi-technique petrographic–isotopic–spectroscopic study suggest that MET 00639 is a highly aqueously altered (close to petrologic type 1) and moderately heated CM chondrite.

**Bulk isotopes.** Bulk isotopes (specifically H-C-N) can be used to classify meteorites but are also indicative of the degree of alteration a sample experienced on its parent body. The bulk H and N isotopic composition of MET 00639 is consistent with type 1.6 on the petrologic scale of [11] (though this is an upper estimate as heating of this sample likely led to H-loss), which is the equivalent of petrologic type 2.0–2.1 on the scale of [12]. Furthermore, bulk H data for MET 00639 indicate that it is moderately heated, some-
where between MET 01072 and MacAlpine Hills (MAC) 88100 (see [11]).

**Bulk mineralogy.** The total abundance of phyllosilicates (secondary alteration minerals including Mg-serpentine and Fe-crostanite), as determined by PSD-XRD, provides a measure of the degree of aequous alteration experienced by extraterrestrial material on its parent body (e.g., [8, 9]). MET 00639 contains ~83 vol.% phyllosilicates and ~12 vol.% anhydrous silicates indicating that it is a highly aequously altered CM1.3 according to the scheme of [9]. In addition, we find that the intensities of the Fe-crostanite peaks in the XRD pattern of MET 00639 are lower than for typical CM chondrites, which could reflect a difference in crystallinity due to partial dehydration.

**Petrography.** MET 00639 exhibits highly variable alteration, with some regions consisting almost entirely of phyllosilicates while others have almost no phyllosilicates (Fig. 1). The overall phyllosilicate abundance is consistent with that determined via PSD-XRD. Chondrules, including FeO-rich and FeO-poor chondrules, are predominantly <500 µm in diameter and commonly possess fine-grained rims. Some chondrules have undergone pseudomorphic replacement of the silicates. Iron metal is very rare (<0.5 vol.%) and exclusively Ni-poor (<7 wt.% Ni). Iron-bearing hydroxide minerals are more abundant and commonly Ni-bearing. Chrome-spinel is subhedral to euhedral, indicating MET 00639 did not experience significant thermal metamorphism (e.g., [13]). All sulfides are compositionally consistent with low-temperature aequous formation (i.e., pyrrhotite has low Fe/S ratios), regardless of the degree of aequous alteration experienced locally in the thin section. These sulfides are consistent with sulfides in the CM1/2 Allan Hills (ALH) 83100 [14].

**Aguas Zarcas:** Preliminary data indicate that the different lithologies within Aguas Zarcas likely experienced variable degrees of aequous alteration and thermal metamorphism on the meteorite’s parent body.

**Bulk isotopes.** Bulk H-C-N abundances and isotopic compositions indicate that Aguas Zarcas is slightly heated and a petrologic type 1.4–1.6 on the scale of [11], equivalent to 2.2–2.4 on the scale of [12].

**Bulk mineralogy.** Preliminary PSD-XRD data indicate that the four Aguas Zarcas lithologies are intermediately aequously altered CM chondrites, with petrologic types CM1.3–1.5 according to the scheme of [9]. The abundance of phyllosilicates and minor phases, in particular tochilinite, vary between the lithologies.

**Petrography.** Fine-grained chondrule rims and phyllosilicates are common in each lithology, though the extent and morphologies of alteration products vary. One lithology is particularly rich in tochilinite. Minor amounts of metal, predominantly Ni-poor, are present in all lithologies, and also detectable via PSD-XRD. Magnetite is more abundant than metal and sulfide combined. Like MET 00639, sulfides in all Aguas Zarcas lithologies are compositionally consistent with low-temperature aequous formation. The compositions of chrome-rich spinel vary significantly between lithologies, though this may be due to sampling bias. Chrome-spinel morphologies are generally euhedral. The average Cr-contents of ferroan olivine vary between lithologies, indicating that they experienced different degrees of thermal metamorphism (e.g., [15]).


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Fig. 1. Back-scattered electron image of MET 00639, 7. Brighter regions are more Fe-rich and more aequously altered (contain abundant phyllosilicates) than darker regions.
Introduction: Fine-grained material is ubiquitous in primitive chondrite meteorites, interplanetary dust, and comet samples. This material can include a wide variety of mineral and carbonaceous phases that existed during the initial phases of the nebular disk (e.g., interstellar grains), condensation phases that formed during disk cooling (e.g., calcium-aluminum inclusions), and exotic phases injected into the solar nebula from extrasolar sources (e.g., presolar grains). Determining the histories of these various materials is complicated by the fact that many of the phases can form via multiple mechanisms. For example, amorphous silicates, which are abundant in the fine-grained matrices of the most unaltered chondrites, have been argued to be an interstellar component or to have formed by nebular condensation (e.g., [1]). Similarly, some nanodiamonds in primitive chondrites contain signatures of a supernova origin [2], yet some researchers have argued that many nanodiamonds may have an interstellar or nebular origin [3,4].

Petrographic context can be key to unraveling the various histories of these primordial components. High resolution microscopy methods are valuable due to the small grain sizes of these components (typically less than 1 µm), particularly techniques that can also provide compositional or chemical information, such as electron energy-loss spectroscopy (EELS) in a scanning-transmission electron microscope (STEM) or X-ray absorption near-edge structure spectroscopy (XANES) in a scanning-transmission X-ray microscope (STXM). Here we highlight recent work using these methods to unravel the complex histories of primitive fine-grained phases in planetary materials.

Methods and Instrumentation: STEM imaging and EELS was performed with an aberration-corrected Nion UltraSTEM 200 at NRL, operated at an electron beam energy of 60 keV to reduce the amount of knock-on damage and H loss in organic samples. The microscope also includes a large angle (0.7 sr) windowless energy dispersive spectroscopy (EDS) detector for measuring sample composition. EELS spectral resolution, as measured by the full-width half-maximum of the zero loss peak, is typically 350-400 meV, providing sufficient resolution to resolve fine structure at the C core-loss edge.

XANES was performed with the STXM instrument at beamline 5.3.2.2 at the Advanced Light Source, Lawrence Berkeley National Laboratory. This microscope uses Fresnel zone plate optics to produce a beam spot around 35 nm, and includes a monochromator grating to select X-ray energies with a precision of 100 meV.

Results: Mapping Aqueous Alteration Microenvironments. The primitive CR chondrite La Paz Icefield (LAP) 02342 contains an C-rich clast with compositional and isotopic affinities to ultracarbonaceous Antarctic micrometeorites [5]. To assess the level of parent body aqueous alteration experienced by this clast, we performed Fe-XANES and C-XANES mapping of focused ion beam (FIB) lamellae extracted from the clast, from the edge of the clast, and from nearby fine grained matrix [Figure 1]. The Fe L-edge contains split peaks that can be used to estimate the ratio of Fe$^{2+}$/Fe$^{3+}$ in Fe-bearing silicates [e.g., 6]. After XANES mapping of the sample, the valence ratio of Fe was quantified using peak fitting and a linear calibration curve between Fe$^{2+}$ and Fe$^{3+}$ endmembers. Fe-bearing materials within the clast were found to contain 20-30% Fe$^{3+}$, while similar phases in the surrounding matrix contained 60-70% Fe$^{3+}$ (as estimated previously [6]). In addition, the range of oxidation state in clast phases was much broader than that of matrix phases.

Figure 1. (a) STXM image of a FIB-extracted lamella from the LAP 02342 C-rich clast, showing the locations of two fine-grained polyphase particles. (b) Fe-XANES of the two silicate grains in (a). Fe valence mapping of the (c) matrix and (d, e) clast lamellae, along with the distribution of Fe valence.
In addition, both C-XANES and C-EELS data reveal that the organic matter within the C-rich clast contained a lower abundance of oxygen-bearing functional groups than that observed in matrix organics. Together, the XANES and EELS data provide a picture of isolated aqueous microenvironments. The homogenously oxidized matrix material is typical of parent body aqueous alteration. However, the clast appears to have been relatively isolated from parent body aqueous fluids, possibly due to the high abundance of organic matter coating mineral phases.

Locating Nanodiamonds In Situ. As mentioned above, presolar nanodiamonds with demonstrable supernovae heritage may be rare within the entire nanodiamond population in chondrites. While individual nanodiamonds may be too small to measure their isotopic composition, if we can identify nanodiamonds in situ, then we may still be able to infer their origins based on the isotopic composition of their host organic matter. To that end, we used C-EELS mapping to identify in insoluble organic matter (IOM) from the Murchison, Elephant Moraine (EET) 92042, and Bells chondrites. The core loss C edge of diamond is distinct from that of other carbonaceous phases, lacking an aromatic absorption at 285 eV and containing a second band gap at 302 eV [7,8]. In addition, the low energy plasmon peak is shifted from 25 eV to 33 eV. Because the plasmon peaks are significantly more intense than the core-loss peaks, high resolution low-loss EELS maps, containing several tens of nanodiamonds or nanodiamond clusters, were obtained from 1 µm² regions in 10-20 minutes [9].

In all three IOM samples, nanodiamonds were only observed within porous IOM, and were absent in dense, non-porous IOM or in globular IOM. Porous IOM represents diffuse organic matter dispersed in chondritic fine-grained matrix, while dense and globular IOM are found as larger carbonaceous particles and veins. Therefore, future in situ work looking for nanodiamonds should target diffuse IOM in FIB lamellae and crushed samples.

Discussion: STEM-EELS and synchrotron-based XANES work together to provide geochemical and petrographic information of primordial planetary materials at the nanoscale. While STXM-XANES can map out an entire FIB lamella, it cannot achieve the sub-nm spatial resolution of an aberration-corrected STEM. Thus, STXM is often necessary for large scale mapping, with STEM providing higher resolution mapping of sub-regions of the sample. However, if low-loss EELS can provide the same information as core-loss XANES (as in the case for locating meteoritic nanodiamonds), then the entire experiment can be performed using STEM. In most cases, STEM-EELS has sufficient spectral resolution to observe chemical features seen in XANES spectra, although beam damage is a known issue for STEM work.

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Fractures in boulders on asteroid (101955) Bennu: Searching for evidence of thermal cracking.


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Abstract: NASA asteroid sample return mission Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) [1] arrived at the near-Earth asteroid (101955) Bennu on December 3rd, 2018 [2]. Images of Bennu, obtained by OSIRIS-REx’s PolyCam instrument [3] at spatial resolution ranging from 33 cm/pixel to a 1 cm/pixel revealed a surface covered by boulders of different sizes, many of which present fractures and exfoliation features [4] that could be indicative of thermal cracking processes. Many studies claimed this process to be active on asteroids and comets [7–9 and ref. therein], but a definitive proof is still missing. Here we present our mapping of fractures on boulders across the surface of Bennu. Our preliminary analysis indicates a preferential direction of the fractures. We discuss how this could be related to thermal cracking i.e. a mechanism of fracture propagation driven by surface temperature variations.

Introduction: Formation and propagation of fractures (cracking) on rocks, which can eventually lead to their exfoliation, breakdown, and rockfalls are important landscape evolutionary process on Earth [5,6], Mars [7], and are claimed to be also important on asteroids [8,9] and comets [10]. Different driving forces can cause cracking, including impacts, stresses from thermal cycling, dehydration, volatile loss, freeze-thaw in presence of water, and variation in regional and tectonic stresses.

Morphology of fractures, their arrangements, and spatial density on rocks, boulders and outcrops may clarify which of the aforementioned processes is dominant on the surface of a given planetary body. Moreover, when a weathering process creates fractures, spatial density and the distribution of the fractured to non-fractured terrain ratio may shed light on relative surface unit ages.

In addition, different types of rocks or geological units can react differently to the process generating the fractures (e.g. impacts, thermal cracking). The distribution of the orientation of fractures may indicate the dominant process at play [6]. For instance, in the case of impact-generated fractures on a randomly oriented boulder population, fractures are expected to have propagated along all possible azimuthal directions. On the other hand, rocks in Earth’s mid-latitude deserts and on Mars present fractures that are oriented in statistically preferred directions [5,7]. Models show that this preferred direction can be due to fractures propagating along a direction forced by the cyclic Sun-induced thermal stresses [8]. Preliminary observations of the asteroid Bennu by OSIRIS-REx [1,2] reveal a body covered with boulders ranging in size from some tens of meters down to a few centimeters that are the spatial resolution of images acquired so far [3]. Some of the boulders are fractured, and some present arrangements consistent with them having broken down in place [2,4,11].

Observations and Methods: We primarily used a series of images obtained by the OSIRIS-REx Camera Suite (OCAMS), with a scale of 5–6 cm/pixel, during the first and third “baseball diamond” flybys of the Detailed Survey mission phase, which occurred on 7 and 21 March 2019, respectively. Other, lower-resolution images were composited into two global mosaics whose x and y coordinates correspond to the longitude and latitude on the asteroid. We used different visualization tools, such as SAOimageDS9 (ds9.si.edu) and J Asteroid (jmars.mars.asu.edu/j-asteroid-and-3d-shapes), to visually identify and map fractures on boulders. We drew line segments along each fracture. When we identified on a single boulder multiple fractures, we mapped each one of these fracture with a different broken line (Fig. 1). This fracture mapping effort was carried out by different co-authors on similar asteroid regions to minimize the biasing effects of having only one person in charge of fracture identification.
Preliminary Results: We will present the global mapping of fractures on the boulders on Bennu. Preliminary results from our boulder mapping indicate that the fractured boulders are a few percent of the total boulder population. It also appears that there is a preferential direction of the fractures. Fracture mapping is still ongoing, at the time of writing of this abstract, and will be completed at the time of the meeting. We will present updated results and discuss the possible preferred direction of the fractures, which likely indicates a preferential fracture propagation mechanism.

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RESULTS FROM SPECTRAL CLUSTERING ANALYSIS APPLIED TO OSIRIS-REx COLOR IMAGES OF (101955) BENNU. J. de Leon\textsuperscript{1,2}, J. L. Rizos\textsuperscript{1,2}, J. Licandro\textsuperscript{1,2}, H. Campins\textsuperscript{3}, M. Popescu\textsuperscript{1,2}, E. Tatsumi\textsuperscript{1,2,4}, D. N. DellaGiustina\textsuperscript{5}, D. R. Golish\textsuperscript{6}, B. Rizk\textsuperscript{5}, D.S. Lauretta\textsuperscript{2}; \textsuperscript{1}Instituto de Astrofísica de Canarias, Tenerife, Spain (jmlc@iac.es), \textsuperscript{2}Departamento de Astrofísica, Universidad de La Laguna, Tenerife, Spain, \textsuperscript{3}University of Central Florida, Orlando, FL, USA, \textsuperscript{4}University of Tokyo, Tokyo, Japan, \textsuperscript{5}Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA.

Introduction: NASA’s OSIRIS-REx spacecraft is currently orbiting primitive near-Earth asteroid (101955) Bennu. The spacecraft is acquiring thousands of images using the OSIRIS-REx Camera Suite (OCAMS;[1]), which includes SamCam, PolyCam and MapCam. Color images are obtained with MapCam, equipped with four filters based on the Eight-Color Asteroid Survey (ECAS,[2]), $b^\prime$, $v$, $w$, and $x$, centered at 473, 550, 698, and 847 nm respectively. These filters permit measuring spectral slopes that can be used to constrain surface composition and identify the effects of space weathering. We have recently validated a spectral clustering methodology to analyze color images based on an unsupervised machine learning tool [3]. In this work we will present the first results obtained after applying this technique to the color images of Bennu, including the highest spatial resolution images (~ 7cm/pix) obtained during the Recon phase.

Methodology: The first step is to photometrically correct the images. To do so, we use the images taken during the Approach, Preliminary Survey, Orbital A, and Detailed Survey mission phases in the four color filters. Photometric angles for each pixel are obtained using ISIS software and the shape model developed by the OSIRIS-REx Altimetry Working Group [4]. We implemented the most commonly used empirical photometric models (Akimov, Minnaert, Lommel-Seeiger and Lambert) with several empirical phase functions [5]. Once the images are photometrically corrected we apply an equirectangular projection to create mosaics. In the case of the global mosaic we will use the photometric corrections following the methodology described in [6]. We run our spectral clustering method on both normalized (at 550 nm) and not normalized color images. We remove from our analysis those pixels that: have reflectance values lower than 0.001 (shadows), are out of the linearity limit of the CCD, and have emission and incidence angles larger than 80°. For the latter case, the photometric model does not work properly.

Results: We have applied our clustering technique to several global mosaics obtained during different flybys, and to specific regions of interest selected as potential sampling sites on the surface of Bennu. As an illustration of our method, we show in Fig. 1 the results obtained for one of the candidate sample sites (24 lat, 330 lon).

![Figure 1](image-url)

**Figure 1.** An example of the clustering analysis carried out using images from Detailed Survey Baseball Diamond Flyby 2 (~ 25 cm/pix). Top panel, left: $v$ filter color image of the selected region for study; Top panel, right: location of the identified clusters over the analyzed area (black pixels are out of the defined limits); Bottom panel: the three representative spectral clusters with their corresponding error bars (standard deviation), using the same color code as in the top panel.

For this particular example we find three distinct clusters in normalized reflectance (at 550 nm) clearly consistent with the albedo variations and the morphology of the terrain. Regions of lower albedo tend to present redder spectral slopes, a behavior that has been observed throughout the entire surface of the asteroid [7]. The clustering technique is particularly sensitive to the presence of shallow absorption features, better identified in the normalized images, once the dominant contribution of the albedo is removed. We will apply this technique to the highest spatial resolution images obtained during the last flyby (Recon phase), including the images of the final four candidate sites for sample collection.
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A GLOBAL COLOR MAP OF ASTEROID BENNU. D. N. DellaGiustina, D. R. Golish, K. N. Burke, E. B. Bierhaus, L. Le Corre, C. A. Bennett, K. Becker, P. H. Smith, B. Rizk, C. Y. Drouet d’Aubigny, H. Campins, H. H. Kaplan, A. A. Simon, V. E. Hamilton, K. J. Walsh, R.-L. Ballouz, E. R. Jawin, J. L. Molaro, M. Delbo, J. L. Rizos, E. Tatsumi, M. Popescu, M. A. Barrucci, J.D.P. Deshapriya, M. Al Asad, B. E. Clark, H. C. Connolly Jr, and D. S. Lauretta; 1Lunar and Planetary Laboratory, University of Arizona, USA; 2Lockheed Martin Space, USA; 3Planetary Science Institute, USA; 4University of Central Florida, USA; 5Southwest Research Institute, USA; 6Goddard Spaceflight Center, USA; 7Smithsonian Institution National Museum of Natural History, USA; 8UCAC-NRS-Observatoire de la Côte d’Azur, France; 9Instituto de Astrofísica de Canarias, Spain; 10LESIA, Observatoire de Paris, France; 11Ithaca College, USA; 12University of British Columbia, Canada; 13Rowan University, USA

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Introduction: The surface of Bennu displays significant albedo and color diversity [1],[2]. In mosaics created from the OSIRIS-REx Camera Suite (OCAMS) [3] MapCam images, boulders are the dominant source of spectro-photometric heterogeneity on the asteroid, but craters also show subtle color trends. Relationships between surface morphology, texture, albedo, and color can provide insight into the composition, structure, and evolution of Bennu’s surface materials. Reflectance (I/F) values of individual boulders range from 3.4% to >20%. Although Bennu’s average terrain is blue-sloped, slopes from the near UV to the near IR vary from negative (blue) to positive (red) at spatial scales <2 m.

Color and Albedo Trends: Studies of Bennu’s surface from PolyCam images taken during the Preliminary Survey phase indicated that bright (>6.5% normal reflectance) boulders are well sorted and primarily exist at smaller sizes (<8 m), whereas dark-to-average (3.4 to 5.5% normal reflectance) boulders are poorly sorted [2]. Notably, Bennu’s 30 largest boulders (>20 m) all have low to average reflectance [2]. MapCam color images from the Detailed Survey phase confirm these findings, and also reveal relationships between color and albedo among Bennu’s boulder population.

Global trends and examination of individual areas show that red units on the asteroid are often darker, whereas smaller, brighter boulders tend to be bluer (Fig. 1). Although albedo and color variation are commonly found between discrete boulders, differences are also observed along the face of individual large boulders (Fig 2). Studying the spectrophotometric changes within a single geologic feature can untangle the relationship between color, albedo, morphology, and exposure age. Certain boulders contain rough, hummocky surface textures and tend to be darker and redder, while smoother boulders tend to be brighter (>30%) and bluer (Fig. 2a). However, in some cases color changes do not correspond to any resolvable textural changes across the boulder surface.

The very brightest areas (>15% reflectance) appear as small boulders (<5 m) primarily in Bennu’s southern hemisphere. These have a distinct w/x band ratio indicative of an absorption beyond 847 nm, which is consistent with the presence of mafic minerals, such as pyroxene or olivine. The substantial albedo and colour deviation of this population of boulders, as well as their rarity, suggests a separate provenance from rest of Bennu’s regolith. Kaplan et al. [4] has shown that these boulders bear pyroxene and have a compositional affinity with the HED meteorites.

Figure 1. The b'/x band ratio (473:847 nm) versus normal reflectance at 550 nm across Bennu. In general, higher albedo areas correlate with bluer materials, as indicated by the best-fit dashed line, but other populations of material are also evident.

We have uncovered preliminary trends among morphology, color, and albedo for the global crater population. Smooth areas of unresolvable fine material (including small candidate craters) are generally lower albedo and redder than Bennu’s average terrain. The observed reddening may be linked to space weathering or can result from particle size effects; decreasing grain size tends to redden and brighten laboratory spectra of CM chondrites (and silicates in general) [5]. The latter brightening effect is difficult to reconcile with the presence of darker, finer material, unless that material is compositionally distinct or contains opaques [5].

Interpretation: Bennu’s population of large boulders (>20 m) could not have originated from impacts on Bennu itself [2]. Instead, crater scaling laws suggest that these blocks are fragments from the catastrophic disruption of Bennu’s parent body and the subsequent rubble-
Asteroid boulders are typically morphologically distinct from the inherited from Bennu’s parent body. These small bright fragmented in situ from the population of boulders by a separate formation mechanism [2]. A statistically distinct population of boulders on Bennu is not yet well constrained, we hypothesize that younger boulders are likely smaller, though the corollary is not necessarily true.

Figure 2. [a] Color and albedo variation across a single boulder (−5°, 250°). MapCam x/b’ and b/v band ratio mosaic (25 cm/pix). Here, negative-sloped areas appear blue and positive-sloped areas appear red. [b] A higher-resolution PolyCam image of this boulder acquired at a similar phase angle as panel a (7 cm/pix). [c] The same boulder acquired by PolyCam at a 40° phase angle at the opposite side of the subsolar point (5.5 cm/pix). Differences in texture and relief on the bright area of this boulder are more visible at these illumination conditions.

Examining the color and albedo across an individual boulder face can further inform this relationship. Some recessed areas on the face of individual boulders have an appearance suggestive of recent exfoliation or fragmentation in high-resolution PolyCam images (Fig. 2b-c); these areas also correspond to albedo and color differences in MapCam data (Fig. 2a). Specifically, surfaces that appear recently exposed are both bluer and brighter than their surroundings on individual larger boulders. If we extend this result to the wider population of boulders on Bennu, we can predict that the smaller, brighter, and commonly bluer boulders are likely younger than the average terrain. Brighter boulders follow a power-law size-frequency distribution that is different from the global distribution and appear to be a statistically distinct population of boulders developed by a separate formation mechanism [2].

Accordingly, we also hypothesize that younger boulder surfaces will be bluer and brighter, and that the population of young boulders on Bennu’s surface has fragmented in situ from the population of boulders inherited from Bennu’s parent body. These small bright boulders are typically morphologically distinct from the dark hummocky-texture boulders, which could also suggest a distinct composition or formation rather than an age relationship.

If low reflectance (<3.5%) boulders are compositionally distinct and more friable than their brighter counterparts, they may be more susceptible to breakdown, and dust on Bennu may contain a higher proportion of fine material from dark red constituents. Dust cover or microscopic roughness could explain why visible reddening does not always correspond to resolvable textural changes across individual boulders. The presence of fine particles may also account for the dark red material found in smooth areas associated with candidate craters. Otherwise the finding that craters are redder than Bennu’s global average spectrum potentially links reddening to freshness, which is a different trend than what is observed for boulder surfaces. This may indicate that multiple space weathering trends are at work on Bennu.

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PHOTOMETRIC PROPERTIES OF RYUGU’S SURFACE FROM BOTH THE HAYABUSA2 NIRS3 AND ONC-T INSTRUMENTS. D. Domingue1, K. Kitazato2, M. Matsuoka3, E. Tatsumi4,5,6, S. Sugita7, Y. Yokota7, R. Honda1, T. Iwata1, M. Abe3, M. Ohtake3, F. Vilas1, and the NIRS3 and ONC Instrument Development Teams.

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Introduction: Photometric studies, as defined here, are the analysis of how the amount of reflected light changes with illumination and viewing geometries. The ability to describe how reflectance changes with incidence, emission, and phase angles provides a mechanism for standardizing observations to a common set of angles, in addition to setting constraints on the physical properties of the optically active portion of the regolith. Understanding and comparing the photometric properties as a function of wavelength (visible versus infrared, for example) also places constraints on the spatial scale of some of the physical properties. We present results, to date, for both the NIRS3 and ONC-T instruments.

Data Sets: The NIRS3 data used in this study were acquired between 30 June 2018 and 28 February 2019, and include observations acquired near opposition. The wavelength range covered in this study is from ~1850 nm to 3100 nm. The ONC-T data used in this study were acquired 3 July 2018 through 8 January 2019, and also include opposition measurements. Images from all seven filters (ranging from 400 nm to 950 nm) were used in the study. These datasets cover much wider ranges of phase angles than the initial reports for NIRS3 and ONC [1, 2]. The NIRS3 data are all disk-resolved while the ONC-T data are predominately disk-integrated observations.

Figure 1. The variation in SSA as a function of wavelength. ONC-T values are in red, NIRS3 values are in blue.

Figure 2. The variation in b as a function of wavelength. ONC-T values are in red, NIRS3 values are in blue.

Analysis: The data from both instruments were analyzed using Hapke’s set of equations [3] and calibrations by [4] for NIRS3 and by [5] for ONC-T. The parameters used included the single scattering albedo (SSA or w), the opposition amplitude (B0), the opposition width (h), the surface roughness (θ), and the single particle scattering function partition parameter (b). The single particle scattering function used was a single-term Henyey-Greenstein function.

Results: The Hapke model parameter values vary as a function of wavelength across both instruments. The graphs below show the single scattering albedo (Fig. 1) and the single particle scattering function partition parameter (Fig. 2) variations. The NIRS3 data is represented by 9 channels, to be comparable with the ONC-T in number of data points over wavelength span (and to show the 2700nm feature effects). The surface roughness value from the ONC-T data set was found to be 32° ± 5.63° across all visible wavelengths, while the surface roughness from the NIRS3 data set was found to be 29° ± 1.68°. These values overlap within the error-bars, however it should be noted that the ONC-T value is based on
disk-integrated data, which maybe affected by the asteroid’s shape [6].

**Discussion:** The incongruity in parameter values with wavelength between the visible ONC-T and infrared NIR3 data are most likely due to the different types of data sets: one is disk-integrated and the other is disk-resolved. Surface roughness values are both high, and are similar within the uncertainties. Both instruments predict a backward scattering regolith, commensurate with the dark, opaque nature seen in the imaging data.

![Figure 3. The ONC-T color spectrum (red) acquired at 0.14° phase is compared with the NIR3 spectrum (blue) acquired at 0.15° phase. The ONC-T is a disk-integrated spectrum, the NIR3 spectrum is the average of five disk-resolved spectra acquired across Ryugu’s surface. A sixth-order polynomial is fit to the entire spectrum across both instruments.](image3.png)

Of interest is examining spectra from both instruments acquired at similar phase angles. The graphs below compare the disk-integrated reflectance from the ONC-T with the disk-resolved reflectance from the NIR3. Within the opposition region (Fig. 3) the visible portion of the spectrum is brighter than the infrared portion of the spectrum. The opposite relation is seen at 18.5° phase (Fig. 4). Thus the opposition amplitude is larger in the visible compared to the infrared, yet note that the single scattering albedo (Fig. 1) shows smaller variation from visible to infrared than the reflectance values. The difference in particle scattering function suggests that Ryugu’s surface is more strongly backward scattering in the infrared than the visible.

What does this imply for the physical properties of the optically active portion of the regolith? From these results we can conclude: 1) the regolith is highly absorbing across both wavelength regions, 2) the opposition amplitude differences imply the illumination of shadowed regions is greater at the 100 nm scale than the 1000 nm. The properties of the scattering centers are either more absorbing in the visible than the infrared, or more forward scattering in the visible than the infrared. The next iteration of this study will be to examine and compare disk-resolved reflectances from both instruments.

![Figure 4. The ONC-T color spectrum (red) is compared with the NIR3 spectrum (blue), both acquired at 18.5° phase. The ONC-T is a disk-integrated spectrum, the NIR3 spectrum is the average of three disk-resolved spectra acquired across Ryugu’s surface. A sixth-order polynomial is fit to the entire spectrum across both instruments.](image4.png)

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**Introduction:** For more than 40 years, members of the International Occultation Timing Association (IOTA) have observed occultations of stars by asteroids, the large majority of them being main-belt objects [1]. Of the over 4000 asteroidal occultations observed between 1999 and 2019, almost all involved asteroids of 30km or more in diameter. As part of IOTA’s process of predicting occultations, an occultation of 7.3-mag. SAO 40261 = HIP 24973 in Auriga by (3200) Phaethon that was observed in 1999 helped us identify Phaethon as a possible source of the strong Geminid meteor shower. Most meteor streams originate from comets, so the mechanism for Geminids originating from Phaethon is unknown. Observations of the July 29th occultation might give new information, but with a diameter of less than 6 km, the path would be hard to predict; would a large campaign even succeed, or be worth the effort, considering that Phaethon’s shape was already determined rather well from radar observations during the close approach in December 2017 [2,3].

**Preparation for the July 29th Event:** The Japan Aerospace Exploration Agency (JAXA) plans to fly by Phaethon in 2025 with its DESTINY+ mission [4]. Tomoko Arai, Principal Investigator of DESTINY+, asked NASA and IOTA to try to observe the July 29th occultation, mainly to resolve uncertainties in the size of Phaethon, and provide an accurate astrometric fix to improve the orbit. The path of the occultation missed most known observatories and cities with astronomy clubs, so all observations would need to be made with mobile equipment; the bright star allowed very small systems to be used. But the occultation would only last half a second, requiring video and CCD observations to obtain accurate enough timings. We wanted to deploy 50 or more stations in a tight “fence” coordinated across four States to catch the fleeting shadow. This required calculations at the milli-arc-second level, and better than 100m for the path on the ground; meeting these requirements necessitated changes in software and consideration of ever smaller effects. Even the difference in the gravitational deflection of light by the Sun, for Phaethon and the star, became significant.

**Deployment for the July 29th Event:** The final plan included 71 stations (63 by IOTA and 8 by SwRI), to be set up by 45 observers (29 from IOTA and 16 from SwRI). With this many stations, the agreed-upon spacing was 680m, covering a range of 45 km. That covered the 3-sigma uncertainty zone plus 10 km on each side, since an event like this had never been tried before, Phaethon had been unobserved after its perihelion passage a few months before, and Phaethon’s orbit is modeled with a small comet-like non-gravitational term that was uncertain for this unusual object. Most stations were deployed north of Las Vegas, NV, while several were deployed in and southwest of the southern San Joaquin Valley in California, and several more south of Pueblo, Colorado where tests showed that the dawn twilight there would be manageable. A number of IOTA observers deployed unattended remote “pre-pointed” small telescopes with video cameras and timers at several sites [5].

**Observations:** The target star was recorded at the right time from 52 stations. 10 stations that were deployed failed to record the target star for one reason or another (only one was clouded out). Another 9 stations that were planned, were not set up, due to 100 “new” AA batteries purchased the day before, needed to power the equipment, were all were dead.

Below is a sky plane plot showing the lines for all stations except the northernmost one, which was 10 km north of the northern (red) line shown. The six positive chords near the center showed that the JPL Horiz-
Zon's solution 702 for Phaethon turned out to be very accurate, showing only about a 2-km south shift from the prediction, a little less than 1-sigma.

The positive observations are shown in more detail in the sky plane figure below; it includes a fit to the radar-determined shape model projected at the time and direction of the occultation. The station numbers for this figure are different from those for the first figure on the previous page. The miss line 40 tightly constrains the fit on the north (upper left) side. In spite of our efforts to space stations apart, stations 13 and 45 on this plot were virtually in line, and reveals a small timing error for one of them. The reason that the chords are virtually the same was because the observers did not take height above sea level into account and they were at very different heights; we knew before the event that an increase in height of 1 km resulted in a shift of the path to the north of 0.48 km, but the prediction map used for selecting observing sites didn’t take this into account. Nevertheless, the coverage of the asteroid was rather good, and will allow a tighter spacing of stations for future occultations.

Other Occultations: IOTA has a Web site showing predictions for future Phaethon occultations [6]. Fifteen stations were deployed in northern Japan for an occultation of an 11.9-mag. star on August 21, but it was very cloudy at all stations so that no observations were obtained. There are some promising events between the abstract deadline and the conference, so we may be able to report more observations at the conference.

Acknowledgments: We thank the many IOTA observers who participated in this event, travelling long distances (3 travelled by air, and others drove their vehicles as much as 4200 miles round-trip) at their own expense, with the full knowledge that most would have no occultation, guaranteeing the success of the overall effort.

OVERVIEW OF OSIRIS-REX THERMAL OBSERVATIONS. J. P. Emery\textsuperscript{1}, B. Rozitis\textsuperscript{2}, P. R. Christensen\textsuperscript{3}, V. E. Hamilton\textsuperscript{4}, C. Haberle\textsuperscript{5}, A. A. Simon\textsuperscript{6}, D. C. Reuter\textsuperscript{7}, M. Delbô\textsuperscript{8}, L. F. Lim\textsuperscript{5}, B. E. Clark\textsuperscript{7}, A. Ryan\textsuperscript{6,8}, S.R. Chesley\textsuperscript{9}, W. V. Boynton\textsuperscript{8}, A. Politi\textsuperscript{8}, M. Westerman\textsuperscript{6}, T. Becker\textsuperscript{8}, R. Garcia\textsuperscript{6}, D. Lambert\textsuperscript{8}, J. Kidd\textsuperscript{8}, E. S. Howell\textsuperscript{9}, M. C. Nolan\textsuperscript{8}, H. L. Enos\textsuperscript{8}, D. S. Lauretta\textsuperscript{8}, \textsuperscript{1}Northern Arizona University (joshua.emery@nau.edu), \textsuperscript{2}Open University, Milton Keynes, UK; \textsuperscript{3}Arizona State University, Tempe, AZ; \textsuperscript{4}Southwest Research Institute, Boulder, CO; \textsuperscript{5}NASA Goddard Space Flight Center, Greenbelt, MD; \textsuperscript{6}Observatoire de la Côte d’Azur, Nice, France; \textsuperscript{7}Ithaca College, Ithaca, NY; \textsuperscript{8}Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ; \textsuperscript{9}NASA Jet Propulsion Lab, Pasadena, CA.

Introduction: NASA’s OSIRIS-REx spacecraft arrived at its target asteroid, (101955) Bennu, in December 2018. The primary objective of the mission is to return a pristine sample from Bennu in order to address fundamental questions, such as: How did the Solar System form? How did life evolve in the Solar System? Are asteroids harbingers of life or death – or both? \textsuperscript{[1]}

Before picking up the sample from the surface, OSIRIS-REx will have spent more than a year characterizing the surface with cameras, spectrometers, and the laser altimeter that are onboard the spacecraft \textsuperscript{[1]}. Surface temperatures at multiple local times of day, orbital positions, and viewing geometries are among the important quantities to be determined and mapped. Global and local surface temperatures are the basis for determining thermophysical properties of the surface, and they inform maps of sampleability, spacecraft safety, and science value of the surface. The thermophysical properties are crucial for studies of the Yarkovsky and YORP effects.

We will present an overview of thermal observations of Bennu by OSIRIS-REx and the associated mission and long-term science goals.

Methods: The primary data set for determining surface temperatures consists of infrared (6–100 \textmu m) spectra from the OSIRIS-REx Thermal Emission Spectrometer (OTES) \textsuperscript{[2]}. OTES is a point spectrometer with a FOV of 8 mrad, leading to a spatial resolution of ~40 m during the main global mapping phase, when the spacecraft is 5 km above the surface. The long-wavelength end of spectra obtained by the OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS; 0.4 to 4.0 \textmu m) \textsuperscript{[3]} is also dominated by thermal emission. As a result, the OVIRS spectra can also be used to determine temperatures. OVIRS is a point spectrometer with a FOV of 4 mrad and a resulting spatial resolution half that of OTES.

Approach and Preliminary Survey Observations: Disk-integrated spectra of Bennu were obtained with OVIRS on November 2 and 3, 2018. During each observing sequence, spectra were collected continuously while Bennu completed slightly more than one rotation. The FOV of OVIRS was scanned in a small zig-zag pattern on November 2, and Bennu was entirely in the FOV for all spectra. The zig-zag pattern was larger on November 3, and Bennu was entirely in the FOV for ~5400 of the spectra.

Disk-integrated thermal radiance measurements of Bennu with OTES were obtained on November 8 and 9, 2018. Pointing remained relatively fixed while Bennu completed slightly more than one rotation, collecting over 8,000 spectra each day. Results from these Approach phase thermal observations are published in \textsuperscript{[4]}. The first spatially resolved observations of Bennu with OVIRS and OTES occurred on December 2, the last day of the Approach phase. The two spectrometers also collected spatially resolved spectra during the Preliminary Survey phase in early-to-mid December 2018. OTES and OVIRS obtained spectra during passes over both poles and the equator. The range to the surface and viewing geometry changed throughout each of these passes. The minimum distance during OVIRS and OTES observations was ~7.3 km, and the maximum was ~12.6 km, corresponding to spatial resolutions of ~30 to 50 m for OVIRS and ~60 to 100 m for OTES.

Detailed Survey: During the Baseball Diamond sub-phase of Detailed Survey (March to April 2019), the spacecraft observed Bennu from various stations having different sub-spacecraft latitudes and local times of day. OTES collected data during all of these stations and OVIRS during the first three. These observations were optimized for imaging, but the ride-along thermal observations enabled production of the first temperature and thermal inertia maps of Bennu.

The Equatorial Stations sub-phase of Detailed Survey (April to June 2019) was designed for global mapping of Bennu at seven different local times of day (3:20 am, 6:00 am, 10:00 am, 12:30 pm, 3:00 pm, 6:00 pm, and 8:40 pm). The spacecraft was positioned above the equator at each local solar time and scanned N-S while Bennu completed a full rotation. We used the diurnal thermal radiance measurements to determine and map the thermal inertia of Bennu at a spatial scale of ~40 m with OTES data and ~20 m with OVIRS data. These maps reveal exciting correlations
between thermophysical properties and geology of the surface of Bennu [5, 6].

Orbital A and Orbital B: Two orbital phases of the mission focused on obtaining data required for developing detailed shape and topography models of Bennu. The orbits for both phases were approximately over the terminator. OTES was turned on for ride-along observations during portions of both phases, but no OVIRS data were collected during these orbits due to limitations in downlink data volume. During Orbital A, the spacecraft was pointed toward the sunlit side of the asteroid, resulting in observations over a range of local times of day. OTES collected data for about five days (Feb 22 – 27, 2019) of Orbital A, during which the spatial resolution of OTES was ~10 m. Coverage is therefore sparse.

During Orbital B, OTES collected data over the course of more than a month (July 1 – Aug 5, 2019). The spacecraft was nadir-pointed during these observations and optimized for laser altimetry measurements, leading most observations to occur at local times of ~6:00 am or 6:00 pm. Orbital B had a lower altitude than Orbital A, leading to a spatial resolution of ~6 m for OTES. Coverage was better than in Orbital A, because of the longer duration of observations, but was still not complete. Nevertheless, these data from the orbital phases are valuable for their better spatial resolution than the Detailed Survey phase.

Reconnaissance: As part of the systematic analysis of the surface that will result in selection of the best site on Bennu to sample, the spacecraft will perform Recon flyovers of four potential sample sites. The thermal analysis goals for these Recon data are to produce measured temperature maps and thermal inertia maps of the sites. From this information, we will also predict the temperature of the surface at the time of sample acquisition. These high spatial resolution local maps will be scientifically valuable for assessment of the variability of thermal properties at small spatial scales on Bennu.

Emission Phase Function: The directional dependence of thermal emission is not very well studied for asteroids. This dependence can affect the inversion of radiance data into thermal inertia and influences the Yarkovsky and YORP effects. The suite of thermal observations described above provided some different viewing geometries, but would not have allowed a detailed analysis of the emission phase function. Several additional observations were conducted to more completely sample the global emission phase function. These included E-W scans from above the equator after several of the Equatorial Station observations and E-W zig-zag scans at mid-latitudes during two of the transit legs between equatorial stations. Figure 1 shows an example of the emission angle and azimuth angle coverage at a certain time of day (~3:00 pm) at the equator. Similar plots at other times of day and latitudes reveal good overall coverage for studying Bennu’s emission phase function.

Summary: The OSIRIS-REx mission is providing a wealth of thermal data of Bennu. Both spectrometers have returned excellent thermal radiances that reveal boulders with a much lower thermal inertia than anticipated prior to arrival. The Hayabusa2 mission is finding Ryugu to be a similarly fascinating asteroid in terms of its thermophysical properties [e.g., 7,8]. Analyses are just beginning to mine the deep potential of these thermal data.

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INVESTIGATING THE LINK BETWEEN CHONDRITES AND THEIR ASTEROIDAL PARENT BODIES.
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Introduction: Reflectance spectroscopy is currently the main measuring method for the remote characterization of asteroidal bodies besides the laboratory characterization of asteroidal samples collected through space missions. It is thus important to improve the understanding we have of the different spectral features observed in the asteroidal reflectance spectra. As these features are generally very faint [e.g., 1] in the 0.45 - 2.45 μm spectral region, this task becomes increasingly difficult. Analyzing the reflectance spectra acquired for different carbonaceous and ordinary chondrite types in the laboratory allows to further interpret the asteroidal spectra and establish some genetic links between meteorites and asteroids. This has been the subject of several papers in the past [e.g., 2]. Here we are taking advantage of a new spectro-radio goniometer available at IPAG [3] to measure a large set of samples with a well-constrained post-accretion history. Our objectives are to (i) deepen our understanding of spectral features, (ii) understand if some of these features are controlled by secondary processes such as thermal metamorphism, and (iii) establish some genetic link between asteroids and chondrites, that are in some cases only very faint.

Samples and Methods: In this work a total of 21 CV chondrites, 15 CO chondrites, 4 CR chondrites and 19 Unequilibrated Ordinary Chondrites (UOC) are measured using the SHADOWS instrument [3]. The measurements are done on powdered bulk material in the 0.4 – 4.2 μm spectral region, at 80°C and under vacuum (P < 10^-4 mbar). These measuring conditions significantly improve the quality of the spectra. The selected samples feature a wide range of metamorphic grades, that were previously determined through Raman spectroscopy [4]. Following previous works [e.g., 2] a set of well-defined spectral properties, including absorption band depths, positions and spectral slopes, are considered to describe the individual whole-rock reflectance spectra. Additionally, 17 mean reflectance spectra from the asteroidal belt [1] of the types A, C, Cg, Cgh, Ch, K, L, O, Q, R, S, Sa, Sq, Sr, Sv, V, and Xk, 24 EOS family member spectra [5] and 8 CK chondrites (RELAB database (http://www.planetary.brown.edu/relab/)) were treated in the same way as the other chondrites and added for comparison purposes.

Results and Discussion: A large variability in the reflectance spectra of chondrites of the same group is observed. On the other hand, there are clear differences in the reflectance spectra of different chondrite groups. For example, UOCs systematically exhibit deeper absorption features which are located at lower wavelengths in comparison to carbonaceous chondrites. Type 2 CR chondrites exhibit absorption features in the 1000 nm region at even lower wavelengths than UOCs, thus clearly separating them from type 3 chondrites. On the other hand, none of the considered spectral parameters allow to separate CV and CO chondrites. This is not surprising due to their comparable mineralogical composition [6].

Several spectral features appear to be controlled by the metamorphic grade of the samples. The depth of the 1000 nm absorption band becomes indeed deeper with increasing metamorphic grade along the considered series of CV chondrites. This was not observed previously [2]. This apparent discrepancy might be related to the significantly greater number of CV chondrites considered in this work. To be noted, this correlation is not observed for the other chondrite groups. The absence of the trend within the considered CO chondrites might be explained by their metamorphic grades which are systematically lower than those of the considered CV chondrites. Perhaps it is only above a given metamorphic temperature that sufficient chemical modification of olivine [7] occurs resulting in significant spectral changes. For CO chondrites, the 2000 nm absorption feature becomes deeper with increasing metamorphic grade of the samples possibly due to the transfer of iron in the pyroxene in chondrules. This trend is absent for other chondrite groups.

For UOCs, the visual slope becomes less steep with increasing metamorphic grade. Interestingly, two specific trends are observed. The cause of this dichotomy is not understood yet. A possible explanation, still to be investigated, could be the metal content in the sample. The spectral slope in the 2000 nm region seems to be negatively correlated to the metamorphic grade for all samples indicating a decrease in pyroxene content with increasing peak metamorphic temperature [2,4].

The comparison of spectral features of asteroids and chondrites led to a good match between the following types: S-type asteroids have similar 1000 nm and 2000 nm absorption band depths as ordinary chondrite samples. This is expected [8], and legitimates our approach. The parent bodies of CK and CV/CO chondrites have previously been suspected to be K-type asteroids, particularly EOS family members [e.g. 9]. This genetic affiliation is confirmed by our data for CK
chondrites which exhibit similar 1000 nm and 2000 nm absorption features as K-type asteroids. For CO/CV chondrites the absorption band depths and 1000 nm absorption band position match those of the EOS family but also those of L-type asteroids (Fig. 1). The link between Calcium-Aluminum-Inclusion (CAI) rich chondrites and L-type asteroids has been suggested in previous works before [10,11].

Figure 1: 1000 nm spectral band depth over the 2000 nm spectral band depth. Comparison of chondrites with asteroids.

THE BENNU EPSHMERIS BASED ON OSIRIS-REX DATA THROUGH ORBITAL B. D. Farnocchia¹, S. R. Chesley¹, Y. Takahashi¹, B. P. Rush¹, N. Mastrodemos¹, D. Vokrouhlický², B. Rozitis³, J. P. Emery⁴, A. B. Davis⁵, B. M. Kennedy¹, J. Bellerose¹, D. P. Lubey¹, D. Velez¹, D. S. Lauretta⁶, ¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA (Davide.Farnocchia@jpl.nasa.gov), ²Charles University of Prague, Prague, Czech Republic, ³The Open University, Milton Keynes, UK, ⁴University of Tennessee, Knoxville, Tennessee, USA, ⁵University of Colorado, Boulder, Colorado, USA, ⁶Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA.

Introduction: The orbit of the near-Earth asteroid (101955) Bennu is well-constrained from ground-based observations. The wealth of ground-based optical and radar data collected since the Bennu discovery in 1999 over about 15 years allowed an estimate of the semimajor axis accurate to within 20 m. These data also allowed a 200-σ detection of the Yarkovsky effect acting on Bennu as well as deterministic ephemeris predictions through the Earth close approach in 2135 [1].

OSIRIS-REx data: The OSIRIS-REx mission to Bennu [2] has provided data that further constrain the asteroid’s trajectory to an unprecedented level. On 2018-08-17 Bennu was first detected with OSIRIS-REx’s PolyCam [3], and optical navigation measurements [4] during the Approach phase constrained the location of Bennu in the OSIRIS-REx plane of sky to within a few kilometers [5]. Upon arrival, the OSIRIS-REx spacecraft started operating in Bennu's proximity. During Preliminary Survey, Orbital A, Detailed Survey, and Orbital B radio ranging data [6] to OSIRIS-REx constrained the distance between Earth and Bennu to within a few meters from December 2018 to August 2019.

High-fidelity trajectory modeling: While these data greatly improve the knowledge of Bennu's trajectory, they also require high-fidelity modeling of the perturbations affecting Bennu's motion. For example, the fit to OSIRIS-REx ranging data is sensitive to short-term perturbations caused by the Yarkovsky effect, which depends on Bennu's thermal inertia. Therefore, accurately tracking the motion of Bennu provides an indirect, but completely independent, estimate of Bennu’s thermal inertia that can be compared to OSIRIS-REx’s direct thermal measurements [7]. Even errors of few degrees in the Bennu rotation pole cause errors in the Yarkovsky modeling that are visible in the fit to the ranging data. Moreover, radiation effects such as the Poynting-Robertson drag [8], so far only considered for interplanetary dust dynamics, now become a consideration for modeling the trajectory of a 500-m asteroid.

Hazard assessment: Bennu is a potentially hazardous asteroid and, based only on ground-based data, there is about 0.04% probability of an Earth impact between 2175 and 2196 [1]. We will show how the OSIRIS-REx mission data through the Orbital B phase change the statistical assessment of the possibility that Bennu reaches the Earth late in the 22nd century. Given the formal precision achieved on the Bennu orbit estimate, systematic modeling errors become a consideration. Special care must be taken in assessing the errors caused by the uncertain masses of perturbers as well as the path delay calibration for the OSIRIS-REx spacecraft antennas. While many potential impacts previously detected can now be ruled out, we identify those that might persist and refine the estimated impact probability.


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A SEARCH FOR THE NEAR-INFRARED SPECTRAL SIGNATURE OF BRIGHT BOULDERS ON OSIRIS-REX TARGET ASTEROID (101955) BENNU. S.M. Ferrone¹, B.E. Clark¹, H. Kaplan², X. Zou¹, R. Ballouz², C.A. Bennet³, D.N. DellaGiustina⁴, K.N. Burke⁴, D.R. Golish⁴, K. Becker⁴, A.A. Simon⁴, D.C. Reuter², V.E. Hamilton², G. Poggiali⁵, A. Praet¹, J.D.P. Deshapriya⁶, A.M. Barucci⁷, D. Trang⁴, and D.S. Lauretta⁴, ¹Ithaca College, Department of Physics and Astronomy, Ithaca NY, 14850 (sferrone@ithaca.edu), ²Southwest Research Institute, Boulder, CO, ³Planetary Science Institute, Tucson, Arizona, ⁴Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, ⁵Goddard Space Flight Center, Greenbelt, MD, ⁶INAF Arcetri Observatory, Florence, Italy, ⁷Paris Observatory, Paris, France, ⁸Hawai‘i Institute of Geophysics and Planetology, University of Hawai‘i, HI

Introduction: The Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) is a NASA New Frontiers asteroid sample return mission. The OSIRIS-REx spacecraft is equipped with a suite of scientific instruments to characterize the surface of the target asteroid (101955) Bennu [1], including the OSIRIS-REx Camera Suite (OCAMS) [2] and the OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS) [3]. OCAMS’ high spatial resolution images of Bennu’s surface facilitate the identification of regions of interest, characterization of surface morphology, and mapping of relative surface albedo [2]. OVIRS is a point spectrometer that measures surface composition [3]. The OVIRS footprint during the Detailed Survey phase of the mission has field of view diameter of 14 to 20 m/spectrum.

We compare the OVIRS data (high spectral resolution) with an OCAMS global mosaic (high spatial resolution) and find spatially consistent variations in albedo [4, 6]. The lower albedo (~4%), regions of interest span areas that are larger than the OVIRS spectrometer footprint. Kaplan et al. 2019 [7] show the spectral trends in OVIRS spectral data of dark areas and DellaGiustina et al. 2019 [6] show spectro-photometry trends of these dark regions with the color imaging data from the OCAMS instrument. However, there are many higher albedo features having ~12-15% albedo that are much less spatially expansive than the dark regions, with size scales on the order of a few centimeters to 5 meters—all of which are smaller than the OVIRS field of view.

In this study, we search for the best expression of the sub-field-of-view spectral characteristics of the brighter boulders on Bennu. Our goal is to find out if there are correlations between boulder geological and spectroscopic properties. Our research question is: what are the spectral differences between the bright and dark rocks on Bennu, and are the differences consistent with other evidence of space weathering on Bennu, or not.

We have a 3-pronged approach: (1) We complete a census of OVIRS spots on the biggest bright boulder regions (those that approach 25 to 50% of the spot size). (2) We invert the above census and complete an inventory of the brightest OVIRS spots on Bennu and catalog what the imaging reveals about those spots. (3) We conduct a global study of the albedo distributions of the OVIRS data, using photometrically corrected brightness values. Here, we describe these three approaches and present initial results from the 3rd approach.

Data Summary: The OCAMS images were mosaicked to create a global basemap, and photometrically corrected to standard viewing geometry (incidence = 30°, emission=0°, phase=30°). Likewise, the global OVIRS data from the third equatorial station of the Detailed Survey were photometrically corrected to the same geometry.

Methods: For the global approach, we have started by viewing the distributions of spectral and geological quantities between three albedo populations (high, moderate, and low). For the inventory approaches, we create a census of images of the bright boulders that fall within the OVIRS field of view.

Albedo populations. We partitioned the data into three different albedo populations; high, moderate, and low. To define the three populations, we computed a mean and standard deviation of the albedo of all OVIRS observations from the third Detailed Survey station. The high and low albedo populations are greater than and less than one standard deviation of the mean, respectively. There are 942 high albedo OVIRS observations, there are 1040 low albedo OVIRS observations, and there are 5111 moderate albedo OVIRS observations. We compare the three different populations in terms of their spectral and geological characteristics. Figure 1 shows the visible-near infrared slopes of the different populations.

Census. The positions of the rocks with highest albedo were recorded during a global boulder mapping campaign [5]. In the census we conducted, we searched for OVIRS spectra that cover those boulders. In the inverted census, we find the positions of the OVIRS footprints from the high and low albedo populations. We then look at OCAMS’ imaging data to characterize
the properties of the boulders that fill the OVIRS field of view.

![Figure 1: VIS-NIR slope values of three different albedo populations binned into probability density functions with their respective best-fit Gaussians.](image)

**Initial Results and Future Work:** In Figure 1, we show that high and moderate albedo regions on Bennu have VIS-NIR continuum slope values that are normally distributed with the high albedo regions being the most blue in slope. We find that the low albedo regions have the reddest slopes on Bennu, and their distribution is not well described with a Gaussian curve fit. The skewness and red slope of the low albedo population could be due to compositional differences and/or alteration of the brighter material by space weathering processes.

Our census is work in progress. As part of the census we note any smooth rock faces, unique textures, unusual boulder sizes, etc. We hope to search for correlations between geological features and OVIRS spectral features as well as determine if there are rock types that are unique to one albedo population and not another. Correlations between spectral features and rock textures may help to explain the spectral variations we observe on Bennu, and they will also help to constrain the nature of space weathering spectral signatures, if they are detected on Bennu.

**Acknowledgements:** This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program. INAF participation was supported by Italian Space Agency grant agreement n. 2017-37-H.0. US Antarctic meteorite samples are recovered by the Antarctic Search for Meteorites (ANSMET) program, which has been funded by NSF and NASA, and characterized and curated by the Department of Mineral Science of the Smithsonian Institution and Astromaterials Acquisition and Curation Office at NASA Johnson Space Center.

Introduction: Comets are primitive small bodies witness of the Solar System formation. Together with asteroids, their study provides important insights on our Solar System formation, composition, and evolution processes. Moreover, comets and primordial asteroids like the B, C and D types, whose composition experienced small changes since their formation, have a high biological importance because they may have enriched our planet of organic and volatile materials favoring the appearance of life.

The deepest investigation of a comet nucleus was recently performed thanks to the Rosetta mission. Launched on 2 March 2004, Rosetta arrived on August 2014 at its target, the comet 67P/Churyumov-Gerasimenko (67P hereafter), and had orbited around it for more than 2 years from 4 AU inbound, to the perihelion passage (1.37 AU) and up to 3.6 AU outbound.

We will present an overview of the main results achieved by the Rosetta mission on the surface, activity, and evolution of comet 67P [1]. These results, coupled with those obtained on Bennu and Ryugu, currently under study by the sample return missions OSIRIS-REx and HAYABUSA2, will cast light on the interpretation of our Solar System formation and evolution, and on the contribution of the small bodies to the appearance of life on the Earth.

Geomorphology and physical properties: The 67P’s nucleus has a peculiar bilobated shape (Fig. 1) with a surface characterized by a variety of astounding morphological regions including both fragile and consolidated terrains, dusty areas, depressions, pits, boulders, talus, fractures and extensive layering, with layers up to 1 km in length and having a depth up to 650 m (2, 3). Twenty-six regions were defined (3, 4). The nucleus bulk density is 537.8±0.7 kg m$^{-3}$ and the rotational period is 12.4043±0.0007 h (1, 5). The low density implies a large value of porosity of 70–80%.

The study of the extensive layering revealed that the layers of the main lobe are independent from those of the small lobe, indicating that the comet is a binary object resulting from the collision at low velocity (1 m/s) of two bodies in the primordial Solar System.

The comet surface is dark, with a geometric albedo of 5.9 % at 535 nm (6). Important phase angle reddening effects, i.e. the increase of spectral slope with phase angle, were observed since the first resolved images of the comet, and attributed to the increased contribution of the multiple scattering at large phase angles as the wavelength and albedo increase, plus a contribution of surface roughness effects. The phase reddening effects were observed to change and evolve, together with the surface color, with the heliocentric distances, reaching a minimum at perihelion, where the high activity removed part of the dust mantle.

A number of localized morphological changes were reported for several regions of 67P during the mission. A region with extensive changes is Imhotep, which showed exhumation of structures (boulders and roundish features) by the removal of 4 m dust coating and the appearance of two roundish structures with a diameter of ~240 and 140 m and a height of 5±2 m (7, 8). Extensive changes were also observed in the Aswan site, with a cliff collapse originated from an outburst producing a mass loss of ~$10^6$ kg and exposing water-ice (9). Cliff collapses with exposure of water ice were also observe in the Anhur region (10). Other morphological changes include the sublimation of some thick dust layers (up to 10-15 m in depth) in Anhur, Khonsu and Imhotep (10, 11), and boulder displacements in Khonsu and Anhur region (7, 10, 11). However, even though numerous localized changes were reported, they did not substantially change the cometary landscape, which was very probably shaped much earlier in its history (7).

Boulders of various sizes have been observed on the nucleus, with a cumulative size-frequency distribution represented by a power-law with index of -3.6
globally on the nucleus [12]. Differences in the boulders cumulative size distribution are observed in some areas, notably the smooth Hapi region. The southern hemisphere has a larger number of boulders per km² than the northern one, consistent with stronger activity, erosion and thermal processes in this hemisphere, which is illuminated during the perihelion passage.

The 67P’ nucleus surface composition: The OSIRIS cameras and VIRTIS spectrometer have shown that the 67P nucleus has a red spectral behavior with spectral properties similar to those of bare cometary nuclei, of primitive D-type asteroids like the Jupiter Trojans, and of the moderately red transneptunians population (2, 13). The surface is globally dominated by dehydrated and organic-rich refractory materials (13) showing a broad signature in the 2.8-3.6 micron region, and shows some color heterogeneities at different spatial scales. Three kind of terrains, from the spectrally bluer and water ice enriched terrains to the redder ones, associated mostly to dusty regions, have been identified by visible spectrophotometry (6).

Although water is the dominant volatile observed in the coma, exposed water ice on the cometary surface has been detected in relatively small amounts (a few percent) in several regions of the comet (14, 15), and in higher amounts (> 20%) in localized fresh ice patches (16, 9). In the Anhur region there was also the first and unique detection of exposed CO₂ ice (17).

Water frost was observed close to the morning shadows in several regions, putting in evidence the diurnal cycle of water (14, 16). Seasonal color and spectral variations have also been observed when the comet approached perihelion, indicating that the increasing activity had progressively shed the surface dust, partially showing the underlying ice-rich layer (16).

The comet nucleus is largely dominated by the refractory material. In fact, the average dust/ice mass ratio is 7.5 inside 67P. Fulle et al. [18] deduced that the nucleus is composed of a mixture of (20 ± 8) % of ices, (4 ± 1) % of Fe sulphides, (22 ± 2) % of silicates and (54 ± 5) % of hydrocarbons, on average volume abundances.

The 67P/CG dark terrains are interpreted as made of a complex mixture of dark disordered poly-aromatic compounds, opaque minerals and several chemical species containing -COOH, NH₃⁺, CH₂ / CH₃, -OH (19). The organic rich nature of the 67P nucleus was confirmed also by the results of ROSINA mass spectrometer and COSIMA dust grain analyzer [20, 21, 22]. In fact, more than 60 molecules were detected by Rosina, including complex organics compounds and glycine, the simplest amino acid. Rosina also determined a D/H ratio of 67P three times higher than that of the Earth water (19).

The fact that the 3.2 micron band is ubiquitous (13) on the surface of 67P/CG, and that the erosion rate is important and estimated to be of 1.0±0.5 meters per orbit, globally averaged (23), and even higher locally (~15 m in places) is a clear evidence that the composition of the material at the surface is representative of the non-volatile component of the bulk material and not the result of surface alteration due to space weathering.

Summary: We will present the main results on the 67P nucleus obtained by the Rosetta mission, and we will compare them to those of the 2 primitive NEA Bennu and Ryugu, under investigation by the OSIRIS-REx and HAYABUSA2 missions.

**Introduction:** Vesta and Vesta-like asteroids have been convincingly linked, through spectral analysis, to a clan of basaltic achondritic meteorites – howardites, eucrites, and diogenites (HEDs) [1], [2], and [3]. The pyroxene present in the HEDs create, due to Fe²⁺ electronic transitions, two broad absorption features, called Band I and Band II, with minima near 0.9 and 1.9 µm, respectively (Figure 1). Band I Centers (B1Cs) and Band II centers (B2Cs) are useful parameters for calculating the pyroxene mineralogies of the HEDs.

Using a sample of 13 HED meteorites with laboratory measured mol% Fs (ferrosilite) and mol% Wo (wollastonite) values and spectrally measured B1Cs and B2Cs, Burbine et al. established a set of calibration equations, hereafter, the Burbine equations, linking spectrally measured B1C and B2C values to mineral chemistry [2], [3], [4]. The Burbine equations rely on reflectance spectra with sufficient wavelength coverage to completely identify Band I. Ideally, these equations can be used to extract mineralogical information from Vesta-like asteroid spectra. However, the wavelengths covered by near-infrared observations of asteroids are often limited by the available near-infrared spectrometers available for asteroid observations. Commonly, reliable spectral data shortward of 0.8 µm are not available. In these cases, either follow-up observations with a visible light spectrometer are required, or a new set of calibration equations to a more limited wavelength range are necessary. Otherwise, the current calibration equations may lead to erroneous mineralogical interpretation. We refer to this as the “Blue Edge Problem.” The Blue Edge Problem is similar to the previously studied Red Edge Problem [5], with some notable exceptions: one, it focuses on the short wavelength portion of the spectra, rather than the long wavelength portion; two, the Red Edge paper dealt with ordinary chondrites rather than HEDs; and three, we focus on the mineral chemistry (mol% Fs and Wo) of pyroxene. We derive new calibration equations for the molar contents of ferrosilite and wollastonite that can be used on the aforementioned spectra whose wavelength range is limited.

**Data:** The same 13 HEDs (Bouvante, EETA79005, EET 87503, EET 87542, EET 90020, Johnstown, Juvinas, LEW 87004, Pasamonte, Petersburg, PCA 82502, Stanner, Tathouine) used in [4] are used for this analysis. The reflectance spectra came from the RELAB database [7], and the average pyroxene chemistries came from EMPA (Electron Microprobe Analysis) [8].

**Methods:** The visible and near-infrared (VNIR) wavelengths relevant to this research range from 0.7 µm to 2.5 µm. The short-wavelength edge of Band I, referred to here as the “blue edge,” has been historically defined as the reflectance maximum near 0.75 µm, referred to here as the “real” blue edge. The long-wavelength edge of Band I is defined by drawing a straight-line continuum from the blue edge to a point that lies tangent to the spectrum shortward of the reflectance maximum near 1.5 µm. The B1C is defined as the minimum of the Band I absorption feature, after having dividing out the straight-line continuum. Since there is a non-zero slope for the continuum, dividing the absorption band by the slope shifts the wavelength location of the band minimum. Therefore, the blue edge, on which the continuum relies, is critically important to extracting the B1C. The short-wavelength edge of Band II is defined as the reflectance maximum near 1.5 µm, and the long-wavelength edge (the red edge) of Band II has no universally and easily-determined value, so we chose three for this study which reflect common usage, including the ones used for the analysis of the Red Edge Problem [5].

In order to calculate new calibration equations, we use the real blue edge, and impose a blue edge of 0.8 µm, to determine two separate B1Cs, and we impose red edges of 2.5, 2.45, and 2.4 µm to determine three separate B2Cs. We use the IDL-based Spectral Analysis Routine for Asteroids (SARA) [6] to determine the band parameters. SARA measures band centers using the average of 3rd-, 4th-, and 5th-order polynomial fits to the bottom half of Band I and the entirety of Band II. All of these results are compared to the older set of Burbine et al. 2009 [3] calibration equations, as well as the recent 2018 Burbine equations [2] (Figures 2 and 3).

**Results:** Using the B1Cs and B2Cs for the 13 HED meteorites, we empirically derived a total of 10 new calibration equations for asteroids with V-type spectra. The “real” and 0.8 µm blue edges each give two calibration equations relating B1Cs to mol% Fs and Wo. The three red edges each give two calibration equations relating B2Cs to mol% Fs and Wo. For the “real” blue edge, we find calibration equations almost identical to those derived by Burbine et al. For the Band 2 red edge at 2.5 µm, we find a calibration
equation that differs from the Burbine equations. The discrepancy is due to the Burbine equations not dividing Band 2 by its continuum prior to finding the band minimum. The entire set of 10 equations with their R^2 values are given in Table 1.

Conclusions: We derived ten new calibration equations for the molar contents of ferrosilite and wollastonite using B1C and B2C. In order to determine mineralogical information of Vesta-like asteroids, we suggest using the calibration equations that most closely correspond to their methods used to determine B1Cs and B2Cs.

Figure 1: The howardite EET87503 spectrum showing different blue and red edges. The vertical blue dashed line is the “real” blue edge, the purple is the 0.8µm blue edge, and the red is the 2.4µm red edge. The colored wedges represent the portions of band areas lost due to the clipped edges. This plot is a modified version from SARA’s output.

Figure 2: Two different calibration equations for mol% Fs. The red line is for the real blue edge [4], and the blue line is for the imposed 0.8 µm blue edge. The data points are 13 HEDs from [4].

Figure 3: Two different calibration equations for mol% Wo. The red line is for the real blue edge [4], and the blue line is for the imposed 0.8 µm blue edge. The data points are 13 HEDs from [4].

Table 1:

<table>
<thead>
<tr>
<th>Blue Edge</th>
<th>Mol% Fs Equation</th>
<th>R^2</th>
<th>Mol% Wo Equation</th>
<th>R^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>real</td>
<td>y=1023.43*B1C-913.84</td>
<td>0.853</td>
<td>y=396.13*B1C-360.56</td>
<td>0.881</td>
</tr>
<tr>
<td>0.8 µm</td>
<td>y=1451.75*B1C-1316.13</td>
<td>0.808</td>
<td>y=585.55*B1C-538.41</td>
<td>0.906</td>
</tr>
<tr>
<td>Red Edge</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 µm</td>
<td>y=239.84*B2C-429.74</td>
<td>0.911</td>
<td>y=90.23*B2C-168.04</td>
<td>0.889</td>
</tr>
<tr>
<td>2.45 µm</td>
<td>y=250.84*B2C-450.49</td>
<td>0.915</td>
<td>y=93.82*B2C-174.76</td>
<td>0.882</td>
</tr>
<tr>
<td>2.4 µm</td>
<td>y=263.07*B2C-473.03</td>
<td>0.901</td>
<td>y=100.03*B2C-186.42</td>
<td>0.899</td>
</tr>
</tbody>
</table>

Photon Factory BL-19: a new STXM beamline with wide energy range for Aquaplanetology. K. Fukushi, Y. Takeichi, H. Suga, Y. Kebukawa, D. Wakabayashi, S. Yamashita, M. Kimura, and Y. Takahashi, Institute of Nature and Environmental Technology, Kanazawa University (Kakuma, Kanazawa, Ishikawa 920-1192, Japan and fukushi@staff.kanazawa-u.ac.jp), 2Institute of Materials Structure Science, High Energy Accelerator Research Organization (Oho 1-1, Tsukuba 305-0801, Japan and yasu.tokeichi@kek.jp, daisuke.wakabayashi@kek.jp, shohei.yamashita@kek.jp, masao.kimura@kek.jp), 3Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo (Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan and hiroki-suga@eps.s.u-tokyo.ac.jp), and 4Faculty of Engineering, Yokohama National University (79-5 Tokiwadai, Hodogaya-ku, Yokohama 240-8501, Japan and kebukawa@ynu.ac.jp).

Introduction: Scanning transmission X-ray microcopy (STXM) frequently employed at soft X-ray energy region has been used for the distribution of various elements with a spatial resolution around 30-50 nm. In particular, coupling of STXM with X-ray absorption near-edge structure (XANES) spectroscopy enables us to determine chemical species of the elements such as distribution of functional group of carbon and oxidation state of iron with high spatial resolution. This novel characteristics having high spatial resolution and rich chemical information that cannot be obtained by other methods is quite useful for the analysis of extraterrestrial materials with high heterogeneity such as meteorite [1] and comet [2]. Due to its unique characteristic as an imaging tool of functional group of carbon and chemical species of other elements, STXM is regarded as an important tool to study returned samples from Ryugu by the Hayabusa2, which is likely to have similar characteristics to CM or CI group carbonaceous chondrite meteorites [3]. Chemical analysis of Ryugu samples is an important mission of our project of Aquaplanetology launched in 2017, which quests for planetary habitability in the solar system and beyond [4]. Characterization of organic matter and analysis of water-rock interactions are important in the geo and cosmochemical studies in Aquaplanetology.

Construction of beamline 19 and installation of STXM: STXM has been installed in synchrotron facilities in many countries, and the capability of STXM depends on the beamline used to run STXM such as energy range and applicability of polarized light. The STXM at Photon Factory in Institute of Materials Structure Science, High Energy Accelerator Research Organization, Japan was formerly operated at BL-13A [5]. The energy range allowed in the beamline was from 200 to 1600 eV, which does not include absorption edges of important elements in terms of Aquaplanetology such as sulfur and silicon. Thus, a new beamline (BL-19) with larger energy range capable of studying various chemical interactions has been developed from 2017 in Photon Factory. Construction of BL-19 was almost completed in Sep., 2018. The STXM at BL-13A was moved to BL-19, and alignment of the X-ray beam in the beamline consisting of grating monochromator, slits, and STXM apparatus mainly constituted of Fresnel zone plate (FZP), order sorting aperture (OSA), and detector was optimized.

Performance of STXM at BL-19A: Until the end of March, 2019, performance of STXM at BL-19A was optimized for the analysis of samples. The polarized beam is also available for its application to molecular orientation and magnetic materials. Two FZPs can be loaded for high and low energy regions, which can be readily changed during measurement of one sample. Consequently, the STXM can cover wide an energy range from 200 to 2000 eV, so that we can study carbon and silicon K-edges in the sample. The beam size reached ca. 30 nm at carbon K-edge with energy resolution of $E/\Delta E = 5000$. A unique feature of this beamline is that we can obtain XANES of bulk samples in the branching BL-19B. The BL-19B employs same optics to BL-19A, or same energy calibration, but designed to measure reference materials essential for the determination of chemical species by XANES for STXM analysis using two detection modes, electron and fluorescence yields. This is very effective for STXM study, since measurement of reference materials normally in powder form, which is generally too large for the transmission mode in STX, takes long time if done by STXM.

Application of STXM at BL-19A: Application of STXM at BL-19A to extraterrestrial and terrestrial materials has started from May, 2019 including chondrites and Martian meteorites at carbon, nitrogen, and oxygen K-edges and iron and manganese L-edges. The application was extended to terrestrial natural organic matters, microbes, palaeomagnetic samples, and aerosols. Any users in the field of cosmochemistry and geochemistry from all over the world are welcome to use the new STXM beamline in Photon Factory.

Introduction: The C-type Near-Earth asteroid 162173 Ryugu is the target of JAXA Hayabusa2 spacecraft, which approached it on June 2018 [1]. Since then, images and spectral data of surface have been acquired by using the Optical Navigation Camera-Telescopic, with a wideband and seven narrow band filters (ONC-T) [2] and the NIR3 spectrometer, spanning in the 1.8-3.1 µm spectral range [3]. Ryugu is a top-shaped dark object, and ONC data showed a surface covered by boulders [4,5]. NIR3 data acquired on 10 and 11 July 2018 and on 19 July 2018, taken from an altitude of 20 km (Home Position) and 13 km, respectively, cover almost the entire asteroid surface, with a spatial resolution of 40 m and 20 m, respectively. Reflectance spectra of Ryugu are characterized by a narrow 2.72 µm absorption band, suggesting the occurrence of (OH)-bearing minerals and a weak positive spectral slope between 2.0 and 2.5 µm [6]. The aim of this work is to investigate areas with variations in spectral slope and constrain their physical/chemical properties to obtain information about the processes experienced by Ryugu.

Method: The calibrated and thermally corrected NIR3 data, acquired on 10, 11 and 19 July 2018 were spectrally analyzed. For each NIR3 data, the spectral slope, evaluated between 1.9 and 2.5 µm was retrieved. The values of spectral slope range from 0.10 to 0.29 and the mean value (MS, i.e. Means Slope) is 0.163. Starting from the mean value of slope and moving in steps coincident with 1σ, that is 0.022, different families of slope have been defined. All families are characterized by positive spectral slope, but we identify as “High-Red-sloped families (HR)” the areas with a spectral slope higher than MS and as “Low-Red-sloped families (LR)” the regions with a spectral slope with a lower value than MS. The HR1 family involves areas with a spectral slope included between MS and MS+1σ; in the HR2 families are included areas with a slope between MS+1σ and MS+2σ, and so on. Similarly, the LR1 family includes areas with a slope between MS-σ and MS. A total of 3 “LR” families and 6 “HR” families have been detected.

<table>
<thead>
<tr>
<th>Family</th>
<th>Range</th>
<th>Min/Max Slope value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LR1</td>
<td>MS-1σ/MS</td>
<td>0.141/0.163</td>
</tr>
<tr>
<td>LR2</td>
<td>MS-2σ/MS-1σ</td>
<td>0.119/0.141</td>
</tr>
<tr>
<td>LR3</td>
<td>MS-3σ/MS-2σ</td>
<td>0.103/0.119</td>
</tr>
<tr>
<td>HR1</td>
<td>MS/MS+1σ</td>
<td>0.163/0.184</td>
</tr>
<tr>
<td>HR2</td>
<td>MS+1σ/MS+2σ</td>
<td>0.184/0.206</td>
</tr>
<tr>
<td>HR3</td>
<td>MS+2σ/MS+3σ</td>
<td>0.206/0.227</td>
</tr>
<tr>
<td>HR4</td>
<td>MS+3σ/MS+4σ</td>
<td>0.228/0.249</td>
</tr>
<tr>
<td>HR5</td>
<td>MS+4σ/MS+5σ</td>
<td>0.250/0.271</td>
</tr>
<tr>
<td>HR6</td>
<td>MS+5σ/MS+6σ</td>
<td>0.273/0.290</td>
</tr>
</tbody>
</table>

Table 1: Definition of slopes’ families.

Results: For each family of slope, a mean spectrum was obtained and a spectral analysis was performed, estimating parameters such as the depth of 2.7 µm band and the reflectance factor at 1.9 µm, and comparing them with spectral slope.

A dichotomy between northern and southern hemisphere emerges, since the former hosts the LR families and the latter the HR families. The southern hemisphere, is, therefore, characterized by more red-sloped spectra. The HR families are further localized in the floor and wall of impact craters, whereas the crater rims host the LR families. Ejiima and Otohime saxum are included in the HR families.

![Figure 1. Map of spectral slope, estimated between 1.9 and 2.5 µm, of the Ryugu surface.](image-url)
A strong anti-correlation is observed between spectral slope and reflectance at 1.9 µm (Pearson coefficient is about -0.83) and between spectral slope and band depth at 2.7 µm, suggesting that the HR families are the darkest regions on Ryugu surface, poor in OH-minerals.

Dark asteroids as Ryugu are supposed to become brighter and bluer as a consequence of space weathering effects [7]: areas related to HR families could be, then, indicative of fresher and less altered material.

Figure 2: Scatterplot of 1.9 µm reflectance vs slope estimated between 1.9 and 2.5 µm for the families of slope (green diamonds) and mean Ryugu (red diamond).

**Introduction:** Since asteroids are thought to be survivors of planetesimals or fragments of planetesimals[1], they maintain primordial information about history of the solar system[2]. Therefore, observation of current asteroids and analysis of meteorites and returned samples originating from asteroids provide us with important keys to understanding the origin and evolution of the solar system.

On all solid bodies including asteroids in the solar system, collisions are ubiquitous events. Collisions between two planetary bodies at speeds of several km/s cause significant heating of materials[3], resulting in a loss of Ar, dehydration, and/or the generation of impact melts. Since the degree of impact heating depends strongly on the impact velocity, detailed geochemical analyses of such heated samples allow us to characterize the impact environment in the solar system through its history.

**Effect of Material Strength:** Recently, we reported that the degree of heating during impacts with less than 10 km/s is expected to be much higher than previously expected[4]. We used the two-dimensional model of the iSALE shock physics code[5]. The strength model for rocks and ANEOS for dunite were applied for both projectile and target. We found that the post-shock temperature in strength-supported media could be much higher than that in the case without strength, i.e., purely hydrodynamic (Fig. 1). Plastic deformation of the pressure-strengthened comminuted rocks dissipates the energy, and converts the kinetic energy of the flow field to internal energy. Thus, the required impact velocities for producing the unique features produced mainly by the rise in temperature is greatly lowered.

This additional heating can also be observed in an oblique impact (Fig. 2) by using the three dimensional version of the iSALE code[6]. It was expected that the heated mass in an oblique impact would be lower than that in a vertical impact, because the vertical component of the impact velocity is generally thought to govern pressures and temperatures experienced during the impact. However, our models show that vertical and oblique impacts can generate nearly the same amount of heated mass in total, indicating that the additional shear heating is more effective in oblique impacts.

Figure 1: Snapshots of a head-on impact between a spherical impactor and a flat target at 3 km/s in the case without strength (left panel) and with strength (right panel). Color represents the temperature.

Figure 2: Cumulative target mass of peak temperature normalized by the impactor mass. Black and green lines are the impact of 45º and 90º, respectively. Solid and dotted lines are without and with material strength, respectively.
Deydration During Collisions: Focusing on dehydration of hydrous minerals, we numerically performed head-on planetesimal collisions. The target planetesimals are assumed to be 100 km in radius with 90 km sized core of hydrous materials and 10 km anhydrous layer. In our numerical calculations[7], we vary the size of impactor that does not contain hydrous materials and impact velocity. Here, we focus on occurrence of dehydration reaction in hydrous core triggered by planetesimal collisions. We assume the dehydration reaction occurs at 600ºC based on experimental works.

The mass fraction of surviving hydrous materials in ejected materials and remaining largest body are plotted in Figure 3. In most cases, nearly half of the ejecta seems to be hydrous material. On the contrary, the ratio of hydrous materials forms a major component in the remnant. We can conclude that hydrous materials can avoid the dehydration reaction and also be ejected from the system of planetesimal collisions for a typical impact velocity (~ 5 km/s) in the current asteroid belt.

Considering this realistic additional heating, we will discuss the fates of hydrous materials in parent bodies of carbonaceous chondrites like Ryugu and Bennu during disruptive collisions.

Acknowledgements: We appreciate the developers of iSALE, including G. Collins, K. Wünnemann, B. Ivanov, J. Melosh, and D. Elbeshausen.

EXTRATERRESTRIAL AMINO ACIDS IN THE CM2 AGUAS ZARCAS AND MURCHISON CARBONACEOUS CHONDRITES. D. P. Glavin1, J. E. Elsila1, H. L. McLain1,2, J. C. Aponte1,2, E. T. Parker1, J. P. Dworkin1, D. H. Hill1, H. C. Connolly Jr.3,4, D. S. Lauretta3, 1NASA Goddard Space Flight Center, Greenbelt, MD 20771, E-mail: daniel.p.glavin@nasa.gov, 2Catholic University of America, Washington DC 20064, 3Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721, 4Rowan University, Glassboro, NJ 08028.

Introduction: Meteorites provide a record of the chemical processes that occurred in the early solar system before life began on Earth. The delivery of organic compounds by carbonaceous chondrites to the early Earth and other planetary bodies could have been an important source of prebiotic material required for the emergence of life [1]. The amino acid contents of a variety of carbonaceous chondrites, in particular the CMs, have been studied extensively because these prebiotic molecules are essential components of life as the monomers of proteins and enzymes. To date, 96 different amino acids have been named in the Murchison CM2 meteorite including 12 of the 20 most common protein amino acids found in biology [2]; however, the vast majority of amino acids identified in Murchison are rare or absent in the terrestrial biosphere. Several non-protein α-dialkyl amino acids in Murchison contain significant L-enantiomeric excesses of prebiotic origin up to ~18% [3,4], suggesting that the origin of life on Earth could have been biased towards L-amino acid homochirality from the very beginning. Large excesses of L-alanine (~33%) have also been reported in Murchison [5], however confirmation of an extraterrestrial origin of L-protein amino acid excesses can be more difficult due to terrestrial contamination.

On April 23, 2019, a meteorite fall was reported in Aguas Zarcas (hereafter AZ), San Carlos county, Alajuela province, Costa Rica. Hundreds of individual fragments were recovered from the strewn field totaling 27 kg in mass, of which ~11 kg was recovered before it rained in the area [6]. Based on its mineralogy, elemental abundances, and O-isotope composition, AZ has been classified as a CM2 carbonaceous chondrite and some of the pre-rain fragments were noted to give off a “Murchison-like” odor [6]. The recent fall and rapid recovery of AZ provides a rare opportunity to investigate a carbon-rich meteorite using state-of-the-art analytical techniques that will also be used to study the samples returned from asteroids Ryugu and Bennu by Hayabusa2 and OSIRIS-REx in late 2020 and 2023, respectively.

Here, we report the first amino acid analyses of the AZ meteorite. The total abundances, enantiomeric ratios and stable C-isotope compositions of amino acids extracted from two different pre-rain fragments of the AZ meteorite, a soil sample collected from the AZ fall site, and the Murchison meteorite were determined using a combination of ultrahigh performance liquid chromatography with UV fluorescence and time of flight mass spectrometry (LC-FD/ToF-MS) detection and gas chromatography-mass spectrometry coupled with isotope ratio-mass spectrometry (GC-MS/IRMS).

Materials and Methods: Two individual (~0.5 g) pre-rain fragments of AZ obtained by the University of Arizona from Mike Farmer (UA 2741) and Robert Ward (UA 2746) were separately crushed to powder and homogenized by mixing using a ceramic mortar and pestle inside a positive pressure HEPA filtered laminar flow hood at NASA’s Goddard Space Flight Center. Tiny plant fragments were observed in the powdered sample of UA 2746, but not in UA 2741. As controls, a soil sample collected from the AZ strewn field by Greg Hupe, and a sample of Murchison (Chicago Field Museum) were processed in parallel.

The samples were individually extracted in water at 100°C, acid-hydrolyzed under HCl vapor, desalted, and 1% derivatized by o-phthalaldehyde/N-acetyl-L-cysteine (OPA/NAC) and analyzed by LC-FD/ToF-MS to determine the total amino acid abundances and enantiomeric ratios [4]. The remaining ~99% of the extracts were derivatized with isopropanol and trifluoroacetic anhydride to measure the stable carbon isotope values (6δ13C) of the individual amino acids using GC-MS/IRMS as described elsewhere [7].

Amino Acid Results: A variety of two- to six-carbon amino acids were identified in the AZ meteorite UA 2741 with abundances ranging from ~0.1 to 20 nmol/g (Table 1). Two rare, non-protein amino acids α-aminoisobutyric acid (AIB) and isovaline were present at elevated abundances in UA 2741 relative to the AZ soil sample UA 2745 where they were only present at trace levels (Fig. 1), providing evidence that AIB and isovaline are extraterrestrial in origin. The total abundances of AIB and isovaline in UA 2741 and UA 2746 were similar (~5 to 6 nmol/g, Table 1); unsurprisingly, UA 2746 and the soil had higher relative abundances of alanine (Fig. 1) and several other common protein amino acids including glycine, aspartic and glutamic acids, serine and valine indicating that UA 2746 has more terrestrial amino acid contamination. Moreover, the enantiomeric ratios of alanine in UA 2741 and UA 2746 (D/L ~ 0.5) were much lower than
in Murchison (D/L ~ 0.85), also indicating some terrestrial L-alanine contamination of the AZ meteorites.

Table 1. Summary of the total amino acid abundances (nmol per gram) and D/L ratios measured in the CM2 Murchison and AZ (UA 2741) meteorites.

<table>
<thead>
<tr>
<th></th>
<th>Murchison</th>
<th>AZ (UA 2741)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>D/L</td>
</tr>
<tr>
<td><strong>Acidic amino acids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D-glutamic acid</td>
<td>0.85 ± 0.13</td>
<td>1.18 ± 0.16</td>
</tr>
<tr>
<td>L-glutamic acid</td>
<td>0.72 ± 0.10</td>
<td>0.40 ± 0.12</td>
</tr>
<tr>
<td><strong>Hydroxy amino acid</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D-serine</td>
<td>1.36 ± 0.14</td>
<td>4.24 ± 0.20</td>
</tr>
<tr>
<td>L-serine</td>
<td>0.49 ± 0.08</td>
<td>3.91 ± 0.22</td>
</tr>
<tr>
<td><strong>C2 amino acid</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glycine</td>
<td>0.21 ± 0.07</td>
<td>0.43 ± 0.17</td>
</tr>
<tr>
<td><strong>C3 amino acids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D-alanine</td>
<td>0.19 ± 0.09</td>
<td>0.43 ± 0.17</td>
</tr>
<tr>
<td>L-alanine</td>
<td>0.49 ± 0.08</td>
<td>3.91 ± 0.22</td>
</tr>
</tbody>
</table>

Even including the small terrestrial amino acid contributions to AZ, the total amino acid abundance of UA 2741 (~50 nmol/g, Table 1) is roughly one third that of the Murchison meteorite (~162 nmol/g). The relative distribution of α-amino acids found in UA 2741 and Murchison is quite similar, however it is notable that both AZ meteorites are depleted in β-amino acids (β-alanine and D.L.-β-ABA) relative to Murchison. The lower β-alanine abundances in AZ (Table 1, Fig. 1) may indicate that this meteorite experienced less parent body aqueous alteration compared to Murchison based on previous trends observed for CI, CM, and CR carbonaceous chondrites [8].

Carbon isotope values (δ13C) of amino acids that fall outside of the typical terrestrial range (Table 2) prove that many of the amino acids in AZ and Murchison are extraterrestrial in origin, although for some protein amino acids in the meteorites, the L-enantiomer is less enriched in 13C than the D-enantiomer suggesting a terrestrial contribution to the L-enantiomer. The δ13C values of the protein amino acids in UA 2746 are also less enriched than UA 2741 and similar to the soil, which is consistent with higher levels of terrestrial amino acid contamination in UA 2746. Interestingly, the δ13C values of D- and L-isovaline in UA 2741 are similar within errors and highly enriched in 13C, indicating the measured L-isovaline excess of ~10% is non-terrestrial in origin.

Figure 1. Comparison of the molar abundances relative to glycine of D.L-alanine, β-alanine, α-aminoisobutyric acid (AIB), and D.L-isovaline in the AZ meteorites (UA 2741 and UA 2746), a soil sample from the AZ strewn field (UA 2745), and Murchison.

Table 2. Summary of the δ13C values (% VPDB) of amino acids in the AZ meteorites and soil and the Murchison meteorite.

<table>
<thead>
<tr>
<th>Amino Acids</th>
<th>AZ (UA 2741)</th>
<th>Soil (UA 2746)</th>
<th>Murchison</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-alanine (AIB)</td>
<td>-15 ± 2</td>
<td>-18 ± 7</td>
<td>nd</td>
</tr>
<tr>
<td>L-alanine (AIB)</td>
<td>-9 ± 2</td>
<td>-13 ± 4</td>
<td>nd</td>
</tr>
<tr>
<td>D-glutamic acid</td>
<td>+20 ± 8</td>
<td>-14 ± 9</td>
<td>+31 ± 3</td>
</tr>
<tr>
<td>L-glutamic acid</td>
<td>-10 ± 4</td>
<td>-15 ± 5</td>
<td>+13 ± 3</td>
</tr>
<tr>
<td>Glycine</td>
<td>+15 ± 6</td>
<td>+55 ± 4</td>
<td>+25 ± 4</td>
</tr>
<tr>
<td>D-serine</td>
<td>+10 ± 3</td>
<td>-18 ± 4</td>
<td>+49 ± 5</td>
</tr>
<tr>
<td>L-serine</td>
<td>+10 ± 3</td>
<td>-18 ± 4</td>
<td>+49 ± 5</td>
</tr>
<tr>
<td>Ivaline</td>
<td>+10 ± 3</td>
<td>-18 ± 4</td>
<td>+49 ± 5</td>
</tr>
<tr>
<td>D-alanine</td>
<td>+17 ± 5</td>
<td>+33 ± 6</td>
<td>nd</td>
</tr>
<tr>
<td>L-alanine</td>
<td>+20 ± 5</td>
<td>+33 ± 6</td>
<td>nd</td>
</tr>
</tbody>
</table>

No error since the value was derived from a single measurement. nd = not determined due to trace levels and/or analytical issues.

Conclusions: The discovery of extraterrestrial amino acids including L-isovaline excesses in AZ provides evidence of an early solar system formation bias towards L-amino acids prior to the origin of life. Future analyses of samples returned from asteroids Ryugu and Bennu that have experienced much less exposure to the terrestrial environment will provide the first opportunity to measure the extent of chiral asymmetry produced solely by non-biological processes.


Acknowledgments: This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program. D.G., J.E., H.M., J.A., E.P., and J.D. also appreciate funding support from the NASA Astrobiology Institute through award 13-13NAI7-0032 to the Goddard Center for Astrobiology.
NEAR-FIELD INFRARED SPECTROSCOPY AS A TOOL FOR ANALYSIS OF CHONDRITIC RETURNED SAMPLES. Timothy D. Glotch¹, Jordan M. Young¹, Ziheng Yao¹,², Hans A. Bechtel², Victoria E. Hamilton³, Philip R. Christensen⁴, and Dante S. Lauretta³. ¹Stony Brook University (timothy.glotch@stonybrook.edu), ²Advanced Light Source, Lawrence Berkeley National Laboratory, ³Southwest Research Institute, ⁴Arizona State University, ⁵Lunar and Planetary Laboratory, University of Arizona.

Introduction: The relationships between organic and mineral components in meteorites have been a topic of extensive study [e.g., 1-3]. It will be especially important to understand these relationships in pristine carbonaceous chondrite samples returned by the Hayabusa2 and OSIRIS-REx missions. Our previous work has focused on using the Raman spectral properties of the disordered and graphitic (D and G) bands of polycyclic aromatic hydrocarbons (PAHs) to constrain the peak metamorphic temperatures experienced by a range of ordinary chondrite samples [4]. We found two populations of organic carbon in these samples that appear to reflect different thermal histories. We are currently working to further investigate this intriguing result using scattering-type scanning near field infrared spectroscopy and imaging (s-SNOM or nano-FTIR). This work describes imaging and spectroscopy of organic/silicate boundaries in H5 ordinary chondrite Allan Hills (ALH) 77012 at ~20 nm spatial scales, but also serves as a proof of concept for analyses of returned carbonaceous samples.

Methods: We acquired nano-FTIR spectra and images at the Synchrotron Infrared Nano Spectroscopy (SINS) beamline at the Advanced Light Source at Lawrence Berkeley National Laboratory. Images and spectra were collected on a standard petrographic thin section. For spectroscopy, the synchrotron infrared beam was focused onto a conductive atomic force microscope (AFM) tip in a neaspec neaSNOM near-field system. Phase and amplitude spectra referenced to a gold standard were collected at harmonics of the AFM tip tapping frequency to remove the far-field signal. The spatial resolution of point spectroscopy measurements is controlled by the radius of curvature of the AFM tip, which is < 20 nm. Spectra were collected with a spectral sampling of ~2 cm⁻¹.

For imaging, a tunable laser centered at ~6 μm was used to illuminate the sample tip as the sample was rastered underneath it. The image was acquired with a spatial sampling of 53 nm/pixel. As with the spectroscopic measurements, near-field infrared phase and amplitude data were collected at harmonics of the tapping frequency.

Results and Discussion: Using Raman maps collected by [4] at Stony Brook University as guides, we focused our nano-IR measurements on organic/silicate boundaries in the H5 ordinary chondrite ALH 77012. Figure 1 shows a 6-μm nano-IR map of one of these boundaries. From the multiple datatypes that were collected simultaneously, we constructed an overlay of colorized optical amplitude (O3A) at a wavelength of 6 μm over the mechanical phase (M1P). The map shows a clear boundary trending from lower left to upper right. The upper portion of the image (yellow/white) has weak or absent spectral features between ~700 and 1200 cm⁻¹ (Figure 2). Based on the amplitude spectrum and the high reflectance of the material in reflected light micrographs, we interpret this phase to be a metal sulfide or oxide.

We collected multiple spectra on the Raman-identified organic material (displayed as red/orange in the lower right portion of the image in Figure 1). Multiple diagnostic features are present, in both the phase and amplitude spectra, although there is some variation from point to point. Major peaks in the phase spectra occur at ~880, 974, 1010, 1074, 1120, and 1290 cm⁻¹. Corresponding peaks in the amplitude

[Image: Figure 1. Overlay of the near-field amplitude at 6 μm (O3A) on the mechanical phase (M1P). Red/dark tones indicate lower amplitudes and yellow/bright tones indicate higher amplitude. Squares indicate the positions of spectra displayed in Figure 2.]
spectra occur at ~860, 950, 1009, 1054, 1114 cm\(^{-1}\), and 1280 cm\(^{-1}\). Most of these features correspond to pyroxene Si-O stretching and bending modes, although the shortest wavelength (highest wavenumber) feature is absent from spectra of pyroxene standards, and may correspond to weak features documented in some PAH spectra [5].

**Comparison to OTES Spectra of Bennu:** Direct comparison of nano-IR spectra with traditional far-field (e.g., reflectance, emissivity, absorbance) spectra remains challenging due to the strong interaction of the AFM tip with the sample, which can cause substantial shifts in band shape and position for strong vibrational modes. Nevertheless, we will work to acquire spectra of finely and poorly crystalline phases in Bennu- and Ryugu-relevant CI and CM meteorites to provide additional standards for analysis of OTES data. Several models exist to calculate the complex refractive indices of minerals from nano-IR data, and from these, standard reflectance models can be used to calculate far-field spectra from nano-IR measurements [6-8]. We are actively working to improve these models to provide direct links between meteorites and/or returned samples and remotely sensed data.

**Additional Work:** We will refine band identifications and pursue investigations of additional mineral and organic features in ALH 77012 and initial analyses of CI and CM chondrite meteorites relevant to the samples to be returned from Ryugu and Bennu.

At present, our imaging capability is limited to the ~6 micron region due to the laser available at the ALS SINS beamline. Imaging at wavelengths more relevant to chondritic silicates and organics would be enabled by modern tunable lasers or a multiple laser setup easily incorporated into the neaSNOM system. At the time of sample return, instruments with hyperspectral imaging capability from ~3-20 μm are likely to exist at multiple laboratory facilities.

**Acknowledgements:** This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program. We are grateful to the entire OSIRIS-REx Team for making the encounter with Bennu possible.

**References:**

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DISTINGUISHING DIFFERENTIATED DARK ASTEROIDS FROM PRIMITIVE DARK ASTEROIDS: CLUES AND CAUTIONS FROM ASTEROID 2008 TC3 AND THE ALMAHATA SITTA METEORITE. C. A. Goodrich1, M.E. Zolensky2, A.M. Fioretti3, M.H. Shaddad4, H. Downes5, T. Hiroi6, I. Kohl7, E.D. Young8, N.T. Kita8, V.E. Hamilton9, M. Riebe10, H. Busemann10, R.J. Macke11, M. Fries2, M. Sanborn12, Q-Z. Yin12, D.K. Ross13, P. Jenniskens14. 1Lunar and Planetary Institute, USRA, Houston TX 77058 USA (goodrich@lpi.usra.edu); 2ARES, NASA-JSC, Houston TX USA; 3CNR, Padova Italy; 4Univ. Khartoum, Khartoum Sudan; 5Birkbeck Univ. London, London UK; 6Brown Univ., Providence, RI USA; 7UCLA, Los Angeles, CA USA; 8Univ. Wisconsin, Madison, WI USA; 9SwRI, Boulder, CO USA; 10ETH, Zürich Switzerland; 11Specola Vaticana, Vatican City State; 12UC Davis, Davis, CA USA; 13Jacobs-JETS, NASA-JSC, Houston TX USA; 14SETI, Mountain View, CA USA.

Introduction: Asteroid 2008 TC3 was the first near-Earth object to be detected and studied in space before it hit the Earth [1-6]. More than 700 cm-sized (~0.2-400 g) stones were recovered from the predicted fall area and named the Almahata Sitta (AhS) meteorite [7]. AhS is the first meteorite observed to originate from a spectrally classified asteroid. It provides an unprecedented opportunity to correlate spectral, compositional, and physical properties of a meteorite with those of the asteroid from which it was derived.

The reflectance spectrum of 2008 TC3 was measured in the 0.5-1 µm range [4] and most closely matches F-type asteroids [8]. The average F-type albedo of 0.046 [9] is consistent with independent estimates of the asteroid’s size [4]. F-type asteroids belong to the C complex of dark asteroids commonly identified with carbonaceous chondrites (CC) [8-11]. If Almahata Sitta had not been recovered, 2008 TC3 would have been assumed to be a CC-type asteroid.

However, AhS turned out to be a unique and complex meteorite. The AhS stones are diverse, with ~70-80% of those studied so far being various types of ureilites (achondrites from the mantle of a differentiated asteroid), and 20-30% being various types of chondrites (mainly enstatite-, ordinary- and Rumuruti-types) [12-14]. Based on the apparent dominance of ureilites, AhS was classified as an anomalous polymict ureilite [4]. It has been inferred that 2008 TC3 was a loosely-consolidated, heterogeneous breccia that disintegrated in the atmosphere, with its clasts landing on Earth separately and most of its mass lost [4,13]. Determining its structure and composition has been hindered so far because none of the studied AhS stones showed contacts between ureilite and chondritic lithologies.

We have now discovered AhS 91A and AhS 671, the first AhS stones to show contacts between ureilite and chondritic materials and provide direct information about the structure and composition of asteroid 2008 TC3. Combined petrologic, geochemical, physical, and spectroscopic studies of these stones [14] provide clues and cautions to distinguishing differentiated dark asteroids from primitive dark asteroids in remote spectroscopy.

The First AhS Stones Showing Contacts Between Ureilite and Chondritic Lithologies: AhS 91A and AhS 671 are friable breccias, dominated volumetrically by hydrous CC-like (C1) material which encloses rounded to angular clasts (<10 µm to 3 mm) of olivine, pyroxenes, plagioclase, graphite, and metal-sulfide, as well as chondrules (~130-600 µm) and chondrule fragments. The C1 material consists of fine-grained phyllosilicates (serpentine and saponite) and amorphous material, magnetite, bruennerite, dolomite, fayalitic olivine (Fo 28-42), an unidentified Ca-rich silicate phase, Fe,Ni sulfides, and minor Ca-phosphate and ilmenite. It has similarities to CI1, but the Ca-rich silicate (dehydrated saponite + CaO?) is unique and may indicate post-aqueous alteration thermal metamorphism. Its bulk oxygen isotope composition (δ18O = 13.53‰, δ17O = 8.93‰) is unlike that of any known CC. Its Cr isotope composition is also unique, with the highest ε56Cr of any known solar system material.

The clasts and chondrules do not belong to the C1 lithology. The olivine (Fo 75-88), pyroxenes ( pigeonite of Wo ~10 and orthopyroxene of Wo ~4.6), plagioclase, graphite, and some metal-sulfide are unquestionably ureilite, based on mineral compositions, textures, and oxygen isotope compositions, and represent at least six distinct ureilite lithologies. The chondrules are probably derived from type 3 OC and/or CC, based on mineral and oxygen isotope compositions. Some of the metal-sulfide clasts are derived from EC.

AhS 91A and AhS 671 are plausible representatives of the 99% of the mass of asteroid 2008 TC3 that was lost. The bulk density of AhS 91A (2.35 ± 0.05 g/cm³) is lower than densities of other AhS stones and closer to estimates for the asteroid (~1.7-2.2 g/cm³) [15]. Its porosity (36%) is higher than porosities of other AhS stones, but near the low end of estimates for the asteroid (33-50%), consistent with significant macroporosity [15]. They contain most previously known AhS stone types but, importantly, are dominated by hydrous CC, rather than ureilite, material.

Reflectance spectra of AhS 91A are dark (reflectance ~0.04-0.05) and relatively featureless in VNIR, with an ~2.7 µm absorption band due to OH- in phyllosilicates, similar to ungrouped C2 (Fig. 1a). They are
much closer to the spectrum of 2008 TC3 than spectra of other AhS stones measured so far (Fig. 1b). Spectral modeling, using mixtures of VNIR reflectance spectra of AhS stones to fit the F-type spectrum of the asteroid (Fig. 2), suggests that 2008 TC3 could have consisted of up to 79% AhS 91A-like (i.e., hydrous CC) material, with the remainder being mostly ureilitic, and <10% all other meteorite types. If this is the case, 2008 TC3 could have had a 2.7 μm absorption band.

Discussion: [13] suggested that 2008 TC3 was a piece of regolith from a ureilitic asteroid. [14] suggested that AhS 91A/671 represented a volume of such regolith dominated by a CC-like impactor, as has been suggested for dark regions on Vesta and Psyche [16,17]. However, based on current knowledge, it is also possible that 2008 TC3 originated from a CC-like asteroid that had acquired minor foreign ureilitic (and other types of) materials. For several reasons (see also [19]), ureilitic regolith may be difficult to distinguish from hydrous CC material in remote spectra. A 2.7 μm absorption band may not imply a primitive asteroid.

Fig. 1. (a) Reflectance spectra of AhS 91A chips and powders [14]. (b) Reflectance spectra of various AhS stones [14,18] compared with the spectrum of 2008 TC3 at a range (yellow region) of albedo estimates [4,18].

Fig. 2. (a) Results of spectral modeling, comparing mixes of various AhS stones with spectrum of 2008 TC3. Within the uncertainty of the asteroid, mixes dominated by the CC lithology AhS 91A give matches comparable to those dominated by ureilites. (b) Similar comparison, showing that mixes dominated by AhS 91A fit the albedo of the asteroid better than mixes dominated by ureilites.

MACRO-POROSITY AND GRAIN DENSITY OF C-TYPE ASTEROID (162173) RYUGU. M. Grott\textsuperscript{1}, J. Biele\textsuperscript{2}, P. Michel\textsuperscript{3}, S. Sugita\textsuperscript{4}, S. Schröder\textsuperscript{1}, N. Sakatani\textsuperscript{5}, W. Neumann\textsuperscript{1}, S. Kameda\textsuperscript{6}, T. Michikami\textsuperscript{7}, C. Honda\textsuperscript{8}, \textsuperscript{1}German Aerospace Center, Berlin, Germany (Matthias.Grott@dlr.de), \textsuperscript{2}German Aerospace Center, Cologne, Germany, \textsuperscript{3}Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Laboratoire Lagrange, Nice, France, \textsuperscript{4}University of Tokyo, Tokyo, Japan, \textsuperscript{5}ISAS/JAXA, Sagamihara, Japan, \textsuperscript{6}Rikkyo University, Tokyo, Japan, \textsuperscript{7}Kindai University, Hiroshima, Japan, \textsuperscript{8}University of Aizu, Aizu-Wakamatsu, Japan.

Introduction: Upon arrival of the Hayabusa2 spacecraft [1] the C-type asteroid (162173) Ryugu was found to be a spinning top-shaped rubble pile [2], whose surface is dominated by large blocks and boulders [3]. A regolith cover of fine particles appears to be absent [4]. Boulders on Ryugu are predominantly dark and rugged [4, 5], and these boulders appear to be similar to CI chondritic meteorites [5, 6]. Thermal properties a boulder measured in-situ indicate high intrinsic porosities [6], consistent with the overall low bulk density of the asteroid [4]. Assuming typical grain densities for carbonaceous chondrites, bulk porosities close to 50% would be expected [2].

Porosity inside rubble pile asteroid Ryugu can be separated into two contributions: the first one stems from the intrinsic porosity of rocks and boulders and is termed micro-porosity $\phi_m$, whereas the second contribution refers to voids in between individual rocks and is termed macro-porosity $\phi_M$ [7]. Given the size distribution of particles, the macro-porosity of the asteroid can be calculated using semi-empirical mixing models [7, 8], assuming the surface distribution of boulders to be representative for the entire asteroid.

Data: Boulder size and shape distributions have been determined by [3] using data from the Hayabusa2 on-board navigation camera (ONC). Images were taken at altitudes between 20 km and 6.5 km with resolutions of up to 0.65 m/pixel, and size-frequency and shape distributions were determined in the 0.02 to 140 m size range (Figure 1). Size-frequency data was fitted using power laws, and power law indices between 1.65 and 2.65 have been obtained [3], with 2.65 being the best fit for the global dataset. Furthermore, particles are generally elongated, and axis ratios for boulders >2m are close to 0.70, consistent with boulder generation by impact processes [3].

We fitted the data provided by [3] to a simple polynomial, and data can be adequately represented by a second order function in log-log coordinates. Results of the fitting are shown together with the uncertainty of the data in Figure 1. It is worth noting that representing the data using a single power law for the entire size range does not adequately represent the data [3].

Modeling: Here we compute the macro-porosity $\phi_M$ of Ryugu using semi-empirical mixing models [7, 8] given the size-frequency distribution of observed boulders [3]. For poly-disperse particles, macro-porosity can be much lower than the canonical 36% for a random close packing or ~42% for a random loose packing of spherical mono-sized particles [7], as smaller particles start filling the gaps between larger ones. Once $\phi_M$ has been computed, macro-porosity $\phi_M$, micro-porosity $\phi_m$, and bulk porosity $\phi_B$ are related by

$$\phi_M = 1 - \frac{1 - \phi_B}{1 - \phi_m} \quad (1)$$

where $\phi_B = 1 - \rho_b/\rho_s$ Here, $\rho_b$ and $\rho_s$ are Ryugu’s bulk and grain density, respectively. While the bulk density of Ryugu has been estimated to be $1190 \pm 20$ kg/m$^3$ [4], the boulder’s micro-porosity $\phi_m$ cannot currently be unambiguously constrained due to the difficulties associated with extrapolating meteorite thermal conductivities to porosities in excess of 20% [9]. However, end-member models [10, 11] suggest micro-porosities $\phi_m$ between 28-35% and 41-55% for Ryugu’s dark and rugged boulders [6]. Here we use Monte-Carlo simulations to propagate these uncertainties to the uncertainty of Ryugu’s grain density $\rho_s$.

Results: Assuming minimum and maximum particle sizes of 0.02 and 140 m, Ryugu’s macro-porosity $\phi_M$ is calculated to be $15 \pm 2.5\%$, and results of the Monte-Carlo simulations using 1000000 draws are

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure1.png}
\caption{Cumulative size-frequency distribution of boulders observed on Ryugu. The global fit represents the data of [3], spanning the size range between 0.02 and 140 m.}
\end{figure}
shown in Figure 2, where a histogram of the grain density $\rho_s$ is shown. Owing to the two different models used to extrapolate boulder micro-porosity, two separate peaks are obtained for the distribution of admissible grain densities. Extrapolation of thermal properties using the porosity model of [11] results in lower micro-porosities and higher grain densities. Overall, grain densities $\rho_s = 2002 \pm 85$ kg m$^{-3}$ and $\rho_s = 2672 \pm 229$ kg m$^{-3}$ are obtained for the two different models.

**Figure 2:** Results of the Monte-Carlo simulations showing the histogram of grain density $\rho_s$ assuming two endmember models for the micro-porosity $\phi_m$ [6].

**Discussion:** In the above analysis, we have neglected the influence of particle shape on the porosity. In general, particle sphericity can have a significant effect on the porosity of particle mixtures, but this effect only becomes important for sphericities of less than 0.8. For the Ryugu boulders, axis ratios b/a of close to 0.7 have been reported [3], resulting in sphericities of 0.84. Therefore, particle shape can be considered a second order effect here.

The grain densities obtained here are much lower than typical grain densities of ordinary chondrites, which range from 3520 to 3710 kg m$^{-3}$ [10], and also lower than those of most carbonaceous chondrites, which typically have grain densities in excess of 3360 kg m$^{-3}$. Only the CM and CI sub-classes show lower grain densities, and $\rho_{s,\text{CM}} = 2960 \pm 40$ kg m$^{-3}$ while $\rho_{s,\text{CI}} = 2420$ kg m$^{-3}$ [10]. The Tagish Lake meteorite, an ungrouped carbonaceous chondrite, exhibits similar grain densities in the range between 2430 and 2840 kg m$^{-3}$ [12]. While the larger grain densities obtained here are consistent with the CM, CI, and Tagish Lake results, the lower densities are inconsistent with those of known meteorite samples.

Support for extrapolating boulder porosities using the model by [10] rather than the model by [11] is provided by laboratory measurements of thermal conductivities at high porosities [13]. The UTPS Tagish Lake simulant [14] has a grain density of 2813 kg m$^{-3}$ and a porosity of 47%, while at the same time exhibiting thermal conductivities similar to those obtained for Ryugu’s rugged boulders. This falls within the range predicted by the model of [11], favoring grain densities of $\rho_s = 2672 \pm 229$ kg m$^{-3}$. However, more laboratory measurements at high porosity are needed to confirm these results and reduce uncertainties.

Results presented here assume that the size-frequency distribution observed on the surface is representative for the entire asteroid, but it has been argued that particle size sorting may take place during rubble pile re-accretion, with larger particles accreting first [15]. On the other hand, seismic shaking and the Brazil Nut Effect could lead to an overrepresentation of large particles on the surface [16]. This topic can be addressed once grain density and micro-porosity have been determined from the returned samples.

**Summary:** Rubble pile asteroid (162173) Ryugu’s boulder size-frequency distribution is consistent with a macro-porosity close to $15 \pm 2.5 \%$, provided the observed surface distribution of boulders is representative for the bulk asteroid. In this case, a grain density of $\rho_s = 2672 \pm 229$ kg m$^{-3}$ is best compatible with the available data, consistent with a CI or CM composition.

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**References:**
**Overview:** The Regolith X-ray Imaging Spectrometer (REXIS) has four back-illuminated CCDs similar to the Suzaku X-ray imaging spectrometer. [1] REXIS has a unique directly deposited Aluminum optical blocking filter (OBF) designed to block visible light from impinging directly on the detector [2].

This presentation will show the methods of REXIS CCD calibration for X-ray events registered within a single pixel and multiple pixels. Calibration is being performed separately below 1 keV and above 1 keV because of the different noise sensitivities of the detector in these two energy ranges.

We use REXIS measurements of the Crab Nebula as a standard source in X-ray astronomy. [3] REXIS executed its Crab Nebula calibration in March 2019. We will present the resulting background subtracted spectrum for the Crab Nebula and the corresponding estimate for the energy dependent detector efficiency.

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**References:**
SIMULATIONS OF THERMAL PROCESSING IN CARBONACEOUS ASTEROIDS WITH IN-SITU HEATING OF METEORITIC MATERIALS. Pierre Haenecour1, Thomas J. Zega1,2, Jane Howe3 and Takeshi Sunaoshi4. 1Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA. 2Dept. of Materials Science and Engineering, University of Arizona, Tucson, AZ, USA. 3Dept. of Materials Science and Engineering, and Dept. of Chemical Engineering and Applied Chemistry, University of Toronto, Ontario, Canada. 4Hitachi High Technologies America, Inc., Clarksburg, MD, USA. (pierre@lpl.arizona.edu).

Introduction: The asteroid sample-return missions Hayabusa2 and OSIRIS-REx will return new samples of the carbonaceous asteroids Ryugu and Bennu in 2020 and 2023, respectively. Spectroscopic observations of the surface of Bennu show the presence of hydrated minerals suggesting that it has spectral features that are most similar to those of aqueously altered CM-type meteorite [1, 2].

Carbonaceous chondrites contain fine-grained material consisting of a mixture of crystalline and amorphous silicates, oxides, sulfides, Fe-Ni metal grains, and carbonaceous matter that accreted together from the solar protoplanetary disk, e.g. [1]. Some of this ‘primary’ material was affected by both aqueous and thermal ‘secondary’ processing on their host asteroid [3, 4]. Many carbonaceous chondrites contain alteration products, e.g., hydrous minerals and carbonates, providing evidence for water-rock interactions at low temperature [4].

The response of primary fine-grained materials in carbonaceous chondrites to secondary alteration is important for understanding active processes on the surfaces of and within the chondrite-parent asteroids. Thermal metamorphism, in particular, could have played an important role in processes such as melting, volatile loss, elemental diffusion between grains, and driving hydrothermal processing. To better understand the effect(s) of heating on the composition and microstructure of fine-grained material in asteroids, we carried out in-situ flash- and step-heating experiments of matrix material of the Murchison (CM2), Tagish Lake (C2-ung.) and Acfer094 (C2-ung.) chondrites inside a transmission electron microscope (TEM). We selected these meteorites because, while they were affected by different degree of aqueous alteration on their parent-body asteroids [e.g., 5-8], they experienced minimal thermal alteration.

Sample and Experimental Methods: Fine-grained material of the three meteorites were crushed and then deposited onto Norcada heating chips. Using the Hitachi Blaze heating holder, we the carried out in-situ heating of each sample in a Hitachi SU9000 scanning transmission electron microscope (STEM) at the Kuiper Core Imaging and Microscopy Facility, University of Arizona. The in-situ heating experiments were carried out in vacuum (<10⁻⁵ Pa) at temperatures up to 1075°C. The SU9000 is equipped with an Oxford X-Max 100TLE energy-dispersive X-ray spectroscopy (EDS) system and Hitachi electron energy-loss spectroscopy (EELS) system.

Fig. 1. STEM images (secondary electron, SE; bright-field, BF) and false-color EDS maps of a Murchson silicate grain after heating up to 1000°C.

Heating of the Murchison meteorite: Initial EDS analysis of a local part of the sample before heating show that it is composed of ferromagnesian silicate, oxide, sulfides, Fe-Ni metal, and carbonaceous grains. We did not observe any noticeable change to the meteorite in terms of grain structure, surface morphology, or elemental composition of the sample until it was heated up to 600 ºC. After heating at 800 ºC, STEM imaging and EDS measurements revealed changes in the surface morphology and formation of Fe-Ni nanoparticles on the surface of silicate grains (Fig. 1). These particles appear to have similar elemental compositions as the space-weathering-induced nanophase iron that form on the surface of lunar soil particles [9]. Heating to 1000 ºC caused the particles to sinter and form larger assemblages. Previous stepped heating experiments of the Murchison meteorite [6] showed the formation of Ni-rich magnetite particles. However, EDS mapping indicate that the Fe-Ni nanoparticles formed in our experiment do not contain much O but rather have an elemental composition consistent with Fe-Ni metal.

Heating of the Tagish Lake meteorite. Initial EDS mapping before heating shows that the two Tagish Lake (TL) samples are composed of a mixture of
carbonaceous material, Fe-Mg silicates, iron sulfides, and Fe-Ni metal. The two TL samples were subjected to distinct heating regiments: 1) flash heating to 800ºC (~1 min) and then heated for longer periods to 900ºC and 1075ºC (10-20 min isothermal holds); and 2) step-heating from 200 to 1000ºC by 100 ºC increments (1 to 2 hours at each step). Between each step, the samples were cool down to 200 ºC to acquire detailed STEM images and EDS elemental maps.

STEM imaging shows that flash heating to 800ºC caused significant melting and a reduction of the overall size of the grains. Increased melting and sintering occurred progressively at 900ºC and then 1075ºC. Slow and longer heating by 100 ºC steps caused similar melting and sintering at temperatures above 500ºC. Similar to the Murchison sample, heating above 600ºC also caused the formation of nanoparticles. However, these nanoparticles contain minor Si and are not pure Fe-Ni metal (Figs. 2 & 3). This observation is consistent with identification of Si in Fe-Ni metal grains in some carbonaceous chondrites [10]. Furthermore, STEM imaging and EDS mapping showed loss of volatile elements, such as sulfur from the iron sulfide grains, and graphitization of the carbonaceous material at temperatures above 700ºC (Fig. 2).

Heating of the Acfer 094 meteorite. The Acfer 094 material was heated from 400 to 800ºC (with steps of 100ºC) and isothermally held at each temperature for 30 min to 1h. Similar to the TL samples, heating above 500ºC caused the formation of Fe-Ni-Si nanoparticles from the silicate grains. As the temperature increased, the nanoparticles progressively agglomerated together to form larger particles.

Fig. 2. STEM images (secondary electron, SE; bright-field, BF) and false-color EDS maps of a Tagish Lake sample on the heating chip after heating up to 1000ºC. The figure also shows the Fe-Ni particles in chondrule ‘dusty olivines’ from [11].

Fig. 3. STEM bright-field (BF) images of Fe-Ni nanoparticles in TL sample after heating to 900ºC.

The Fe-Ni-Si nanoparticles that formed in both the Tagish Lake and Acfer 094 samples after heating above 500ºC are similar to the particles observed in ‘dusty relic olivines’ identified inside type I chondrules in unequilibrated ordinary chondrite [11]. They are hypothesized to have formed in a previous generation of chondrule formation when the chondrule melted in the presence of a reducing agent in the solar nebula before their accretion on their parent asteroid.

Summary: Our initial results from in situ heating of Murchison, Tagish Lake, and Acfer 094 fine-grained material indicate that significant changes to their microstructure and elemental compositions, such as melting and formation of Fe-Ni nanoparticles, occurred only after heating above 500ºC. Our observations suggest that they formed by the in situ reduction of iron from olivine grains at temperatures above 500ºC. Heating up to 1075ºC caused a significant loss of volatiles (e.g., S) and the graphitization of the carbonaceous matter. Our initial in-situ heating experiments demonstrate that simultaneous STEM/EDS imaging during in situ heating is a viable method for studying thermal history of carbonaceous asteroids.


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THE GLOBAL MINERALOGY OF (101955) BENNU FROM VNIR AND TIR OBSERVATIONS DURING THE DETAILED SURVEY PHASE OF THE OSIRIS-REx MISSION. V. E. Hamilton1, A. A. Simon2, H. H. Kaplan1, D. C. Reuter2, P. R. Christensen3, R. D. Hanna4, D. N. DellaGiustina5, E. S. Howell5, T. J. McCoy6, H. C. Connolly, Jr.7, J. P. Emery8, B. E. Clark2, and D. S. Lauretta9. 1Southwest Research Institute, 1050 Walnut St. #300, Boulder, CO 80302 USA (hamilton@boulder.swri.edu), 2Goddard Space Flight Center, Greenbelt, MD, 3Arizona State University, Tempe, AZ, 4University of Texas, Austin, TX, 5Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 6National Museum of Natural History, Smithsonian Institution, Washington, D.C., 7Rowan University, Glassboro, NJ, 8University of Tennessee, Knoxville, TN, 9Ithaca College, Ithaca, NY.

Introduction: Spectral data of Bennu acquired just after OSIRIS-REx arrived at the asteroid in December 2018 showed globally homogeneous signatures dominated by features attributable to hydrated minerals most similar to low petrologic type CM chondrites [1]. Since then, global mapping data acquired at spatial resolutions of ~20-40 m/pixel and under optimized observing conditions have revealed that Bennu’s surface is not as compositionally homogeneous as it initially appeared. Here we describe the full range of spectral variability that has been identified so far during the Detailed Survey phase of the mission and implications for the future returned sample.

Spectral Instruments: OSIRIS-REx carries two point spectrometers: OVIRS, the visible and near infrared (VNIR) spectrometer, and OTES, the thermal emission spectrometer. OVIRS and OTES measure mineralogy, chemistry, and temperature on the surface of Bennu. OVIRS has a 4-mrad field of view (FOV) and measures reflected solar energy from 0.4 to 4.3 μm with a spectral sampling of 2 nm (0.002 μm) from 0.392 to 2.4 μm, and 5 nm (0.005 μm) from 2.4 to 4.3 μm [2, 3]. OVIRS spectral band positions are reported in units of microns. OTES has an 8-mrad FOV and measures emitted energy from ~1650-100 cm⁻¹ (~5.5 to 100 μm) at a spectral sampling of 8.66 cm⁻¹ [4]. OTES spectral feature positions are reported in wavenumbers. The OVIRS FOV is within that of OTES but the boresights are not precisely co-aligned.

OVIRS Results: Visible wavelength spectra from the early mission phases are consistent with ground-based spectra having a blue slope and no discernible features; we have not yet made any determination as to the effects of space weathering, which can cause both blueing and reddening of the spectral slope [1, 5]. The most prominent spectral feature observed at longer wavelengths is a ~2.7-μm hydration band whose position (2.74 μm ±0.01) is most consistent with CI and low petrologic subtype CM carbonaceous chondrites (CC) [1, 6]. During the Detailed Survey phase of the mission, this feature remains the most prominent and is observed in every spectrum; the band depth is strongly correlated with temperature, and separation of this effect is an ongoing effort. OVIRS spectra of very rare, bright (albedo = ~0.14 at 0.55 μm) boulders identified in color imagery have ~1 and ~2-μm bands attributed to pyroxene [7]. The band positions, as determined by modified gaussian modeling (MGM) [8], represent pyroxene solid solution compositions that are most consistent with the howardite-eucrite-diogenite (HED) group meteorites that are believed to originate from the asteroid (4) Vesta [e.g., 9, 10]. Based on their rarity and composition, these boulders are inferred to have an exogenous origin [7]. Absorption features also are evident in the 3.2 - 3.6 μm region and are attributed to C-bearing compounds that could be hosted in organics and/or carbonate minerals. These features are quite complex and variable in shape and are not readily attributed to specific compounds in most spectra. As a result, we are presently mapping these features by their total band area rather than by specific band positions. The mapped band area does not correspond with the distribution of other spectral or geologic features.

OTES Results: As with the OVIRS data, OTES spectra acquired early in the mission appeared globally homogeneous and are characterized by spectral properties best matched by aequously altered carbonaceous chondrites of the CI and CM groups [1]. Data acquired in the Detailed Survey phase have now revealed that there appear to be two globally prevalent spectral end members. These end members differ in shape in the region dominated by silicate bending mode features (~1100-650 cm⁻¹), where one of the end members has a strongly asymmetric band shape with a minimum near 987 cm⁻¹, and the other has slightly less asymmetric band with a similar depth and a minimum near 814 cm⁻¹. At the wavenumbers dominated by silicate bending vibrations (~525-300 cm⁻¹) the two end member spectra have a similar shape but differing depths relative to each other and the Si-O stretching bands. By comparison with CC meteorite spectra [e.g., 11, 12], the low wavenumber spectral shape, regardless of depth, is consistent with meteorites of petrologic type <2.5. The ratio of the two spectral types strongly resembles a phyllosilicate or amorphous/poorly crystalline/disordered phase. The spectra are not well mod-
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...eled by a library containing spectra representing coarse/solid (non-scattering) and volume scattering particulate (<90 µm) minerals and meteorites (where the fine particulates were measured under simulated asteroid conditions [13]). The origin of the observed spectral variations remains enigmatic, potentially arising from differences in one or more of the following: composition, phyllosilicate crystallinity/ordering, particle size effects not replicated by available laboratory spectra, space weathering, surface textural effects, porosity, and others. The distribution of the two spectral types corresponds with visible albedo and thermal inertia [14], which in turn correspond with areas that are relatively rich or poor in large boulders. Surprisingly, the spectral shape that might be expected to represent a contribution from fine, scattering particulates corresponds to the most boulder-rich areas.

Characterization of Candidate Sampling Sites: OVIRS and OTES spectra over all candidate sampling sites were examined for their diagnostic features relative to the global average spectrum for that instrument. Here we summarize the results for the final four sites in wavelength order (OVIRS followed by OTES).

Sandpiper. This southern hemisphere site is generally similar to the global average in OVIRS data other than having a deeper hydration band (which is correlated with temperature). This site has greater spectral contrast than the global average OTES spectrum and resembles the spectral end member having an Si-O stretching band minimum near 987 cm⁻¹.

Nightingale. At OVIRS wavelengths, this site is redder than the global average with a comparable hydration band depth. Nightingale differs from the global average OTES spectrum by its strong resemblance to the spectral end member having a silicate stretching band minimum near 814 cm⁻¹.

Osprey. Like Nightingale, Osprey is also characterized as being redder than the global average and having a similar hydration band depth in OVIRS data. The average thermal spectrum of this site is most similar to the global average OTES spectrum, but nonetheless exhibits characteristics of the end member having the Si-O stretching band minimum near 987 cm⁻¹.

Kingfisher. This site’s average spectrum is very similar to the global average OVIRS spectrum, exhibiting only slight reddening. OTES spectra of this site have greater spectral contrast than the global average and also resemble the end member with the silicate stretching minimum near 987 cm⁻¹.

Implications for the Returned Sample: Based on the combined spectral results to date, we can be quite certain that the OSIRIS-REx returned sample will contain abundant hydrated minerals that will inform our understanding of aqueous alteration on Bennu’s parent body. There appear to be at least two globally-distributed spectral types that may represent compositional or physical variations on Bennu’s surface. As a consequence of the mission requirements for selecting a sample site, the candidate sampling sites are in relatively boulder-free regions that preferentially correspond to one of the two OTES spectral end members, but they exhibit differences at OVIRS wavelengths. There are tantalizing hints that carbon-bearing compounds (organic and/or inorganic) are widespread and will be sampled. Only a few of the exogenous, bright, pyroxene-enriched boulders are large enough (~1 meter) to be readily detected at the scale of existing OVIRS observations and they have not been detected yet in OTES data; depending on the global distribution and abundance of these materials, they may be present within the sampling site and might also be collected.

Summary and Conclusions: The surface of Bennu not only exhibits evidence of hydrated silicates but appears to be dominated volumetrically by such minerals and remains consistent with a bulk composition similar to the most aqueously altered CM carbonaceous chondrites with a potentially included component of CI-like material. Detailed Survey data display heterogeneity that was not previously identified although the origin of this heterogeneity is not entirely understood at this time. The Reconnaissance phase of the mission, starting in September 2019, is expected to result in the acquisition of spectral data at resolutions of ~5-10 m/pixel for the further characterization of the top four candidate sampling sites. These higher spatial resolution data may reveal additional details of the compositional diversity of Bennu.

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Revisiting the Analysis of the MARA Measurements on Ryugu’s Surface with a Multi-Scale Shape Model

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Introduction: The Japanese sample-return mission Hayabusa2 [1] reached the Near-Earth Asteroid (162173) Ryugu on June 27 and observed the surface of Ryugu with various instruments including a thermal infrared mapper (TIR) [2]. Hayabusa2 released the lander MASCOT [3] which carried, among other instruments, an infrared radiometer (MARA) [4]. MARA measured brightness temperatures of a single boulder for a full diurnal cycle, and the thermal inertia of this boulder was estimated to be 247-375 J K^{-1}m^{-2}s^{-1/2} [5]. While this value is low for competent rock, it is consistent with TIR and ground based observations, and appears to be representative for the majority of boulders on the surface [6].

Prior to the visit of Hayabusa2, the low thermal inertia of Ryugu was interpreted in terms of a regolith cover with dominant grainsizes in the millimeter to centimeter range [7]. However, Ryugu’s surface is covered by a surprisingly large number of decimeter to meter sized boulders with thermal properties similar to the ones observed by MARA [6]. The low thermal inertia was interpreted as the consequence of a high intrinsic boulder porosity of 28 – 55 % [5].

The large uncertainty of the thermal inertia estimate was mainly driven by the lack of information about the surface orientation that determines the insolation. In the first analysis of the MARA data, the surface orientation was varied as a free parameter in the thermal model. Now, by constraining the 3D shape of the observed boulder and its surroundings, the illumination and observation geometries are fixed and should allow for a more precise estimate of the boulders bulk thermal inertia.

Methods: From the MASCOT Camera (MasCam) images [8], a detailed 3D shape model of the observed boulder was derived [9]. It was integrated into a reduced regional shape model of the landing site of MASCOT [10]. The illumination and shadowing on this multi-scale shape model determines the upper boundary condition of the 1D heat-conduction equation which is solved for each facet of the combined shape model as described in [11] and [5].

Results: The modeled insolation is shown figure 1 for the times when the MARA instrument observed local sunset, noon, and sunrise. The modeled sunrise and sunset are delayed with respect to the MARA observation. These differences in the timing are likely caused by smoothing effects within the shape model.

Around noon, the facets within the field of view of MARA show a maximum insolation around 800 W m^{-2} which corresponds to intermediate values compared to the initial analysis of the MARA data where the sur-
face orientation was a free parameter of the thermal model, and the results of which are shown in figure 2. Here, the retrieved thermal inertia is plotted as a function of surface orientation, parametrized by the maximum insolation, with color indicating the goodness of fit. Further free model parameters were the emissivity and the heat exchange between the observed spot on the boulder and the environment (methods of [5]).

![Figure 2: Thermal inertia estimates derived from MARA brightness temperature measurements as a function of maximum insolation [5].](image)

**Discussion:** As apparent in figure 2, the main spread of the thermal inertia estimate is due to the unknown orientation of the surface. By fixing the illumination condition through the use of a 3D shape model, we expect to reduce the uncertainty of the thermal inertia estimate significantly. Since the shape model also fixes the heat exchange between the spot on the boulder observed by MARA and its surroundings, the only free parameter left is the emissivity of the surface, which adds little to the uncertainty of the thermal inertia.

Furthermore, the 3D shape model fixes the observation geometry and a consistent implementation of a roughness model becomes feasible. This allows for the analysis of the daytime observations of the four narrow-band filters of MARA. With such an analysis the emissivity of the surface could be estimated at wavelength of 6, 9, 10 and 13 μm and a spectral slope could be determined.

Currently, the thermal model calculating the surface temperatures for each face of the shape model is being implemented. We expect that the new upper limit of the thermal inertia estimate will be below 350 J K^{-1} m^{-2} s^{-1/2} compared to the initial upper estimates of 375 J K^{-1} m^{-2} s^{-1/2}.

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WHAT IS THE HYDRATED PHASE ON BENNU’S SURFACE? R.D. Hanna1, V.E. Hamilton2, C.W. Haberle3, H.H. Kaplan2, E.S. Howell4, D. Takir5, M.E. Zolensky2, and D.S. Lauretta4; 1Jackson School of Geosciences, University of Texas at Austin, TX, (romy@jsg.utexas.edu), 2Southwest Research Institute, Boulder, CO, 3School of Earth and Space Exploration, Arizona State University, Tempe, AZ, 4Lunar and Planetary Laboratory University of Arizona, Tucson, AZ, 5ARES, NASA JSC, Houston, TX, USA

Introduction: The OSIRIS-REx spacecraft observes a large wavelength region from the near to far infrared with two point spectrometers, the OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS) [1] and the OSIRIS-REx Thermal Emission Spectrometer (OTES) [2]. Globally-averaged spectra of Bennu from both instruments have been found to be most consistent with CM-type material [3-4]. However, no meteorite spectrum measured to date is an exact match to the Bennu spectra across the full wavelength region.

The ~3 micron hydron band on Bennu observed by OVIRS has a reflectance minimum at 2.74 μm (±0.01) and is most consistent with an Mg-bearing phyllosilicate typical of CM chondrites [3, 5-7]. This reflectance minimum is not consistent with an Fe-rich phyllosilicate, present in CM petrographic subtypes ≥ 2.5 (scale of [8]), that has a reflectance minimum >2.75 μm [5,7]. It is not consistent with CI chondrites, which have a minimum near 2.71-2.72 μm [e.g., 5, 7]. Therefore, the reflectance minimum at 2.74 μm is most consistent with a CM subtype ≤ 2.4. The globally-averaged TIR spectrum of Bennu collected by OTES is also consistent with a relatively highly-altered CM (≤2.4 petrologic subtype) based on the location of the Christiansen Feature (CF) and Si-O bending minimum [3-4]. However, the globally averaged OTES spectrum (and all individual OTES spectra examined by us to date) lack a discernable Mg-OH band near 16 μm [4]. This is particularly puzzling as this band, due to OH bending (libration) in Mg-bearing phyllosilicates [9], is typical of CM chondrites and is prominent in relatively highly altered (≤2.4) CMs [4, 7].

That Bennu displays a 2.74 μm hydration band, CF, and an Si-O bending minimum consistent with a CM-type material rich in Mg-bearing phyllosilicate but no 16 μm Mg-OH band is surprising. There are four possibilities that could explain this discrepancy: 1) heating or 2) space weathering of CM-type material, 3) particle size effects that may modify or mask the Mg-OH 16 μm or 2.7 μm hydration band, and/or 4) the presence of a poorly crystalline or disordered Mg-bearing phyllosilicate. We are exploring all of these possibilities.

Methods: We have collected infrared (4,000–400 cm⁻¹; 2.5–25 μm) reflectance spectra of several CM and ungrouped C2 carbonaceous chondrites in thin section with a Thermo Scientific iN10 FTIR microscope (μFTIR) at a spectral resolution of 4 cm⁻¹ [10]. We performed complementary chemical, mineralogical, and textural analysis of the sample sections using backscattered electron (BSE) imagery and energy-dispersive (EDS) x-ray analysis.

Results: Heating of a CM-type material. We first investigated heating of CM-like material to explain the absence of the Mg-OH band (as well as broadening of the Si-O stretching band) [4]. However, our previous vacuum heating experiments with Allan Hills (ALH) 83100 (CM2.1) show that although the Mg-OH band is weakened and the Si-O stretching band is broadened with heating, the 2.71 μm OH stretching band grows sharper and more symmetric before disappearing by 800°C. This is consistent with a previous study of chrysotile dehydration [11] and suggests the relatively broad and asymmetric shape of Bennu’s 2.74 μm feature is inconsistent with heating. In contrast, Ryugu’s relatively weak and sharp 2.72 μm band is consistent with heating (or shock) of a CM- or CI-type material [12].

Space weathering of a CM-type material. Similar to heating, simulated space weathering (ion irradiation) of hydrous, CM-type material produces broadening of the Si-O stretching band due to phyllosilicates amorphization [13-14]. The ~2.7 OH stretching band also moves to longer wavelengths (~40 nm) after ion irradiation, although it is unclear if adsorbed water is contaminating the pelletized powders and therefore the 3-micron region [e.g., 5]. On the other hand, simulated micrometeorite bombardment (laser irradiation) on Murchison (CM2.5) found no measurable shift with increasing irradiation [15]. We could find no published work that discusses the effect of simulated space weathering (of any kind) on the Mg-OH libration band, but Figure 7 of [13] suggests that it is not significantly affected by ion irradiation.

Particle size effects. Particle size variations influence reflectance and emission spectra in a variety of ways. In the 2.7 μm hydration band area, some previous work has noted no variation in band depth or shape with particle size [16]. However, when comparing the 2.7 μm band of a chip or thin section spectrum to that of a powdered particle spectrum of the same sample, a solid sample spectrum displays a 2.7 μm
band with sharper features positioned at a slightly shorter wavelength [17–18] (Fig. 1). Although the powered samples were heated to removed terrestrially adsorbed water, it is possible that residual water may still be influencing the shape of the 2.7 µm band. Regardless, it is intriguing that Bennu’s 2.74 µm band minimum resembles the more rounded shape of a powdered CM sample with decreased reflectance out to 2.86 µm rather than the sharp minimum of a solid sample. Particle size effects at OTES wavelengths (>6 µm) manifest themselves primarily as changes in spectral contrast and the introduction of transparency features for the finest grainsizes [e.g., 19]. Previously published spectra suggest that in some cases, such effects are masking the 16 µm Mg-OH libration band and in other cases they are not, although sample heterogeneity can be a complicating factor [20–21].

Poorly crystalline or disordered Mg-bearing phyllosilicate. The final possibility is the presence of a poorly crystalline or disordered Mg-bearing phyllosilicate that results in a modified Mg-OH libration band. This disorder could be caused by cation substitution or intimate mixing (on the scale of nanometers) of phyllosilicate types (e.g., serpentine, saponite, chlorite). This type of highly disordered and intergrown phyllosilicate is characteristic of ungrouped C2s such as Essebi and Tagish Lake [22–24] and indeed, the 2.7 µm hydration bands of these samples are a good match to the OVIRS Bennu spectrum (Fig. 2). Although their TIR spectra are not a match to the OTES spectrum of Bennu, their 16 µm absorptions do not look like typical CMs and require more investigation.

Ongoing Work: Our ongoing work includes investigating co-located spectral and EDS maps of select CMs and ungrouped C2s Essebi and Tagish Lake (Fig. 2) to determine if higher-resolution analysis will yield insights into the hydrous phase(s) present on Bennu. We will also utilize Gaussian deconvolution [18] to deconstruct the 2.7 µm hydration band at both bulk and intrasample map (<300x300 µm²) scales.

Acknowledgements: This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program, and under grant 80NSSC18K0229 to R.D.H. through the Participating Scientist Program. We are grateful to the entire OSIRIS-REx Team for making the encounter with Bennu possible.


Figure 1. Reflectance spectra of powders compared to thin sections. Grey line marks minimum of LAP 02277 thin section (2.71 µm). Powdered spectra from [5-6].

Figure 2. Bennu global average spectrum from [3] to powdered spectra from [6]. Grey lines mark minima of the Bennu (2.74 µm) and Tagish Lake (2.72 µm) spectra.
**Introduction:** Electrostatic dust levitation has been hypothesized to occur on the Moon (following observations of the Lunar Horizon Glow [1]). Electrostatic levitation is the suspension of dust particles above the surface of an airless body due to the balancing of the forces accelerating the dust towards and away from the surface. Since the gravitational acceleration is much weaker on asteroids than the Moon, larger particles may stably levitate [2]. Additionally, solar radiation pressure is a significant force in determining the dynamics of electrostatic levitation about asteroids [3].

Particles on the surface of airless bodies are electrically charged due to the interaction of the surface with the solar wind plasma. Similarly, a plasma sheath (a region where the ion and electron densities are not equal) is formed in the first 10’s of meters above the charged surface. The electrostatic force on a levitating particle is the product of the particle’s charge and the local electric field in the plasma sheath.

Electrostatically levitating dust may be launched off the surface of an asteroid due to a variety of effects including micrometeoroid bombardment, spacecraft operations and electrostatic lofting. The dynamical state of levitation is agnostic to the launching mechanism and only requires that dust particles are lofted within a small window of initial velocities.

**Investigation:** Our prior investigations of electrostatic levitation about Bennu [3] have used a semi-analytical model of the plasma sheath. This sheath model (described by [4]) is not valid in the terminator or night regions. We have implemented a fully numerical model of the plasma environment about the asteroid’s 2D equatorial cross section. In this poster, we will present simulations of electrostatic levitation about the asteroid’s cross section in the 2D plasma model. We are particularly interested in exploring the fate of the levitating grains: specifically, are the majority of levitating particles swept away due to solar radiation pressure, or is there a preferential region of reimpact? The questions influence our interpretation of the particle sizes observed on Bennu’s surface.

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Reflective surface texture through OCAMS and OVIRS on-board OSIRIS-REx: What single-scattering processes can tell us about the surface of dark asteroids like (101955) Bennu?

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Introduction: The OSIRIS-REx mission has revealed a boulder-rich and dark surface for the B-type asteroid (101955) Bennu [1], presenting therefore a challenge for the reflectance modeling. With a estimated geometric albedo of 4.5% [2], Bennu is darker than many comets, and has its reflectance distribution dominated by single-scattering processes, i.e., single-particle scattering function and shadowing effects due to microscopic-relief and particle size distributions.

The general approach to model a dark asteroid’s reflectance distribution is to rely on the radiative transfer equation. It is assumed their surfaces to be packed by layers of totally diffusive particles and to apply a largely approximative shadowing functions [3]. These two assumption can generally lead to parameters that may imprecisely describe the asteroid’s surface [4]. For example, many collected rough surfaces in nature have been shown to diverge from the standard Hapke shadowing function [5,6]. While the “totally diffusive” assumption can even negate an important specular back-scattering contribution of few percentages of mineral inclusion in the composition of the asteroid [7].

Therefore, in hope to achieve a more complete photometric modeling out of Bennu’s scattering curve, we rely on the radiative transfer model of Van Ginneken et al. [8]. The model has the quality to be adaptive to different scattering laws and micro-relief distributions. It has successfully described the reflectance distribution for high reflectivity lab samples and also the lunar phase curve [9].

Observations: Our analysis focused on the MapCam images obtained as well as the OVIRS spectra at the same wavelength range from data obtained during the Preliminary Survey phase (distance of ~20 km, December, 2018) and Equatorial Stations 1, 3, 4 & 6 (May-June, 2019). We aim at determining the parameters for each instrument to cross-check the results. MapCam is a medium-range camera with four wideband filters ranging from blue (0.470 microns) to near-infrared (0.860 microns). Its field of view (FOV) is 0.068 mrad [10].

OVIRS is a VIS-NIR point spectrometer ranging from 0.4 to 4.7 microns. Every point spectra is obtained in a circular FOV of 4 mrad [11].

Methodology: The methodology consists of the following steps:

a) The most recent NAIF SPICE kernels and 1Million-facet Shape Model are ingested into a ray-tracing code for rendering shadowed images for Bennu’s surface. This makes possible to discount for the effects of macroscopic shadows, leaving only the sub-facet texture to be modeled. These high-quality simulated images are essential to obtain the geometric angles (incidence, emergence, phase & azimuth) for every facet & pixel.

b) For every shape model facet we build a table containing the radiance factor measurements & geometric angles gathered from all images and/or spectra. Then, every facet is represented by an Gaussian distribution of relief slopes. Moreover, every relief scatters according to the Lommel-Seeliger law.

c) We apply the Van Ginneken’s radiative transfer model to obtain the associated radiance factor to every facet. The model has two major components: the analytical expression for the specular reflection; and the numerically-integrated diffusive reflection. At total, the model has three parameters, plus the one more related to the single-scattering phase function (mono-lobe Henyey-Greenstein): w (single-scattering albedo), r (RMS roughness slope), g (specular-to-diffuse ratio) and ξ (asymmetric factor).

d) Inverse problem: For obtaining the global set of parameters (w, ξ, r, g) from imaging data, we first bin every image to reduce the data amount and local albedo fluctuations. We used the basin-hopping minimization tool combined with L-BFGS-B algorithm from the Scipy.Optimize package to explore the best minimizing solution in the multi-parametric space. Basin-hopping dispatches several different initial conditions “hopping” through the space and registering the best local minima. The global solution is assigned to the best Chi^2 minimization between data and modeling. We have generally dispatched 300-500 hops, keeping the best 50-100 solutions for evaluation. The number can vary by depending on the amount of local minima & convergence of the problem.
For building a geographical-parametric map, we have to resort to similar procedure to the global solution search, but with less “hops” & kept solutions. Only 50 max hops and 3 minima kept. First, we split the Shape model into thousand surface patches containing about hundred facets each and tens of thousand pixels. Every “patch” takes a surface box of few given meters size. This measure was taken reduce the pole distortions, wayward facet artifacts & image misalignments in the analysis.

**Preliminary Results:** Our preliminary OCAMS modeling show that the best solutions are clustered between 30-40% contribution of the specular component (g), with the RMS roughness slope (r) well centered around 10-14 degrees. The single-scattering albedo (w) is strongly correlated to the amount of specular reflection, with best solutions coming out between 3-3.5% albedo. The asymmetric factor (ξ) is the most stable parameter, centered at 0.45±0.02. The best total of squared residues reaches 69.58.

We have also tested solutions without specular component, but their total of squared residues were never under 70. Moreover, only diffuse component solutions overestimates the reflectance for small scattering angles & poorly describes the dark reflectance values at large negative scattering angles. We only start fitting these key regions in the scattering curve when we add at least 25% of specular reflection.

We have yet to verify if incorrect facet tilts coming out of the shape model may interfere to increase this specular contribution. These limitations can lead to wrong estimation of geometric angles and therefore to misleading assumptions on the back- and forward-scattering [12].

**Discussion:** The addition of specular reflection can explain some of the strong back-scattering and weak forward-scattering in the reflectance distribution of asteroids. However, this effect has been generally put aside for the assumption of only totally diffusive particulate surfaces in many other scattering models. One of the main motivation for this is the observation of the very fine grains on solar soils and therefore the simply reproduction of the solar scenario onto asteroids. Bennu’s surface as well as Hayabusa II Ryugu’s show however an apparent lack of widespread very fine grains and seems mostly composed by boulder-size distributions. Interestingly, few boulders imaged by OCAMS show large inclusions of bright material [12] and many elevated back-scattering reflection due to apparent “flat rock sides”. Yet, it is difficult to correspond the percentage of specular component and the real amount of such “specular agents” without knowing their average normal albedo.

In the literature, specular reflection have been evoked to partially model the broad backscattering observed at the phase curve of large asteroids [7]. This contribution have been attributed to very limited presence of crystals [7], as clasts or inclusions, as well as to a peculiar planar symmetry of wavelength-size scatterers [13]. Symmetry such that it can reproduce some crystalline structures.

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**References:**

Planetary Sample Analysis Laboratory (SAL) at DLR  J. Helbert¹, A. Maturilli¹ and J.-P. deVera
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Introduction: Building on the available infrastructure and the long heritage in spectral studies of planetary (analog) materials DLR is creating a Sample Analysis Laboratory (SAL). The setup has started with the installation of a vis-IR-microscope at the Planetary Spectroscopy Laboratory in 2018.

SAL will add over the next 4 years capabilities for detailed mineralogical and geochemical characterization of material return by sample return missions in a clean room facility. The step-wise extension follows the successful development approach used for the Planetary Spectroscopy Laboratory (PSL) and Astrobiology Laboratories. The goal is to test and validate each extension step before planning the follow-up step. The first step is focused on analysing samples from asteroids missions like Hayabusa 2 mission, Osiris-REX and lunar sample return missions. SAL can later be extended to a full Sample Curation facility.

Global reconnaissance of planetary surface can only be obtained by remote sensing methods. Optical spectroscopy from UV to far-infrared is playing a key role to determine surface mineralogy, texture, weathering processes, volatile abundances etc. It is a very versatile technique, which will continue to be of importance for many years to come. Providing ground truth by in-situ measurements and ultimately sample return can significantly enhanced the scientific return of the global remote sensing data. This motivates the planned extension of PSL with a SAL by support of the Astrobiology Laboratories.

SAL will focus on spectroscopy on the microscopic scale and geochemical and geo-microbiological analysis methods to study elemental composition and isotopic ratios in addition to mineralogy to derive information on the formation and evolution of planetary surfaces, search for traces of organic materials or even traces of extinct or extant life and inclusions of water.

The DLR SAL will be operated as a community facility (much like PSL), supporting the larger German and European sample analysis community

Current facilities: PSL at DLR (http://s.dlr.de/2siu) is the only spectroscopic infrastructure in the world with the capability to measure emissivity of powder materials, in air or in vacuum, from low to very high temperatures [1-3], over an extended spectral range. Emissivity measurements are complimented by reflectance and transmittance measurements produced simultaneously with the same setup. It is the ground reference laboratory for the MERTIS thermal infrared spectral imager on the ESA BepiColombo mission [4, 5]. Members of the PSL group are team members of the MarsExpress, VenusExpress, MESSENGER and JAXA Hayabusa 2 missions [6]. For the latter mission PSL has performed ground calibration measurements. In addition PSL has been used extensively in support of the ESA Rosetta mission. The samples analyzed at PSL ranged from rocks, minerals, to meteorites and Apollo lunar soil samples.

In a climate-controlled environment PSL operates currently two Fourier Transform Infrared Spectrometer (FTIR) vacuum spectrometers, equipped with internal and external chambers, to measure emittance, transmittance and reflectance of powdered or solid samples in the wavelength range from 0.3 to beyond 100 micron. Recently a Hyperion 2000 microscope has been added in preparation of the SAL setup. For details on PSL see the accompanying presentation.

In addition the institute is operating a Raman microscope lab (http://s.dlr.de/e49q) as part of the Astrobiology Laboratories with a spot size on the sample in focus of <1.5 μm. The spectrometer is equipped with a cryostat serving as a planetary simulation chamber which permits simulation of environmental conditions on icy moons and planetary surfaces, namely pressure (10-6 hPa – 1000 hPa), atmospheric constituents, and temperature (4K – 500K). The samples, which are analyzed in the laboratory range from minerals, Martian analog materials, meteorites, biological samples (e.g. pigments, cell wall molecules, lichens, bacteria, archaea and other) to samples returned from the ISS (BIOMEX) [7, 8, 9] and the asteroid Itokawa (Hayabusa sample).

All laboratory facilities undergo regular evaluations as part of the DLR quality management process. The evaluations address laboratory protocols, documentation, safety, data archival and staff training.

PSL is a community facility as part of the “Distributed Planetary Simulation Facility” in European Union funded EuroPlanet Research Infrastructure (http://www.europlanet-2020-ri.eu/). Through this program (and its predecessor) over the last 7 years more than 60 external scientists have obtained time to use the PSL facilities. PSL has setup all necessary protocols to support visiting scientist, help with sample preparation, and archive the obtained data.

Sample Analysis Laboratory: The near-term goal of the first step is the preparation to receive samples from the JAXA Hayabusa 2 and MMX missions, the Chinese Chang-E 5 and 6 missions as well as the NASA Osiris-REX mission. The current PSL and Raman facilities are operating in climate-controlled rooms and...
follow well-established cleanliness standards. The SAL will be housed in two ISO 5 clean rooms. The clean rooms are equipped with glove boxes to handle and prepare samples. All samples will be stored under dry nitrogen and can be transported between the instruments in dry nitrogen filled containers.

To characterize and analyze the returned samples the existing analytical capabilities are currently been extended. PSL was just upgraded with a vis-IR-microscope to extend spectral analysis to the sub-micron scale.

For the SAL this will be complemented by the following capabilities:

1. Electron Microprobe Analyse (EMPA) for elemental analysis with a supporting Transmission Electron Microscope (TEM)
2. Laser ablated inductive coupled Plasma Mass Spectrometer for elemental and isotope analysis
3. Dual Source TXRF & Grazing Incidence ED-XRF for mineralogical and structural analysis
4. Supporting equipment incl. microtome to prepare thin sections, optical polarization microscope, etc.

Based on current planning the first parts of SAL will be operational and ready for certification by end of 2021. Analysis of first Hayabusa 2 samples can start by beginning to mid of 2022.

**Outlook:** DLR has started establishing a Sample Analysis Laboratory. Following the approach of a distributed European sample analysis and curation facility as discussed in the preliminary recommendations of EuroCares (http://www.euro-cares.eu) the facility at DLR could be expanded to a curation facility. The timeline for this extension will be based on the planning of sample return missions. The details will depend on the nature of the returned samples. Through the BIOMEX project a collaboration has been established with the Robert-Koch Institute (RKI) (http://www.rki.de) for question of samples that might pose a bio-hazard. RKI is operating BSL 4 facilities, which might be used as part of the DLR curation facilities.

**References:**

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**Figure 1 Current layout for the SAL**
OBSEVATIONAL COMPLETION LIMIT OF MINOR PLANETS FROM THE ASTEROID BELT TO JUPITER TROJANS

Nathanial P. Hendler¹ and Renu Malhotra¹, 1 Lunar and Planetary Laboratory, The University of Arizona, Tucson, AZ

Introduction: The distributions of orbital elements and the physical characteristics of the minor planets between Mars and Jupiter retain important clues about the formation and evolution of the Solar System.

As of July 2019, more than seven hundred thousand minor planets have been discovered, offering a statistically large sample to permit deep analyses for dynamical structures and their correlations with their physical properties. However the discovered sample is subject to observational biases that must be understood for the proper interpretation of their demographics. Because these minor bodies are detected by their reflected sunlight, the observed sample suffers from the selection effect that brighter objects are more easily detectable than fainter objects. This bias manifests as an artificial peak in the distribution of the absolute magnitude $H$, even when the intrinsic population of fainter/smaller objects grows rapidly with $H$. In attempting such analyses, it is often important to identify an observationally complete sample. Previous studies have adopted a single value of the observational completeness limit, $H_{lim}$, for the entire asteroid belt. For example, [1] and [2] adopt an $H_{lim} = 15$, and [3] and [4] adopt $H_{lim} = 15.5$. However, in order to better assess the demographics of the asteroids at higher resolution in semi-major axis, $a$, we have found a need to model the completion limit as a function of semi-major axis, $H_{lim}(a)$, and to make sure that its value is contemporary with our sample population since $H_{lim}$ evolves with time as observational surveys go deeper with technological advances.

In the previous literature, the absolute magnitude, $H$, at which a sample becomes observationally incomplete, $H_{lim}$, has typically been determined using one of two methods. The first, and not uncommon method is for a single value to be given without explicit justification, or to be sourced from an older work. The second approach makes the reasonable assumption that the intrinsic population is expected to increase as a power-law as one considers objects of smaller and smaller diameters (hereafter referred to as the power-law method). Then, the $H$ value at which a decline in the population of observed objects is seen (i.e. a break in the power law) is taken to be the completion limit. Use of the power-law method requires several assumptions. First, it must be assumed that the asteroids follow a single power law size distribution. Second, a range of $H$ must be chosen with which to apply a linear regression. Third, the magnitude at which the deviation from linear is extreme enough to define $H_{lim}$ must be defined. The latter two require subjective decision-making.

We have developed a method to measure $H_{lim}(a)$ from observations, and describe it with a simple physically motivated model. We think that using our approach will provide researchers with completion limit models for the main belt asteroids and Jupiter Trojans that can be used to more accurately and consistently simulate observations, debias observations for statistical analyses, and model/synthesize minor-planet populations. This approach will lead to more reproducible and comparable results, and allow for the completion limit to be updated consistently over time as more minor bodies are discovered.

Methodology: Using the records for $\sim 7 \times 10^5$ objects from the Minor Planet Database, we measure the empirical $H_{lim}$ at each radial location by binning objects in both $a$ and $H$ and then identifying the $H$ bin with the greatest number of objects to be the value of $H_{lim}$ at that radial distance. This method is a generalization of the power-law method. However, our method requires fewer assumptions and fewer subjective decisions to be made in its application, making results more transportable and comparable between studies that implement it.

To these measured values, we then fit a simple, physically motivated model of $H_{lim}$ as a function of semi-major axis:

$$H_{lim} = -5 \log_{10}(a(a-1)) + C$$  \hspace{1cm} (1)

where $a$ is semi-major axis and $C$ is the only free parameter in the model. The model fitting is done with the use of Monte Carlo Markov Chains (MCMC) which determines $H_{lim}$ and $C$ as well as the associated confidence intervals. Details will be presented in a forthcoming paper.

Results: We report our preliminary results in Figure 1 and in Table 1. Across the main belt, our model finds a completion limit of $H_{lim} = 18.3$ at the innermost edge, and $H_{lim} = 15.9$ at the outermost edge. The lowest value found is larger than the completion limit values adopted in recent studies, confirming that those studies adopted somewhat conservative completion limits. We also find deviations between our best-fit model for the main belt and $H_{lim}(a)$ values for populated regions outside the main belt (the Hungarias, Hildas and Trojans), suggesting potential demographic differences.
Figure 1: The $H$ bin with the largest population of asteroids at each semi-major axis bin is shown as the black points; the associated uncertainties are indicated with the vertical black lines. The best-fit non-linear model for the limiting magnitude (Eq. 1) is shown as the dark-blue line with the corresponding confidence interval shown in light blue. The dashed vertical lines in red indicate the locations of selected mean motion resonances with Jupiter.

Table 1: Model fitting results

<table>
<thead>
<tr>
<th>Region</th>
<th>inner (au)</th>
<th>outer (au)</th>
<th>$H_{lim}$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hungarias</td>
<td>1.780</td>
<td>2.000</td>
<td>18.26</td>
</tr>
<tr>
<td>Main Belt</td>
<td>2.120</td>
<td>3.250</td>
<td>16.95</td>
</tr>
<tr>
<td>Inner Belt</td>
<td>2.120</td>
<td>2.500</td>
<td>17.62</td>
</tr>
<tr>
<td>Middle Belt</td>
<td>2.500</td>
<td>2.960</td>
<td>17</td>
</tr>
<tr>
<td>Outer Belt</td>
<td>2.960</td>
<td>3.250</td>
<td>16.23</td>
</tr>
<tr>
<td>Hildas</td>
<td>3.920</td>
<td>4.004</td>
<td>15.72</td>
</tr>
<tr>
<td>Trojans</td>
<td>5.105</td>
<td>5.319</td>
<td>13.86</td>
</tr>
</tbody>
</table>

such as changes in albedo, size and/or eccentricity distributions.

The range of 2.4 magnitudes across the main asteroid belt suggests that a single value of $H_{lim}$ will not provide the most accurate statistical confidence when debiasing, modeling, or simulating observations of the entire main belt as the inner asteroid belt is significantly more complete than the outer belt.

The observational completion limit of minor planets is a function of semi-major axis, and will increase over time as surveys get deeper and wider. It is our recommendation that future studies consider our parameterized model for identifying observationally complete samples of asteroids. Our code, which can recalculate the completion limit for any set of objects using the MPCORB database will be available soon at http://github.com/quant/completion_limit/.

We thank the Marshall Foundation for support. This research has made use of data and/or services provided by the International Astronomical Union’s Minor Planet Center and by NASA’s Astrophysics Data System.

References

C-COMPLEX ASTEROIDS: UV-VISIBLE SPECTRAL CHARACTERISTICS AND IMPLICATIONS FOR SPACE WEATHERING EFFECTS. Amanda R. Hendrix¹ and Faith Vilas¹, ¹Planetary Science Institute, Tucson, AZ (arh@psi.edu)

Introduction: Space weathering effects on the rocky S-class asteroids are well-understood. However, on the low-albedo C-complex asteroids, such as spacecraft targets Bennu and Ryugu, the situation is more complicated, especially due to a lack of spectral features throughout the visible-near infrared spectral region. Here we show, through a combination of observational data and laboratory data of carbonaceous chondrites, phyllosilicates and mixtures, that the UV-visible spectral region is a diagnostic regime for studying space weathering effects on C-complex asteroids. We show that space-weathering-produced opaque constituents, such as graphitized carbons, darken mixtures with phyllosilicates and weaken the UV absorption, consistent with what is seen on the asteroids compared with carbonaceous chondrites. Furthermore, we show that diagnostic spectral signatures of carbons of varying levels of graphitization can be used to study relative ages of low-albedo surfaces in the solar system.

Background: Low albedo C-complex asteroids are typically rather spectrally featureless at visible-near infrared (VNIR) wavelengths. Roughly half of the low-albedo asteroids in the main asteroid belt exhibit an absorption feature near 3 µm, indicative of some form of hydration (OH and/or H₂O). Roughly half of the asteroids with the 3 µm feature also exhibit a shallow absorption feature near 0.7 µm, attributed to a ferrous-ferric charge transfer transition likely resulting from aqueous alteration (the interaction of material with liquid water formed by melting of water upon a heating event) of iron-bearing phyllosilicates. Some asteroids have spectra that likely do not exhibit these features due to a history of heating that has been experienced at some point in the asteroid’s evolution. Despite having little spectral activity in the VNIR, all low-albedo asteroids exhibit a UV absorption (or UV “dropoff”) at wavelengths shorter than ~0.5 µm, attributed to a strong ferric oxide intervalence charge transfer (IVCT) transition (e.g. [1][2]).

In spectra of terrestrial phyllosilicates, both the 0.7 µm absorption and the UV absorption are very strong and steep (e.g. [3]). Hiroi et al. [4] compared UV-VIS characteristics of 14 low-albedo class asteroids (using 24-color data) with laboratory spectra of carbonaceous chondrites. They noted that the asteroids exhibited weaker UV absorptions than the meteorites. They suggested this behavior could be due to thermal history, by demonstrating that heating carbonaceous chondrites can diminish the strength of the UV absorption edge. Vilas and Sykes [5], however, pointed out that heating carbonaceous chondrites removes the aqueous alteration spectral feature at 0.7 µm, which is seen in many of the asteroid spectra, suggesting that all of the observed surface material has not been heated to a stage of metamorphism.

In this study, we combine space-based UV data from International Ultraviolet Explorer (IUE) and Hubble Space Telescope (HST) along with ground-based data and laboratory data of relevant materials and mixtures to show that UV-visible (UV-VIS) spectral differences between C-complex asteroids and carbonaceous chondrites are likely linked to the effects of space weathering. We first demonstrate the UV-VIS characteristics of C-complex asteroids and of CM chondrites and phyllosilicates, to understand relationships. We then look at the UV-VIS characteristics of phyllosilicate-opaque mixtures.

Comparisons with Carbonaceous Chondrites: C-complex asteroids are commonly linked with CI and CM chondrites due to their relatively low albedos and muted spectral signatures at VNIR wavelengths (e.g. [6]). CM chondrites are dominated by serpentine minerals (including cronstedtite), tochilinite and olivine [7]. CI chondrites generally are rich in phyllosilicates (namely serpentine and saponite) and magnetite [8].

As has been shown for a set of asteroids and chondrites [4], C-complex asteroids in general have a less steep UV dropoff compared to carbonaceous chondrite meteorites. The effect is that the asteroids are relatively bright, compared to the meteorites, at UV wavelengths. At VNIR wavelengths, differences in spectral characteristics between C complex asteroids and CM/CI chondrites are less obvious.

We investigate these meteorite-asteroid UV-VIS spectral differences by inspecting the spectral trends in CM chondrites, using the RELAB library of 39 chondrites (after [7]), many with multiple spectra. Comparing our composite asteroid spectra with the spectra of the CM chondrites, we find that indeed most of the CM chondrites exhibit a stronger UV absorption than the asteroids, though there is clearly variation among these chondrites, where some exhibit stronger UV absorptions and some not as strong.

Links with Space Weathering: A reasonable explanation for the differences between the asteroid spectra and the meteorite spectra (the relative blueness of the asteroids) is space weathering effects, i.e. those due to solar wind and micrometeoroid impacts.

Space weathering effects on asteroids have been studied for decades. On S-class asteroids, the link be-
tween parent asteroids and ordinary chondrite meteorites was finally understood to be due to the production of nanophase iron [9] that darkens and reddens spectra at VNIR wavelengths (e.g.[10]) and results in a spectral bluing at UV wavelengths [11]. Weathering effects on C-class and other low-albedo class asteroids have been less well-understood. At VNIR wavelengths, both spectral bluing and reddening of VNIR asteroid spectra have been attributed to weathering (e.g. [12][13][14]).

In the laboratory, several experiments have been performed on carbonaceous chondrites and analog materials to simulate the effects of micrometeoroid bombardment (via laser irradiation) and solar wind exposure (via ion irradiation). A common result of these simulations is the production of opaque materials ([15][16][17]), notably carbonized materials ([18][19][20]). These examples of laboratory measurements of simulated space weathering on C-complex-type materials demonstrate that, analogous to SMFe being a weathering product on S-type asteroids, carbonized/graphitized materials or other opaques are likely to be present on the surfaces of C-complex asteroids as a result of space weathering. We thus look at the spectral effects of mixtures of phyllosilicates and opaques and suggest that a driving difference between the UV-VIS spectral differences in C complex asteroids and CI/CM chondrites is the presence of space weathering-derived opaques on the surfaces of the asteroids, consistent with the results of [21].

SPIN-DRIVEN EVOLUTION OF TOP-SHAPED ASTEROIDS AT FAST AND SLOW SPINS SEEN FROM (101955) BENNU AND (162173) RYUGU. M. Hirabayashi1, Y. Cho2, T. Morota2, E. Tatsumi3, K. J. Walsh4, O. S. Barnouin5, R.-L. Ballouz6, P. Michel7, D. J. Scheeres8, S. Watanabe9, and S. Sguia2, 1Auburn University, Auburn, AL 36849, U.S.A. (thirabayashi@auburn.edu), 2University of Tokyo, Japan, 3Instituto de Astrofísica de Canarias, Spain, 4Southwest Research Institute Boulder, U.S.A., 5Applied Physics Laboratory/Johns Hopkins University, U.S.A., 6University of Arizona, U.S.A., 7University of Arizona Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, France, 8University of Colorado Boulder, U.S.A., 9Nagoya University, Japan.

Summary: A top-shaped asteroid may evolve its shape due to global deformation at a fast spin and surface mass movements at a slow spin.

Introduction: Since 2018, two international exploration missions have observed different target asteroids, B-type asteroid (101955) Bennu and C-type asteroid (162173) Ryugu. The Hayabusa2 spacecraft arrived at Ryugu on June 27, 2018 [1] while the OSIRIS-REx spacecraft started proximity remote-sensing observations of Bennu on December 1, 2018 [2]. Since then, both of the mission teams have conducted detailed proximity observations and experiments of their target asteroids [e.g., 1-9].

Their formation and evolution processes are controlled by their initial accumulation phase [10, 11], followed by deformation processes at a fast spin [e.g., 12]. For the rotation-driven evolution, possible shape deformation modes of Ryugu and Bennu were discussed separately [1,5]. Ryugu is in general considered to have evolved due to global deformation at a spin period at ~3.5 hr. On the other hand, Bennu’s geomorphological features including long linear grooves imply its internal strength [7] while the surface slope fits the spin slope that is potentially minimum at the current spin condition, 4.3 hr [5], implying that its surface may have evolved even at the current spin period. This finding is consistent with the finding of active surface modification on this asteroid [6]. Here, we use the finite element model (FEM) results [1,5] to reduce the gap of this understanding.

Brief Overview of Structural Analysis: Our structural analysis was established based on the use of a FEM technique for computing inelastic deformation modes of irregularly shaped bodies. In the earlier work [1,5,14], we analyzed the structural failure conditions of Bennu and Ryugu to give insights into the rotation-driven shape evolution mechanisms of top-shaped asteroids. This technique develops a FEM mesh model from a polyhedron shape model, computes the loadings based on self-gravity and centrifugal forces, and defines the boundary conditions (as a numerical artifact). Inelastic deformation is detected by using the Drucker-Prager model, which includes three physical parameters: cohesive strength, friction angle, and dilatancy angle. In this approach, the friction angle and dilatancy angle are both fixed at 35 degrees [1,5,14].

Results: In this presentation, we consider the structural failure conditions of Bennu and Ryugu at two spin period conditions from [1,5,14]. The first spin condition is the current spin period; Ryugu is spinning at a spin period of 7.6 hr while Bennu is doing so at a spin period of 4.3 hr. The second spin condition is that both of these asteroids rotate at a spin period of 3.5 hr. At this spin period, the evolution of Ryugu’s top-shape was considered to be completed [1,14] while surface modifications were also observed [3]. Bennu is also expected to experience a similar failure mode at this spin period because of the same bulk density, 1.19 g/cm³ [5].

Figure 1. Bennu’s failure mode at a spin period of 4.3 hr. Panel a shows the equatorial plane while Panel b gives the top surface. The yellow regions are structurally failed while the green areas are intact. The cohesive strength of this case is 0.2 Pa [5].

Figure 2. Ryugu’s failure mode at a spin period of 7.6 hr. The format follows Figure 1. The cohesive strength of this case is 1 Pa [1].

Figure 1 shows the failure mode of Bennu at a spin period of 4.3 hr while Figure 2 describes that of Ryugu at a spin period of 7.6 hr. Bennu and Ryugu
are both structurally intact inside their bodies. However, the surface condition is different; Bennu's surface is significantly sensitive to failure while Ryugu's is almost intact everywhere. Importantly, Bennu's structurally failed regions widely spread in an almost axisymmetric way.

Figure 3. Bennu's failure mode at a spin period of 3.5 hr. The format follows Figure 1. The cohesive strength of this case is 0.8 Pa [5].

Figure 4. Ryugu's failure mode at a spin period of 3.5 hr. The format follows Figure 1. The cohesive strength of this case is 3 Pa [14].

Figures 3 and 4 give the failure modes of these asteroids at a spin period of 3.5 hr. The results show that the interiors of these objects fail structurally. However, while the failed region in Bennu is almost axisymmetric, that in Ryugu is not. The asymmetric failed region in Ryugu implies that the Western region of this body may structurally be relaxed due to a large scale deformation process that may have occurred in the past [14].

Discussions: In this work, we compared the FEM results for Bennu and Ryugu under the assumption the structure is uniform [1,5]. There are two key findings. First, at the current spin conditions, Bennu has sensitive surface conditions (4.3 hr) while Ryugu does not (7.6 hr). Second, if the structure is uniform, both Bennu and Ryugu should be sensitive to internal failure at a spin period of 3.5 hr. However, the structurally failed regions in Ryugu is more asymmetric than those in Bennu.

Ryugu's asymmetric failed region may be indicative of a global deformation process that may have occurred at a short spin period [1] and caused structural relax in the Western region [14]. This argument comes from the fact that even small structural heterogeneities in a body can induce axisymmetric deformation processes [17]. However, applying this hypothesis to Bennu does not explain its symmetric failed regions. If Bennu’s top-shape has evolved due to global failure, we should see asymmetric structure in this asteroid as it may be difficult for it to experience axisymmetric deformation beautifully.

We consider that Ryugu's shape may have mainly been developed due to global, asymmetric deformation at a fast spin (~3.5 hr) while Bennu's may have been driven by frequent surface mass movements at shallow depth at the current spin period (4.3 hr). Deformation at a fast spin can occur globally in a short timescale, change the spin period, and modify the shape significantly. This may explain the almost perfect circularity of Ryugu's equatorial ridge as fluidized materials may settle within the Hill sphere uniformly [1]. On other hand, surface mass movements at shallow depth at a relatively slow spin can occur locally but frequently, inducing the shape change gradually. This supports earlier reports that the surface of Bennu is active currently [6, 7]. Also, this explains the imperfect circularity of Bennu’s equatorial ridge [7] and the observed slope variations [5].

In summary, top-shaped asteroids may evolve at a wider spin period range than thought with different deformation mode. In this scenario, immediately after the initial accumulation stage of rubble pile asteroids, many may start evolving to become top-shapes even at relatively slow spin conditions. This hypothesis supports that the majority of asteroids in the solar system have top-shapes.

Acknowledgments: M.H. thanks support from NASA/SSW (NNH17ZDA001N/80NSSC19K0548). This study was supported by Japan Society for the Promotion of Science (JSPS) Core-to-Core Program International Network of Planetary Sciences.

NEW FEATURES OF AiGIS FOR HAYABUSA2 MISSION: A 3D-GIS FOR VISUALIZATION OF MAP AND SHAPE OF IRREGULAR-SHAPED SMALL BODIES. N. Hirata¹, H. Demura¹, K. Kitazato¹, T. Tsuchiy¹, Y. Yamaguchi², T. Endo², H. Sato³, H. Kikuchi³, and H. Otake³, ¹ARC-Space, the University of Aizu (Aizu-Wakamatsu, Fukushima, 965-8580, Japan, naru@u-aizu.ac.jp), ²Aizu Laboratory Inc., ³JLPEDA/ISAS/JAXA.

**Introduction:** AiGIS is a GIS-oriented tool to visualize geographic information of irregular-shaped small bodies developed by the research group ARC-Space at the University of Aizu under collaborations with JLPEDA/ISAS/JAXA and Aizu Lab. Inc. [1-4]. AiGIS can display a polygon-based 3D shape model of the target body, and users can manipulate viewing conditions and a lighting condition by mouse operations. Map data and graph map data on AiGIS are a set of data that are associated with polygons consisting of the shape model. Polygons of the shape model are displayed with a color that is assigned according to a value in the selected map data with the look-up table. While a map data store a single value for each polygon, graph map data can handle multiple values, such as reflectance spectra and time-series data. AiGIS is capable of showing a plot with data extracted from the graph map data at the selected polygon. The 3D model display pane of AiGIS can be divided into two or four panes, and different models or different map data displays are assigned to each pane. Viewing geometries can be spontaneously synchronized in all panes. This Multi-View mode helps users to make cross-comparison among various map data and models.

In this presentation, we will introduce several new functions implemented into AiGIS in this season. AiGIS is intensively used in the Japanese asteroid exploring mission Hayabusa2, and publically released at our website (https://arcspace.jp/).

**Technologies:** The current version of AiGIS is developed by Java and runs on macOS, Windows, and Linux. Java Binding for the OpenGL API (JOGL) [5] is used to access 3D graphics APIs offered by OpenGL. JFreeChart provides the capability to generate charts [6]. AiGIS is designed as a stand-alone application. Thus no connection to the remote data server is required. AiGIS supports a 3D model with the Wavefront 3D Object (OBJ) File format (.obj). The OBJ file format is commonly used to store shape data of small bodies, and other tools for small bodies also support OBJ files [7].

**Image Mapping:** One of the main new features of AiGIS is the image mapping function. Any images of the target body with imaging geometry information can be projected onto the shape model as surface texture. We initially adopted the INFO format as the format for imaging geometry information. The INFO format is defined and used in Small Body Mapping Tool (SBMT) developed by JHU/APL [7] to store imaging geometry information. The latest update of AiGIS newly supports geometry information files in the SUMFILES format also used by the stereophotoclinometry (SPC) and SBMT. By supporting a standard file format, interoperability among relating tools is a benefit for all potential users. Imaging geometry information for an image taken by any spacecraft can be computed from spacecraft ancillaries. Because the SUMFILES format data are direct outputs from SPC, this update expands usability during on-going mission analyses.

AiGIS also supports mapping of a global image with the simple cylindrical projection. Major image formats, including JPEG, PNG, and TIFF are supported in this feature. FITS images are newly supported by the latest update of AiGIS. AiGIS can read multiple images. Loaded images appear in the image list. Users can control the Show/Hide setting, the order of overlaying image layers and selective unloading of images for every image. In coordination with the Multi-View mode, users can flexibly design the combination of display views.

**Map Data Handling:** Loading and displaying of various map data are critical functions of AiGIS. Users can produce new map data for the target body from observation data and/or their analysis. The current version of AiGIS has the capability to handle and organize multiple map data files. Loaded map data appear in the map data list. Users can sort data in the list by their filename or name of map data defined in the file header. Also, AiGIS can quickly reload all map data in the specified directory. This quick reloading is faster than usual data loading with the initialization process and makes it possible for users to load a newly produced map data with on-the-fly manner.

Previously, AiGIS only supported visualization of map data in two built-in look-up tables (LUTs); rainbow and grayscale. This situation was less flexible to produce color figures with the universal color scheme for people with color blindness. Now updated AiGIS has a new capability to load external color LUTs. Currently, a text LUT format developed by [8, 9].

**Acknowledgment:** AiGIS is an open source software and opens to the public at a website of ARC-Space/University of Aizu (https://arcspace.jp/). Precompiled executables for supported platforms, a
source code package, and sample data are available. Comments and questions are welcome to the author’s e-mail address (see author information). Development of AiGIS is supported by KAKENHI from the Japanese Society for Promotion of Science (Grant No. JP17K05639) and the FY2017-2019 Coordination Funds for Promoting Aerospace Utilization from MEXT, Japan.


Fig. 1. A screenshot of AiGIS. A 4-panes view shows the shape model of Ryugu, Ryugu with an image, a geopotential height map with an external LUT, and a slope map.
SHAPE RECONSTRUCTION OF THE ASTEROID RYUGU IN HAYABUSA2 MISSION. Naru Hirata, Naoyuki Hirata, S. Tanaka, N. Nishikawa, T. Sugiyama, R. Noguchi, Y. Shimaki, R. Gaskell, E. Palmer, K. Matsumoto, H. Senshu, Y. Yamamoto, S. Murakami, Y. Ishihara, S. Sugita, T. Morota, R. Honda, M. Arakawa, K. Ogawa, Y. Tsuda, S. Watanabe. 1ARC-Space, the University of Aizu (Aizu-Wakamatsu, Fukushima, 965-8580, Japan, naru@u-aizu.ac.jp), 2Kobe University, 3ISAS/JAXA, 4Planetary Science Institute, 5NAOJ, 6Chiba Institute of Technology, 7NIES, 8University of Tokyo, 9Kochi University, 10Nagoya University.

Introduction: The Hayabusa2 spacecraft arrived at the asteroid Ryugu in 06/2018 and started its proximity observation to select candidates of landing sites for touchdown operations. The shape of the asteroid is one of the most critical information not only for landing site selection but also for scientific discussions.

We successfully reconstructed and updated the shape models of Ryugu with images taken by the optical navigation camera (ONC) onboard the spacecraft and relating ancillary data acquired during proximity observation of the asteroid [1]. Here we report the current status of our shape models and introduce several scientific applications.

Methods for Shape Modeling: Two different methods are applied to model the shape; one is Structure-from-Motion (SfM), and another is stereophotoclinometry (SPC). SfM is a method to be able to estimate the shape of the target object from multiple images (e.g., multiple exposures of a moving camera) by stereogrammetry. It can solve the shape from just the images themselves, without requiring information on the spacecraft positions and attitudes. The SfM technique is a popular shape modeling method in computer vision, and there are many open source and commercial implementations. We adopted Agisoft Metashape version 1.5 (formerly released as PhotoScan until version 1.4), one of the commercial implementations of SfM.

SPC is a method combining stereogrammetry and photoclinometry and is adopted by many planetary missions including Hayabusa, NEAR Shoemaker, Dawn, Rosetta, and OSIRIS-REx both for shape modeling of a target body and optical navigation of a spacecraft. Because it was developed for space missions, SPC can simultaneously determine the target shape, spin state, and position and attitude of the spacecraft in the astronomical reference frame. Although SfM models are scaled and aligned in the body-fixed frame defined by SPC, the topographic shape models are derived by two independent methods. This gives us a unique opportunity for making a comparison between the shape models of Ryugu by two methods to evaluate the consistency of the models.

Source Image Data: Early versions of shape models of Ryugu were produced from images obtained during initial observation campaigns from 07/2018 to 08/2018. These campaigns include the Box-A (20 km altitude), Box-B (6.5 km altitude), and Mid-Altitude (5.1 km altitude) observations. Models were then revised with data from following various observations, including close-up imaging during decent operations, high- and low-phase angle observations, and high sub-spacecraft latitude observations. Because of constraints on the relative position of the spacecraft to the asteroid, the sub-spacecraft altitude is limited within ±30°. This limitation affects the performance of the shape model on the polar regions. The emission angle of the observation on the polar regions is restricted to be less than 60°.

During the proximity operation, the spacecraft and Ryugu experienced a solar conjunction in 12/2018. The illumination condition of the asteroid viewing from the spacecraft was reversed after the conjunction. Because SfM is based on image feature matching, it has difficulty handling an image set including different illumination conditions. Thus, shape model production with SfM is separated into two parts; the pre- and post-solar conjunction periods. SPC is safe from this issue and is able to update the model with new images sequentially.

Because of a large number of images and high spatial resolutions, ONC-T [2] images are primary sources of shape modeling both with SfM and SPC. Even though images with the v-band filter consists of the majority of the image set, other color data are also used. Sequential color observations during decent operations are important image sources covering local regions with high spatial resolutions. Wide-angle images obtained by ONC-W1 and ONC-W2 are also incorporated into an SPC data set to register on the shape model and to determine the spacecraft positions and attitudes.

Shape Models and Relating Byproducts: Currently, shape models and their byproducts are produced by both modeling methods. SPC products include the global shape model in the Wavefront OBJ format and the SPICE DSK shape kernel format, determined spacecraft position and attitude in the SPC native SUMFILES form and the SPICE SPK and CK kernels, the spin state information file in SPICE PCK kernels. The latest model is constructed from ~ 5,000
ONC images, and the best spatial resolution of MAPLETs is 0.1 m.

SfM products also contain the global shape models with the same data format to the SPC ones. SfM also produces digital elevation models (DEMs) on several local regions of interest such as landing sites and the SCI impact target region from very high-resolution images. Those local DEMs are aligned to the global body-fixed frame.

![Image](https://example.com/image1.png)

**Figure 1.** 6-sided views of the shape model reconstructed by SPC (top panel) and SfM (bottom panel).

Model Evaluation: Performance of the shape models was evaluated by several different ways: 1) errors or residuals computed during the shape reconstruction, 2) consistency among obtained shape models, and 3) comparison between synthetic images from the shape models with ONC-T images (Fig. 2), 4) evaluation with LIDAR ranging data. Residuals of shape reconstruction give a quality of image matching and overall self-consistency of the model. Consistency among models with different methods shows a bottom-line of the model quality. Comparison between synthetic images and observed images evaluates the reproducibility of the models in small scales. Comparison with the individual LIDAR altitude profiles is another evaluation of small-scale topographic features. Statistical analysis of the LIDAR data with the shape model gives a constraint on the asteroid size.

![Image](https://example.com/image2.png)

**Figure 2.** Schematic diagram of shape model evaluation by comparison between synthetic images from the shape models with ONC-T images.

Acknowledgement: This work is supported by KAKENHI from the Japanese Society for Promotion of Science (JSPS, Grant No. JP17K05639) and JSPS Core-to-Core Program "International Network of Planetary Sciences".

The Regolith X-ray Imaging Spectrometer (REXIS) [1,2] is designed to measure relative elemental abundances of key elements on the surface of the asteroid Bennu. REXIS detects the X-ray fluorescence spectrum from the surface (stimulated by the solar X-ray flux) over the range of energies 0.5 to 7 keV. REXIS is composed of an array of four back-illuminated CCDs, a coded aperture mask to constrain the incident angles of X-rays from Bennu's surface, and a Solar X-ray Monitor to provide an onboard measurement of the incident solar X-ray spectrum.

The REXIS data analysis pipeline is a suite of Python-based modules that calibrate, characterize, and model the data from the REXIS instrument. The end product of the analysis pipeline is the X-ray flux measurements from each element and the best-fit relative abundances that reproduce the observed flux, given the observation parameters and the incident solar spectrum.

In this presentation, we will describe the end-to-end steps of the REXIS analysis pipeline, demonstrate the calibration of the data across three years of in-flight operations, and report on the data quality and instrument performance from the observing period in July-August 2019.


Acknowledgements: This material is based upon work supported by NASA under Contract NN-M10AA11C issued through the New Frontiers Program and the OSIRIS-REx Team.
Introduction: JAXA’s asteroid explorer Hayabusa2 has been continuing the observation of asteroid Ryugu since its arrival to Ryugu on 28th June, 2018. Optical navigation camera suite (ONC) \(^1\) onboard Hayabusa2 is composed of two wide-angle camera ONC-W1, ONC-W2 and the telescopic multiband camera ONC-T capable of taking 7 narrow-band images ranging from 0.40 to 0.95 \( \mu \)m (ul, b, v, na, w, x, p) using a filter wheel. Hayabusa2 succeeded in two touchdown to Ryugu for sampling in February and July, 2019 and also succeeded in artificial cratering experiments using a Small Carry-on Impactor (SCI). Variety of images including global mapping, high resolution images of limited areas during descending operation, sequential images during touchdown and change due to SCI cratering have been obtained during 14 month observation. We are now preparing the dataset for release to public. In this presentation, we introduce a overview of the ONC image dataset, plan of image archiving for multi-purpose analysis including geomorphology, photometry and spectroscopy such as \([1]\)\([2]\). The schedule of public release is also introduced.

The overview of ONC image dataset: Table 1 summarizes the contents of the major ONC image data subset in chronological order. Total of about 8700 images are acquired at the end of August, 2019. As shown in Fig. 1, during 14 month observation after the arrival to Ryugu, solar phase angle has changed from 19 deg. to 0 deg. at solar conjunction in December, 2018. After that the solar phase angle has increased up to 39 deg. As a result, several set of global mapping at home position (altitude 20 km) are acquired at different phase angles. These data can be utilized to photometric studies or geomorphological study at the different illumination condition.

As global mapping, ONC-T’s v band images are taken at the 3 deg. rotational angle for shape model construction. Total of five data set (20180630, 20180710, 20190115, 20190121, 20190725) are acquired in this mode. On the other hand, ONC-T’s multi band images are taken at every 30 deg. rotational angle interval are obtained as four dataset at Box-A (Home position, 20180703, 20180710, 20190131, 20190521) and six data set of BOX-B (tour observation in longitudinal direction, 20180831, 20190108, 20190124, 20190814, 20190819, 20190824).

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The product and schedule of public release: Table 2 shows the definition of product that we are planning to create as a data archive. The data is going to be prepared in PDS4 format. To improve the availability of the image data set, we are also preparing the pixel to pixel backplane data of the images including such as longitude, latitude, geometrical viewing conditions such as ones created for first Hayabusa’s camera (AMICA) [5]. Together with this backplane data, multi-dimensional dataset including backplane and spectrum information and time will be composed. By extracting relevant cross section from this data set, studies utilizing machine learning techniques such as clustering[4][5] or flexible analysis on photometry[6] will become easier. In addition, correlation analysis of the multiple attributes will be enabled by a such database.

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Table 3 shows the current public release schedule. The data is planned to be released to public stepwisely. Since we are still under the review process of PDS4, we are planning to release data in provisional format firstly from September-October, 2019, and update them afterwards. A complete data set of proximity phase in authentic PDS4 format will be released in Dec. 2020.

Acknowledgments: We thank the entire Hayabusa2 team to achieve the observation and analysis. This study was supported by Japan Society for the Promotion of Science (JSPS) Core-to-Core Program "International Network of Planetary Sciences.

**OVERVIEW:** The main instrument of the Regolith X-ray Imaging Spectrometer (REXIS) is a coded-aperture imaging soft X-ray telescope [1]. It consists of $2 \times 2$ X-ray CCDs (MIT Lincoln Laboratory CCID-41) and a stainless steel mask, covering $\sim 30$ deg Full Width Half Maximum (FWHM) Field of View (FoV) with 26 arcmin resolution in the 0.4 – 8 keV band. Each X-ray CCD in REXIS has $1024 \times 1024$ pixels, which are grouped into four independent nodes ($256 \times 1024$ pixels), each read out with its own signal processing chain.

In order to track the spectral gain and resolution of the REXIS X-ray CCDs, REXIS carries a set of $^{55}$Fe radioactive sources with the combined activity of $\sim 2 \mu$Ci at the time of the launch. The $^{55}$Fe sources are arranged to monitor the spectral performance of each node of the REXIS CCDs as well as the Charge Transfer Inefficiency (CTI) with monochromatic X-ray lines at 5.9 and 6.4 keVs.

In addition to the onboard radioactive sources, REXIS performed a series of calibration operations to characterize the REXIS instruments: (1) Internal Calibration before the cover opening, (2) The Cosmic X-ray Background (CXB) measurement, (3) Crab nebular observations, (4) the OBF verification, and (5) the mask calibration with observations of Sco X-1.

We will present the results of our calibration operations, describing what we learned from the data, and how they feed into the optimization of the REXIS CCD operational parameters. We will also address the lessons learned from these calibrations that will be of value to future missions employing similar advance planetary x-ray imaging spectrometers.

**Acknowledgements:** This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program. We are grateful to the entire OSIRIS-REx Team for making the encounter with Bennu possible.

**References:**
COMPARING OVIRS SPECTRA OF THE BRIGHT BOULDERS ON BENNU WITH ASTEROID SPECTRA. E. S. Howell¹, H. Campins², A. A. Simon¹, H. H. Kaplan², M. A. Barucci³, D. N. DellaGiustina¹, D. C. Reuter³, R. P. Binzel⁴, C. W. Hergenrother¹, M. Popescu⁵, B. E. Clark⁶, and D. S. Lauretta¹, ¹Lunar and Planetary Laboratory, U. Arizona, (Tucson, AZ 85721, ehowell@orex.lpl.arizona.edu), ²U. Central Florida, ³Goddard Space Flight Center, ⁴Southwest Research Institute, ⁵Observatoire de Paris, Meudon, France, ⁶MIT, ⁷Instituto de Astrofísica de Canarias, Tenerife, Spain, ⁸Ithaca College.

Introduction: Although the overall geometric albedo of Bennu is very low (0.044 ± 0.002) [1] there are a few very bright boulders first discovered in the MapCam images [1]. These meter-scale boulders have geometric albedos greater than 0.14, and also have distinctive spectral signatures [2,3]. DellaGiustina et al. [2] have analyzed these spectra by comparing them to likely meteorite analog materials. We extend this analysis to asteroid spectra, primarily near-Earth asteroids (NEAs) to bridge the size range from meteorite scale (~cm) to the possibly more heterogeneous compositions that are represented by the NEA population. DellaGiustina et al. [2] note that the bright boulder albedos and spectra are so unlike the rest of Bennu that they are likely to be exogenous material, either inherited from Bennu’s parent asteroid, or from collisions at the time of formation or later. In this presentation, we will explore the range of NEAs that might be consistent with such collisions, to constrain the possible origin and history of the exogenous material on Bennu.

S-complex and V-type asteroids: The pyroxene-like spectra seen by the OVIRS instrument are similar to several taxonomic groups of NEAs. The spectral range of the OVIRS instrument (0.4–4 microns) includes the diagnostic visible and near-infrared region for which we have a large database of asteroid observations. The MITHNEOs program [4], among others, has provided a large public archive of spectra which may be more representative of the material impacting the Earth than the meteorite collection. Some asteroidal materials may be too fragile to survive transport through the Earth’s atmosphere.

Figure 1 shows two of the spectra of bright boulders on Bennu along with some comparison asteroid spectra. The spectrum of 4 Vesta, parent of the Vesta family and the NEA family member 2003 YT1 are also shown. The smaller V-type NEAs have deeper bands than 4 Vesta, perhaps due to having fresher surfaces. The S-complex groups Sq and Q-types also have prominent pyroxene features in their near-infrared spectra. NEAs 1685 Toro (Sq) and 2001 SG276 (Q) (whose spectra look more similar to OC meteorites than HED meteorites) are shown for comparison. These spectra have been normalized to 1.0 at 0.8 microns and scaled in band depth to more easily compare them.

Although the spectra of S-complex asteroids bear many similarities to spectra of ordinary chondrite meteorites, there are also differences in continuum slope and band depth that have been the source of much debate (e.g. [5] and references therein). Space weathering effects have been suggested to explain many of these differences, but laboratory simulations have not always shown consistent spectral trends.

The size of the bright boulders (~1-4m) is smaller than most of the NEAs for which we have measured spectra (~0.1-1km). But they are also much larger than most of the carbonaceous chondrite meteorite samples (~1-10cm). Thus, the boulder spectra are likely to be an average of a variety of distinct clasts, similar to hemispherically averaged NEA spectra.

Figure 1. Spectra of asteroid 4 Vesta and some pyroxene-rich NEA taxonomic groups are shown together with two example spectra of the bright boulders on Bennu.

The OVIRS footprint during the Detailed Survey: Equatorial Stations phase was about 20m, so the region surrounding the boulders was also included. The spectra are distinctive enough that the pyroxene bands are clearly seen after dividing by the global average spectrum, which is featureless in the 1–2.5 micron region. We will compare the normalized spectra of the pyroxene material with various asteroid taxonomic groups to look for the best matches using a chi-squared test over the appropriate spectral range.

The bright materials have only been found in a few locations in the global spectral data of Bennu, but our
sensitivity is limited by the large spatial scale of the spectra (~20 meters per spectrum). During the Reconnaissance phases of the mission we expect to get spectra with higher spatial resolution (~4 meters per spectrum), so we may be more sensitive to bright materials at smaller size ranges, if they are present at the candidate sample sites. We will use these data to further explore the nature and distribution of this exogenous material.

Acknowledgments: We are grateful to the entire OSIRIS-REx team for making the collection and processing of the data possible, in particular the SAWG and OVIRS instrument team. This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program.

REGOLITH BUDGET OF ASTEROIDS.  H.-W. Hsu, X. Wang and M. Morányi, LASP, University of Colorado, Boulder, CO, USA (email: sean.hsu@lasp.colorado.edu).

Introduction:

The surface of airless bodies is a direct manifestation of space weathering processes. Understanding the surface characteristics has broad implications ranging from the study of the airless bodies evolution to the associated science and exploration activities. It was thought that regolith is a common surface component of airless bodies, and it plays a key role in determining the thermal, optical, and structural properties of their observable surface [1]. However, in contrast to previous results from the Apollo, NEAR Shoemaker, and other missions, recent observations of asteroids Itokawa, Ryugu, and Bennu revealed that the regolith (especially the submillimeter component) can be largely depleted on asteroids [2,3,4,5].

In this work, we utilize recent space and laboratory results to model the regolith budget of asteroids in the inner solar system environment. We consider meteorite impacts [6], thermal fatigue fragmentation [7], and electrostatic lofting [8] as the major processes that determine the regolith budget. Our preliminary results explain the (non-)presence of regolith on asteroids visited so far and could be helpful to inform future scientific studies and exploration activities regarding the regolith environment of asteroids.

References:

Hayabusa2 Radio Science Investigation around Asteroid Ryugu. H. Ikeda¹, Y. Tsuda¹, D. Scheeres², A. French², J. McMahon², H. Takeuchi¹, S. Soldini³, Y. Mimasu¹, K. Yoshikawa¹, Y. Takei¹, N. Ogawa¹, S. Kikuchi¹, Y. Oki¹, G. Ono¹, F. Terui¹, T. Saiti¹ and M. Yoshikawa¹, ¹Japan Aerospace Exploration Agency (3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa, 252-5210, Japan, ikeda.hitoshi@jaxa.jp), ²University of Colorado (Boulder, CO 80309, USA). ³University of Liverpool (Liverpool L69 3BX, United Kingdom).

Introduction: The Hayabusa2 spacecraft arrived at its destination for exploration asteroid Ryugu on June 27, 2018. During the final approach phase from early June, the initial observation was carried out by onboarded scientific instruments in order to grasp the specification of the target asteroid. After the arrival, spacecraft maintains its altitude about 20 km (which is referred to as Box-A) from the center of asteroid and continue the global observation of Ryugu. In order to perform the observation from a lower altitude, special operation in the area called Box-C at an altitude of about 6.5 km was carried out several times. After the intensive observations for landing site selection, we implemented an operation to measure the gravity of asteroids precisely.

The Hayabusa2 mission adopts a hovering approach for scientific observation and sampling like Hayabusa1 mission [1]. Since the operation method in the vicinity of the target body is largely different from other small body missions [2], and the spacecraft is not injected into the orbit around the asteroid, the method of gravity estimation also adopts unique approach. The gravity estimation operation consists of a ballistic descent phase and a ballistic ascent phase at a low altitude. In addition to this specific operation, there were several opportunities to move to the low altitude region without any propulsion system operations (i.e. ballistic flight). We are currently conducting gravity estimation analysis that integrates whole valid measurements. This paper reports the progress of the analysis. In addition, we are investigating the target maker (TM) orbiting experiment to improve the accuracy of gravity field estimation. The results of the preliminary study are also reported.

Gravity Estimation: We used a method to simultaneously estimate the precise orbit of the spacecraft and the gravity of the asteroid by using radiometric, optical, and altimeter observables together. One of the most important observables is two-way coherent radiometric tracking between the earth ground station and the Hayabusa2 spacecraft. The Usuda Deep Space Center (UDSC) antenna is used as the domestic ground station and NASA’s Deep Space Network (DSN) antennas and ESA’s European Space Tracking Network (ESTRACK) antennas are also used as the overseas ground station. In the usual operation, X-band uplink and X-band downlink mode is used. The optical measurements acquired by the optical navigation camera, a distance between the spacecraft and asteroid surface can be measured by laser range instruments are also used for the orbit determination.

Dynamical Environment Evaluation: Using the estimated gravity information and shape model, the dynamic environment in the vicinity of asteroid Ryugu was evaluated. In this evaluation the constant density gravity field is calculated based on the technique by Werner and Scheeres [3]. As for the shape model of Ryugu, the 49152 facets and 24578 vertices shape model is used for this analysis.

The surface acceleration varying from 0.109 to 0.149 mm/s². The total acceleration becomes maximum in the polar regions and becomes minimum in the equator regions. This trend is due to the relationship between the magnitude of gravity and centrifugal force. Since its rotation speed is relatively slow, there is not large difference in the acceleration distribution of the surface.

As for the geopotential, its minimum is not at equator region but is at middle latitude region. The maximum potential is at the polar regions and the equator regions is lower than polar regions. A more dynamically meaningful characterization way of the potential difference across the asteroid surface is to calculate the amount of speed that a particle would obtain in going from the high potential regions to the lower potential regions. Following the (Scheeres et al. 2016)[4] method, we can calculate the speed that can be attained from the highest point to the lowest point is 17.1 cm/s. From the pole to the equator region the speed obtained would be about 11.0 cm/s, and from the equator to the middle latitude region would be 7.0 cm/s.

The slope is calculated over the surface based on 49K facet shape model as previously mentioned. The variation and extremes of slope are expected to change for an increasing resolution of shape. At this order of resolution, the maximum slope is over 76 deg, although 0.3 % of the surface has slope excess of 45 deg. The high slope regions occur on the surfaces of boulders mostly, especially in the polar regions. The overall average slope at this resolution is 12.9 deg.

The return speed is computed from the geopotential and the equilibrium points. The Roche lobe of the asteroid is also related with these values. A particle on the surface of Ryugu must have speed greater than this
value if it has sufficient energy to pass through the lowest energy equilibrium point of the body and enter orbit outside of the body. Just having a speed in excess of this level of speed does not ensure that its trajectory will be able to pass outside of the Roche lobe, however a speed less than this value means it cannot. The Roche lobe is defined as the 3D surface of the geopotential which is same value of minimum equilibrium point. Although for the spheroidal, fast spinning asteroids the lobe is generally intersect with its body [5], in the case of Ryugu, the rotation speed is relatively slow, and the Roche lobe does not intersect with its body. The return speed of Ryugu vary from 11.5 cm/s in the geopotential high regions to 20.6 cm/s in geopotential low regions. Here we compare it with Bennu’s return speed. A particle on the surface in the polar region of Bennu can achieve up to 11 cm/s when move to the equator region. Although, this value is lower than the escape speed, is greater than return speed and it is possible to enter the orbit. It is important to note that a particle rolling down hill on the Ryugu (e.g., move from the pole to middle-latitude, move from equator to middle-latitude) cannot obtain sufficient energy to escape from the Ryugu, and this situation is opposite to the case of Bennu.

The escape speed is also computed across the surface of Ryugu. We follow the definition of this speed described in Ref. [6]. The return speed is defined as the speed a particle on the asteroid surface would need to be launched perpendicular to the surface in order to achieve escape from the body. This value relates with the geometry (i.e., distance from the COM, direction of the surface normal vector) and rotation, the distribution this quantity is not as smooth across the asteroid surface. On Ryugu, the maximum escape speed is 42.9 cm/s in the middle latitude regions (i.e. low potential regions) and the minimum is 26.6 cm/s at the equator.

**Orbital Dynamics Environment:** Consider the orbital dynamical environment independent of non-gravitational forces such as solar radiation pressure, in other words, the motions described here would apply to the objects with small area to mass ratios (A/M) and the effect of solar radiation pressure would be smaller than that of gravitational forces.

The Ryugu has 6 equatorial equilibrium points. There are 3 center equilibria and 3 saddle equilibria. The point E2 has the minimum geopotential value, which equal to -5.457874e-02 (m^2/s^2) and the return speed calculated based on this value. Dynamical structures for Ryugu is investigated in terms of z*, zh*, and barrier of potential [7].

**Target Marker Orbiting Experiment:** In order to improve the estimation accuracy of the gravity coefficients of Ryugu, we will carry out the target marker orbiting experiment. In this experiment, two TMs will be used for gravity estimation. One is inserted into a polar orbit and the other is put into an equatorial orbit, respectively. The measurements for orbit determination of TMs are direction information as seen from the spacecrafts and which derived from optical navigation cameras. According to the preliminary analysis, two different orbits provide us the stable and high accuracy gravity estimation results.

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FIRST RESULTS FROM AN OBSERVING CAMPAIGN TO DETECT THE METEOROIDS OF BENNU AT EARTH. P. Jenniskens¹, D. S. Lauretta², M. C. Towner³, P. A. Bland¹, S. Heathcote¹, E. Jehin², T. Hanke⁶, T. Cooper¹, and J. Baggaley⁸. ¹SETI Institute, Mountain View, CA (petrus.m.jenniskens@nasa.gov), ²Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ (lauretta@orex.lpl.arizona.edu), ³Space Science and Technology Centre, Curtin University, Perth, Australia (P.Bland@curtin.edu.au), ⁴Cerro Tololo Inter-American Observatory, La Serena, Chile (sheathcote@ctio.noao.edu), ⁵University of Liege, Liege, Belgium (ejehin@uliege.be), ⁶High Energy Stereoscopic System Consortium, Windhoek, Namibia (cthes@afol.com.na), ⁷Astronomical Society of Southern Africa, Bredell, South Africa (tpcoope@mweb.co.za), ⁸University of Canterbury, Christchurch, NZ (jack.baggaley@canterbury.ac.nz).

Introduction: Asteroid (101955) Bennu passes only 0.0029 AU from Earth's orbit, a distance that will further decrease towards the end of this century. NASA's OSIRIS-REx showed Bennu to be an active asteroid [1]. Some meteoroids were found on hyperbolic orbits, which evolve to elliptical orbits around the Sun. For material ejected since 1500 CE, ejection velocities are too small and planetary perturbations not sufficient to bridge the gap to Earth [2]. However, if Bennu was active in the past, and the ejected particles can survive for thousands of years, planetary perturbations may create a meteor shower on Earth.

Figure 1. Only two possible meteoroids from Bennu in 2010–2016 CAMS data during solar longitude 174.6–187.4 have semi-major a = 0.5–1.5 AU.

Meteors are expected to radiate from a geocentric R.A. = 5°, Decl. = -34°, entering at a geocentric speed of 6.0 km/s (apparent speed 12.7 km/s), around September 22–26. This southern hemisphere meteor shower has not yet been detected (Fig. 1).

Here, we describe an effort to detect this shower at Earth in the coming years.

Methods: The particles ejected from Bennu are about 1–10 cm in size [3]. If the luminous efficiency is ~0.7% [4], they are expected to have an apparent brightness of +2 to -5 magnitude when impacting Earth at 12.7 km/s. Meteors in this range of brightness are detected by low-light video cameras.

The CAMS meteor shower survey deploys large numbers of video cameras to track meteors against the star background and triangulate those tracks to calculate the trajectory radiant and speed [5]. The software is capable of detecting slow-moving meteors efficiently [6]. In early 2019, 299 video cameras spread over 8 networks were routinely mapping meteor showers on the northern hemisphere, but only 34 on the southern hemisphere (32 in New Zealand, 2 in Brazil).

Now, new CAMS networks are being established in Australia, Chile and southern Africa. Since mid-June, CAMS Australia is deployed near Perth. The network consists of three stations with 16 cameras each. Since mid-July, CAMS Chile is deployed at Cerro Tololo Observatory and at La Silla Observatory, with a third station near La Serena. We also added one 16-camera station to the CAMS New Zealand network near Christchurch, and a two-station 8 each network has come online near Johannesburg, South Africa.

Results: At the time of writing, the Bennu shower is still a month away. We expect to be able to present first results of the observations at the workshop.

In the meantime, the new southern hemisphere networks are producing hundreds of meteor orbits per night. This has already resulted in the detection of a compact meteor shower associated with long-period comet C/1939 H1 (Jurlof-Achmarof-Hassel) on August 4–6, 2019. This comet is now a newly established parent body of one of our meteor showers.

Discussion: The survey is intended to continue for the duration of the OSIRIS-REx mission and is expected to greatly increase our understanding of meteor showers in the southern hemisphere, including potentially detecting streams from other active asteroids. This can help understand the population of large meteoroids on short orbits in the interplanetary medium [6].


Additional Information: The National Aeronautics and Space Administration supported this work under Contract NN10AA11C issued through the New Frontiers Program. The project website is at http://cams.seti.org. Results are posted in near-real time at the website: http://cams.seti.org/SDL/.
ACTIVE ASTEROIDS. David Jewitt, University of California at Los Angeles, 595 Charles Young Drive, Los Angeles CA 90095 (jewitt@ucla.edu).

Introduction: The purpose of this talk is to provide an up-to-date overview of our current knowledge concerning the Active Asteroids. This is a relatively new subject of particular relevance to the meeting given the reported ejection of particulate solids from asteroid Bennu.

We will first present examples of the data showing the varied properties of almost 30 Active Asteroids, and their distribution in orbital element space (Figures 1 and 2). Second, we will describe, with examples, the surprisingly varied physical processes thought to underlie asteroid activity, including sublimation, rotational instability and break-up, impact, thermal fracture, desiccation stresses and electrostatic effects [1,2]. Lastly, we will describe the role of activity in the evolution of asteroids [3] and the production of dust.

Figure 1: Distribution of Active Asteroids in the semimajor axis vs. orbital eccentricity plane. Small blue circles show (dynamical) comets, small yellow circles denote asteroids, while large colored circles mark different types of the known Active Asteroids. Diagonal arcs show the loci of orbits that cross the aphelion of Mars and the perihelion of Jupiter, as marked.


Figure 2: Sample morphologies of some of the Active Asteroids, showing their diversity of appearance.
Our group has previously examined design considerations for motor units of space probes and unmanned aerial vehicles for use in Mars missions. With the recent landing of Hyabusa2, we would hereby extend these design considerations from this existing model for its use in designing motor units for mineral sampling in asteroids. These considerations include: (i) power considerations, (ii) high climb and loiter speed, (iii) data-link bandwidth capabilities, (iv) navigation, (v) rotor use in gravitational fields, and (vi) emergency considerations including loss of contact with ground control. Of these space probe motor units should be required to fulfill all capacities, however differences in gravitational field, asteroid spin and orbit potentially interfere with maneuverability and function of probes. Calibration to account for dipole torque differences and forces on motor units as well as an accounting of the expected frame dragging effect is necessary in light of high interference asteroid surface and orbit is necessary for future missions.

SPACE IMPACT EXPERIMENT ON RYUGU: ARTIFICIAL CRATER. T. Kadono¹, M. Arakawa², K. Wada³, K. Shirai⁴, K. Ogawa⁵, N. Sakatani⁶, K. Ishibashi⁷, Y. Shimaki⁸, Y. Takagi⁹, H. Yano⁵, C. Okamoto⁸, M. Hayakawa⁴, T. Saiki¹, H. Sawada¹, H. Imamura¹, S. Nakazawa¹, Y. Iijima¹, R. Honda⁶, S. Sugita², ¹University of Occupational and Environmental Health, ²Kobe University, ³Chiba Institute of Technology, ⁴Japan Aerospace Exploration Agency, ⁵Aichi Toho University, ⁶Kochi University, ⁷The University of Tokyo.

Introduction: The near-earth asteroid 162173 Ryugu was explored by the Japanese spacecraft Hayabusa2 since June 2018, providing the first detailed images of a small asteroid belonging to the C taxonomic class and the entire surface was found to be covered with countless boulders with a maximum size larger than 100 m [1, 2]. The surface regolith layer of Ryugu was expected to have strength originating from cohesion forces among regolith grains under the microgravity condition at about $1 \times 10^{-4}$ m s$^{-2}$, and the maximum strength of the surface layer was estimated theoretically to be 1 kPa [3]. In principle, this surface strength should control the crater formation process under the microgravity condition and reduce the impact crater size drastically compared to the expected size on a strengthless surface [4]. Crater scaling laws used to predict the crater size formed by high velocity impacts of small bodies are necessary in order to construct a crater chronology on asteroid Ryugu and depending on the considered law, the surface age could differ by more than one order of magnitude [1].

A Small Carry-on Impactor (SCI) was equipped with Hayabusa2 spacecraft in order to form an artificial impact crater (SCI crater, hereafter) on the surface of Ryugu. The SCI crater enables us to access the asteroid interior for investigating the subsurface properties by remote sensing and for acquiring the subsurface material by active sampling [5, 6]. Furthermore, the SCI impact is the first precious opportunity to study the impact crater formation process under a microgravity environment on a real asteroid surface. Thus, its results can be applied to natural craters on Ryugu directly in order to evaluate the crater chronology and investigate the subsurface structure. Besides these applications, conventional crater scaling laws for the crater size and the ejecta velocity distribution can be verified at these conditions, and the SCI impact is the only one valuable anchor to compare with numerous numerical simulations of the impact cratering processes in a microgravity environment [7].

Space Impact Experiment: The SCI instrument is a separable unit of a 30-cm cylinder shape containing explosive of 4.7 kg for acceleration of the projectile [5]. In the impact experiment, SCI was separated from the spacecraft and launched a copper projectile of 2 kg onto Ryugu at 2 km/s to make an artificial crater. The SCI operation was carried out on 5 April, 2019 and was successfully accomplished to form a visible artificial impact crater on Ryugu. The production and evolution of impact ejecta from the surface of Ryugu were also successfully observed by a Deployable CAMera 3 (DCAM3). About 2 weeks after the SCI impact, Hayabusa2 and its Optical Navigation Camera (ONC) looked for the SCI crater at the altitude of 1.7 km, then found it very close to the aiming point at latitude 6.00° N and longitude 303.00° E in the north area of the equatorial ridge. The impact angle was estimated to be approximately 60° measured from the local horizontal surface.

Low-altitude remote-sensing observation tours by the spacecraft were also conducted before and after the impact experiment. Surface maps of images were made by ONC, Thermal Infrared Imager (TIR), and Near Infrared Spectrometer (NIR3) at 1.7 km altitude, and the images of both tours were compared to identify the newly excavated crater.

Artificial Crater: An image of the new crater is shown in Figure 1. This image was taken by ONC-T in the low-altitude operation at 1.7 km altitude. By comparing with images in the pre-impact observation, the excavated topography and surrounding dark splashes were newly found in the post-impact images. A crater rim also appeared as a part of a semicircle in the image.

Figure 1: The image of the SCI artificial crater taken by ONC during the low-altitude operation after the impact experiment.
The estimated location of the crater rim is shown as a dashed curve. The deposition rim is a strong evidence for the crater formation occurring in the gravity-dominated regime [8]. The diameter from a point on the rim to an opposite \( D_{\text{rim}} \) was \( \sim 15 \) m. Using an empirical equation \( D = D_{\text{rim}}/1.3 \), where \( D \) is the crater diameter at an initial surface elevation [9], we determine the crater radius of the SCI crater \( R = D/2 \) to be \( 6.5 \) m.

We calculate the SCI crater radius using the conventional \( \pi \) scaling law applied for a typical sand surface [9]. We find that the SCI impact crater is about 5% smaller than that calculated for sand. In spite of the difference, it should be formed on a cohesionless surface such as one made of sand, because even a small amount of cohesion limits the crater growth in this microgravity environment and prohibits the crater diameter to be larger than 10 m. Thus, we can reasonably conclude that the surface of Ryugu is composed of sand-like cohesionless materials.

We found a pit close to the impact point on the crater floor (an arrow in Fig. 1). The pit entrance is at a depth of 1.7 m from the initial surface; the diameter and the depth of the pit is \( \geq 2 \) m and 0.6 m, respectively. The pit has a conical shape similar to a simple crater in laboratory experiments [8]. The pit might result from the SCI impact on a subsurface layer with a cohesion strength. The cohesion strength of the subsurface layer is estimated by the dynamic pressure generated on the layer, which is caused by the material flow with the particle velocity. We calculated this pressure from the Maxwell’s Z-model [9]. Assuming the typical z value of 3 for granular materials, \( R = 6.5 \) m, a non-cohesive upper layer with a thickness of 1.7 m, and a pit diameter of 2 m formed on a cohesive subsurface layer, the dynamic pressure can be obtained as about 300 Pa at the center of the pit and about 130 Pa at the rim of the pit. Thus, the cohesion strength of the subsurface layer is speculated to be smaller than about 300 Pa and larger than about 130 Pa.

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TOUCHDOWN-INDUCED DYNAMIC MOTION OF BOULDERS NEAR THE SAMPLING SITE ON RYUGU. S. Kameda1, S. Kikuchi2, T. Koyama3, S. Tachibana4, S. Sugita4, R. Honda5, T. Morota6, N. Sakatani7, M. Yamada8, E. Tatsumi9, Y. Yokota9, H. Suzuki8, C. Honda8, K. Ogawa10, M. Hayakawa2, K. Yoshioka4, M. Matsuoka2, Y. Cho4, H. Sawada2, 1Rikkyo University, (3-34-1 Nishi-Ikebukuro, Tokyo, Japan, kameda@rikkyo.ac.jp). 2Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency. 3National Institute of Advanced Industrial Science and Technology, Japan. 4University of Tokyo, Japan. 5Kochi University, Japan. 6Chiba Institute of Technology, Japan. 7Instituto de Astrofisica de Canarias, Tenerife, Spain. 8Meiji University, Japan. 9University of Aizu, Japan. 10Kobe University, Japan.

Introduction: The Hayabusa2 spacecraft arrived at the target asteroid Ryugu in June 2018, and subsequent global observations revealed that the surface of Ryugu is globally covered by boulders [1] and its bulk density is 1.19 ± 0.02 g/cm³, which indicates a high porosity [2]. The 1st touchdown operation for sampling was performed on February 21, 2019. In ascending phase of the spacecraft after the sampling, Optical Navigation Camera (ONC) images show many pebbles and boulders were moving around. It is clearly seen in ONC images that some boulders were moved by thruster jet from propulsion system of the spacecraft.

It is highly possible that the 0.1-mm samples were captured, however, ~10-cm boulders were not captured because of small size of sampling system. In this study, we attempt to estimate the mass density of a boulder from its motion induced by touchdown to aim to know middle-scale structure of the surface material of Ryugu.

Observation: ONC-W1 is on the bottom panel of Hayabusa2 spacecraft as shown in Figure 1 [3]. ONC-W1 took images continuously before and after touchdown with an interval of 2 seconds. The pixel resolution is ~1.3 mm/pixel because the distance from the surface was ~1.1 m and angular resolution is 0.068 degree/pixel [4, 5].

Motion of boulders: Comparing the two ONC images obtained just before and after the 1st touchdown, we found a boulder in the images could be a good target. Figure 2 shows the parts of the images obtained before and after touchdown. We measured size of the boulder as ~0.3 m using the image before touchdown (Fig. 2A). The area projected to the plane perpendicular to the line of sight with a distance of 1.12 m/s ~0.011 m². In Fig. 2B, we can see several streaks on the surface of boulder caused by motion of bright spots during the exposure time (0.13 s). The average length of these streaks is 16 mm. Thus, the velocity of the boulder can be estimated as 124 mm/s. According to the start time of gas injection, acceleration is calculated as 0.11 m/s².

Thruster gas pressure at the position of the boulder and the cross-section to the gas injection are used to estimate the force on the boulder. Thus, the mass of boulder can be estimated, and the density is estimated as 1.26 ± 0.25 g/cm³ from the estimated mass and volume.

Discussions: The estimated density of the boulder matches the bulk density estimated from global observation result within error. The surface of Ryugu shows a rubble-pile structure, and high porosity interior is indicated. However, if the average boulder density is so low as estimated in this study, the interior porosity might not be so low. Further careful error analysis is still to be done.

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DETECTION OF PYROXENES ON BENNU WITH THE OSIRIS-REx VISIBLE AND INFRARED SPECTROMETER. H. H. Kaplan, D. N. DellaGiustina, A. A. Simon, V. E. Hamilton, G. Poggiali, M. A. Barucci, D. C. Reuter, and D. S. Lauretta. Southwest Research Institute, Boulder, CO, USA (kaplan@boulder.swri.edu). Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA. Goddard Space Flight Center, Greenbelt, MD, USA. Department of Physics and Astronomy, University of Florence, Florence, Italy. LESIA, Observatoire de Paris, Paris, France.

Introduction: The OSIRIS-REx Visible and Infrared Spectrometer (OVIRS) recently conducted a global mapping campaign revealing the spectral variation of asteroid (101955) Bennu’s surface. During this campaign, OVIRS detected regions of the surface with spectral properties consistent with pyroxene minerals. These pyroxenes, initially identified with the OSIRIS-REx Camera Suite (OCAMS) MapCam instrument, are associated with Bennu’s brightest rocks [1, 2]. We describe the search for pyroxene features in OVIRS spectra, their composition, and implications for the source material.

Methods: The OVIRS instrument measures visible – near-infrared wavelengths (0.4 – 4.3 microns) with ~20 m spatial resolution during global mapping. Although we see minor differences in spectral slopes and albedo [3], Bennu is mostly spectrally homogenous at the spatial scale of these observations [4].

We searched for a pyroxene signature in data acquired at two spacecraft stations: 10 am and 12:30 pm local solar time. These data were converted from calibrated radiance to I/F. We divided each I/F spectrum by a global average spectrum, an average of all spectra from the same station, to distinguish subtle variations and remove spectral artifacts. We searched these ratioed spectra both manually and using spectral indices and identified ~14 OVIRS footprints acquired during a single global survey with broad absorptions features at 1 and 2 microns that are consistent with the mineral pyroxene [e.g., 5].

We characterized the band centers and depths for each spectrum, and performed a Gaussian deconvolution to determine the composition of these pyroxenes. To find band centers, we removed the spectral continuum from the OVIRS data between 0.4 and 2.6 microns using a two-part linear continuum [e.g., 6]. We fit Gaussian curves at 1 and 2 microns to the continuum removed data and find the Gaussian center wavelength, which we use as the band center. Using a fit to the spectrum keeps noise spikes from influencing the derived position of the minimum.

Additionally, we deconvolved the pyroxene 1 and 2 micron bands into individual absorptions using the Modified Gaussian Model (MGM) [7], which enables identification of contributions from low calcium pyroxene (LCP) and high calcium pyroxene (HCP). We applied the MGM to OVIRS data from 0.4 to 2.6 microns and fit five or more Gaussians to the region. The MGM simultaneously fits the Gaussian curves and a continuum. We used the Gaussian amplitude value to estimate band strengths for the LCP and HCP components. We employed a Monte Carlo approach to ensure that the model converges and to estimate uncertainties on each parameter in the model. We used the relative proportions of LCP and HCP to estimate the degree of melting experienced by the pyroxene parent body [8].

Context: There are five sites on Bennu with strong pyroxene detections in the OVIRS data, each associated with a bright boulder. The boulders are ~1.4 – 4.3 m in size, representing 1% or less of the OVIRS footprint. As a result, the pyroxene signatures are weak, with band depths < 1% at 0.92 microns. We likely only see these pyroxenes in OVIRS because the material is bright compared to average Bennu and therefore contributes more strongly to the spectral signal.

OCAMS observations reveal that the pyroxene boulders correspond to the brightest areas on Bennu’s surface and have a distinct color signature [1, 2]. These properties, along with geologic context, support an exogenous origin.

Spectral Features and Interpretation: We used band centers and the MGM to constrain pyroxene composition after initially comparing the spectra to pyroxene-rich meteorites. Pyroxenes can crystallize in different crystal systems (monoclinic – clinopyroxenes and orthorhombic – orthopyroxenes) and with variable cation composition, including variable amounts of calcium, all of which will influence the absorption features at 1 and 2 microns.

Band centers at 1 and 2 microns shift position with pyroxene composition and can be used to distinguish between orthopyroxene and clinopyroxene endmembers [e.g., 5, 9]. The pyroxenes on Bennu have band centers similar to laboratory orthopyroxenes, suggesting all boulders have similar compositions. Some ordinary chondrites (H and LL groups) and the Howardite-Eucrite-Diogenite (HED) meteorites can have band centers with similar positions [10].

The MGM is useful for further determining composition where pyroxene mixtures are present and has been used in a number of planetary applications [e.g.,...
For the Bennu pyroxenes, a total of seven Gaussians are fit to the spectrum, with two of those Gaussians fit to LCP absorptions (≈0.92 and 1.90 microns) and three fit to HCP absorptions (≈1.00, 1.20, and 2.30 microns) [10]. We use the relative strength of the HCP and LCP bands to estimate HCP%, which is indicative of igneous differentiation [e.g., 8, 13, 14]. We find an HCP% that matches those of the eucrite meteorites, which indicates that the pyroxenes experienced partial melting to a degree similar to the eucrites on their parent body, Vesta [14].

We use this compositional information to narrow down the source of the pyroxenes. First, we confirm that the pyroxene compositions are not indicative of material indigenous to Bennu. In terms of band center and HCP%, the pyroxenes are most similar to the eucrites and would be consistent with material from the Vesta family.

**Summary and Conclusions:** We present the discovery and analysis of spectral signatures associated with exogenous material in the OVIRS visible – near-infrared spectra. These meter-scale bright boulders were first identified in the OCAMS albedo and color data. OVIRS spectra confirmed that these bright boulders are dominated by the mineral pyroxene, despite accounting for one percent or less of the field of view of the instrument. Analysis of the OVIRS pyroxene spectra suggests that these boulders are compositionally similar to the eucrites and may be fragments of Vesta on Bennu.

Given the size of the OVIRS footprint compared to the boulders on Bennu, it is possible that additional exogenous material is present [2] that is not discernable at the current OVIRS ~20 m spatial resolution. Upcoming reconnaissance of the candidate sample sites will provide an opportunity to search for spectral signals associated with pyroxenes and other exogenous materials that may not have been identified to date.

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SPACE WEATHERING OF PRIMITIVE ASTEROIDS: IRON OXIDATION STATE CHANGES IN ION IRRADIATED MURCHISON CM2 CHONDRITE MATRIX.  L. P. Keller1 and R. Christoffersen2, 1ARES, Code XI3, NASA/JSC, Houston, TX 77058 (Lindsay.P.Keller@nasa.gov). 2Jacobs, NASA/JSC, Code XI, Houston, TX, 77058.

Introduction. Space weathering processes affect all airless bodies in the Solar System to some degree, and sample analyses combined with lab experiments furnish critical insights into the chemical, spectroscopic and mineralogic effects that result from exposure to the space environment. While much is known about lunar-style space weathering, the physical and chemical response of hydrated carbonaceous chondrite materials to space weathering processes is still at an early stage [1-3]. Space weathering experiments aid in the interpretation of remote-sensing data, as well as understanding regolith evolution on primitive carbonaceous asteroids. In addition, studies of this type will help guide the planning for analyses of the returned samples from the Hayabusa2 and OSIRIS-REx missions. In particular, the behavior of iron and its oxidation states play a critical role in controlling optical properties measured by remote-sensing instruments. Here, we report the results of our preliminary ion irradiation experiments on a hydrated carbonaceous chondrite with emphasis on microstructural and chemical changes, focusing on Fe oxidation state changes.

Samples and Methods. A polished thin section of the Murchison CM2 carbonaceous chondrite was irradiated with 4 kV He+ (normal incidence) to a total dose of 1x1018 He+/cm2 over an area of ~5x5 mm2 [2]. The irradiated area included abundant matrix and chondrules. We obtained ex situ Fourier-transform infrared (FTIR) reflectance spectra from multiple areas of matrix, ~150 μm2 in size, using a Hyperion microscope on a Vertex Bruker FTIR bench. A JEOL 7600F field emission scanning electron microscope (SEM) was used to study the morphological effects of the irradiation. Following the SEM analyses, we extracted thin sections from both irradiated and unirradiated regions in matrix using focused ion beam (FIB) techniques. We used electron beam deposition for the protective carbon strap to minimize surface damage artifacts from the FIB milling. The FIB sections were analyzed using a JEOL 2500SE scanning and transmission electron microscope (STEM) equipped with a Gatan Tridiem imaging filter and a Thermo-Noran energy-dispersive X-ray (EDX) spectrometer. Electron energy-loss spectroscopy (EELS) data were collected from 50 nm diameter regions with an energy resolution of 0.7 eV FWHM at the zero loss peak. EELS spectra were collected using low electron doses to minimize possible artifacts from electron-beam irradiation damage [4,5].

Results and Discussion. SEM imaging shows that the irradiated matrix regions have a “bubbly” or “frothy” texture, with numerous sub-μm rounded holes and voids relative to the un-irradiated material. TEM analysis of the FIB sections show that the frothy texture in the irradiated matrix results from the formation of irregularly-shaped 50-100 nm voids at the sample surface. In addition, there are smaller (20-50 nm dia.) vesicles in some of the surface-exposed grains.

High-resolution TEM imaging shows that the fine-grained Mg-rich serpentine group minerals have been amorphized from the He irradiation to a depth of ~150-200 nm. Assuming a target density of ~1.3 (the density of serpentine with 50% porosity), and allowing for reasonable changes in target density during the irradiation, there is excellent agreement between the total thickness of the amorphized layer and the He+ ion damage depth obtained from SRIM calculations [6]. We obtained quantitative EDX line scans from the surface down to unirradiated matrix and did not observe any statistically significant compositional changes in Mg, Si, S, and Fe. Large (μm-sized) FeNi sulfides exposed at the surface however, show a preferential loss of sulfur by sputtering and the development of a thin 5-10 nm rim of nanophase Fe metal, similar to experimentally irradiated FeS [7]. A sub-μm CaCO3 grain also appears to have been amorphized by the He+ irradiation.

There is a distinct chemical shift in the Fe L2,3 edge position for EELS spectra from Fe2+ versus Fe3+ phases (Figure 1). The Fe L2,3 EELS spectra we obtained from the the Mg-rich phyllosilicates in Murchison matrix show mixed Fe2+/Fe3+ oxidation states. The Fe L2,3 spectra from the irradiated/amorphized matrix phyllosilicates show higher Fe2+/Fe3+ ratios compared to spectra obtained from pristine material at depths beyond the implantation/amorphization layer. We used well-characterized standards to fit the L3 edges to obtain quantitative Fe2+/Fe3+ ratios. The unirradiated Mg-rich phyllosilicates have a ratio of Fe2+/Fe3+≈0.28, whereas the irradiated phyllosilicates show an enhanced ratio of Fe2+/Fe3+≈0.52 (Figures 2 and 3). We found no evidence from the EELS data for the presence of metallic Fe in the irradiated material. We also obtained O K spectra from phyllosilicates in both regions of the sample. The O K spectra show a pre-edge feature at ~530.5 eV that is related to O 2p states hybridized with Fe 3d states [5]. The intensity ratio of the O K pre-edge peak relative to the main part of the O K
edge (that results from transitions of O 1s to 2p states) is lower in the irradiated layer compared to the pristine material and may reflect the loss of O (as OH) as was observed by IR spectroscopy [2].

Conclusions. Irradiation of Murchison matrix with 4 keV He⁺ produced several results including: the amorphization of the phyllosilicates to a depth of ~200 nm, blistering and void development, and a loss of OH from the hydrated silicates. In addition to these effects, EELS spectra of He⁺ irradiated matrix serpentines show that they are significantly reduced during irradiation with an ~ 2X increase in Fe²⁺/Fe³⁺ in the irradiated material compared to the un-irradiated serpentine.


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Experimental and Thermodynamic Approach to Study Aqueous Alteration of Chondrite at Low Temperature. S. Kikuchi1 and T. Shibuya1, 1Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

Introduction: It is becoming well recognized that aqueous alteration could be a widespread process in the primitive solar system materials [1]. The typical evidence of this process is the common presence of hydrous minerals (e.g., serpentine, smectite, oxyhydroxide) in carbonaceous chondrites. In addition to these direct observations, indirect analytical methods such as infrared spectrometer revealed the presence of phyllosilicates in various small asteroids (e.g., Ceres [2], Ryugu [3]) that might be the parent bodies of the carbonaceous chondrites.

These observations provide an important evidence that water played an important role in the evolution of early solar systems. However, the physicochemical properties of water (e.g., temperature, pH, water/rock ratio, redox potential) which reveal the alteration history of parent body, asteroid size, and the location where alteration took place, are still poorly constrained. One of the reasons for this poor understanding is that alteration processes and secondary mineral assemblages under various temperature and water (e.g., pH) conditions remain unsolved and very few relevant experimental data are available.

In this study, we studied alteration process and secondary mineral assemblage of chondrite by the combination of alteration experiments and thermodynamic modeling. We especially focused on aqueous alteration under anoxic and low temperature (<100°C) condition, which was indeed suggested to occur in some carbonaceous chondrites [1] but has been rarely experimentally examined in previous studies.

Experimental Methods: As a starting material for the alteration experiments, we used synthetic chondrite that has a mean chemical composition of CI chondrite [4] except for C concentration. The synthetic chondrite composed predominantly of olivine, troilite, Fe_{metal}, pyroxene, and glass.

The alteration experiments were conducted in an anoxic chamber. The synthetic chondrite (particle size < 90 μm) were mixed with NH₄-containing solutions at a water to rock mass ratio (W/R) of 10. The samples were heated in an oven at 25 and 80°C for 1 day to 200 days. After the experiments, solid phase was characterized by X-ray Diffraction (XRD), scanning electron microscope (SEM), and transmission electron microscope (TEM). The fluid was collected for the measurements of dissolved ion concentration by ion chromatograph and ICP-OES.

Modeling Methods: We use the program EQ3/6 computer code [5] which can simulate mineral-fluid equilibria to provide altered mineral assemblage and coexisting water chemistry (e.g., dissolved ion concentration, pH). The thermodynamic database required for the calculation (e.g. equilibrium constant) were generated by SUPCRT 92 [6]. For the modeling, the W/R, initial dissolved ions in reactant water, and the composition of the starting rock was set to the same conditions as were used in the alteration experiments. The temperature was set between 0 to 100°C.

Results: Changes in solution chemistry. Immediately after the beginning of the experiment, the oxidation-reduction potential (ORP) rapidly decreased from -471 mV (initial) to -578 mV and to -700mV at 25°C and 80°C, respectively. The ORP was below the thermodynamic stability of H₂O(l) at 80°C, which is corresponding to the production of H₂ in the system. Concomitantly with the rapid redox potential change, the concentration of major ions (Si, Na, H₂S) also rapidly changed in the first few days of the experiment followed by the relatively steady state.

Formation of secondary minerals. Two different secondary mineral phases were formed in the 7-month experiments at 80°C (Fig. 1). One is pyrrhotite that formed within a day after the start of the experiment. The formation of this phase was correlated with a decrease of troilite. The other secondary mineral phase
was smectite that is shown in the existence of a broad XRD peak at 2θ = 6.4° after 100-day of the experiment. The altered samples were further examined by TEM to understand the spatial distribution of secondary minerals. The newly-formed fibrous minerals were notable in the experiment both at 25 °C and 80 °C after 100 days. These minerals encrusted the surface of the original olivine, troilite, pyroxene, and glass (Fig. 2). The fibrous minerals have 1.0 to 1.4 nm basal lattice fringes, indicative of saponite. The saponite coexisted with secondary Si-rich amorphous phases.

When the chondritic rock (consists of anhydrous minerals and troilite) reacts with anoxic liquid water, the formation of pyrrhotite could be the first alteration mineral observed in the system, which is resulted from the rapid dissolution of troilite. This process also results in the decrease of ORP and corresponding H₂ production. After the formation of pyrrhotite, the formation of saponite appears to be the main process. The saponite develops by encrusting the original rock, which is likely resulted from the dissolution of olivine, glass, and pyroxene followed by the precipitation of saponite. The formation of saponite, however, is inconsistent with the results of thermodynamic calculations that indicate the dominance of serpentine rather than saponite as a main phyllosilicate mineral. It is possible that serpentine precipitates after the precipitation of saponite in our systems, as is observed in the intimate intergrowth of saponite and serpentine during artificial Allende meteorite weathering at 200 °C [7]. Alternatively, serpentine formation might be kinetically much slower than that of saponite at low temperatures (<100°C). Further alteration experiments will reveal a more detailed processes of the early stage of aqueous alteration of chondritic rock.

We finally note that a part of alteration phases obtained from our experiment is similar to that observed in several carbonaceous chondrites and micrometeorite [8, 9]. For example, Kaba CV3 carbonaceous chondrite lacks serpentine but contains a predominance of fibrous saponite with submicron Fe-Ni sulfides [8]. Although more detailed mineralogical comparison such as the sized of the saponite and the mineral species of Fe-Ni sulfide between Kaba and our experimental results should be done, the dominance of saponite and Fe-Ni sulfide in Kaba CV chondrite might be explained by the alteration of anoxic water at low temperature, and short duration of time. Therefore, our data also provide some constrains on the temperature and timescales of aqueous alteration of chondrites in the primitive solar system.

**References:**

NEAR-INFRARED SPECTRAL VARIABILITY ON ASTEROID RYUGU. K. Kitazato1, R.E. Milliken2, T. Iwata3,4, M. Abe3,4, M. Ohtake1,4, S. Matsuura5, T. Arai6, Y. Nakauchi1, T. Nakamura7, M. Mastuoka8, H. Senshu9, N. Hirata1, T. Hiroi9, C. Pilorget9, R. Brunetto9, F. Poulet9, L. Riu3, J.-P. Bibring9, D. Takir10, D.L. Domingue11, F. Vilas11, M.A. Barucci12, D. Perna13,14, E. Palomba14, A. Galiano14, S. Watanabe15, and the Hayabusa2 team. 1The University of Aizu, Fukushima, Japan (kitazato@u-aizu.ac.jp), 2Brown University, Providence, RI, USA, 3Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Sagamihara, Japan, 4The Graduate University for Advanced Studies (SOKENDAI), Kanagawa, Japan, 5Kwansei Gakuin University, Hyogo, Japan, 6Ashikaga University, Tochigi, Japan, 7Tohoku University, Sendai, Japan, 8Chiba Institute of Technology, Chiba, Japan, 9Institut d’Astrophysique Spatial (IAS), Université Paris-Sud, Orsay, France, 10Astromaterials Research and Exploration Science, NASA Johnson Space Center, Houston, TX, USA, 11Planetary Science Institute, Tucson, AZ, USA, 12Laboratoire d’Etudes Spatiales et d’Instrumentation en Astrophysique (LESIA), Observatoire de Paris, Meudon, France, 13Osservatorio Astronomico di Roma, Instituto Nazionale di Astrofisica (INAF), Mote Porzio Catone, Italy, 14Istituto di Astrofisica e Planetologia Spaziali, INAF, Roma, Italy, 15Nagoya University, Nagoya, Japan.

Introduction: In June 2018, the JAXA’s Hayabusa2 spacecraft arrived at the target C-type asteroid 162173 Ryugu, and has since then continued its observations with the onboard remote sensing instruments. The Hayabusa2 NIRS3 instrument acquired near-infrared spectra of Ryugu in the wavelength range from 1.8 to 3.2 µm to provide direct measurements of the surface composition [1,2]. On June 21, 2018, NIRS3 made the first observations of Ryugu at a distance of 70 km and proceeded to acquire more than 400,000 spectra of Ryugu’s surface through July 27, 2019. In order to acquire near-global coverage, NIRS3 operated in a scanning mode, in which slens of the spacecraft were combined with the rotational motion of the asteroid. During the descent operations, NIRS3 had acquired spectra down to 50 m altitude, corresponding to a spatial resolution of 9 cm. In addition, in April 2019, Hayabusa2 conducted an artificial cratering experiment using the small carry-on impactor. On May 30 and June 13, 2019, NIRS3 successfully observed the subsurface materials ejected from that experiment at a spatial resolution of 2 m. Together, these data provide an unprecedented view of a C-type asteroid at near-infrared wavelengths that can be used to constrain surface composition of the asteroid.

Spectral features: The thermally and photometrically corrected NIRS3 spectra of Ryugu exhibit several common features. The first is a very low reflectance value across nearly the entire body. The globally-averaged reflectance value at 2.0 µm is 0.017 ± 0.002, which is consistent with values at visible wavelengths observed by the Hayabusa2 ONC-T camera [3]. Reflectance values vary within 15% across the entire observed surface, excluding regions in shadow. Brighter surfaces are primarily observed along the equatorial ridge, crater rims and for individual boulders, again similar to visible wavelength images. NIRS3 spectra of Ryugu also commonly exhibit a weak positive spectral slope (0.2 to 0.6 %/µm) between 2.0 and 2.5 µm. Finally, all spectra of Ryugu exhibit a weak, narrow absorption feature centered at 2.72 µm, with intensities ranging from 7 to 10%. The intensity of the 2.72 µm feature exhibits a positive correlation with estimated surface temperatures, which indicates that uncertainties in the radiometric calibration and/or thermal emission component could be responsible for the observed variations in the band depth of this feature. When normalized by the observed temperature trend, no significant variations correlated with topographic features are observed in the intensity of the 2.72 µm feature.

The detection of an absorption feature at 2.72 µm indicates the presence of OH attached to a cation, and the position of the reflectance minimum indicates is most likely Mg. The band position is similar to Mg-OH features observed in Mg-rich phyllosilicates, such as serpentine and saponite, which are known to be present in aqueously altered CI and CM chondrites [4,5]. Ryugu spectra indicate that the OH band position does not vary across the surface of Ryugu within the ~18 nm spectral sampling of the instrument, suggesting a relatively homogeneous phyllosilicate cation composition.

Comparison with meteorites: There are currently no meteorite samples whose reflectance spectra perfectly match that of Ryugu at visible to near-infrared wavelengths. However, spectra of thermally-metamorphosed CI chondrites and shocked CM chondrites are most similar to Ryugu at near-infrared wavelengths in terms of brightness and shape. Laboratory spectra of an Ivuna (C1I) sample heated to 500°C and a MET 01072 (shocked CM2) sample are relatively dark and flat yet retain a weak 2.72 µm feature. These meteorite data suggest that thermal alteration processes such as partial dehydration and decomposi-
tion of hydrated minerals induced by static or shock heating can act to darken hydrated carbonaceous chondrites. Such processes are consistent with current interpretations of Ryugu’s formation history. The low bulk density (~1.2 g/cm³) of Ryugu suggests that it is a rubble-pile asteroid formed by a collisional event with the parent body [6], thus it is likely to have experienced shock and post-shock heating. However, it is also possible that the weak OH absorption is because the degree of aqueous alteration on Ryugu was never extensive to begin with, perhaps due to low water-to-rock ratios or slow/incomplete hydration reactions on the parent body.

Alternatively, it has been suggested that Ryugu’s orbit might have had shorter perihelion distances in the past, a characteristic that would have increased radiative heating from the Sun [7] and altered the mineralogy of the uppermost surface. Similarly, the surface of Ryugu has experienced solar-wind irradiation and micrometeorite impacts (space weathering), which can alter surface composition and spectral properties. These processes represent near-surface phenomena that continue to operate at Ryugu today, whereas the other interpretations for the apparent low hydration state represent inherent chemical and mineralogical attributes of the asteroid as a result of its early geological history.

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References:

MODELING OF INFRARED REFLECTANCE SPECTRA OF VOLATILE-RICH ASTEROIDS

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Introduction: The mineral assemblages on asteroids are useful to constrain the aqueous environments—the temperature (T), pressure (P), water to rock ratio (W/R), and bulk chemical composition—existed in them or in their parent bodies. The aqueous conditions reflect their formation and evolution processes: when, where, and how they have formed and evolved. The understanding of these small bodies would ultimately unveil the dynamic history of the solar system and the origins of volatile elements on terrestrial planets.

Near- to mid-infrared (IR) reflectance spectroscopy of asteroids contains the information of the surficial minerals in their characteristic absorption features, spectral slopes, and overall brightness or darkness. Recent remote-sensing of asteroids by Hayabusa2, OSIRIS-Rex, and Dawn spacecrafts as well as telescopic observations by AKARI infrared space telescope provided detailed IR reflectance spectra of asteroids [1–4]. These observations would allow us to constrain their paleo-aqueous environments.

This study aims to connect the observed IR spectra of asteroids to the original bulk compositions and T-P conditions of them or their parent bodies. We performed a series of chemical equilibrium calculations to obtain the mineral compositions. We computed the model IR reflectance spectra from the obtained mineral compositions. In this presentation, we compare the model results to the IR reflectance spectra of Ryugu, Bennu, Ceres, and the main-belt asteroids. We discuss their paleo-aqueous environments and the dynamic history of solar system.

Model: The chemical equilibrium calculations assumed the rocky bulk compositions of CV chondrites. We treated W/R as a parameter (0.2–10). We fixed the relative abundance of volatiles to water. Model 1 assumed a pure water and rock mixture. Models 2–4 assumed CO₂: 1, 3, and 10%, NH₃: 0.5%, and H₂S: 0.5% relative to water. The temperature T is a parameter and P equals the saturation vapor pressure of water. We used EQ3/6 computation software. In our model, pyrene represents organic phases, which would eventually form high-molecular-weight insoluble-organic-matter (IOM) typically found in meteorites.

The model IR reflectance spectra were calculated by adopting the radiative transfer theory for granular surfaces [5]. The refractive indices of endmembers were calculated from their reflectance spectra taken from RELAB database and [6, 7]. We computed single scattering albedo (SSA) of each endmember for an assumed grain size (D), which is treated as a parameter. The reflectance of the mixture was calculated from the linear mixing of endmember SSAs. We employed the incident angle i = 30° and the emergence angle e = 0°, respectively. We note that, though we carefully chose the endmember reflectance, the existing data sometimes contain the features caused by absorbed water on samples (e.g., at 1.4 µm and 1.9 µm in Figure 1).

Results: Model spectra show the dominance of OH-absorption at 2.7–2.9 µm due to abundant hydrous minerals (Figure 1). Addition of CO₂, NH₃, and H₂S leads to absorption at 3.1 µm and 3.4 and 4.0 µm, which are attributed to NH₄-saponite and carbonates, respectively (Figure 1a). As W/R decreases, carbonate absorption disappears and overall reflectance becomes lower because carbonates are converted into organics (CO₂-reduction) and magnetite dominates over organics eventually (Figure 1b). Decreasing W/R also causes the shift of OH-absorption to shorter wavelength because the dominant hydrous phases change from Fe-rich to Mg-rich. Ammonia-related absorption appears at limited W/R: W/R ~ 1 in Case 4 (Figure 1b) and W/R > 1 in Cases 2 and 3 (not shown), both at T = 0 °C. Raising T higher than 0 °C also removes NH₄-absorption, whereas carbonate-absorption keeps existing (Figure 1c). Raising T also causes the shift of OH-absorption to longer wavelength as dominant hydrous phases change from Mg-serpentine to ferrosaponite and clinocllore for W/R=1 (Figure 1c) or unhydrous minerals for W/R < 0.5 (not shown). Finally, increasing D darkens the overall reflectance (Figure 1d), as reported for natural samples [e.g., 8].

Discussion: Ryugu’s IR reflectance spectra observed by The Near Infrared Spectrometer (NIRS3) onboard Hayabusa2 (1.8–3.2 µm) are very low (~0.02) and contain sharp absorption at 2.72 µm [1]. Our model assuming equilibrium chemistry excludes high T (> 350 °C) and high W/R (> 2) to reproduce the position by Mg-serpentine (Figures 1b and 1c). A large grain size (D ~ 1 mm) may be favored by the low reflectance (Figure 1d). The low T and large D may be consistent with images taken by The Mobile Asteroid Surface Scout (MASCOT) lander, where inclusions are preserved and no fine-grained deposits are found [9].

Bennu’s reflectance spectra observed by OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS) showed the absorption near 2.7 µm [10]. Our model
again excludes high $T$ (> 350 °C) and high W/R (> 2) (Figures 1b and 1c).

For both Ryugu and Bennu, currently published data are insufficient to confirm the presence or absence of 3.1 μm absorption. If confirmed, it further constrains their parent bodies’ conditions.

Ceres’ reflectance spectra observed by Visible-Infrared Mapping Spectrometer (VIR) on the Dawn spacecraft showed absorptions at 2.7, 3.1, 3.4, and 4.0 μm, suggesting the presence of Mg-phyllosilicates, ammonia-bearing phases, and carbonates [3]. Our model constrains the condition to be $T \sim 0$ °C and W/R ∼ 1 or higher (Figures 1b and 1c).

Finally, the IR reflectance spectra of the C-complex main-belt asteroids observed by AKARI show ~2.7–2.8 μm, 3.1 μm, and 3.4 and 4.0 μm absorptions, in order of detection frequency [4]. The origins of this trend would be the diversities of original compositions and of quenching temperature. Our model showed that, when the starting materials contain CO$_3^-$, carbonate-absorption appears in a wide $T$ range. Therefore, the presence or absence of 3.4 and 4.0 μm absorption is likely to be attributed to the variety of original compositions, for instance, due to the different formation locations in the protosolar nebula. In contrast, NH$_4$-absorption appeared in limited conditions: $T \sim 0$ °C and W/R ~ 1 or higher. If the quenching temperature is the dominant factor, our model predicted that the 3.1 μm absorption is accompanied by OH-absorption at relatively short wavelength. On the other hand, if the original composition is the dominant factor, no such correlation would be observed. Future analysis of asteroids’ spectra will distinguish the scenarios and unveil the formation and migration history of these bodies.

DECODING SPACE WEATHERING ON CARBONACEOUS OBJECTS USING INFRARED SPECTROSCOPY. C. Lantz$^1$, R. Brunetto$^1$, D. Baklouti$^1$, E. Hénault$^1$, T. Nakamura$^2$, T. Le Pivert-Jolivet$^1$, S. Kobayashi$^2$, and F. Borondics$^3$. $^1$Institut d’Astrophysique Spatiale, CNRS/Université Paris-Saclay, bâtiment 121, Université Paris-Sud, 91405 Orsay, France (cateline.lantz@ias.u-psud.fr), $^2$Division of Earth and Planetary Materials Science, Graduate School of Science, Tohoku University, Aoba, Sendai, Miyagi 980-8578, Japan, $^3$SMIS, Synchrotron SOLEIL, 91190 Saint-Aubin, France.

Introduction: In the past 5 years, we performed ion irradiation of carbonaceous chondrites from different petrologic groups (CO, CV, CM, CI, C2) to simulate space weathering effects on dark asteroids. Through our experiments, we highlighted a dichotomy in the spectroscopic behavior of the irradiated samples in the visible range. The anhydrous meteorites show darkening/reddening, whereas hydrated meteorites show brightening/blueing upon irradiation. This trend seemed to be related to the meteorite initial composition. All samples presented a systematic change/shift towards longer wavelength of features in the 10 µm region [1].

As a follow-up of this study, we performed new ion irradiation of one CK, one CR, and three CM meteorites to further test composition effects. We also measured the FIR spectra of some samples, including the ones of the first study, to investigate the IR band shift in a broader range [2].

Method: We selected and prepared fragments of two other types of CCs: a CK4 (NWA 5515-1498) and a CR2 (EET 92159). The CM MET 01070 (aqueously altered with Mg-rich phyllosilicates) and the CM QUE 97990 (poorly altered and Fe-rich) [3] have also been irradiated. The four meteorite fragments were crushed and pressed into pellets. The fifth sample was a bulk piece of Murchison (polished and cut). We irradiated the samples with He$^+$ ions using ion flux $\sim 10^{13}$ ions/cm$^2$/s, fluence up to $6.10^{16}$ ions/cm$^2$, and energy at 40 and 15 keV to investigate two different energy regimes (Murchison only at 20 keV). We monitored the evolution of the samples upon irradiation by measuring VISNIR reflectance spectra in situ under vacuum (INGMAR setup). MIR and FIR micro-spectroscopy of the irradiated samples were performed ex situ at room pressure and temperature (at the Synchrotron SOLEIL). In the case of MIR, we used an imaging micro-spectrometer with spot size down to 20 µm to study the effects of irradiation on individual mineral components [4].

Results: Preliminary results in the VISNIR show that the CK follows the reddening/darkening trend of CO and CV, whereas both CM pellets get brighter and bluer after irradiation. The CR has a more complex behavior with no strong albedo change upon irradiation but a reddening of the slope.

In the MIR and the FIR, the main bands of silicate minerals (both anhydrous and hydrated) of all five new samples show band shift towards longer wavelengths after irradiation, while the MIR bands of carbonates remain unaffected. The FIR spectral range also shows a deformation of the silicate bands. The IR bands of silicates can thus constitute a reliable proxy of the time-bound effects of irradiation on airless bodies. We discuss the results of our experiments in the context of the current sample return missions Hayabusa2/JAXA and OSIRIS-REx/NASA. We show that the detection of irradiation effects is within the reach of IR spectral resolution of the OSIRIS-REx mission and of the future James Webb Space Telescope.


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COLOR AND SPECTRAL SLOPE MAPS OF ASTEROID RYUGU FROM HAYABUSA2 OPTICAL NAVIGATION CAMERA IMAGES. L. Le Corre¹, V. Reddy², K. J. Becker³, J.-Y. Li⁴, E. Tatsumi⁵, R. Honda⁶, S. Sugita⁷, N. Hirata⁸, and the Hayabusa2 ONC team, ¹Planetary Science Institute, Tucson, AZ, USA (lecorre@psi.edu), ²University of Arizona/Lunar and Planetary Lab, Tucson, AZ, ³University of Tokyo, Japan, ⁴JAXA/ISAS, Japan, ⁵University of Aizu, Japan.

Introduction: JAXA’s Hayabusa2 spacecraft arrived at its target, the near-Earth asteroid (NEA) Ryugu, on June 27, 2018. The Optical Navigation Camera - Telescopic (ONC-T) acquired images of Ryugu in seven color filters during the approach phase and after arrival to characterize the surface composition, the photometric properties, and map the color units. The ONC-T color filters span the wavelength range between 0.4-1.0 microns.

We will present the results of our image processing and analysis using the color data of Ryugu from the Optical Navigation Camera (ONC), one of the scientific instruments onboard the Hayabusa2 spacecraft. Using color image sets and image mosaics, we attempt to constrain the spectral properties and the surface composition of Ryugu, a C-type NEA, thought to be rich in carbonaceous material and hydrated silicates. We studied the correlations between color units identified in our maps and geologic features such as impact craters, boulders and ridges.

Data Processing: For the creation of image products such as color sets and image mosaics, we used ONC images generated with the latest calibration (flat field, distortion coefficients, etc.) in reflectance provided by the ONC team. We implemented the ONC camera model (for ONC-T, -W1, and -W2) and a specific ingestion routine for ONC images in USGS’s Integrated Software for Imagers and Spectrometers (ISIS) to retrieve precise geometry information for each pixel in the images, and also for map projection. Images were processed to produce color sets with seven bands and we derived image mosaics using those sets.

Image registration: Part of our processing includes checking for alignment between geometric backplanes and images. This is a critical step to be able to generate color image sets and image mosaics. A byproduct of the shape modeling is improved pointing and trajectory information for the images (Fig. 1). Therefore, images used for shape reconstruction (such as stereophotoclinometry or SPC) can be used without further adjustments to create controlled image mosaics. However, pointing and trajectory updates are not available for all images and different methods have been tested to correct the backplanes in this case.

Image mosaics: Color maps of Ryugu are generated using the latest ray-tracing engine available in ISIS and are based on the best resolution shape model of Ryugu at the time of our processing in DSK (Digital Shape Kernel) format. We discarded pixels that are not directly illuminated by the sun and applied a Lommel-Seeliger photometric correction using the geometric backplanes. All pixels included in the color mosaic are sorted by best spatial resolution so that the end product retains the best information available from the ONC dataset. Our preliminary global image mosaics included images from the proximity phase acquired in July 2018 (figure 2).

Fig. 1: RGB images of Ryugu with Red as I/F, Green as local incidence angles and Blue as local emission angles. The left image has been generated using the predicted CK and SPK kernels (from JAXA team) whereas the image on the right was created based on the pointing information from the SUMFILEs generated by the shape modeling process also done by the Hayabusa2 team at JAXA.

Spectral properties: Most color differences on Ryugu are found in mosaics of color ratios and spectral slope. In the visible-IR spectral slope map (figure 3), the equatorial ridge presents a bluer slope relative to the average surface material. Perhaps the equatorial ridge is made of fresher material with slightly brighter reflectance (albedo of ~0.022 at 550 nm compared to the global average value of ~0.020), and was less affected by space weathering (SPWE). This trend would be consistent with changes in spectral slope observed when irradiating some CM2 meteorites in the lab to simulate SPWE. The biggest boulder, Otohime, has the bluest slope and might represent the most pristine material from Ryugu. Interestingly, only the fractured faces of the boulder have this blue slope while the rest of the boulder, appearing darker and more eroded, has a spectral slope similar to the background terrain. Other terrains at the south pole and around Otohime also have a bluer spectral slope. We did not find strong absorption features in the ONC data.

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Fig. 2: RGB color composite map with images from July 2018 at 2 m/pixel after photometric correction using Lommel-Seeliger model. This RGB composite is close to true color using filters Na (589 nm), V(550 nm), and B (480 nm). Ryugu appears quite homogeneous in these colors with some terrains at the equator that have higher reflectance.

Fig. 3: Map of the slope between the V and P bands displayed as blue-red color scale overlaid on a 550 nm map. This map is derived from the same multi-band image mosaic as figure 2. The regolith material located at the equatorial ridge has a more negative slope in the visible compare to other surrounding terrains. This blue slope unit corresponds to the brighter reflectance unit found on the equatorial ridge on figure 2. At the south pole, other terrains and part of the Otohime boulder also exhibit a bluer spectral slope.
**MAIN-BELT INFRARED SPECTRAL ANALOGUES FOR (101955) BENNU: AKARI AND SPITZER IRS ASTEROID SPECTRA.** L. F. Lim, H. H. Kaplan, V. E. Hamilton, P. R. Christensen, A. A. Simon, D. C. Reuter, J. P. Emery, B. Rozitis, M. A. Barucci, H. Campins, B. E. Clark, M. Delbo, J. Licandro, R. D. Hanna, E.S. Howell, J. P. Emery, B. Rozitis, M. A. Barucci, H. Campins, B. E. Clark, M. Delbo, J. Licandro, R. D. Hanna, E.S. Howell, D. S. Lauretta, Goddard Space Flight Center, Greenbelt, MD, USA (lucy.f.lim@nasa.gov), Southwest Research Institute, Boulder, CO, USA, Arizona State University, Tempe, AZ, USA, University of Tennessee, Knoxville, TN, USA, Open University, Milton Keynes, UK, LESIA, Paris Observatory Meudon, France, University of Central Florida, Orlando, FL, USA, Ithaca College, Ithaca, NY, USA, CNRS, France, Instituto de Astrofísica de Canarias, Tenerife, Spain, University of Texas, Austin, TX, USA, University of Arizona, Tucson, AZ, USA.

**Introduction:** The Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) mission has measured the spectrum of asteroid (101955) Bennu in reflectance (OVIRS instrument; [1]) and thermal emission (OTES instrument; [2]). Here we place the global average spectra of Bennu [3] in the context of the wider asteroid population as represented by infrared reflectance spectra from the AKARI mission [4] and thermal emission spectra from the Spitzer Infrared Spectrometer (IRS) [5].

![Figure 1: Dynamical context of AKARI and selected Spitzer asteroids in the asteroid main belt relative to the probable Bennu source region](image1.png)

On dynamical grounds (101955) Bennu has been considered most likely to have originated in the inner-Main-Belt families of (495) Eulalia (C-type, semimajor axis \(a = 2.49\) AU) or (142) Polana (B-type, \(a = 2.42\) AU) [6, Fig. 1]. However, neither Eulalia nor Polana nor their family members were observed spectroscopically either with AKARI or with the Spitzer IRS.

**B-type Main Belt asteroids in the AKARI spectral catalogue:** (2) Pallas, (704) Interamnia, and (24) Themis were observed spectroscopically by AKARI. Although all three asteroids are dynamically distant from the Polana/Eulalia complex and the \(v_6\) secular resonance, Pallas and Interamnia are close spectral matches in the 2.6–3.5 \(\mu\)m wavelength region, in which Bennu's strongest spectral feature is located (Figs. 2 and 3) [3]. Bennu's observable 2.7-\(\mu\)m band depth after thermal tail subtraction is weaker than that of Pallas by a factor of approximately 2 and weaker than that of Interamnia by a factor of 1.4. The shape of the band is a closer match to that of Pallas in the 2.85–3.0 \(\mu\)m region. Preliminary Gaussian fits (fig. 2b) show that the difference in shape can be explained by the Gaussian at \(\sim 2.89\) \(\mu\)m.

![Figure 2 (a) OVIRS spectrum of Bennu vs. AKARI spectra of B-type asteroid (2) Pallas, B- or Ch-type asteroid (704) Interamnia, and inner-main-belt Cgh-type asteroid (51) Nemausa (b) Preliminary 5-Gaussian fit to the AKARI spectrum of 2 Pallas. The two deepest absorptions are the most similar in wavelength to the "Band 1" (2.72) and "Band 2" (2.76) identified in the Gaussian deconvolution of the NIRS3 spectrum of Ryugu [7].](image2.png)
In contrast, (24) Themis (Fig. 3) is a comparatively poor match to Bennu in this region and also contains a deep 3.1-μm band [9,10] not matched by corresponding structure in Bennu’s spectrum. The preliminary Gaussian fit to this spectrum is shown in Fig. 3b.

**Spitzer IRS asteroid spectra:** Emissivity spectra for several low-albedo binary asteroids have been published [12]. Among these, the spectrum of (4492) Debussy (Fig. 4) is the closest match to that of Bennu in the 20–30 μm region but is dissimilar in the 8–14 μm region, with a narrow emissivity minimum at 12 μm that is absent from the spectrum of Bennu. Debussy was classified as a C-type in [13]. A low Bennu-like density was reported for Debussy (ρ = 0.9 ± 0.1 g/cm³) [12].

**Summary and Conclusions:** Although dynamically distant from the most likely Bennu source regions in the main belt, (2) Pallas is a close spectral analogue to Bennu in the 2.6–3.2 μm region. There are no Spitzer IRS spectra of Pallas or its family members.

Bennu’s thermal IR spectrum is unlike those of “10-μm plateau” main-belt and Trojan low-albedo objects, including the B-type asteroid (24) Themis and its large family members. Thus, the low-thermal-inertia boulders that dominate the surface of Bennu are not producing the same spectral emissivity behavior that has been attributed to underdense fairy-castle surface structure in these larger objects (e.g. [11]). We note that the main-belt "plateau" asteroids have thermal inertias in the range 5–85 J s⁻¹K⁻¹ m⁻² (5–85 for (45) Eugenia, 5–65 for (130) Electra; [12]) whereas the average thermal inertia for Bennu is ~300 in the same units, with values as low as ~200 observed in some of the larger boulders [14]. (24) Themis is also not a close spectral match in the 2.5–3.5 μm region.

Small B-type family members in the main belt have not yet been spectrally characterized in the thermal IR. Measurements of small Polana/Eulalia family members in the main belt would be the most directly relevant to understanding the origin of Bennu.

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**References:**

DEDUCING THE THERMODYNAMIC ORIGINS OF PLANETARY MATERIALS: IMPLICATIONS FOR THE HISTORIES OF MATERIALS TO BE RETURNED BY HAYABUSA 2 AND OSIRIS-REx

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Introduction: The primary goal of the OSIRIS-REx mission is to understand the role that the primitive asteroids may have played in the origins of life and planet formation by studying the returned samples [1,2]. A detailed analysis of the bulk chemistry, microstructure, mineralogy, and crystal chemistries of the samples can reveal their thermodynamic origins and post-formation histories. Successful completion of such an objective demands thermodynamics models of meteoritic materials in conjunction with the experimental studies that provide information on composition and structure of samples over a range of spatial scales. To this end, we describe thermodynamic modeling of planetary materials within a predictive framework of first-principles quantum-mechanics starting from electronic structure calculations to support the laboratory analysis of the returned samples.

Theoretical methods and calculations: Thermodynamic modeling is conducted within CALculation of PHAsic Diagrams (CALPHAD) framework to model condensation and stability of minerals by combining quantum-mechanics calculations and available experimental thermochemical data with accurate crystal structure-based models. Gibbs free energy models of solution phases in their entire composition space are developed to calculate their crystal chemistry and precise thermochemical origins under nebular conditions in addition to predicting their post-formation histories. The modeling includes, but not limited to all the experimentally identified inorganic and organic phases. As a part of our ongoing effort, we calculated revised condensation sequence of refractory minerals that are found within primitive meteorites [3]. The modeling includes all the pertinent phases such as V-alloyed CaTiO3 and MgAl2O4, grossite (CaAl2O4), hibonite (CaAl2O4), melilithe (CaAl2SiO6), corundum (Al2O3), pyroxene in addition to the other solid-solution phases that are found within calcium and aluminium-rich inclusion (CAIs) [4]. For the gas phase, we consider all the elements/species pertinent to the solar nebula. The gas phase is modeled by incorporating all the species (O2, O, O3, Al, Mg, Ca, Ti, V, Al2O3, Al2O3, Al2O3, Al2O3, MgO, CaO, Mg2, Ca2H, H2O, H2O, H2O, H2O, H2O, O2, C2O2, C2O2, Si, TiO, TiO, 2, V2O5, V2O5, SiO, SiO).

First-principles quantum-mechanics calculations employing Vienna Ab initio Simulation Package (VASP) [5] are performed to calculate thermochemical data of the solid solutions. Special quasirandom structures (SQS) predict enthalpies of mixing in solid solutions as a function of composition with respect to their end-members. The entropic contributions to the free energy are obtained from phonon and Debye calculations. The exchange correlation functional as described by the Perdew-Burke-Ernzerhof (PBE) is used in the calculations [6].

The employed first-principles framework enabled a quantum leap in comprehensive thermodynamic modeling of the phases. The sparsity of the thermochemical data, which was mainly obtained from the experimental measurements has been a limitation not only for the planetary materials but in general for all materials that involve solid solutions over a large composition space. The earlier thermodynamic efforts dealing with such situations modeled many of the solution phases as stoichiometric or solutions in reduced composition space [7-9]. In addition, several new refractory and ultra-high refractory phases have been continuously reported from the experimental characterization of meteorites, in the last few years.

The employed computational framework predicts the thermochemical data such as the heat capacity (Cp), enthalpies and entropies of mixing of stoichiometric endmembers and of the solid solution compositions. For example, pyroxene is among the primary phases in CAIs and it occurs in meteorites in both orthorhombic and monoclinic structures, the latter of which is found to exhibit an extensive range in composition space involving three different sublattices for cation-mixing (Ca2+,Mg2+,...)M2(Ti3+,Mg2+,Ti4+,...)M4(Al3+,Ti4+,Si4+)3/2O6 within its crystal structure. Thermochemical data for the full range of compositions within this family of solid solution is not available and experimental determination of them would be exceedingly challenging. As a result, condensation of many Al-Ti-rich pyroxene compositions within that family cannot be predicted using existing models in literature.
Results and Discussion: Figure 1 depicts condensation sequence of various mineral phases shown as function of temperature assuming equilibrium condensation in a solar-composition gas (at $10^4$ bar). We find that cubic perovskite is the first phase to condense with a condensation temperature varying between 1682 K and 1637 K in the pressure range of $10^3$ to $3 \times 10^5$ bar. This result is in stark contrast to existing calculations in the literature [7-9], which invariably predicted Al$_2$O$_3$ corundum as the first phase to condense from a gas of solar composition. The reason for the difference is that our calculations take into account the all three polymorphs of perovskite for which we calculated the thermochemical data employing DFT. Similarly, in contrast to the previous calculations, Al-Ti-rich pyroxene with an endmember composition of CaTiAl$_2$O$_6$ condenses at temperatures as high as 1670 K at a total gas pressure of $10^4$ bar. The pyroxene phase exhibits a miscibility gap with Al-Ti-rich and Mg-Si-rich phases that are stable at high- and low-temperature regions, respectively (Figure 2).

The revised condensation calculations have important implications for the identification of equilibrium versus non-equilibrium nature of condensation based on the reported microstructures and phase relationships within CAI mineral assemblages. Further, as revealed in this work, the incorporation of solid-solution phases that are relevant to these refractory assemblages, are crucial to predict accurate interpretations of the thermal processing in the high temperature region of the solar protoplanetary disk.

Fig. 1. The calculated condensation sequence of refractory minerals that are found within the calcium- and aluminium-rich inclusions.

Fig. 2. The stability diagram of refractory mineral phases as a function of T and P, depicting the conditions of their condensation within solar nebula.

References

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Introduction: Bennu is a rubble-pile asteroid with an equatorial bulge that suggests a rotational (centrifugally-driven) distortion of the asteroid at some time in its history [1-3]. The bulge could be an equatorial accumulation of regolith that has drifted latitudinally to the equator, but primarily of near-surface material, or it could be an expression of pseudo-plastic distortion of the whole asteroid, or both (re-accumulation from a debris disk is a third possibility).

If surface creep of regolith is involved, we would expect it to be expressed by alignment of elongate rocks and boulders parallel with the direction of transport towards the equator. This assertion is based on the idea that orientation occurs in order to minimize flow resistance of an object in a streaming medium of similar material. This alignment would be weak or absent at the poles, strong at mid latitudes, and jumbled in equatorial regions owing to the collision of two opposing (N and S) drift directions (Fig. 1).

![Image of regolith surface creep on asteroid Bennu](image-url)

**Figure 1:** Notional model for orientation of boulders.

To test this alignment hypothesis, we examined OSIRIS-REx spacecraft photographic imagery and compared it with results from laboratory experiments and the predictions of a geometrically-based stress-vector model.

Geometrical Model: The geometrical model was set with centrifugal forces equal to gravity at the equator as the maximum asteroid rotational condition before centrifugal shedding of material into space. Resolved force vectors for this predefined condition indicate a maximum of horizontal soil stress at mid latitudes and no significant net horizontal (creep-inducing) component of stress at the poles or equator. Negligible stresses at the poles predict a lack of boulder alignment. Mid latitudes should express maximum alignment, increasing with equatorward transport distance. Compressive collisions of north and south equatorward drifts predict a realignment of boulders on the equatorial bulge to an E-W trend.

Image Analysis: These model predictions are supported by direct photographic imagery of Bennu’s surface, although we stress that our database is preliminary, consisting to date of five analyzed sites in total. The sites were selected at arbitrary locations on Bennu’s surface at equatorial latitudes and mid northern and southern latitudes. Many tens of boulders were measured at each location using elliptical fitting of boulder long axes. Locations were chosen to avoid major features such as craters and boulder fields where localized soil movements could overprint any general global alignment trend.

In order to deal with shadowing and other illumination issues, we analyzed images with low incidence angles, and therefore little shadow. In the locations where some shadows were present, we only measured boulders with visible boundaries.

Rose diagrams expressing boulder alignment trends are shown in Fig. 2. Diagrams A and B are from mid northern latitudes and show prominent (roughly) N-S alignment trends. Similarly, diagram C from a southern mid latitude shows a north-south trend. Diagrams D and E are from equatorial locations; the N-S trend is absent. Whilst there is general agreement between observed boulder alignments and modeled expectations, there are also unexplained NW-SE and NE-SW trends seen in four of the five diagrams (southern mid latitude being the exception).

Although boulder alignment trends are quite recognizable in the rose diagrams, they are not recognizable by eye; the trends are very subtle and are only exposed statistically be multiple alignment measurements. We note that Schwartz et al. [4] have also observed N-S alignment trends of boulders which they associate with Bennu’s contemporary global slope directions that are also aligned north-south.

Laboratory Experiments: These corroborated the results of image analysis. We physically simulated Bennu’s boulder motion in the laboratory by horizon-
tally shearing thin layers of loose granular materials. The materials were light weight in order to reproduce the low frictional relationships in a low gravity environment. The grain inertia/friction ratio was the experimental similitude parameter.

Spherical/equant grains (peppercorns), disk-shaped grains (lentils), and elongated grains (rice) of ~0.5 cm were made into mixtures and spread with random orientations in a plume or channel and then subjected to horizontal shear by mechanically dragging the top layer across the base layer. This induced a boundary-layer shear through the body of the grain mass down to a depth of several grain diameters. We postulate a similar boundary layer structure on Bennu, with unconfined surface material entraining material just beneath, but effective drag ceasing at some small depth on the order of a few boulder diameters.

The lentil disks became imbricated with their overlap in the direction of drag. At the same time, a significant fraction of the rice population became aligned with the shearing direction (long grain axis parallel with drag). Rose diagrams will be made of the grain alignments for comparison with our image analysis.

**Next Steps:** Our database is small and many more boulder alignment measurements are planned. The lab experiments are in their infancy and the test matrix will be expanded, in particular, to test the travel distance required to generate alignment, the effect of different mixtures (relative proportions of grain types), and the way in which multiple alignment trends are able to co-exist in a mobile granular mass.

**Conclusions:** The modeling, photographic image analysis, and laboratory experiments are consistent with a drift of near-surface material towards the equator, but they do not preclude concomitant bulk distortion of the whole asteroid due to the same centrifugal influence.

This investigation is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program. We are grateful to the entire OSIRIS-REx Team for making the encounter with Bennu possible.

LOW ENERGY H$^+$ AND HE$^+$ ION IRRADIATION EXPERIMENTS OF IRON SULFIDE. T. Matsumoto$^1$, Y. Nakauchi$^2$, A. Takigawa$^3$, A. Tsuchiyama$^4$,5, Y. Asada$^6$, M. Abe$^7$, N. Watanabe$^8$, D. Harries$^9$, and F. Langenhorst$^10$, $^1$Faculty of Arts and Science, Kyushu University (matsumoto.toru.502@m.kyushu-u.ac.jp), $^2$Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, $^3$The Hakubi Center for Advanced Research, Kyoto University, $^4$Research Organization of Science and Technology, Ritsumeikan University, $^5$Gunazhou Institute of Geochemistry, $^6$Division of Earth and Planetary Sciences, Kyoto University,$^7$Institute of Low Temperature Science, Hokkaido University, $^8$Institut für Geowissenschaften, Friedrich-Schiller-Universität Jena.

**Introduction:** Space weathering refers to alteration of materials exposed to the space environments [e.g., 1]. Solar wind ions, 1 keV H$^+$ ions (95.41%) and 4 keV He$^{++}$ ions (4.57%) [2], are one of main causes of space weathering as with micrometeorite bombardment [1]. Iron sulfides are common minerals in early solar system materials and are important solid reservoir of cosmochemically major elements, iron and sulfur. Remote-sensing observation of the surface of S-type asteroid 433 Eros revealed significant sulfur depletion compared to the composition of ordinary chondrites [e.g., 3], which is considered to be caused by space weathering. Besides the remote-sensing data, intensive space weathering of iron sulfide has been reported in regolith grains from S-type asteroid Ito- kawa [4]. Understanding of space weathering of iron sulfide is essential for evaluation of chemical composition and surface evolution of S- and C- complex asteroids. Prior ion irradiation experiments of iron sulfide with 4 keV He$^+$ and 5 keV Ga$^+$ suggested selective sulfur loss by sputtering of sulfur atoms [5, 6, 7]. In addition, structural change by MeV Kr$^{+}$ irradiation has been reported [8]. On the other hand, little is known about alteration of iron sulfides irradiated by hydrogen ions with low-energy, which are the most major components of solar wind [2]. Here, we report ion irradiation experiments of 1 keV H$^+$ and 4 keV He$^+$ to pyrrhotite (Fe$_7$S$_8$) that is one of common sulfide minerals in primitive chondritic materials.

**Experiments:** We prepared rectangular wafers (3 mm x 5 mm x 0.5 mm) from a single crystal of natural pyrrhotite (Chihuahua, Mexico). The (001) surfaces of the pyrrhotite were mechanically polished until 0.25 µm roughness. Then, we performed the chemical polishing with colloidal silica to remove the damage layer of the surface. The low-energy ion irradiation equipment developed in ISAS/JAXA was used in the experiments. A target holder with samples was transferred in an ultra-high vacuum chamber. The polished pyrrhotite surfaces were irradiated with 1 keV H$^+$ with doses of $10^{16}$, $10^{17}$, $3 \times 10^{17}$, and $10^{18}$ ions/cm$^2$. We performed 4 keV He$^+$ irradiation experiments with doses of $10^{16}$, $10^{17}$, and $10^{18}$ ions/cm$^2$. During the ion irradiation, the flux of H$^+$ ions and He$^+$ ions were kept at ~3x10$^{12}$ and ~5-7x10$^{13}$ ions/cm$^2$/sec, respectively. All experiments were carried out in room temperature. The surface structures of irradiated samples were observed with an FE-SEM (Hitachi SU6600) with the accelerating voltage of 1-2 kV. We lifted out ultra-thin sections from pyrrhotite samples irradiated by H$^+$ or He$^+$ with 10$^{17}$ ions/cm$^2$ using focused ion beam systems (FEI Quanta 200 3DS; Quanta 3D FE). To protect the irradiated surface during FIB sectioning, the irradiated surfaces were covered with carbon. We then, coated the surface with an electron-beam-deposited Pt layer followed by a Ga ion-beam-deposited Pt layer. We observed the sections using field-emission transmission electron microscopes (FE-TEM; JEOL JEM 3200FSK, FEI Tecnai G$^2$ FEG).

**Results:** H$^+$ irradiation: No morphological change was observed on the irradiated pyrrhotite surface with dose of $10^{16}$ ions/cm$^2$. Blister of below 100 nm in diameters were distributed on the surface of the pyrrhotite samples irradiated with dose of higher than $10^{17}$ ions/cm$^2$. We observed numerous vesicles beneath the surface with blisters within 10-20 nm in depth (Fig. 1). The vesicles often possess euhedral shapes (Fig. 2) and are elongated parallel to the c-plane of the pyrrhotite. Electron diffraction revealed that the pyrrhotite crystal used in this study consists predominantly of 4C pyrrhotite (Fig. 2). Selected area diffractions from the damaged rim showed slight rotation of spots from the basic NiAs structure. Fast-Fourier-Transforms (FFT) of high resolution TEM images of the damaged rim showed absence of 4C superlattice reflection spots. This suggests disordering of cations and cation vacant sites in the pyrrhotite. Increase of the Fe/S ratio in the damaged rim was detected by energy dispersive X-ray spectroscopy (EDX).

He$^+$ irradiation: No morphological change was observed on the irradiated pyrrhotite surface with dose of $10^{16}$ ions/cm$^2$. Blister of below 250 nm in diameters were distributed on the surface of the pyrrhotite samples irradiated with dose of higher than $10^{17}$ ions/cm$^2$. Elongated vesicles appeared beneath the surface with blisters (Fig. 1). Widely expanded vesicles are located just beneath blisters at 30-40 nm in depth. Electron diffraction showed slight rotation
of diffraction spots of the basic NiAs structure and absence of 4C superlattice reflection spots as with samples irradiated by H⁺ ions. Increase of the Fe/S ratio in the damaged rim was also detected.

**Discussion:** The depth of the vesicles in the pyrrhotite broadly match the peak concentration depth of 1 keV H⁺ of 10-20 nm and 4 keV He⁺ of 20-40 nm, calculated by SRIM software [9]. These depths suggest that vesicles developed through accumulation of implanted gases. The euhedral vesicles formed by H⁺ irradiation could explain euhedral voids found in pyrrhotite of interplanetary dust particles [10].

Our study showed that pyrrhotite retained short-range NiAs structures by low energy ion irradiation, although their longer-range vacancy-ordered superstructures is disordered. The similar tendency was observed in iron sulfides irradiated by 1 MeV Kr⁺ irradiation [8]. The behavior of iron sulfides contrasts with silicate minerals, which become fully amorphous by keV to MeV ion irradiation [e.g., 8, 11]. The susceptibility of ion-beam-induced amorphization has been explained based on the thermal spike model [12, 13]. The concept of the model was that an ion impact could create a small disordered region equivalent to a melt. This region cools rapidly to form an amorphous, or crystallization begins when the local temperature falls below the melting point. Iron sulfides have non-quenchable behavior from melts [14] and have simple atomic arrangement compared to silicate minerals. Hence, thermal spike mechanism was adopted for interpretation of amorphization resistance of iron sulfide to 1 MeV ion irradiation [8]. The thermal spike model may account for the crystalline features of the damaged layers in pyrrhotite with low energy H⁺ and He⁺ irradiation. The decrease of Fe/S ratio might be caused by preferential sputtering of sulfur [5,6,7], suggesting that solar wind can contribute to sulfur depletion on asteroids. Nucleation of iron metals observed in previous irradiation experiments [6,7] and natural samples [4] were not clear in this study. Further investigation focusing on the difference of chemical composition of iron sulfides, temperature, ion flux, and crystallographic orientation will shed light on the variety of modification of iron sulfide by space weathering.


**Fig. 1** Bright-field scanning transmission electron microscope images of pyrrhotite samples irradiated by H⁺ (upper) and He⁺ (lower) with 1x10¹⁷ ions/cm².

**Fig. 2** TEM bright field image of pyrrhotite surface irradiated by 1keV H⁺ ions with 1x10¹⁷ ions/cm². Euhedral vesicles (arrowed) appear in the irradiation damaged layer. TEM selected area diffraction pattern from intact pyrrhotite in zone axis [100] is shown in the lower left. Pyrrhotite 4C superlattice reflections are marked.
WHITENED DATA-BASED CLUSTER ANALYSIS OF INFRARED SPECTRA OF RYUGU. M. Matsuo1, H. Iwamori2, T. Usui1, K. Kitazato3, and T. Iwata1, 1Institute of Space and Astronautical Sciences, Japan Aerospace Exploration Agency, Kanagawa, 252-5210, Japan (matsuoka.moe@jaxa.jp), 2Earthquake Research Institute, The University of Tokyo, Tokyo, Japan, 3University of Aizu, Fukushima, Japan.

Introduction: The Near-infrared Spectrometer (NIRS3) onboard the Hayabusa2 spacecraft obtained NIR reflectance spectra of C-type asteroid 162173 Ryugu first at an altitude of ~20 km from 10th to 12th of July 2018 with spatial resolution of ~40 m (Box-A). Recent NIRS3 observations at a longer solar distance successfully obtained Ryugu’s NIR spectra with less thermal effects. NIRS3 data showing a 2.72-μm OH stretching absorption and a low reflectance constantly are globally homogeneous and similar to moderately-heated or shocked carbonaceous chondrite spectra [1, 2].

This study performs cluster analysis of Ryugu NIR spectral data by using a new statistical method [3] based on combinations of k-means cluster analysis (KCA), principal component analysis (PCA), and independent component analysis (ICA) for original Box-A data. The results show the NIR spectral heterogeneity within homogeneous morphological terranes in the northern equatorial region of Ryugu, possibly reflecting mineralogical and/or physical properties of Ryugu surface material.

Instrument: NIRS3 has a 128-channel indium arsenide (InAs) photodiode sensor installed in the spectrometric unit and cooled below 193 K (~80 °C) using a passive radiator. The detectable wavelength range of NIRS3 is 1.8–3.2 μm and spectral sampling resolution is 18 nm [4].

Methods: Our cluster analysis is divided into three steps: (1) standardization and whitening of the original data using PCA, (2) dimension reduction of the data by selecting principal components (PCs) with significant eigenvalues and the corresponding scores of individual data, and (3) performing KCA (and ICA) [3]. Whitening is essential to extract the independent features hidden in the data, which is not possible only by standardization. Here we report preliminary results of KCA and PCA using NIRS3 Box-A data obtained on July 10th 2018. Since a parameter study is required to determine the optimal number of cluster, we reduced the data volume and computational time by selecting eight channels of NIRS3 data with ~200 nm interval from original 128 channels with 18 nm resolution.

Results and Discussion: NIRS3 spectral data obtained around a northern equatorial region, where there are no significant morphological features such as large craters, show that the data variation involves three significant PCs. Then, we performed KCA using the scores of three PCs as the whitened and dimension-reduced data. To find the optimal number of cluster (k), k was varied from three to ten. The case with k = 6 (Figs.1,2) captures well the features of a regional heterogeneity despite the homogeneous morphological features obtained by the Optical Navigation Camera Telescope (ONC-T) images [2].

All the cluster have a common strength OH absorption at 2.72 μm with similar depths, yet they have various albedos (Fig.3) and red slopes (in 1.80-2.50 μm wavelength range) (Fig.4). These spectral features possibly indicate that the observed northern equatorial region experiences similar degrees of thermal alteration and space weathering. Alternatively, more plausible causes producing this NIR feature are as follows; (a) carbon content, (b) opaque material (e.g., Magnetite) abundance, and (c) grain size and porosity at the surface of Ryugu. A previous clustering study [5] suggest that NIR clusters reflect difference in hydrous mineral contents. Our study further propose a possibility the grain size effect for spectral reddening.

In this study we found that NIRS3 looks constant but clustering results indicate NIR spectra possibly have heterogeneity depending on the region. For the next steps, we will perform KCA, PCA, and ICA analyses using global NIR data of Box-A sequence.

Figure 1. A NIRS3 cluster map obtained on July 10th 2018. The distribution of six clusters are clearly separated by longitude.
Figure 2. The relationship between PC1 and 2 (upper left), PC1 and 3 (upper right), and PC2 and 3 (lower right) obtained by six-clustering results.

Figure 3. Average spectra of each cluster.

Figure 4. Average spectra of each cluster normalized at 2.60 µm shown in Figure 3.

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LABORATORY STUDIES ON THE 3 µm SPECTRAL FEATURES OF Mg-RICH PHYLLOSILICATES AND INSIGHTS FOR THE INTERPRETATION OF ASTEROID RYUGU SURFACE SPECTRA. Maturilli A.1, G. Alemanno1, J. Helbert1 1Institute for Planetary Research, German Aerospace Center DLR, Rutherfordstr. 2, 12489 Berlin, Germany (Alessandro.Maturilli@dlr.de)

Introduction: The Near Infrared Spectrometer (NIRS3) on Hayabusa 2 mission detected a weak and narrow absorption feature centered at 2.72 µm across the entire observed surface of the asteroid 162173 Ryugu [1]. The presence of an absorption feature at 2.72 µm is indicative of the presence of (OH)-bearing minerals. Furthermore the position of the observed peak can be likely associated to that of the Mg-OH features, as in Mg-rich phyllosilicates. [1] However, the collected spectra from the Ryugu surface show no other absorption features in the 3 µm region. It has been suggested that thermal alteration processes, can darken the surfaces of carbonaceous chondrites, thus decreasing the reflectance values around 3 µm. In addition, thermal alteration processes, have been taken into account to explain the formation of Ryugu asteroid [2]. To investigate on this point and to check the behavior of the spectral features around 3 µm with thermal alteration, we performed laboratory experiments on two Mg-rich phyllosilicates (serpentine and saponite). In particular, we studied two different situations: 1) thermal alteration at increasing T - the samples were heated at different steps of 100°C, starting from 100°C up to 700°C, for 4 hours each; 2) long time heating at constant T - samples were heated at constant T~250°C for 1 month (1st step) and then for 2 months (2nd step).

Experimental setup and procedure: we selected four samples of serpentine and saponite in two different grain sizes: 25-63 µm and 125-250 µm.

Samples preparation, heating processes and measurements were performed in the Planetary Spectroscopy Laboratory (PSL) of the German Aerospace Center (Deutschen Zentrums für Luft- und Raumfahrt, DLR) in Berlin [3] (Figure 1). Three identical FTIR (Fourier Transform Infrared Spectrometers) instruments are operated at PSL, in an air-conditioned laboratory room. The 3 spectrometers are all the same identical model, Bruker Vertex 80V that can be evacuated to ~0.1 mbar. Two spectrometers are equipped with aluminum mirrors optimized for the UV, visible and near-IR, the third features gold-coated mirrors for the near to far IR spectral range. Using three instruments that are identical (apart from the different internal mirrors) has some major benefits. Most importantly it facilitates the cross-calibration between the three instruments. The instruments can also share the collection of detectors, beamsplitters, and optical accessories that are available in our equipment to cover a very wide spectral range.

In the first part of our experiment, samples were heated in vacuum (~0.1 mbar) using the induction system in the external emissivity chamber of the PSL. The temperature of the sample was increased slowly and gradually up to the desired value. T was controlled by means of temperatures sensors located inside the chamber, in contact with the sample cup (stainless steel) rim and bottom part. After reaching the targeted T, the samples were kept stable at these temperature and pressure conditions for ~4 hours. After each step, the heated samples were cooled down in vacuum and then measured in the whole spectral range (from UV to IR) in bidirectional reflectance.

In parallel, two of the selected samples (serpentine 125-250 µm and saponite 125-250 µm) were stored in two autoclaves in an oven at 250°C for 1 month (first set of samples), and then once again at the same temperature for two months (second set of samples). The 1-month and 2-months heated samples, after cooling down in the autoclaves, were measured in reflectance, with the same experimental setup used for the samples heated at different T steps.

Bidirectional reflectance measurements were recorded in vacuum by using two of the Bruker Vertex80V FTIR spectrometers at PSL in two different angles configurations: 1) i=0° e=26°; 2) i=0° e=40°.

Figure 1. Picture of the laboratory set-up at PSL.
Results and discussion:

Figure 2. Saponite 125-250 µm in UV+VIS range.

Figure 3. Saponite 125-250 µm in MIR range.

Figure 4. Saponite 125-250 µm in full range range.

Figure 5. Serpentine 125-250 µm in UV+VIS range.

Figure 6. Serpentine 125-250 µm in MIR range.

Figure 7. Serpentine 125-250 µm in full range.

Figure 2 to 4 show the saponite sample in the UV+VIS, MIR, and the full spectral range (only for $T_{ambient}$, $T_{sample}$=200°, 300°C, and the 1-month and 2-months at 250°C heated samples). Figure 5 to 7 show the same for the serpentine sample. Figure 2 and 5 show a darkening (lower measured reflectance) occurring at increasing temperature for the 2 samples in the UV+VIS spectral range. The same effect is not recorded in the MIR spectral range, as can be seen in figure 3 and 6. Hi-T and longtime heated samples show a prominent feature around 0.38 µm only for the saponite sample. In the serpentine sample the numerous features in the 0.35-0.7 µm region tend to disappear, the spectra look flat (or flatter) already for temperatures from 200°C. The 2.7 µm feature decreases with Hi-T, but is still present in saponite. The peak around 11.4 µm in serpentine disappear as heating begins. The feature around 0.95 µm (present in both sample) is decreasing with increasing T. Similar but narrower feature in saponite is more resistant to increasing T.

OH/H$_2$O ON NEAR-EARTH ASTEROIDS. L. E. McGraw$^1$, J. P. Emery$^1$, C. A. Thomas$^1$, A. R. Rivkin$^2$, and N. R. Wigon$^1$, 1Northern Arizona University, S San Francisco Street, Flagstaff, AZ 86011 (lem366@nau.edu), JHU/APL, 211100 Johns Hopkins Road, Laurel, MD 20723, 3Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, TN 37831.

Introduction: Near-Earth Asteroids (NEAs) are excellent laboratories for processes that affect the surfaces of airless bodies. Most NEAs are not expected to contain OH/H$_2$O on their surfaces because they formed in the anhydrous regions of the Solar System [1] and their surface temperatures are high enough to remove these volatiles. However, a 3-µm feature typically indicative of OH/H$_2$O has been identified on other seemingly dry bodies in the inner Solar System, such as the Moon [2-4] and Vesta [5]. Possible sources for OH/H$_2$O on these bodies include carbonaceous chondrite impacts or interactions with protons implanted by solar wind [6]. NEAs are subjected to the same processes as other “dry” bodies in the inner solar system and recent work has shown several also exhibit a 3-µm feature [7, 8].

Methods: We observed NEAs using SpeX [9] on NASA’s Infrared Telescope Facility on Mauna Kea, Hawaii. Spectra were collected using both prism (0.7-2.52 µm) and LXD_short (1.67-4.2 µm) modes in order to accurately characterize asteroid spectral type and the 3-µm region, where the OH/H$_2$O signature is present. Data reduction and processing was completed using the SpeXtool IDL package [10] and thermal tail removal followed that of [7].

Results & Future Work: We have made 40 observations of 24 NEAs as part of this ongoing project. Of those, at least three NEAs exhibit a shallow (~3%) absorption feature in the 3-µm region: (433) Eros, (1036) Ganymed, and (3122) Florence. All three have been observed multiple times and by multiple observers [7, 8]. Three other NEAs likely exhibit a 3-µm feature – (1627) Ivar, (25916) 2001 CP44, and (2014) JO25 – though the current processing methods cannot definitively confirm the feature due to low S/N in the spectral region of interest. The other NEAs either do not exhibit a 3-µm spectral feature or have too low of S/N to make a determination.

OH/H$_2$O delivery and retention. The mechanisms by which OH/H$_2$O is delivered and retained are poorly constrained. Characterizing the shape of the 3-µm absorption feature can yield information on the source and exact composition (OH vs. H$_2$O) of the OH/H$_2$O on the surface [11]. The shallow band depth and linear band shape suggest that the 3-µm feature on Eros, Ganymed, and Florence is due to OH implanted via solar wind proton bombardment. However, the other targeted NEAs are also impacted by the solar wind yet do not exhibit a 3-µm feature, implying delivery and retention are independently controlled. Comparisons of various physical and orbital factors were conducted to determine the requirements for OH/H$_2$O retention. Size, perihelion, and spectral type appear to be driving factors, as all three NEAs with a 3-µm feature have d ≥ 5 km and q > 1 AU (Fig. 1), and belong to the S-complex. Two of the three NEAs with a potential 3-m feature (Ivar and 2001 CP44) also follow these trends. Continued work in identifying driving factors and determining their statistical significance will enable further clarification of the requirements for OH/H$_2$O retention due to solar wind bombardment.

Spatial variation. The orbital characteristics of both Eros and Florence allow for coarse spatially resolved spectra. Florence’s rotation period (~2.4 hrs [12]) allowed for the observation of two full rotations. Preliminary analysis suggests slight variations in band depth with longitude, though such variation could be a result of varying S/N (Fig. 2). The band depth on Eros is known to vary [7], but the variations have not yet been

![Figure 1:](image-url)
spatially correlated. Recent and future observations of Eros will enable such correlation and the possible identification of spatial variation in band depth.

Spectral variation between observations. The band depth of the 3-μm feature on Eros and Ganymed shows significant variation between observations that are not explained by different observing conditions. The band depth on Eros is shown to vary between 0.0 (±2.0) and 5.0 (±2.7) percent at 2.9 μm and between 0.0 (±1.5) and 6.2 (±2.1) percent at 2.9 μm on Ganymed [7]. No explanation has proved satisfactory in explaining the band depth variation on Eros, though a weak correlation between time since perihelion and band depth exists for Ganymed (Fig. 3). Factors tested include subsolar and sub-observer latitude, heliocentric range, phase angle, beaming parameter, and whether the asteroid was approaching or departing perihelion. Two observations of Eros have not yet been included in this study and Ganymed will be observed again in Fall 2020.

**Introduction:** The OSIRIS-Rex mission has detected particle ejection events resulting in the release of cm-sized particles from the surface of asteroid (101955) Bennu [1]. While many of these particles return to the surface of Bennu, some are able to escape Bennu’s gravitational field. This suggests that there may be a meteoroid stream of Bennu particles following an orbit similar to that of Bennu. These particles may pass close enough to Earth’s orbit to produce Bennu meteors [2].

In line with this suggestion, the OSIRIS-Rex mission has established a collaboration with the Cameras for Allsky Meteor Surveillance (CAMS) project [3]. The goal is to search the Southern Hemisphere sky for evidence of a Bennu meteor shower in September of 2019 and beyond, during Earth’s annual approach to the Orbit of Bennu. In support of this observational search, we estimate the expected flux over the entire Earth and for an observer on Earth (number of meteors per unit time): we are simulating particle ejection and orbit evolution during each annual Bennu orbit crossing.

**Data Collection:** We simulate Bennu meteoroid streams with the use of the REBOUND orbital integrator software [4]. Included in our simulations are non-gravitational forces, such as the Yarkovsky Effect, that produce non-negligible perturbations on Bennu’s orbit [2]. We will accurately model the orbital evolution of Bennu over the interval 1788-2135. Accurate propagations outside this interval are precluded by Earth close approaches. The associated meteoroids will allow us to estimate the potential meteor flux at the present day and beyond.

Observational data of Bennu’s particle ejection events obtained since December 2018 shows that Bennu was active over the entire OSIRIS-Rex observational time range [1]. Following this trend, it is likely that these ejection events will persist throughout Bennu’s entire orbit. The particles we simulate will have a range of densities, sizes, and velocities constrained by the OSIRIS-Rex particle ejection observations [1]. These parameters will serve as endmembers in determining the orbital changes incurred between ejection and recapture. Solar radiation forces will be included in this study.

**Analysis:** The resulting simulations will be developed to accurately represent the statistical particle production rates that we observe, and to appropriately distribute the meteoroid streams in the parameter space of our study. This will allow us to predict the meteor flux that we may see during the annual orbit crossing.

The specific tests we will perform to begin this analysis include:

1) Investigate the timeframe for which ejection event particles would fade into the background meteoroid population [6].

2) Determine significance of ejection direction on orbit evolution results.

3) Observe differences between particles ejected during perihelion and aphelion.

4) Launch endmember particles in the range of observed properties to determine the primary influential parameters.

5) Perform simulations with and without solar radiation and Poynting-Robertson drag forces to understanding the scale of their effect on this timescale.

The results of these test cases could allow for the final simulations to be vastly simplified while retaining realistic conclusions.

**Summary and Implications:** We are seeing Bennu’s MOID drop to zero over the coming century. The results of this study will allow us to predict how dramatically that will affect the future meteor flux at Earth [2].

This work may have broader implications for determining potential meteor activity from a large number of other small NEOs, as there is no reason to suppose the ejection phenomenon is unique to Bennu.

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**References:**

DISRUPTION AND REACUMULATION: FORMING THE TOP-SHAPED ASTEROIDS RYUGU AND BENNU AND EXPLAINING THEIR DIFFERENT LEVELS OF HYDRATION. P. Michel1, R.-L. Ballouz2, O. S. Barnouin3, K. J. Walsh4, M. Jutzi5, B. H. May6, C. Manzoni6, D. C. Richardson7, S. R. Schwartz2, S. Sugita8, S. Watanabe9, H. Miyamoto10, M. Hirabayashi11, W. F. Bottke4, H. C. Connolly Jr.12, D. S. Lauretta1, 1Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Laboratoire Lagrange, France (michelp@oca.eu), 2Lunar and Planetary Laboratory, University of Arizona, USA, 3The Johns Hopkins University Applied Physics Laboratory, USA, 4Southwest Research Institute, USA, 5Physics Institute, NCCR PlanetS, University of Bern, Switzerland, 6London Stereoscopic Company, London, UK, 7Dept. of Astronomy, University of Maryland, USA, 8Dept. of Earth and Planetary Science, School of Science, University of Tokyo, Japan, 9Graduate School of Environmental Studies, Nagoya University, Japan, 10Dept. of System Innovation, School of Engineering, University of Tokyo, Japan, 11Auburn University, Aerospace Engineering, USA, 12Department of Geology, School of Earth and Environment, Rowan University, USA.

Introduction: Images of Ryugu and Bennu from the Hayabusa2 (JAXA) and OSIRIS-Rex (NASA) missions show that both asteroids have top shapes, which are usually considered to be formed by YORP spin-up [1]. Moreover, they have the same bulk density and hydrated minerals, but the depth of the hydration band is much deeper for Bennu than for Ryugu [2,3]. We perform numerical simulations of asteroid disruption and subsequent fragment reaccumulation to investigate the conditions under which the catastrophic disruption of 100 km-diameter asteroid parent bodies can lead to bodies resembling Bennu and Ryugu, including their shapes, their porosity and their hydration level. Considering a range of impact energies, we find that oblate spheroids are commonly formed during the re-accumulation phase following the disruption. In some cases, a ridge can also form directly at the equator of reaccumulated bodies. Such a scenario can explain the old age of the ridges of Ryugu and Bennu based on the presence of large craters covering them [4,5,6]. Moreover, aggregates with different levels of porosities and hydration can be formed in a single collision, supporting a possibly common origin for the two bodies.

Asteroid Disruption Process: Asteroids as small as Ryugu and Bennu are likely reaccumulated fragments formed from the disruption of larger bodies. Large asteroid disruptions include both a fragmentation phase during which the asteroid is broken up into small pieces and a gravitational phase during which fragments may reaccumulate due to their mutual gravitational attraction and form rubble piles. Early simulations of these two successive phases successfully reproduced the size distributions of asteroid families [7], showing that all fragments larger than 200 m are likely rubble piles formed by reaccumulation of smaller pieces. Model improvements [8] allowed assessing shapes, with our initial simulations reproducing the shape of the asteroid Itokawa and the presence of boulders on its surface [9]. Moreover, we can also address the level of heat experienced during the disruption by the material forming the different resulting aggregates, and their level of compaction (or porosity) [10].

Numerical Simulations of Asteroid Disruption: We conducted a series of simulations involving the catastrophic disruption of 100 km-diameter microporous asteroids [11]. We tracked the subsequent gravitational phase where the fragments re-accumulate to form rubble piles. The fragmentation phase was simulated using a Smoothed Particle Hydrodynamics (SPH) hydrocode and the gravitational phase was computed using the N-body code pkdgrav. N-body runs used the Soft-Sphere Discrete Element Method (SSDEM) [12], covering a range of friction parameters between the rubble-pile constituents [13]. Once aggregate growth ceased, we computed a best-fitting ellipsoid to each body and a shape model for certain ones of interest. We also tracked the peak temperature experienced by the components of each aggregate in order to determine whether different aggregates formed in a single disruption can have different levels of hydration, as observed between Bennu and Ryugu, while preserving organic materials.

Results: We find that the final shapes of aggregates formed in a disruption cover a wide range of aspect ratios. However, for angles of friction in the range of that of Bennu [4], a concentration of aggregates of various sizes with aspect ratios as high as those of Bennu and Ryugu, which correspond to oblate spheroids, is remarkable (Fig. 1). Moreover, analyzing in more detail the shapes of our simulated aggregates, we find that some are very close to that of top-shape asteroids like Bennu and Ryugu. Our results imply that these bodies could form with their observed shapes as a direct result of reaccumulation. This is in line with observations that the ridge is one of the oldest features of those asteroids, as suggested by the largest undisturbed craters that overlay the equator of both objects.
the impact point where the material constituting those aggregates originated in the parent body. This average can exceed the threshold temperature at which phyllosilicate minerals may start to dehydroxylate (~400 °C for chrysotile). Therefore, we can expect those aggregates to have different levels of hydration. Thus, the different levels of hydration observed for Bennu and Ryugu do not necessarily mean that they come from two different parent bodies with two distinct thermal histories or that they experienced different surface heating histories after formation. It can actually be the natural outcome of the disruption of the same parent body, regardless of its internal heating history [14].

**Conclusion:** Numerical simulations of catastrophic disruption show that aggregates with a shape corresponding to or close to a top shape can form during such an event, and that these aggregates can show a difference in hydration level. Therefore, the observed hydration level difference between Bennu and Ryugu does not have to be due to a difference in their history once formed, but can be at the heart of their formation by the disruption of a common parent body. Their ridges could also originate from the event that formed them, which would solve the problem of the apparent old ages of these structures.


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**Figure 1:** Example of a distribution of axial ratios of aggregated produced from the catastrophic disruption of a 100 km-diameter asteroid, computed with SSDEM. The marginal distributions of the minor-to-major axes (c/a) and the intermediate-to-major (b/a) axes are also presented. The majority of reaccumulated rubble piles are oblate with axial ratios (b/a and c/a) that are both > 0.7, and only a small number of the rubble piles are prolate. Bennu’s and Ryugu’s shapes are represented with blue and red circles, respectively.

**Figure 2:** Peak temperature change experienced by the material forming one of the top shapes in our simulation as a function of the distance from the impact point where this material originated in its parent body. The level of compaction is scaled using colors and the vertical dashed lines highlight the fraction of escaping material that originate from within a given distance of the impact point (in this example, 50% of escaping material came from within 50 km of the impact point).

We also find that for a given aggregate shape, the average peak temperature change can cover a wide range (Fig. 2) and is correlated with the distance from
THE SHAPE DISTRIBUTION OF SMALL BOULDERS ON ASTEROID RYUGU. T. Michikami1 (michikami@hiro.kindai.ac.jp), A. Hagermann2, T. Morota3, H. Okamura4, K. Nomura5, H. Miyamoto5, M. Hirabayashi6, Eri Tatsumi7, N. Hirata8, T. Noguchi9, Y. Cho5, S. Kameda8, T. Kouyama9, Y. Yokota9, R. Noguchi9, M. Hayakawa9, N. Hirata4, R. Honda4, M. Matsuoka4, N. Sakatani9, H. Suzuki10, M. Yamada11, K. Yoshioka3, H. Sawada9, R. Hammi3, H. Kikuchi3, S. Sugita12. 1Kindai University, 2University of Stirling, 3The University of Tokyo, 4Kobe University, 5Auburn University, 6University of Aizu, 7Kyushu University, 8Rikkyo University, 9National Institute of Advanced Industrial Science and Technology, 10ISAS/JAXA, 11Kochi University, 12Meiji University, 13Chiba Institute of Technology.

Introduction: In laboratory impact experiments, the shapes of fragments from catastrophic collisions defined by axes a, b, and c, these being the maximum dimensions of the fragment in three mutually orthogonal planes (a ≥ b ≥ c), have been found to behave in a very regular way. In catastrophic disruption, the axial ratios of fragments are distributed around mean values of the axial ratios \( b/a \sim 0.7 \) and \( c/a \sim 0.5 \), i.e. corresponding to \( a:b:c \) in the simple proportion 2: √2: 1 [1][2][3][4][5][6].

Michikami et al. (2010)[7], who investigated the shape distributions of boulders on Itokawa and Eros, propose that the actual shape distribution of the boulders on any asteroid is similar to laboratory impact fragments. Their hypothesis is shown by the following three observational results [8].

(i) In laboratory impact experiments, fragment shapes from catastrophic disruptions have been found to behave similarly, independent of various experimental conditions and target materials. A recent study shows that this result has been found to be valid for fragments ranging from several tens of microns to several cm [5][6].

(ii) Although only limited data on boulders whose three-axial lengths have been measured are available, the mean \( b/a \) and \( c/a \) ratios of boulders on Itokawa [5] and Ryugu [8] are similar to laboratory impact fragments. The sizes of these boulders, which are considered to be impact fragments from their parent body, range from several meters to several tens of meters.

(iii) The mean \( b/a \) ratios of small- and fast-rotating asteroids, i.e., those with a diameter < 200 m and a rotation period < 1 h, which are considered to be monolith bodies, are similar to laboratory impact fragments [7].

These three observational results strongly suggest that fragment shapes from catastrophic disruptions are independent of their sizes. However, no three-axial lengths of boulders less than several meters have been measured. In this study, we report the shape distribution of boulders with 0.2-2.1 m on the surface of Ryugu based on the close-up image near the TD2 site.

Methodology: In this paper, we define a boulder as an isolated positive relief feature. In order to obtain the shape distribution of small boulders on the surface of Ryugu, we analyze ONC close-up images taken by the spacecraft at an altitude of 277 m (resolutions ~2.8 cm/pixel) on 30th May 2019 (near the TD2 site, Fig. 1).

Fig. 1. The close-up image near the TD2 site acquired on 30th May 2019. Boulders on the squared marked area are measured. Image ID: hyb2_onc_20190530_023724_tvf_12b.fit.

Small boulders with sizes of 0.2 to 2.1 m are mapped out on close-up images on the SAAOimage DS9, where we measured the ellipses marked for these (a and b). Then, we choose some boulders to measure their apparent \( c \) by assuming that boulders’ apparent height above the surface represent their \( c \) axes. The dimensions of the \( c \) axes are derived from shadow lengths of the boulders.

Observational results: A diagram of \( b/a \) and \( c/a \) of 145 boulders is shown in Fig. 2. The shape distribution of the boulders is similar to laboratory impact
fragments in heavier disruptions. The mean apparent axial $b/a$ and $c/a$ ratios are $\sim 0.7$ and $\sim 0.5$, respectively. According to [5]'s impact experiments, mean $c/a$ ratio around 0.5 is indicative of fragments resulting from catastrophic disruption. This implies that the parent body of Ryugu is likely to have experienced a catastrophic rather than a weak disruption.

**Fig. 2.** Shape distribution of 145 boulders with sizes of 0.2 to 2.1m near the TD2 site. The mean $b/a$ and $c/a$ ratios are $\sim 0.7$ and $\sim 0.5$, respectively.

A GLOBAL VIEW OF THE NEAR-INFRARED REFLECTANCE PROPERTIES OF RYUGU AS SEEN BY THE NIRS3 SPECTROMETER ON HAYABUSA2.


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Introduction: The Japanese Aerospace Exploration Agency (JAXA) Hayabusa2 spacecraft arrived at the target asteroid Ryugu in June 2018 and has been collecting a wealth of data since that time. Classified as a C-type asteroid, the hope is that Ryugu hosts primitive materials and possibly aqueous alteration phases (e.g., clay minerals, salts) and/or organic compounds, similar to what is observed in carbonaceous chondrite meteorites [1-3]. The Hayabusa2 payload includes the NIRS3 instrument, a point spectrometer with a 0.1° field of view that measures radiances over an effective wavelength range of ~18 – 3.2 μm [4-5]. NIRS3 has successfully acquired many tens of thousands of spectra during the course of the mission at a range of altitudes and thus spot sizes (spatial footprints).

High spatial resolution data were acquired during various descent operations, and together with the global spectral properties these data can be used to characterize the surface properties of Ryugu and make predictions of its composition, with particular attention to the role of hydrous phases. Such predictions will ultimately be tested when the collected samples are returned to a laboratory setting. In general, reflectance spectra of Ryugu are relatively flat with a slightly red (positive) spectral slope.

Data Analysis & Processing: NIRS3 measures all radiance from Ryugu over its operating wavelength range. When Ryugu is illuminated by the Sun its surface is warm enough that both reflected sunlight and thermally emitted radiation can contribute to the overall signal at the longer wavelengths (e.g., in the “3 μm” region that is sensitive to the presence of OH and H₂O). As such, in order to accurately retrieve surface reflectance values and to assess the presence or variations in OH/H₂O features, it is necessary to remove the thermally emitted contribution [5]. Raw data (DN values) are first converted to radiance values through multiplication by the radiometric calibration coefficient (RCC) value for each wavelength. The thermal radiance contribution is then estimated via fitting a Planck function to the measured radiance value at a wavelength that is close to, but outside of, the longer wavelength OH/H₂O region. Similar approaches have been successfully applied to near-IR reflectance data of the Moon [6]. The estimated thermal contribution is subtracted from the total radiance, and the residual radiance, believed to be reflected solar radiation, is then converted to I/F or reflectance by accounting for the Sun-Ryugu distance, solar flux, and viewing geometry.

The RCC was first derived based on pre-flight laboratory calibration measurements [4], but post-launch observations indicated an update to the RCC was necessary to retrieve accurate radiance values. Measurements of an onboard calibration lamp were used for this purpose, resulting in a revised RCC that has been used for the data discussed here [5].

Results: Reflectance spectra derived from NIRS3 measurements during the ‘global’ mapping campaign indicate that Ryugu is relatively spectrally homogenous at the ~20–40 m spatial scale. The surface of Ryugu is remarkably dark and exhibits an average albedo value of ~0.017±0.002 [5]. This is darker than other primitive objects visited by spacecraft, including the nucleus of comet 67P/Churyumov-Gerasimenko measured by the Rosetta spacecraft. Though it is relatively small, there is some albedo variation across the surface, with the equatorial region of Ryugu exhibiting an increase in albedo relative to adjacent terrains (Figure 1) [5].

In general, reflectance spectra of Ryugu are relatively flat with a slightly red (positive) spectral slope. The exact strength of this slope for wavelengths >2 μm depends on the accuracy of the thermal correction, and local geometry and physical properties can have strong links to surface temperature. Because of these complications and dependencies, small variations in spectral slope that appear to be correlated with

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physical/morphologic properties of Ryugu are being investigated in detail to determine if they are real surface spectral properties or within the uncertainty of the empirical thermal correction currently applied to the NIRS3 data.

At a global scale, the surface materials of Ryugu do not exhibit spectral evidence for pyroxene. That is, there are no clear indications of absorptions in the ~2 \( \mu \)m region that would be indicative of Fe\(^{2+} \) in the M2 sites of pyroxene [7]. This is not uncommon for certain types of carbonaceous chondrites, particularly aqueously altered samples (type C1/C2) where primary silicates have been converted to secondary phases (e.g., clay minerals). However, the spectra of Ryugu also do not exhibit strong absorption features in the 3 \( \mu \)m region that might be expected for a volatile-rich body. Instead, all spectra of Ryugu exhibit a weak and narrow feature with a reflectance minimum at 2.72 \( \mu \)m. This feature is interpreted to indicate the presence of OH, likely attached to Mg cations based on its position. Though non-unique, this feature is consistent with the presence of Mg-serpentine, and the position of the absorption does not appear to vary across Ryugu’s surface.

Although the OH feature is ubiquitous across Ryugu it is very weak, particularly compared with lab spectra of typical aequously altered C chondrites [8]. The closest meteorite match based on existing spectral libraries is to thermally metamorphosed C chondrites and spectra of heated samples of Ivuna (Figure 2). This suggests that Ryugu may represent a primitive object that was thermally metamorphosed prior to disruption and reformation as a rubble pile. Alternatively, the weak OH feature may indicate destruction of hydrous phases at the optical surface by space weathering processes on what is otherwise a more aqueously altered object. A third alternative is that Ryugu did not experience significant aqueous alteration that would give rise to abundant hydrous phases, and the observed OH feature is indicative of low abundances of phyllosilicates and/or OH formed by solar wind implantation.

**Conclusions:** The surface of Ryugu is rather homogenous at the 20-40 m spatial scale. As summarized in [5], the major characteristics are that Ryugu is (1) extremely dark, (2) spectrally ‘flat’ with only a weak red slope, (3) exhibits spectral evidence for OH across its surface, (4) lacks clear spectral evidence for pyroxene at this scale, and (5) is most closely matched by lab reflectance spectra of thermally metamorphosed C chondrites.

The Hayabusa2 mission has successfully acquired multiple samples from the surface of Ryugu, and the safe return of these samples to Earth for detailed laboratory studies will allow us to test whether or not thermal metamorphism, space weathering, limited aqueous alteration or a combination of these processes best explains the spectral properties observed by NIRS3. Regardless of the origin of these features, it is clear that Ryugu is spectrally distinct from Bennu, and as such it provides a unique and distinct data point for improving our understanding of how to use near-IR reflectance data of C-type objects to infer their mineralogy, chemistry, and geological history.

THERMALLY DRIVEN EXFOLIATION AND PARTICLE EJECTION ON BENNU. J. L. Molaro1, E.R. Jawin2, R.-L. Balouz3, K.J. Walsh4, R.D. Hanna4, C.W. Haberle5, M. Pajola2, A. J. Ryan2, S. R. Schwartz3, H. Campins6, B. E. Clark7, and D.S. Lauretta1. (1) Planetary Science Institute, Tucson, AZ, USA (jmolaro@psi.edu); (2) Smithsonian Institution, National Museum of Natural History, Washington D.C., USA; (3) Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA; (4) Southwest Research Institute, Boulder, CO, USA; (5) University of Texas, Austin, TX, USA; (6) Arizona State University, Phoenix, AZ, USA; (7) INAF-Astronomical Observatory of Padova, Vic. Osservatorio 5, 35122 Padova, Italy; (8) University of Central Florida, Orlando, FL, USA; (9) Ithaca College Department of Physics and Astronomy, Ithaca, New York, USA.

Introduction: Thermally driven fracture processes have been hypothesized to act on the Moon [1, 2], Mars [3, 4], Earth [e.g., 5], asteroids, [e.g., 1, 2, 6, 7] and comets [e.g., 8, 9], driving rock break down and regolith production on their surfaces. Thermal cycling induces mechanical stresses in rocks that drive the propagation of microcracks, which may grow into larger scale features. The interaction between stress fields generated at micro- and macroscopic scales controls the size and shape of disaggregated material [1–2, 4], which in turn affects the volume and distribution of rocks and regolith on these surfaces. Airless bodies in particular are thought to be highly susceptible to this process, and understanding how it operates is critical to characterizing their landscape evolution and surface properties.

While recent modeling and laboratory efforts have provided insight into how thermal breakdown may operate on airless bodies [1–5], observational evidence of its action beyond Earth is extremely limited. This is largely due to challenges distinguishing its signature from that of other weathering processes [e.g., 10], as well as the limited availability and resolution of spacecraft imagery on bodies it is likely to occur. Now, the Origins Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft has obtained images of the surface of asteroid (101955) Bennu at pixel scales down to 2-3 cm/px, providing an unprecedented opportunity to search over a wide range of scales for evidence of thermal breakdown occurring in situ.

We will show observations of boulder morphologies and fractures on Bennu consistent with both terrestrial observations and models of fatigue-driven boulder degradation. Specifically, we show evidence of boulder exfoliation, providing the strongest evidence yet that thermal fracturing plays an important role in airless body surface evolution. We will relate these observations to 3D simulations of thermally induced stress fields in boulders and describe how these stress fields lead to their development. We will also quantify the spacing of exfoliation cracks expected to develop on boulder surfaces, as well as estimate the range of speeds at which particles may be ejected from the surface due this process.

Observations: For this study, we use images acquired by the OSIRIS-REx PolyCam instrument over the period from March 21 to July 26, 2019. These images have pixel scales ranging from 3.8 to 8.8 cm/px, allowing us to identify and characterize fractures and boulder surface textures at the cm scale. We readily observe boulders with single and tiered exfoliation features over a range of latitudes in boulders ~0.7-18 m in diameter. Some observations are also made of other possible signs of fatigue, such as surface disaggregation and linear fractures.

Model: Following [1], we used COMSOL to perform 3D finite element simulations of the response of boulders on Bennu’s surface to diurnal thermal cycling, allowing us to investigate the magnitude and distribution of resulting stresses. We modeled a boulder embedded in unconsolidated, fine-grained material with a thermal inertia matching observations from the OTES instrument. We imposed a solar flux over one day at an equatorial location at Bennu’s semi-major axis (1.1 AU) and solved the heat and displacement equations, accounting for the radiative and conductive interaction between the boulder and regolith. The boulder is assumed to be a CI chondrite, with bulk material properties comparable to terrestrial serpentine-group phyllosilicates [e.g., 11].

Figure 1. Peak exfoliating stresses in boulders of varying diameter with (solid) 10% and (open) 35% porosity. Quantified is the maximum principal stress, where positive stresses are always tensile.
Preliminary Results and Future Work: Figure 1 compares the magnitude of exfoliating stresses (using the maximum principal stress, where tensile stress is positive) induced in boulders with varying size, each simulated with bulk porosities of 10% and 35%. Magnitudes range from ~1.3 MPa, which are comparable to the tensile strengths of terrestrial phyllosilicate rocks (e.g., serpentine) and similar soft, anisotropic materials (e.g., sandstone), and exceed estimates of boulders on Ryugu [12]. On Earth, subcritical crack growth only requires a stress ~10% of the material’s tensile strength to occur, suggesting that even if these idealized simulations represent an overestimate of stress magnitudes or higher stress is required to drive crack growth in vacuum environments, there is a reasonable likelihood that fatigue is possible on Bennu.

These stresses occur in the near-surface of boulders at depths of ~4-30 cm and drive crack propagation along surface-parallel planes. One or more exfoliation fractures may develop in this region, with crack spacing that is narrow near the surface and increasing with depth. The stored strain energy in these boulders represents the amount of energy available for crack propagation, which we can use to estimate the spacing of exfoliation layers. Figure 2 shows a preliminary estimate of the crack spacing in a 1 m boulder, with thicknesses ranging from mm scale up to ~10 cm.

We have observed particle ejection events from Bennu’s surface at a regular cadence since first entering orbit in 2018 [13]. Since exfoliation fractures from fatigue develop progressively, excess thermal strain energy may be available during individual crack propagation events capable of mobilizing disaggregated fragments, which may be the driving mechanism for ejection events.

We will relate our simulated stresses to observations of exfoliation on Bennu’s surface and demonstrate that our estimates of idealized crack spacing are consistent with observed layer thicknesses. We will also compare estimated ejection velocities to those observed by the spacecraft, and assess the extent to which thermal fracturing processes may contribute to asteroid activity.


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Introduction: Hayabusa2 arrived at the target near-Earth asteroid (NEA) Ryugu on June 27, 2019 [1]. It conducted global observations revealing a number of important properties of the asteroid, such as its top-shaped rubble pile nature [2, 3], the presence of a small amount of hydrous minerals [4], a young surface age, and color properties consistent with partially dehydrated carbonaceous chondrites [5]. Furthermore, more subtle properties, such as general spectral uniformity [4, 5] and variation in spectral slope [2, 5, 6] are observed by the telescopic optical navigation camera (ONC-T). The bluer materials are distributed at the equatorial ridge and in the polar regions, while the redder materials widely spread over the mid-latitude regions [5]. However, the nature of these spectral variations is still poorly understood.

On February 21, 2019, the Hayabusa2 spacecraft conducted its first touchdown on Ryugu. In the process of the touchdown operation, Hayabusa2 had an opportunity to take extremely high-resolution (~1 mm/pix) images of Ryugu’s surface and to observe its response to the physical disturbances during the touchdown, including the sampling projectile collision and thruster gas jets. A series of touchdown observations revealed a number of important properties of Ryugu surface’s, regarding space weathering, grain size distribution, mixing of different colors of materials, and stratigraphic relations among different materials. These properties are important for bridging the gap between meteoritic materials and asteroid surfaces. Furthermore, such characterization helps us in understanding the geologic context of samples captured in the capsule chambers of Hayabusa2. We discuss the stratigraphy and geology of the touchdown site, complex dynamic reactions of surface materials on Ryugu triggered by the physical contact of the Hayabusa2 spacecraft, and detailed textures and structures on pebbles and boulders captured in extremely high resolution images during the touchdown operations. Based on these proximity observations and global observations, we infer the nature of stratigraphy expressed in color and albedo of Ryugu.

Color and albedo changes observed in the touchdown operation: The touchdown site was selected based on both the established engineering safety criteria and the scientific merits for material sampling [2, 6]. Materials that contain both bluer and redder components substantially help understand the end-members of compositional elements in Ryugu. The spectral slope on Ryugu indicates regional variations in red/blue mixing ratios on Ryugu, but the presence of impact ejecta and mass wasting suggest Ryugu’s surface has a well-mixed nature [5]. Furthermore, the spectral differences among different touchdown candidate sites are much smaller than the variation within each sites [2]. Thus, a touchdown to any of the candidate sites would have allowed us to obtain both redder and bluer components. However, because of the high boulder abundances [5, 7], the locations for safe landing were limited [2]. We chose L08-B, one of the lowest boulder number density areas on Ryugu, as the primary lading site [2, 6] and deployed a target marker (TM). However, based on the location where the TM settled and the detailed search for areas without boulders taller than 65 cm, which could reach the reaction control system (RCS) of Hayabusa2 during a touchdown, we finally chose a smaller region L08-E1.

During multiple low-altitude (~40 m) descent maneuvers near the L08 region, we conducted high-resolution spectral and morphologic observations of this region. The touchdown spot is generally slightly bluer than the global average, but reddish spots are found within the L08-E1 region. These reddish spots tend to be darker than bluer areas, and this trend is the same as that found globally [2, 5]. The reddish spots are limited to a single flat surface of individual boulders or are not homogeneously distributed on surfaces of boulders. These observations suggest that the redder materials were created from bluer materials by some surface metamorphic processes such as space weathering, thermal metamorphism by solar heating and/or simple pulverization, but a large portion of the redder materials have been scraped off from the boulder surface by impact disruption and/or thermal fatigue. The fact that the surfaces of boulders remain unreddened
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means that the timescale of surface reddening at present is sufficiently slow compared with that of boulder resurfacing by impact disruption and/or thermal fatigue.

The combination of the impact of the projectile shot from the sampler system and the RCS thrust during the touchdown produced a large amount of debris below the Ryugu surface. The motion picture obtained by the nadir-viewing wide-angle optical navigation camera (ONC-W1) indicates that large boulders moved horizontally by more than 5 m. However, the majority of debris disturbed upon the touchdown was small pebbles and fine grains whose diameters are less than the pixel size (1 to a few mm) as observed within the highest resolution ONC-W1 images. The observed high mobility of regolith during the touchdown indicates that the inter-boulder/inter-pebble cohesion may be very weak. This high mobility is consistent with observations of Ryugu’s extremely low number density of small craters suggesting active surface migration on Ryugu and mass wasting on crater walls [5].

Immediately after the RSC thrust upon touchdown, the entire field-of-view of ONC-W1 was darkened uniformly, while a dark ragged boulder nicknamed as “turtle rock” simultaneously became as bright as surrounding brighter boulders [6]. These observations suggest that dark fine grains were originally present on the surface and inside the pores of darker and redder boulders and were lifted up by the RSC thrusting. This process formed a cloud of dark fine grains radiating from the touchdown site that ended up extending ~10 m in diameter, centered at the touchdown site. The pre-touchdown color of this region was slightly bluer than the surrounding region but it became redder after the deposition of the lofted dark fine grains. These observations may suggest that the dark fines grains were created from the redder materials originally coated on boulder’s surfaces.

Global Distribution of Spectral Slope and Stratigraphic Relationship Between Craters and Redder Materials: In addition to the latitudinal variation in spectral slope [5], it was found that the spatial variation in spectral slope correlates with the crater distribution. Stratigraphically upper craters larger than ~20 m in diameter have bluer interior compared to the surrounding materials. This means that the redder materials were covering the bluer materials and the underlying bluer materials were exposed by the crater formation, consistent with the stratigraphic relationship between the redder and bluer materials inferred from the global distribution of spectral slope. On the other hand, as stratigraphically lower craters tend to have redder interiors, the color of the crater interiors has no difference with that of surrounding materials. We investigated the contrasts in spectral slopes between crater interior surfaces and surrounding areas, defined as the area within a crater radius from the crater rim. The obtained histogram of the contrast in spectral slope shows a bimodal distribution, indicating that craters on Ryugu can be divided into two groups: red craters whose interior has spectral slope similar to that of the surroundings and blue craters whose interior is bluer.

A probable explanation of the latitudinal variation in spectral slope is that while the exposure of Ryugu materials to space has led to their reddening, mass wasting from the equator and polar regions to the mid-latitude regions at the current spin of Ryugu exposed fresh bluer subsurface materials [2, 5]. The polar regions exhibit bluer spectra than the equatorial ridge, suggesting the reddening process by thermal metamorphism and/or space weathering by Sun. The color variation of crater interior can be explained by the stratigraphic relation; the craters with redder interiors were formed before the surface reddening and their interiors were discolored by the surface reddening, while the blue craters were formed after the surface reddening and the underlying bluer materials were exposed by the blue-craterr-forming impacts. The bimodal distribution of the contrast in spectral slope suggests that the surface reddening has not been active through Ryugu’s history and occurred within a short time interval after the formation of redder craters and before the formation of bluer craters. These results are consistent with the interpretation that the surface reddening is not so active at present based on the distribution of spectral slope on the boulder surface.

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1064-NM REFLECTANCE AT (101955) BENNU: LOW-ALTITUDE RESULTS FROM THE OSIRIS-REX LASER ALTIMETER. G. A. Neumann1, M. K. Barker1, E. Mazarico1, M. G. Daly2, O. S. Barnouin3, D. S. Lauretta4, 1NASA Goddard Space Flight Center, Greenbelt, MD, USA (Gregory.A.Neumann@nasa.gov); 2The Centre for Research in Earth and Space Science, York University, Toronto, Ontario, Canada; 3The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA; 4Lunar Planetary Laboratory, University of Arizona, Tucson, AZ, USA.

Introduction: The Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx) mission to the dark and primitive asteroid Bennu carries a laser altimeter (OLA) [1], an actively sensing instrument uniquely suited to deriving global shape and preparing for sample return. OLA also records the return intensity of its pulses, from which we derive a spectral albedo at 1064-nm wavelength using the inverse squared dependence of intensity on range. Bennu’s polar regions are scarcely illuminated by sunlight, but the laser spot returns provide the albedo globally at zero phase angle, as has been done for other airless bodies, e.g., [2, 3]. We now report on the results from the Low Energy Laser Transmitter (LELT) campaign during the Orbital B mission phase, with 10-kHz ranges at 600–740 m distance.

Data: From 1 July to 5 August 2019, 897 scans of ~5.5 minute duration were performed at nearly nadir incidence as Bennu rotated beneath the polar-orbiting spacecraft, providing global coverage with >3×10⁵ altimetric ranges and return intensities. The level 2 data stream during this campaign has accurate geolocation, more than sufficient for comparison of albedo with other datasets at sub-meter resolution and includes the outgoing and return intensities as auxiliary measurements. Altimetric detection was virtually 100% at the low altitude of the mapping campaign, but the return intensity digital numbers (DN) varied over a wide range, with a mean of 33 and standard deviation (SD) of 37 about the mean. Roughly 30% of DNs are zero, whereas ~5% of DNs are more than 2 SD greater than the mean. The outgoing intensity recorded DNs vary by ~10% but due to calibration uncertainties we will assume the laser energy, nominally 10 µJ, to be constant. Return intensity measurement precision is limited by the relatively small number of photons collected from a brief laser pulse, the excess noise factor of the detector photodiode, the integrator digital readout, and the heterogeneity of the surface albedo of a rubble-pile asteroid such as Bennu.

Methods: The range to surface $r$ varies by ~25% due to topographic and orbital variation, so we first correct for signal dependence on $r^2$ as previously noted for the High Energy Laser Transmitter (HELT) data [4]. Single measurements have a non-Gaussian distribution and too high a variance, as noted above, to be informative. We average the hundreds to thousands of values within a single ~1 m² spatial element, or pixel, to obtain physically meaningful variations in reflectance. The broad and long-tailed distribution of values suggests that the median rather than the average of values within a single pixel is appropriate, which is implemented by including the zero values as representing one of the tails of the measurement distribution. Roughly 15 seconds out of each minute of scanning are also contaminated by noise from heater circuitry, and so only the remaining ¾ of the data are used here. The LELT intensities lack an absolute calibration so we scale the reflectances to an average normal albedo [5] of ~0.04.

Results: The LELT reflectance at 1064 nm is shown in Fig. 1. The albedo map correlates with many of the large individual boulders on the surface and displays regional variations related to the asteroid geology.

![Figure 1. Median-averaged albedo from LELT, ~1 m pixels, in simple cylindrical projection.](image1)

![Figure 2. Average albedo by degrees of latitude (black) and average range to surface (blue curve). Regions of slope instability are denoted by pairs of dotted lines.](image2)
The latitudinal variation does not appear to be an artifact produced by range variation, outgoing intensity variation, or noise level since all of these (except range) appear to be independent of latitude. Range from the near-circular orbit increases away from the equator because of the equatorial bulge, but the relative brightening at higher latitudes is more pronounced than the range variation. Possible causes of global changes in albedo would be variation in slope stability, localized regional surface failure and thereby exposure to space weathering, and modification of regolith [6] noted within the outlined region.

Since the intensity measurement does not depend on solar illumination or photometric corrections, the polar regions are of particular interest (Fig. 3). Small bright areas correspond to isolated elevated features, while more diffuse dark patches also correspond, in some cases, to prominent boulder-like features. A dark albedo region at the north pole in Fig. 3 corresponds to a likely boulder pair surrounded by prominent blocks in the hillshaded relief map of shape (Fig. 4). The highest point in Fig. 4 lies on the boulder at 86.25°N, 103°E which sits on a ridge extending southward towards 120°E, the bulk of which is somewhat darker than average.

Discussion: The intensity measurements suggest a variety of lithologies for boulders, both darker and brighter than the background (~0.04 average). The darkening of albedo, especially towards the north pole (Fig. 2) could result from shadow hiding (unlikely at nadir incidence), increased porosity and roughness, or space weathering [7]. Albedo variations at 1064 nm may also result from compositional differences involving possibly more mafic or pyroxene-rich rocks [8]. The use of a laser altimeter to independently assess surface characteristics in poorly illuminated polar areas with uniform coverage complements the OSIRIS-REx spectral imaging suite and informs the dynamical evolution of a rubble-pile asteroid.


Figure 3. Median normalized intensity, ~24 cm pixel bins, in stereographic projection from 63°N to 90°N. The mapped area is approximately 240 m in diameter. Contours outline two possibly related boulders discussed in text and shown in the next figure.

Figure 4. Shape (radius), corresponding to Fig. 3.

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PORTOUS BOULDER ON (162173) RYUGU: COMPACTION MODELING AND IMPLICATIONS FOR PARENT BODY'S RADIUS, ACCRETION TIME, AND INTERIOR POROSITY DISTRIBUTION.

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Introduction: Observations of the C-type NEA (162173) Ryugu by Hayabusa II demonstrated that this asteroid is a low-density rubble pile whose surface is dominated by large boulders. MASCOT’s1 measurements during its operational phase on the surface of the rubble pile NEA (162173) Ryugu provided boulder brightness temperatures that allowed estimating thermal inertia2. The latter was interpreted in order to estimate boulder thermal conductivity k and porosity ϕ3. Thermal properties of boulders indicate high intrinsic porosities3, consistent with the overall low bulk density of the asteroid3, resulting in values of k = 0.06-0.16 W m⁻¹ K⁻¹ at 230 K, ϕ ≈ 28-55 % for different models of k(ϕ).

While the bulk porosity of a rubble pile asteroid is due to the contributions of the micro-porosity (the intrinsic boulder porosity) and the macroporosity (the voids in-between boulders), the porosity of a single boulder is a local micro-porosity value. It is a result of processes that were initiated during the thermal evolution of a parent body from which the boulder originated prior to its re-accretion onto Ryugu.

We calculated the evolution of temperature and porosity for planetesimals in order to identify potential parent bodies for Ryugu’s material and likely burial depths for the boulders observed at the surface. By varying planetesimal properties that have strong influence on temperature and porosity, we constrained a field within the (t₀,R)-diagram appropriate for bodies that could have produced such material.

Methods: The calculations were performed using a 1D finite differences thermal evolution model for planetesimals4. It considers heating by 26Al and evolution of the interior temperature as well as compaction of an initially unconsolidated body due to hot pressing. An ice-rich initial composition that leads to a material dominated by phyllosilicates upon aqueous alteration was assumed consistent with spectral observations that suggest a composition close to CI or CM chondrites5,6. Using creep laws for major components antigorite and olivine, the bulk strain rate was considered as a volume fraction weighted arithmetic mean of strain rates of both species for the modelling of compaction. Material properties adopted correspond to the composition assumed and are adjusted with temperature and porosity. The initial temperature of 170 K corresponds to an accretion at ≈ 2.7 AU7, which is close to values assumed to be representative for CI and CM parent bodies8.

A minimum requirement on the mass of a parent body is the mass of Ryugu and a minimum requirement on its initial porosity ϕ₀ is the boulder micro-porosity of 28-55 %. The thermal evolution and gradual reduction of ϕ upon heating of such an object is calculated. Apart from that, the parent body mass (i.e., its size) and accretion time are free parameters.

Results: A sample aqueous alteration chemical reaction of olivine and water to serpentine, talc, magnetite and hydrogen is quasi-instantaneous on a geological time scale (∼ 200 years at 273 K7). Thus, in a first-order approximation, only the melting temperature of water ice must be surpassed for reproducing conditions for the formation of phyllosilicates. Such temperatures can be obtained for a variety of accretion times and planetesimal sizes. However, rapid decay of 26Al limits the accretion times of kilometer-sized objects to t₀ < 1.5 Myr after CAIs. A weaker cooling of larger bodies allows for later accretion times with an increasing size. On the other hand, a very early accretion is less likely for planetesimals with radii larger than approximately 10 km. At least partial melting in the interior of such bodies would erase traces of aqueous alteration contradicting Ryugu’s observed composition.

Another important implication arises from the planetesimal size with regard to the evolution of porosity. Since compaction is driven by both the temperature T and pressure P, different (P, T) conditions over extended time periods of different length can produce the same porosity. Consequently, models produce material with ϕ ≈ 28-55 % in planetesimals of considerably different sizes and
accretion times at different depths, i.e., in the deep interior of kilometer-sized early accreting bodies and in very shallow layers of 10-100 kilometer sized late accreting bodies.

The temperature- and porosity-depth profiles at different times are shown in Fig. 1 for a selected case with \( R = 0.5 \) km, \( t_0 = 0 \) Myr rel. to CAIs, and \( \phi_0 = 70\% \). Conditions for aqueous alteration are established early and persist for up to 2 Myr. Due to a quasi-constant temperature of \( >273 \) K throughout the interior, most of the material is altered except in a thin surface layer of \( \approx 50 \) m. The porosity is reduced throughout the deeper interior at temperatures that are similar to peak temperatures of CM chondrites\(^9\), but not in the outer part. By contrast, in larger planetesimals with \( R > 10 \) km, material with a porosity of 28-55 \% is confined to rather thin layers in the shallow subsurface where the porosity profile shows a strong gradient between \( \phi_0 \) (surface) and \( \phi = 0 \) (interior)\(^4,10\). Such layers experience compaction typically at temperatures that are considerably smaller than CM peak temperatures.

**Summary and Conclusions:** Assuming initial porosities\(^{11}\) of the order of 70\%, Ryugu’s precursor needs to have had a sufficient size to reduce the micro-porosity to values below 55\% by compaction, while simultaneously avoiding porosities to drop below 28\%. This can be achieved in the deeper interior of small kilometer-sized bodies which accreted early while \( ^{26}\text{Al} \) was still active. Alternatively, such material could have been produced in thin subsurface layers of larger \((R > 10 \) km\) parent bodies which accreted later. The main mechanism for porosity reduction is hot pressing, while other mechanisms that could have influenced the porosity require either considerably higher pressures (cold pressing\(^{12}\)) or are rather inefficient (aqueous alteration, dehydration\(^{10}\)). In this way, porosities down to 45\% can be achieved even on small, kilometer-sized bodies if a water ice rich primordial composition similar to those of CI and CM chondrites is assumed\(^{4,10}\). Both compaction by hot pressing and aqueous alteration could have occurred either in the precursors or in the re-accreted “secondary” parent body provided early destruction and re-accretion\(^{10}\). Such a re-accretion event must have occurred relatively late with a smaller concentration of \( ^{26}\text{Al} \), therefore, the secondary parent body must have been definitely larger than several kilometers, if it existed in the first place. The calculated heating of small Ryugu-sized precursors is consistent with the alteration temperatures of CI and CM chondrites\(^{13,14,15}\) but its rapid cooling is inconsistent with CI/CN carbonate formation ages\(^{15}\), which implies that a Ryugu-sized precursor can be ruled out as a parent body for these meteorite groups. However, carbonate formation ages can be reproduced for larger objects, which take longer to cool. Re-accretion of a small part of such a body provides another formation scenario for Ryugu, which would then be a fragment of a CI or CM parent body.

**References:**

COMPARING THE RADAR SHAPE MODEL OF (101955) BENNU WITH GROUND TRUTH FROM OSIRIS-REx.

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Introduction: Nolan et al. [1] presented a shape model and rotation state of (101955) Bennu using radar and lightcurve observations in 1999 and 2005. The rotation state was updated based on additional HST lightcurves obtained in 2012 [2]. The resulting shape model and radar scattering properties were used in planning the OSIRIS-REx mission in the form of a “Design Reference Asteroid” (DRA) [3]. We compare the “as-built” Bennu with the radar modelling results.

Radar Shape Model: The shape model from [1] (hereafter, “radar shape model”) consists of 2692 triangular facets, with a median edge length of 27 m. The radar imaging had 7.5-m (2005) and 15-m (1999) resolution, but to increase SNR the images were binned at 6-degree (~25 m at the equator) rotational resolution. The uncertainty of the overall dimensions of the radar shape model was 10 m in X and Y, but 52 m in Z, because of ambiguities in the radar observations. The radial uncertainty was not reported, but it was likely comparable to the uncertainty in X and Y of 10 m. They saw one “boulder” that they estimated to be 10-20 m in size based on its appearance in the radar images. The shape model reflects this feature because the model resolution was increased to ~5-m edge length in the region of the boulder.

The shape modeling process adjusts the shape of the model to match the data in a chi-squared sense, but also includes a number of “penalties” to enforce “reasonable” shapes. Because the radar data are typically quite noisy, these penalties are required for stability, but it is difficult to a priori decide what is “reasonable”. These penalties tend to smooth the model. [4]

Radar Scattering: The radar scattering properties were measured in both disk-integrated and surface-resolved modes, though resolved properties were only obtained in 1999. [1] Interpreted the radar scattering properties to suggest that the surface is smoother than Eros or Itokawa at ~10-cm scales based on a lower radar polarization ratio, and that it has a near-surface bulk density between 0.9 and 1.7 g/cm³.

Comparison with OSIRIS-REx results: We compare the radar shape model to the OSIRIS-REx images and a stereophotoclinometry (SPC) shape model produced from those images. [5]

The initial images of Bennu in October 2018 looked quite similar to the rendering from the radar shape model (Fig. 1). The dimensions are within 2% of the predicted values, well within 1-sigma. The asteroid appears to be slightly more flattened than the model. The obliquity of the rotation pole is approximately 1-sigma from the prediction, but the actual pole position is approximately 5 (1.5 sigma) degrees away.

The boulder feature in the radar shape model is the largest boulder visible near latitude ~45 and longitude 145, which is ~30 m in height and ~50 m across [6]. It has a flat eastward-facing face, which likely is why it was dramatically visible in the radar imaging. Even this boulder was not clearly visible from other viewing directions in the radar imaging. Another boulder at latitude ~30 and longitude 0 is slightly shorter, and appears in the shape model as topography but not as a separate object. No smaller boulders were clearly distinguishable from noise in the radar imaging. Miller et al. [7] estimated that 20-m boulders should be visible, but smaller ones might not be. This estimate is apparently still optimistic.

Density: The “surface bulk density” is consistent with the prediction from the radar measurements. Many of the largest boulders appear to have a very low thermal inertia, < 300 SI units [8], suggesting that even the dense materials on Bennu are relatively low density. This suggests that the macroscopicity of Bennu’s interior may not be extremely low.

Roughness: We have not specifically measured the roughness at 10-cm scales, but the overall picture of Bennu as a smooth surface based on the radar polarization is not borne out. Bennu is covered with meter-scale or larger rocks, so that the radar scattering is likely dominated by the texture of the rocks rather than the grain size of pebbles. Nolan et al. [1] provided a surface-resolved map of the polarization ratio. We will compare
this map to possible features on Bennu, including roughness derived from shape and from thermal properties [9].

Figure 1. The top row contains three images of Bennu obtained by the PolyCam camera on October 23, 2018, each taken about two hours apart. The images were taken from a distance of 3,000 km from the asteroid and represent Bennu at 13 pixels in the camera’s field of view. The middle row shows renderings of Bennu as predicted by [1]. The shape model representations are rendered as if they were observed by the spacecraft at the same time, distance, and lighting conditions as the images. The bottom row pixelates the shape model renderings to be similar to the observed images to make comparison easier. The images show overall agreement between the observations and the radar model predictions, including some of the large-scale features on the asteroid.

Figure 2. Comparison of the radar-derived and Bennu encounter shape models.

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VOLATILE-RICH ASTEROIDS IN THE INNER SOLAR SYSTEM. Joseph A. Nuth III¹, Daniel P. Glavin¹
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Introduction: In the very early solar system, small bodies likely formed in a roughly continuous sequence from dry asteroids near the Sun, through increasingly water-rich bodies beyond the giant planet region [1]. Prior to spacecraft missions to small bodies it was generally assumed that meteorite parent bodies (asteroids) formed inside the orbit of Jupiter, while comets formed outside this orbit where very low temperatures promoted the condensation of a wide range of volatiles [2]. As a general rule, volatile-rich bodies are thought to be transient visitors to the inner solar system rather than long-term residents. We will argue below that there are two mechanisms that can place volatile-rich bodies, formed well beyond the Snow Line [3], into long-term residence in the inner solar system.

Giant Planet – Disk Interactions: There is evidence that any possible compositional order in the small body population of the early solar system was thoroughly scrambled due to tidal interactions between the growing giant planets and the nebular disk [3-8]. Jupiter may have migrated from ~3.5 au to ~1.5 au before reversing direction to end near its current orbit. The other giant planets migrated in a similar fashion. This large-scale migration threw dry bodies both into the outer nebula and out of the solar system, and drove water-rich bodies into the inner solar system and into the Sun. The numbers of bodies perturbed to any specific destination has not been quantitatively estimated.

Following the chaos caused by giant planet migration the small bodies that then remained in the inner solar system formed the terrestrial planets, the asteroid belt and the Jupiter Trojans. Volatile-rich small bodies that did not fall into the Sun or become incorporated into growing terrestrial planets therefore had a very wide range of environments in which to evolve, from perihelia near 2 au out to nearly 5 au. Given the dusty rich nature of the solar system during the formation of the terrestrial planets [9], even the closest planetesimals could have been shielded from direct sunlight for several thousand years, leading to slow metamorphism of their surfaces.

A volatile-rich body driven in to the main asteroid belt by gravitational interactions with a giant planet may evolve over several billion years, initially losing near-surface volatiles to form a coma and tail until such activity is shut down by natural processes such as by volatile depletion in the regolith or by the formation of a highly insulating crust [10]. Small impacts could disrupt an insulating crust leading to the vaporization of volatiles and the emission of dust until the breach is “healed” by the same triboelectric processes that formed the original insulating layer [10]. Larger impacts could lead to fragmentation, exposing the volatile-rich interior of the body and re-activating the previously dormant comet or cometary fragments to begin evolving all over again.

Because of the long evolutionary timescale and the warmer temperatures in the inner solar system it is possible that diffusion of water vapor through the regolith could result in monolayer to multilayer deposits on upper regolith layers that had previously lost volatiles via sublimation. The reactions of water with these grains could serve to cement such layers into coherent rocks, much like sandstones, though much less dense.

Modern Comets: Comets fall into the inner solar system from the Oort Cloud, the Hills Cloud and the Kuiper Belt via different orbital pathways. Once in the inner solar system their active phase is short (about 1000 perihelion passages) compared to their dynamic stability [11]. For typical Jupiter Family Comets (JFC) this leads to an active lifetime on the order of 10,000 years compared to their dynamic (orbital) lifetime near 500,000 years. Estimated active lifetimes for long period comets may range from 50 – 2000 perihelion passages [11] though uncertainties in their dynamic lifetime are much greater. At least for JFCs, the “comet” spends only a tiny fraction of its dynamic lifetime in the active phase and about 98% of its time as an asteroid. It is estimated that at least 6% of NEOs may be extinct comets [11].

Active asteroids or asteroid-comet continuum objects [12] have been discovered in the main asteroid belt in recent years. These may represent comets heading toward dormancy after losing most of their surface volatiles, but it is difficult to explain how such objects could transition from a cometary orbit to orbits in the main belt. An alternative is that they were emplaced in the asteroid belt during the giant planet migrations and have slowly evolved to the present day. Complementary to the active asteroids are Manx Comets [13] which have nuclei with the spectral properties of dry, rocky asteroids yet still display a coma such as found in comets. These could represent inner solar system (dry) asteroids flung into the Oort Cloud or Kuiper Belt by giant planet migration that condensed water onto their surfaces for several billion years prior to their deflection into the inner solar system.
Evidence from Meteorites: Based on eyewitness accounts of its fall, Gounelle et al. [14] reconstructed the orbit of the Orgueil parent body and estimated an atmospheric entry velocity > 17.8 m/sec, implying that the orbit aphelion was beyond Jupiter’s orbit and therefore that Orgueil was a probable cometary meteorite. Scott et al. [15] have suggested that CR, CO, and ungrouped CCs may have formed beyond the orbit of Jupiter based on a number of significant isotopic differences between these meteorites and non-CCs. Unlike the case for Orgueil, however, there is no evidence that these primitive carbonaceous chondrites fell to earth from a cometary orbit. I therefore propose that such primitive chondrites were emplaced in the inner solar system during the giant planet migration period and evolved in place since that time.

Volatile-rich Asteroids/Dormant Comets?: If an asteroid type represents an evolutionary stage between an active comet and a small body devoid of volatiles, that asteroid type should have some members that fulfill the following criteria: some class members will be dual-classed and have both a cometary and an asteroid designation; some members will be “active asteroids” with the intensity of their activity correlated with solar distance; some class members will be parents of meteor streams; and some class members will occupy traditional “cometary” orbits. Not all class members will fulfill all criteria, and volatile-rich asteroids that evolve in non-traditional locations (e.g., main asteroid belt) might never display these properties. However, as they evolved from high water/rock ratio bodies towards dormancy by the same general processes as traditional comets, their regolith properties, spectra, internal structure and composition should be similar to those of dormant comets evolved in more “comet-like” orbits. B-type asteroids fulfill all of the criteria above to represent an evolutionary stage between active comets and volatile-poor asteroids. Some B-type asteroids are dual class, some are active asteroids, some are parents of meteor streams and some are Jupiter Family asteroids. B-type asteroids do not represent the only asteroid type derived from active comets. Similar (or better) cases can be made for both D- and C-type asteroids.

Spacecraft Observations: Hayabusa2 and OSIRIS-REx are the first missions to study C- and B-type asteroids, resp. and both targets show significant differences from the S-type asteroids (Eros & Itokawa) previously studied by orbital spacecraft. In particular, Bennu shows widespread hydration [16], porous (low thermal inertia) boulders [16] and particle emission [17] consistent with traits expected of evolved water-rich small bodies (comets?). Samples returned from these targets should therefore be more consistent with those expected from comets and less like primitive chondritic asteroids. For example, the organic composition of samples returned from Bennu should be intermediate between the organics found in primitive chondrites and the organics observed in active comets. (It is possible that the organics in Orgueil and Tagish Lake may come closest to those in Bennu, but even these might be more highly processed.) They should have enrichments in D/H and 15N/14N, high C/Mg ratios (> ~7 wt%) and exhibit a greater range of compositions than found in meteorites, including an organic component poor in aromatics, and a more labile organic fraction. Bennu’s organics should have a simple amino acid distribution dominated by glycine and β-alanine. Overall, Bennu’s organics should represent a more primitive distribution of com-pounds than found in carbonaceous chondrites, but a more evolved suite of compounds than found in future samples returned from active comets.

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SPACE IMPACT EXPERIMENT ON RYUGU: EJECTA CURTAIN OBSERVED BY DCAM3. K. Ogawa¹, M. Arakawa¹, M. Shirai², H. Sawada², R. Honda³, K. Ishibashi³, K. Wada³, T. Kadono³, Y. Iijima³, N. Sakatanai³, Y. Shimaki³, Y. Mimasu², T. Toda², S. Nakazawa³, H. Hayakawa³, T. Saiki², Y. Takagi⁶, H. Imamura², C. Okamoto¹, H. Yano², M. Hayakawa³, N. Hirata⁷, ¹Kobe University, ²Japan Aerospace Exploration Agency, ³Kochi University, ⁴Chiba Institute of Technology, ⁵University of Occupational and Environmental Health, ⁶Aichi Toho University, ⁷University of Aizu.

Introduction: The Japanese asteroid explorer Hayabusa2 arrived at C-type asteroid Ryugu in June, 2018. The initial observations have revealed unexpected nature of the top-shape and boulder-rich surface of this asteroid. Ryugu, and also Bennu explored by NASA OSIRIS-REx, have many craters with morphologies consistent with impact origin, and their low number densities of smaller craters suggest their surface is relatively young [1,2]. However, their specific age estimation depends strongly on the crater scaling law on asteroids.

In the first year of the asteroid rendezvous phase, Hayabusa2 succeeded several special operations including two times of touch-down, release of small landers, and the impact experiment by Small Carry-on Impactor (SCI) and Deployable Camera 3 (DCAM3) as one of the most complicated events. Detailed observations of the impact experiment and the artificial crater provides new information for the impact physics on Ryugu.

Scientific Objectives: The scientific objective of DCAM3 focuses on the crater formation process: observations of size, shape, and amount of ejecta, and their growth with time. These results are used to verify the conventional scaling laws of impact ejecta. The impact ejecta profile also reflect physical properties of the subsurface layer, such as strength, particle size, and porosity. Thus, DCAM3 could provide information of the subsurface condition masked by a plenty of boulders [3].

Instrument and Operation: SCI is a separable unit of a 30-cm cylinder shape containing explosive of 4.7 kg for acceleration of the projectile [4]. SCI shoots a copper projectile of a hemispherical shape of 2 kg with 2 km/s onto the Ryugu surface. DCAM3 is also a separable unit of a 10-cm circular cylinder containing two independent camera systems: a real-time low-resolution camera system (DCAM3-A) [5] and a high-resolution scientific camera system (DCAM3-D) [6,7]. The DCAM3-D camera records images of the impact experiment every 1 s for more than 2 hours at the distance of approximately 1 km from the impact point. DCAM3-D has a wide field of view at 74° × 74° and a high resolution of 2000 × 2000 pixels. Thus, spatial resolution of DCAM3 taken on Ryugu is about 1 m/pixel. It gives us an opportunity to observe for the first time an ejecta curtain accompanied by the crater formation resulting from an impact experiment on an asteroid surface, while the main spacecraft escapes behind Ryugu to avoid accidental collisions with impact fragments.

The impact experiment by SCI and DCAM3 was conducted in April 5, 2019. In the operation sequence of the day, SCI was separated from the spacecraft and successfully shot a copper projectile to make an artificial crater. Before the SCI impact, DCAM3 was also separated at a position of about 1-km distance from the collisional location, and successfully took side-view images of the impact.

DCAM3 operated normally and recorded images of Ryugu from 200 s before the impact. Ryugu and the impact site were sometimes out of its field of view: Since a slow rotation about 54° s⁻¹ was given to DCAM3 at the separation to stabilize its attitude, and a small nutation also arose simultaneously, Ryugu was sometimes deviated from the nonetheless wide field of view. However, the DCAM3 cameras could capture a part of Ryugu surface including the impact point and the impact ejecta in many images, as well as the SCI body floating over Ryugu in the time period before the impact.

The SCI impact occurred at 1304 s after the DCAM3 separation, and DCAM3 took the first image of the ejecta at 3 s after the impact. After 498 s from the impact,

Figure 1: The first image of the impact ejecta taken by DCAM3-D at about 3 s after the impact.
the ejecta curtain was too thin to be recognized on the background of the asteroid surface, which was much brighter than the ejecta curtain and therefore hid it. The ejecta curtain then was only found on the space background.

**Ejecta Curtain:** Figure 1 shows the first DCAM3-D image that was taken at approximately 3 s after the projectile collision on Ryugu. The impact ejecta of an inverted truncated cone shape, so-called “ejecta curtain,” generated from the surface was clearly found, and it was found also in subsequent images. The detailed shape of the ejecta curtain and its growth indicated that the impact occurred on rather “non-cohesive” surface, not a hard rock, because only high-velocity fragments without an obvious ejecta curtain was expected if the surface layer of the impact point is cohesive, or a hard rock.

The ejecta curtain in the first image (Figure 1) has an asymmetric shape. This feature is hardly explained by an oblique impact, because the impact angle of the projectile was estimated to be > 45° with respect to the local horizontal plane, and a shape of the ejecta curtain is not influenced by the impact angle in such range of higher angles. Rather, the impact point was estimated to have a rough surface covered with pebbles, or on the edge of the large boulder. It is considered that a large boulder closely located at the impact point interfered the cratering process, and stopped cratering excavation on the half side.

The impact point (impact crater) was observed in detail by ONC (Optical Navigation Camera) and some instruments on the main spacecraft 3 weeks after the impact experiment, and a large boulder close to the impact point was found. This is consistent with the asymmetric shape of the ejecta curtain seen in Figure 1. The crater size was estimated to be almost the same as that predicted on the ideal sand field [3]. Formation of the large crater and the clear and large ejecta imaged by DCAM3 had been unexpected on the pebble and boulder rich field on Ryugu, and this result provide important information on studies of the cratering physics and Ryugu's surface evolution.

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THERMOPHYSICAL PROPERTIES OF ASTEROID 162173 RYUGU REVEALED BY HIGH-RESOLVED THERMAL IMAGING – A LINK TO POROUS ASTEROID FORMATION. T. Okada1−2, T. Fukuura3, S. Tanaka1, M. Taguchi1, T. Ara1, N. Sakatani1, Y. Shimakai1, H. Senshū2, Y. Ogawa4, H. Demura5, K. Suko6, K. Kitazato6, T. Koyama7, T. Sekiguchi8, J. Takita9,9, S. Hasegawa1, T. Matsunaga10, T. Wada1, T. Imamura2, J. Helbert11, T.G. Müller12, A. Hagermann13, Jens Biele11, Matthias Grott11, Maximilian Hamm11, Marco Delbo14, and Hayabusa2 Thermal-Infrared Imager (TIR) Team1, 1Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA), 3-1-1 Yoshinodai, Chuo-Ku, Sagamihara 252-5210, Japan, email: okada@planeta.sci.isas.jaxa.jp, 2University of Tokyo, Japan, 3Rikkyo University, Japan, 4Ashikaga University, Japan, 5PERC, Chiba Institute of Technology, Japan, 6University of Aizu, Japan, 7National Institute of Advanced Industrial Science and Technology (AIST), Japan, 8Hokkaido University of Education, Asahikawa, Japan, 9Hokkaido Kitami Hokuto High School, Japan, 10National Institute for Environmental Studies (NIES), Japan, 11German Space Research Center (DLR), Germany, 12Max-Planck Institute for Extraterrestrial Physics (MP-E), Germany, 13University of Stirling, UK, 14Observatoire de la Côte d’Azur, CNRS, France.

Introduction: C-type Near-Earth asteroid 162173 Ryugu is the target of the JAXA Hayabusa2 asteroid sample return mission, and its surface properties have been investigated through remote sensing and surface experiments. The TIR [1] is a thermal infrared imager on Hayabusa2 and based on uncooled micro bolometer array of 328 x 248 effective pixels, with the field of view of 16.7º x 12.7º, corresponding to 0.051º per pixel. The thermographic instrument has revealed the thermophysical properties of the primitive asteroid, which indicate its possible formation process.

Global Thermal Images of Ryugu: The first two-dimensional high-resolved thermal infrared imaging for an asteroid has been conducted in history, using the thermal infrared imager TIR, on 30 June 2018, from the Home Position (HP), 20 km earthward from the surface of Ryugu. A set of thermal images were taken for one asteroid rotation with the step of every 6º. Since this time, the one-rotation thermal image sets have been obtained so far under various conditions at the solar distance from 0.98 to 1.41 au, and at the solar phase angle from -48º to -4º (morning side) and 0º to +41º (afternoon side).

The average and the maximum temperatures in a day suggest the suitable thermal inertia (TI) to the surface of Ryugu from 300 ± 100 J m² K⁻¹ s⁰.⁵ (hereafter, tiu). This TI value is consistent with the prediction by on-ground and in-space observations of 150 to 300 tiu [2]. It is also consistent with the surface measurement by MARA on MASCOT which measured the thermal inertia of a single boulder [3]. This TI value is much smaller than that of carbonaceous chondrites (> 600 tiu) [4]. In addition, the boulders and the surroundings show almost the same maximum temperature and diurnal profile. The surface materials, even the boulders, must be super porous, and the surroundings must be covered with flakes of porous materials but not with sandy regolith which is typical for high gravity celestial bodies like the Moon and Mars.

Higher resolved global thermal images have been taken during the Mid-Altitude Observation Campaign, on 1 August 2018, at 5 km altitude from the asteroid. During this campaign, the spatial resolution of 4.5 m/pixel have been taken and the most of large boulders larger than 10 m across were discriminated from the surroundings and have proven the results of the global thermal imaging from HP.

TIR mainly imaged the afternoon side of Ryugu before the solar conjunction in November to December 2018, while it takes the morning side since then. The night temperature was included in the morning side images, and the lowest temperature was below 200 K (although no set of precise calibration data exists). This suggested that the surface TI seems to be below 300 tiu.

Close-up Thermal Images of Ryugu: The first opportunity to take thermal images below 50 m altitude was on 21 September 2018, during the release of MINERVA-II-1 twin hopping rovers. More close-up thermal images have been taken around 20 m altitude during two rehearsal descents on 15 and 25 October 2018. Close-up thermal images of the surface of Ryugu have discriminated each of boulders larger than a few tens of centimeter across.

Most boulders have the size of > 10 cm across and show within a same range of temperature about 300 to 310 K at those times, corresponding to 300 ± 100 tiu. We also discovered a few cold boulders apparently below 280 K, corresponding to 600 to 1000 tiu, which were like typical carbonaceous chondrites [5].

A Super-Porous Asteroid Formation: A possible scenario of Ryugu formation is proposed [5] to explain how to build a primitive asteroid consisted of mainly super porous boulders with some minor dense rocks.

Fluffy dust particles in the solar nebula have been accumulated to form planetesimals in the early solar system. Most of planetesimals were kept porous due to a low degree of consolidation under a very low gravity condition. The parent body of Ryugu were formed was kept porous for most of its volume. If the lithostatic
pressure at the center of interior reached the level of its bulk modulus (50 MPa or so for CM chondrite), the region might be more consolidated and altered to form a dense core. Intense impact fragmentation occurred part of impact fragments accreted to form the current asteroid Ryugu. Most surface is consisted of porous materials, and some dense rocks might be from the central part of parent body. Alternative scenario might be that a dense small asteroid impacted and fragmented the porous parent body to form Ryugu by re-accretion of fragments. In this scenario, the dense rocks might be from the impactor (exogenic origin). The hypothesis of asteroid (and planetesimals) consisted of super-porous material should be confirmed by sample return.

Acknowledgments:
The authors appreciate all the Hayabusa2 Project members and the supporting staffs for their technical assistance and scientific discussions. This research is partly supported by JSPS KAKENHI No. JP26287108, No. JP17H06459, and the Core-to-Core program “International Network of Planetary Sciences”.

References:
**Introduction:** Meteorites and comets bear organic molecules ranging in size from one single to an arbitrarily large number of carbon atoms. This contrasts with the limited size of free molecules detected in space environments[1]. Understanding the organic matter cycle in the solar system requires to identify the time and place where the molecules were formed and destroyed.

The High Resolution Mass Spectrometry technique has been used for almost a decade to characterize extraterrestrial material[2]. The technique only accesses the soluble part of the samples and is used both with and without liquid chromatography for molecular identification[3]. Several scenarios have been proposed for the os of soluble organic matter in extraterrestrial samples, with for instance aqueous alteration being invoked to explain the growth of N-bearing molecules[4] detected in Murchison.

During the last years, the IPAG group has developed a tool dedicated to the interpretation of the polymerization degree of any kind of organic sample. We highlighted a peculiar pattern in meteorite extracts that can be only reproduced by highly reducing gas phase polymerization experiments[5]. This is interpreted as a piece of evidence for protoplanetary disk origin. The work presented here is a comparison between the typical protosolar pattern and the features found or not in Martian meteorites and lunar soils.

**Method:** We extracted the organic mixtures from 4 lunar soils and from the NWA7533 “black beauty” Martian meteorite[6] by maceration in Toluen and Methanol for 1 week at room temperature. We did the same for several carbonaceous chondrites including Orgueil, Murchison, 4 CR type samples. Laboratory experiment residues produced from ionized gas[7, 8], photon irradiated ices [9, 10] or reactive liquids[11, 12] were also analyzed to provide comparison to well constrained synthesis environments. Mass spectra were acquired with a Thermo LTQ Orbitrap XL at its highest resolving power, coupled with Electrospray ionization (ESI) source. Anions and cations in the following mass range 150 to 800 u were analyzed on a 4 decades dynamic range.

**Results:** The Orbitrap mass spectrometry provides the mass distribution of mixtures with resolution and precision high enough to undoubtfully identify polymeric patterns. In every sample, CH₃ patterns are detected. A CH₂ family has only molecules with R-(CH₃)ₙ formula. From each CH₂ family, the free parameters of the Wesslau model [13] for polymerization can be adjusted to match the distribution. Each sample has from 3 to 15 CH₂ families with up to 30 members. In the synthetic samples, the parameters depend mainly on the precursor mixtures. The meteorites exhibit larger variations of the polymerization parameters than synthetic samples. We discuss the relevance of the various candidates for the emergence of molecular diversity in asteroids. Polymeric patterns in the NWA7533 involve C, H and O. Only CH₂, C₂H₂ and C₃H₆O patterns seem to be responsible of the molecular complexity. Heteroatomic (O-bearing) pattern is the major difference between chondritic and Martian organics. Another major difference is the absence of nitrogen in any observed cation whereas it was a key feature in Murchison. The patterns in lunar soils are highly variable. Some soils exhibit very little polymerization patterns, if any. One has a pattern comparable to the asteroidal one and one has a peculiar mass distribution that doesn’t match any other extraterrestrial sample. The latter is the most exposed to solar wind and the mass range of its mixture is the most extended. We discuss such features in terms of origin and possible evolution of the organic matter delivered to the moon.


**Introduction:** JAXA’s Hayabusa2 mission arrived at C-type near Earth asteroid Ryugu in June 2018 and the on-board Mobile Asteroid Surface Scout (MASCOT) was dropped by Hayabusa2 on October 3rd, 2018 [1, 2]. MASCOT is equipped with four scientific instruments including a camera (MasCam), a radiometer (MARA), a hyperspectral microscope (MicroOmega) and a magnetometer (MasMag) aiming at investigating the surface’s structure, mineralogical composition, thermal behaviour and magnetic properties [3]. After successfully settling on the surface and activating an internal mobility unit, MASCOT achieved the desired orientation for in-situ observations on the surface where it operated for 17 hours and 17 minutes during day and night time. MasCam [2] imaged the surface during daytime at ambient illumination conditions and during nighttime using four colored LED arrays (red, green, blue, infrared).

The rocks imaged by MasCam on the surface of Ryugu showed an abundance of bright inclusion resembling the texture of carbonaceous chondrites [2]. Spectroscopic as well as inclusion texture comparison suggest a link with CM2 type meteorites (Table 1). Here we report on the comparison of inclusion size frequency distributions on Ryugu with measurements that we acquired for various carbonaceous chondrites of the meteorite collection of the Natural History Museum in Berlin using the qualification model of MasCam.

**Aim:** We aim to constrain the link between the rock imaged by MasCam on Ryugu and carbonaceous chondrites by investigating the color and size frequency distribution of inclusions on Ryugu and a number of typical carbonaceous chondrites.

**Method:** Using the qualification model of MasCam, we imaged a variety of carbonaceous chondrites including all meteorites mentioned in Table 1 at the Natural History Museum in Berlin. The samples were in the order of a few centimeters in size. We tried to mimic the measurements on Ryugu by placing the meteorite samples at a similar distance to the camera and illuminating them with the four color LEDs on a neutral background (Figure 1). The pixel resolution of the so acquired images is approximately 0.2 mm. This approach also allowed us to acquire information on the color of the inclusions and enables us to derive an inclusion size frequency distribution based on spectroscopic characteristics. Please also refer to our second abstract submitted to this meeting focussing on the spectral diversity of inclusions [5].

![Figure 1: Measurement set up with meteorite on a wooden wedge, scale bars and the MasCam qualification model.](https://example.com/fig1.png)

**Example and Outlook:** Figure 2 shows bright inclusions mapped on Ryugu in red illumination and the corresponding grain size frequency distribution (based on a MasCam 3D surface model [6]). Here we assumed a simple correlation between the areal (n_a) and volumetric (n_v) density given by n_v = n_a^{1.5} [7]. We will repeat this procedure for other areas on Ryugu and for the carbonaceous chondrites imaged at the Natural History Museum in Berlin and will compare the results between the different samples and Ryugu. We will also provide a catalogue of our measurements for future in

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Reflectance factor at 0.55 μm</th>
<th>Refractory inclusion abundance (vol%)</th>
<th>Inclusion size (mm)</th>
<th>Chondrule inclusion abundance (vol%)</th>
<th>Chondrule mean diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI1 (Orgueil)</td>
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<td>0.1 – 3*</td>
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<tr>
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<td>20</td>
<td>0.3</td>
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<tr>
<td>CO3 (Ornans)</td>
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<td>13</td>
<td>0.2-0.5</td>
<td>48</td>
<td>0.15</td>
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<tr>
<td>CV3 (Allende)</td>
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<td>0.29 ± 0.38</td>
<td>45</td>
<td>1.0</td>
</tr>
<tr>
<td>Ryugu</td>
<td>0.02</td>
<td>10</td>
<td>0.38 ± 0.55</td>
<td></td>
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</tbody>
</table>

**Table 1:** From Jaumann et al. 2019 [1]. The distribution of inclusions and chondrules in typical carbonaceous chondrites extracted from the literature and the rock imaged by MasCam on Ryugu.
situ missions and as a reference for samples returned by Hayabusa2 and OsirisRex.

![Grain Size Frequency Distribution](image)

**Figure 2:** Grain size frequency distribution of bright inclusions on Ryugu imaged with the red LED.

**References:**


SMALL SCALE SURFACE ROUGHNESS OF RYUGU. Katharina A. Otto$^1$, Rutu Parekh$^{1,2}$, Klaus-Dieter Matz$^2$, Ralf Jaumann$^{1,2}$, Katrin Krohn$^1$, Katrin Stephan$^1$, Nicole Schmitz$^1$, Tra-Mi Ho$^3$, Stephan Elgner$^1$, Maximilian Hamm$^1$, Rie Honda$^4$, Shingo Kameda$^3$, Frank Preusker$^1$, Frank Scholten$^1$, Stefan Schröder$^1$, Hiroki Senshu$^5$, Seiji Sugita$^1$ and Frank Trautmann$^1$

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Introduction: JAXA’s Hayabusa2 mission arrived at C-type near Earth asteroid Ryugu in June 2018 and the on-board Mobile Asteroid Surface Scout (MASCOT) was dropped by Hayabusa2 on October 3rd, 2018 [1, 2]. MASCOT is equipped with four scientific instruments including a camera (MasCam), a radiometer (MARA), a hyperspectral microscope (MicrOmega) and a magnetometer (MasMag) aiming at investigating the surface’s structure, mineralogical composition, thermal behaviour and magnetic properties [3]. After successfully settling on the surface and activating an internal mobility unit, MASCOT achieved the desired orientation for in-situ observations on the surface where it operated for 17 hours and 17 minutes during day and night time. MasCam [2] imaged the surface during day time at ambient illumination conditions and during night time using four colored LED arrays (red, green, blue, infrared).

Observation: During its operation on Ryugu’s surface, MasCam imaged the surface at multiple occasions during day and night time [2]. MasCam uses the Scheimpflug principle and thus the pixel resolution varies starting at ~0.2 mm in the front of the image [4]. During night time the LEDs illuminated the surface from slightly below the camera lens. A vertical offset of the LED array introduces a shadow cast to the top right in the images (Figure 1). These shadows emphasize rough surface structures.

Method: Using LED illuminated night time images of Ryugu we defined surface structures at pixel resolutions of ~0.2 mm using image analysis techniques. We identified areas of similar texture and brightness using a growing region algorithm starting from a representative area of interest (Figure 1). The outline of these areas and their reference surfaces acquired by smoothing the rough outline were subsequently used to derive several commonly used roughness parameters including the fractal dimension, RMS slope, small scale roughness parameter and hemispherical crater density typically used in thermal modelling to approximating sub-resolution roughness.

Outlook: We derived a number of roughness parameters from images of Ryugu’s surface necessary for the correct interpretation of a number of remote sensing and in situ data including thermal emission and reflectance spectra. We also applied our method to images of comet 67P and find that both bodies have similar degrees of roughness.

References:

Figure 1: Outline (red), smoothed outline (yellow) and representative texture (white circle) of surface structure on Ryugu from which roughness parameters were derived.

Introduction: The 27th of June 2018 the Japanese Hayabusa-2 spacecraft approached the C-type Near Earth asteroid 162173 Ryugu [1]. Hayabusa2 is equipped with three remote sensing instruments such i.e. as the Thermal Infrared Imager TIR [2], the NIRS 3 spectrometer [3] and the Optical Navigation Camera-Telescopic (ONC-T) with a wideband and seven narrow band filters [4]. A Lidar instrument [5] allowed to reconstruct the shape model of the asteroid and to measure the altimetry, in order to perform a precise touchdown in sampling the asteroidal regolith. Additionally, by using the robotic landers Minerva-II and Mascot [6], Hayabusa 2 has conducted in situ surface experiments. Ryugu is a top-shaped Cb type asteroid and is covered by a large number of boulders [7,8]. It is one of the darkest object in our Solar System with a quite homogenous composition, including OH-rich materials [7,9].

Fig 1 PCA coefficients distribution maps and eigenvectors (lower right).

Method: We found that the NIRS3 data contains sensible variations, possibly linked to geomorphological structures, even though Ryugu surface varies only of few percent in reflectance. Our approach is to exploit the whole spectrometer dataset, to find correlation that could not be foresee with traditional methods relying on fewer spectral points. Past experience on Mercury data shows that this is a sensible approach, in case of homogeneous featureless targets. We collect NIRS3 data from 20180711_13a and 20180719_13a counting around 20k useful spectra, covering almost the whole surface. The data were windowed between 1.8 and 3.1 um to avoid residual thermal effects at higher wavelength, obtaining a data matrix of 20k row x 75 feature or bands. Then we applied a PCA transformation step to retain 10 component or 98% of the total variance, effectively compressing the data from 75 to 10 components. Even though the PCA components per se doesn’t normally have a clear physical meaning, because they mix spectral feature in an unpredictable way, it is interesting to look at the results. The first PCA component has redder slope between 1.8 and 2.5 um, where the second has an inverted redder slope in the same range. The third is spectrally flatter, with an hint of absorption between 2.4 and 2.5 um. The concentration distribution of those three components is also worth investigating: the PCA.0 is anti-correlated with the equatorial bulge and higher in craters, PCA.1 is also higher in crater but not strongly anti-correlated with the equatorial bulge like PCA.0. PCA.3 this is clearly showing a north-south asymmetry. The PCA component order indicate also the importance in explaining total data variance. After that, we apply T-distributed Stochastic Neighbour Embedding (t-SNE) [10]: this converts similarities between data to joint probabilities, minimize the divergence between the joint probabilities of the low-dimensional embedding and the high-dimensional data, typically 2 or 3 dimensions. Essentially, we can feed high dimensional data and get a lower dimension 2D map representation were closer point are also close in the original data space that is easy to visualize. On top of that we partitioned the data point using an Agglomerative Clustering algorithm: starting from all separated data point it clusters the closest together, where closeness is calculated with complete linkage, i.e. the maximum distances between all observations in each pair of classes. Hierarchical algorithm has the nice advantage to show which partition is more stable via a dendrogram plot. In our case, a 6 classes partiion show as the most suitable one.
Results: The surface of Ryugu could be separated in 6 spectral classes, which have a similar spectral trend (Fig.2) and are spatially coherent (Fig.3)

- Classes (0,1,5,3) have same trend, but different albedo (from lower to higher reflectance).
- Class 0 and 1 (C0/C1) are inter-craters terrains, the former mostly in the north, the latter in the south, with minor outcrops in the other hemisphere. C0 is up to -2% darker than Global Mean Reflectance (GMR) and C1 up to +4% brighter.
- Class 2 (C2) is the darkest class (-5% GMR), and it is found mostly in craters interiors.
- Class 3 (C3) is the brightest (+5% GMR) and it is found on the equatorial bulge, but interrupted by Urashima, Momotaro, Kintaro and Kolobock craters.
- Class 4 and 5 (C4/C5) are two different trend of intermediate terrains. Those are the closest to GMR with a 2% variation around GMR. C4 is mostly found in the north, where C5 in the south, with substantial outcrops in the other hemisphere. The most interesting difference is that C5 follows the global trend of being slightly bluer than GMR between 1.9 um and 2.5 um, but C4 shows an inverted trend, being redder then GMR.

In conclusion, we find an automated approach to extract spatially coherent region on Ryugu surface based only on spectral data using almost the whole NIRS3 spectral range. Those classes show a significant spatial correlation with geomorphological feature and different spectral trends.

SPECTRAL INVESTIGATION OF DARK AND BRIGHT AREAS ON THE SURFACE OF RYUGU.  E. Palomba², A. Galiano¹, M. D’Amore¹, A. Zinzi², F. Dirri¹, A. Longobardo¹, K. Kitazato⁵, T. Iwata⁵, M. Matsuoka³, T. Hiroi⁵, D. Takir², T. Nakamura⁵, M. Abe³, M. Ohtake³, S. Matsuura³, S. Watanabe¹⁰, M. Yoshikawa³, T. Saiki³, S. Tanaka³, T. Okada⁵, Y. Yamamoto⁵, Y. Takei³, K. Shirai³, N. Hirata¹¹, N. Hirata¹, K. Matsumoto¹², Y. Tsuda³,¹

Introduction: The JAXA Hayabusa2 spacecraft approached the C-type Near-Earth asteroid 162173 Ryugu on 27th June 2018 [1] and since then, images and spectral data of the surface have been acquired. The payload of the spacecraft includes a Thermal Infrared Imager TIR [2], the NIR3 spectrometer [3] and the Optical Navigation Camera-Telescopic, with a wideband and seven narrow band filters (ONC-T) [4]. Ryugu is a top-shaped Cb type asteroid and ONC images revealed a surface covered by a large number of boulders, characterized by different roughness and albedo [5,6]. Reflectance spectra acquired by NIR3 span from 1.8 to 3.1 µm, and detected a narrow absorption feature centered at 2.72 µm across the entire observed surface, indicating the ubiquitous occurrence of hydroxyl (OH)-bearing minerals on the surface of Ryugu [7].

NIR3 data also detected Ryugu as a very dark object with a globally-averaged reflectance value at 2.0 µm of about 0.017 [7].

Detection of Bright and Dark areas on Ryugu: Although Ryugu is an homogeneously dark object, the aim of this work was to detect bright and dark areas by using spectral data acquired by NIR3. We used calibrated and thermally corrected data acquired on 10 and 11 July 2018 and on 19 July 2018, when NIR3, operating in scanning mode, obtained a near-global coverage of Ryugu surface. The data acquired on 10 and 11 July are characterized by a spatial resolution of 40 m, since the spacecraft was at an altitude of 20 km (Home Position), whereas the data of 19 July have a spatial resolution of 20 m, since the spacecraft’s altitude was of 13 km.

We used a method yet validated for Ceres and Vesta [8,9] to detect bright and dark areas on Ryugu surface.

For each pixel, we obtained the reflectance factor at 1.9 µm and we estimated the mean value of reflectance at wavelength of 1.9 µm, i.e. 0.017. Bright areas have been defined as regions with a reflectance factor at 1.9 µm larger than the 5.5% than the mean value; dark areas are the regions with a reflectance factor lower than the 8% of the mean value and larger than 0.01 (to avoid false positive due to low S/N).

Results: A total of 36 Bright areas and 28 Dark areas have been detected by the application of method. Bright areas are mainly localized on the equatorial ridge, whereas dark areas are mainly located at middle latitudes and few of them are on the poles.

Figure 1. Distribution of bright (top) and dark (bottom) areas on the Ryugu surface superposed on the reflectance map estimated at 1.9 µm.

Most of Bright areas are boulders, two are coincident with saxa (Catafo saxum and Otohime saxum) and 9 of them are crater rim of impact craters.

Dark areas are mainly boulders. Anyway, 4 dark areas are coincident with the floor of impact craters and 6 dark areas are located in Tokoyo Fossa.

The reflectance map of Ryugu estimated at 1.9 µm, superposed on Ryugu shape model (Figure 2), highlights the different reflectance level between crater floors (darker) and crater rim (brighter).
Figure 2. Reflectance map of Ryugu estimated at a wavelength of 1.9 µm (ranging from 0.014 to 0.019), superposed on Ryugu shape model.

By comparing dark and bright areas with the spectral slope estimated between 1.9 and 2.5 µm, a more positive slope can be observed in darker areas.

Both dark and bright area spectra show a weak absorption band at 2.72 µm, suggesting a widespread occurrence of hydroxylated minerals on the surface of Ryugu. However, by relating the distribution of dark areas on Ryugu surface and the intensity of 2.72-µm band (Figure 3), a moderate anti-correlation emerges in the southern hemisphere, with a Pearson coefficient value of -0.47. Dark areas located toward the south pole seems to be richer in hydroxylated compounds and D28, corresponding to a large boulder located in Tokoyo Fossa, is the most hydrated dark area on the surface of Ryugu.

This result suggests a possible dichotomy in the Ryugu surface, represented not only by the enrichment of hydroxylated compounds but even by a redder slope of the southern hemisphere [10].


Introduction: Beginning in January 2019, the OSIRIS-REx navigation camera NavCam 1 imaged a number of suspected active asteroid ejection events.1,2,3 For some of these events, the only observations of the ejected particles come from the first two images taken immediately after the event by NavCam 1. Without three or more observations of each particle, traditional orbit determination is not possible. However, by assuming that the particles all ejected at the same time and location for a given event, and approximating that their velocities remained constant after ejection (a reasonable approximation for fast-moving particles given Bennu's weak gravity), we show that it is possible to estimate each particles' state from only two observations. We applied this newly developed technique to reconstruct the particle ejection events observed by OSIRIS-REx during orbit about Bennu.

Method: Overview. Non-stellar object detections and track associations are made given sparse data from only two successive images after a suspected ejection event. Using these 2-image object tracks, the object states and ejection event locations and epochs are estimated.

Assuming linear motion of ejecta, the tracks are used to trace back to a single radiant point within the image, which is mapped to two possible Bennu surface points.

The ejection event epoch and particle 3D states are estimated using angular in-image-plane measurements. For objects with a non-zero out-of-image-plane velocity component, there is an apparent angular acceleration seen within the image. Therefore, by assuming a constant 3D metric velocity and calculating the angular or in-plane velocity of an object at different epochs, information on the epoch of the event and the 3D states can be inferred. These assumptions and approximations are needed for initial state estimation of the objects when very sparse information is available and traditional orbit determination cannot be performed.

Detections and Track Identification. For a suspected ejection event, the two NavCam images taken immediately after the event are corrected for distortion, registered on the center of Bennu, and differenced to highlight any objects moving with respect to Bennu. Some detected objects present as streaks or trails in one or more images, and therefore can be treated as multiple observations for the object at the start and end of the image exposure. If a streaked object was present in both images it could be treated as a 4-epoch track.

Associated pairs of detections (tracks) were made from identified repeated patterns and used for the radiant estimation and 3D object state determination.

Figure 1. Ejected particle tracks for the January 19, 2019 ejection event.

Ejection Epoch Estimation. The epoch that each object left the radiant point was estimated by comparing the angular displacements of the object from the radiant at each epoch.

When only 2-epoch tracks were available, the radiant epoch is non-deterministic and coupled with an ambiguity in the 3D orientation of the ejecta cone. However, when 3- or 4-epoch tracks were available, a more robust method was used to determine the time that each object left the radiant point. This allowed for a deterministic solution of the event epoch that removed the 3D orientation ambiguity.

Ejection Location Estimation and Uncertainty. Given the radiant point within the image and the radiant epoch, two unique solutions for the ejection location on the surface of Bennu are found: a point closer to the spacecraft on the near side of Bennu and a point on the far side of Bennu, out of view of the camera. The ray tracing routines in the NAIF SPICE toolkit are used to estimate these two surface locations.
3D Object States. 3D object states are inferred by comparing the observed angular velocity to the angular velocity expected for an object that left the origin point at the estimated event time and traveled perfectly within the plane of the image (perpendicular to the camera's boresight). This assumes that the objects' velocities are constant (they are traveling in straight lines) and that every object left the origin point at the median time determined from 2D analysis. These assumptions hold up well for images that capture the particles within minutes of the event time. Objects appearing faster than expected were inferred to be moving towards the camera and objects appearing slower than expected were inferred to be moving away from the camera.

By combining this 3D information with the two solutions for the ejection location, the 3D positions of each object are found. The 3D velocities are then calculated using the position of each object at the two image times. There are two unique solutions for each object's position and velocity that correspond to the two unique solutions for the ejection location.

Results: Ejection locations and particle velocities were estimated for 11 Bennu particle ejection events. Estimated velocities ranged from 7 cm/s to 3.3 m/s, and most events occurred at similar local solar times as seen in Figure 2.

![Figure 2: Estimated local solar times for 11 particle ejection events.](2151.pdf)

This presentation will present an extended description of our newly developed technique and the results from these 11 ejection events.

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AN IMPACT-CRATER EJECTA DEPOSIT ON BENNU. M.E. Perry1, O.S. Barnouin1, R.T. Daly1, R.L. Ballouz2, K.J. Walsh3, M.G. Daly4, D.N. DellaGiustina5, J.P. Emery6, C.M. Ernst7, E.B. Bierhaus7, E.R. Erwin8, M.C. Nolan2, and D.S. Lauretta2. 1Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA (mark.perry@jhuapl.edu), 2Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA, 3SWRI, Boulder, CO, USA, 4York University, Toronto, M3J 1P3, 5University of Tennessee, Knoxville, TN, USA, 6Lockheed Martin Space, Littleton, CO, USA, 8National Museum of Natural History, Smithsonian Institution, Washington, DC, USA.

Introduction: In the microgravity environment of Bennu, where the escape velocity is less than 20 cm/s, impact ejecta will escape unless the target strength is extremely low, a condition that permits low ejecta velocities. This criterion was apparently met for the event that created the crater at 45S, 325E. An extensive ejecta field covers more than 3% of Bennu’s southern hemisphere downslope of the crater. We present data on the posited ejecta field, the source crater, the range of impact conditions that could emplace an ejecta deposit on Bennu, and the mass flow that created the extensive field.

Crater and distinctive terrain (Fig. 1): The crater has a diameter of ~70 m. Its well-defined topographic signature (raised rim that goes around the entire crater; bowl-shaped floor) marks it as one of the most pristine impact craters larger than 10m on Bennu and indicates that it is relatively young. It has a depth-diameter ratio of 0.08 ± 0.01 with respect to geometric height. The ratio is unremarkable compared to similar-sized Bennu craters [1]. The crater resides on a ~23° regional slope. The northern crater wall slopes more steeply than the southern wall; the northern wall also appears rougher than the southern side.

![OCAMS image with an outline around the crater at 44S 325E and much of the ejecta field to the north. The region behind the two labeled rocks appears free of ejecta.](ocams20190322t233553s104_map_iof2pan_78685)

Fig. 1. OCAMS image with an outline around the crater at 44S 325E and much of the ejecta field to the north. The region behind the two labeled rocks appears free of ejecta.

The distinctive terrain that appears to be an ejecta field fans northward toward the equator and covers approximately 20,000 m². The color is homogenous with a distinct phase slope [2]. The surface is smoother than the surrounding terrain as determined by both boulder counts and measures of roughness such as tilt variation. A small area south of the crater appears to contain the same material. The ejecta field is texturally uniform from the edge of the crater out to two crater diameters in the equatorward direction. The material is absent behind the two boulders indicated in Fig. 1.

The distinctive terrain surrounds and inhabits the crater, a clear indication that the crater and terrain are associated. A crater that post-dated the terrain would produce a disturbed region surrounding the crater, which would also be the case if the impact event initiated a landslide in pre-existing terrain. For the rest of this paper, we assume that the material that comprises the distinctive terrain is ejecta, and we examine the processes by which it reached its current position: ballistic trajectories followed by surface travel.

Impact event: An essential question when employing scaling relationships to estimate the event parameters such as ejection velocities and mass is whether or not material strength controls crater formation [3,4]. The recent impact experiment on Ryugu by Hayabusa2 suggests that gravity scaling (negligible strength) is applicable to rubble pile bodies, at least to those the size of Ryugu and Bennu [5].

During crater formation, most ejecta mass leaves near the crater edge, where ejecta velocities are lowest and the scaling relationship for a gravity-controlled impact [3] can be simplified to \( v = \sqrt{gR} \), where \( g \) is the local acceleration of gravity and \( R \) is the crater radius. For Bennu at 45° S, \( v \approx 5 \) cm/s. Lab experiments show that the ejecta angle will be approximately 45° from the local slope, and that the total ejected volume is approximately half of the crater volume [3,6], which we measure to be 1.5x10⁴ m³ ±50%.

Aftermath of impact event: Material ejected at a uniform angle to the local slope will land on the upslope side closer to the crater than material ejected downslope. More importantly, the downslope ejecta contacts the surface at a relatively shallow angle (27° downslope vs. 87° upslope) with a high velocity component along the surface (Fig 2). In the low-gravity, low-friction environment, downslope material continues in its original direction, radiating away from the crater and flowing along the surface, almost in freefall. Acceleration due to the slope is possible. Material
continues until encountering an obstacle that it cannot dislodge or reaching the equator, the lowest elevation. The environment is essentially frictionless, so, despite slow velocities, material continues moving. For material moving at an angle to the slope, there is a slight downslope acceleration, but this has a small effect on the original velocity for material within 45° of the downslope direction.

Discussion and implications: The asymmetry in the ejecta field is due to slope effects, both the asymmetric deposition of ejecta and the subsequent flow downslope after re-impact with the surface. An oblique impact toward the north could contribute to the asymmetry [7], but it is not necessary. The landed ejecta flowed along the surface radially from the crater, explaining the lack of ejecta material on top or behind boulders 1 and 2, which were too large or too deeply imbedded to be dislodged by the ejecta flow.

The ejecta flow was sufficiently massive to scour the surface over which it flowed, removing the unanchored rocks and boulders and leaving a relatively smooth terrain. With negligible friction, the momentum of the flowing material transferred efficiently to existing material in the path. Filling of low areas also contributed to terrain smoothness. Material continued to the lowest elevations at the equator. The east-west boulder field at the northern edge of the ejecta field may contain rocks displaced by the ejecta flow. The lack of tracks from rolling boulders is not surprising as all of the material flowed together.

There are no other clear ejecta fields on Bennu. The crater at 44S 325E is the only Bennu crater with three necessary characteristics: large size, high latitude, and relative youth. Its ejecta field is highly visible because of its surface flow downslope. The other large craters are near or on the equator, so ejected material is already at low elevation and lands with negligible surface velocity. There are a few other large candidate craters at high latitude, but they appear older and degraded [8], and possible associated ejecta fields are weathered past recognition.

Terrestrial experiments show that for an impact on a slope, the upslope wall undergoes enhanced collapse in granular targets, producing an overall shallower slope on the upslope side [9, 10], as with this crater.

For the ejecta to land and then flow as observed, the rotation rate must be sufficient to create a slope at the location of the crater. If Bennu’s rotation period was 50% longer than its current 4.3 hours, the gravity vector is 10° closer to vertical, producing a more-symmetric ejecta pattern, a lower surface velocity, and less or no surface flow. Future study may be able to put constraints on Bennu’s recent rotation history.

Estimating the volume of ejecta in the flow area to be approximately half of the ejected volume, a uniform thickness would be approximately 0.2 m. The observed terrain may be a mixture of ejecta and pre-existing terrain, creating a thicker layer. The ejecta-free areas behind rocks 1 and 2 are less than 1 m lower than the adjacent ejecta; high-resolution altimetry data will provide a high-fidelity measurement.

Extrapolating results from terrestrial experiments to such low gravity environments is problematic, but the approximations needed to model relatively large craters in the gravity regime are less severe than for smaller craters and for the strength regime. The quoted velocities are plausible and produce a feasible explanation for the ejecta field.

The gravity scaling implied by this crater and its ejecta has implications for interpreting craters distributions and using those to date asteroid surfaces. Negligible strength leads to larger craters for the same impact size and velocity, reducing the estimated age for a given distribution. On Bennu, this could resolve some of the discrepancies between the dynamic evolution of Bennu and its crater-dated surface age [8, 11].


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LINEAR STRUCTURAL FEATURES ON Bennu. M.E. Perry1, O.S. Barnoun2, E.R. Jawin3, K.J. Walsh3, M. Pajola4, M.G. Daly5, C.L. Johnson6, M.M. Al Asad7, R.W. Gaskell7, E.E. Palmer7, J.R. Weirich7, J.R. Weirich7, M.C. Nolan8, D.S. Lauretta3. 1Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA (mark.perry@jhuapl.edu), 2National Museum of Natural History, Smithsonian Institution, Washington, DC, USA, 3SWRI, Boulder, CO, 4INAF - Astronomical Observatory of Padova, Italy, 5York University, Toronto, M3J 1P3, 6University of British Columbia, Vancouver, V6T 1Z4, 7Planetary Science Institute, Tucson, AZ 85719, USA, 8University of Arizona, Tucson, AZ, USA.

Introduction: The surfaces of asteroids of all sizes possess linear features, or lineaments, some of which provide information on the internal structure and history of the body [c.f., 1,2] and others may illuminate characteristic features of surface weathering. On some asteroids, the orientation of lineaments and grooves can be associated with craters, where the asteroid has globally readjusted to the impact event. In a few instances, lineaments are remnants of mass wasting. Long linear grooves are also considered evidence for structural coherence. Linear chains of boulders could hint at subsurface structure or the removal of near-surface fines.

Using images and altimetric data from the cameras [3] and altimeter [4] on board the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx [5]) spacecraft, we identify lineaments on Bennu. The images are also used along with altimetry to build digital terrain models (DTMs) [6] that provide topographic detail on the observed lineaments.

This first global mapping of lineaments on the asteroid (101955) Bennu shows a diverse set of features that include long, longitudinal high-standing ridges, scarps, grooves, troughs, and ridges. We review these features, assess their orientations, and discuss their relevance to our emerging understanding of Bennu’s internal structure. Assessments are consistent with a rubble-pile asteroid that may contain large subsurface blocks or some other form of interior rigidity.

Lineament categorization: We identify and map candidate linear features across the surface of Bennu using the Small Body Mapping Tool [7]. Identification is primarily from images, with topography used to assess a confidence level [1]. The confidence assessment is necessary because of the challenges of identifying lineaments on asteroids, particularly on small, rubble-pile asteroids with rock-strewn surfaces such as those on Bennu. We classify lineaments by their shape: ridges, troughs, grooves, scarps, boulder trails (an assembly of boulders), and global-scale high-standing ridges [4].

Results: There are more than 130 lineaments at scales from 25 m to 400 m (Fig. 1, next page). The global distribution is approximately uniform in both latitude and longitude. 75% of the lineaments are between 35 m and 180 m (Fig. 2). Lineaments are more prevalent on Bennu than on some other small asteroids such as Itohawa. The most common lineaments are ridges and shallow troughs. Boulder trails may be the remnants of ridges where the smaller material and fines have wasted away. There appear to be E-W oriented terraces at the latitudes with highest slopes [6], another indication of mass wasting.

Fig. 2. Global distribution of lineaments on the surface of Bennu. Does not include the 20-m-and shorter lineaments that are found in the smooth areas of some craters. Surface roughness and rocks mask lineaments shorter than 25 m over most of the surface.

Fig. 3. The black lines overlay sharp linear grooves in the smooth interior of the crater at 24N, 207E. There are an additional 20 shorter lineaments in the smoother areas, most of which are in the interior of some craters (Fig. 3). These are usually straight, narrow grooves that appear to be fractures in the crater floors in which they are observed. It is unknown if these are common to Bennu and only observed in smooth crater floors due to lack of masking.
by rocks and boulders or if these apparent fractures were created during the impact that formed the crater. Future high-resolution images and altimetry may provide evidence that these are fractures in subsurface bedrock.

Several aspects of the lineaments indicate Bennu has some degree of internal stiffness. The north-south high-standing ridges can extend from pole to pole and denote internal stiffness because they support material above the surrounding terrain [4]. The few long-linear grooves that can span more than 250 m, longer than Bennu’s mean radius, similarly indicate structural coherence. By showing a tentative link between the orientation of some lineaments and the crater at 44S, 325E, an early analysis using the technique applied to Eros [4] also indicates sufficient internal connectivity to affect far-reaching terrain. Alternatively, a random distribution of lineaments would argue for a blocky underlayment with a lack of global-scale internal cohesion.


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Fig. 1. Four global equatorial views of the Bennu lineaments showing ridges (red), troughs (light blue), boulder trails (green), grooves (black), scarps (white), and combination (yellow).
BASALTIC INTERLOPERS IN THE C-COMPLEX ASTEROID FAMILIES: POSSIBLE SOURCES FOR EXOGENOUS MATERIAL ON (101955) BENNU AND (162173) RYUGU. Marcel Popescu$^{1,2}$, Julia de León$^{1,2}$, Humberto Campins$^3$, Eri Tatsumi$^{1,2}$, Javier Licandro$^{1,2}$, Juan Luis Rizos$^{1,2}$ and D. S. Lauretta$^4$

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Introduction: Asteroid (4) Vesta is the largest (~525 km in diameter) differentiated asteroid showing a basaltic crust. The collisional family of Vesta includes more than 15,000 known members [1]. The results found by the Dawn mission support the hypothesis that this family is a result of cratering events. They revealed two remnant craters, Rheasilvia (the young crater retention age of this basin indicates that it was formed $\approx 1$ Gyr) and Veneneia (the crater counts suggest an age of 2.1 ± 0.2 Gyr ago) with diameters of 500 ± 25 and 400 ± 25 km respectively [2].

Methods: Different all-sky spectrophotometric surveys have allowed the discovery of a large number of basaltic candidates over the entire inner-main belt [7,8,9]. Follow-up spectroscopic surveys confirmed their identification with a success rate of about 90% (e.g. [10,11,12,13,14 and references therein].

Fig. 1 V-types and C-complex asteroid families distribution in the proper orbital elements space.

Results: Figure 1 shows the distribution of proper semi-major axis vs. eccentricity (top panel) and vs. sine of proper inclination (bottom panel) for the currently identified eight C-complex collisional families located in the inner belt [1]. The basaltic asteroids (V-types) are shown for comparison. Dynamically, some of the V-type candidates have orbital proper elements similar to those of the B/C-complex inner-main belt families. Part of these basaltic candidates are dynamically associated as members of these families [1]. There are 166 V-types spectrally confirmed (either in optical or near-infrared region or covering both spectral intervals). A total number of 476 V-type candidates (with a probability higher than 50%) were reported by [7] based on the data obtained with u,g,r,i,z filters by the Sloan Digital Sky Survey. The near-infrared photometric measurements performed with Y, J, H, Ks by the VISTA-VHS survey allows the identification of 778 basaltic candidates [8,9].

These evidences are in favor of the presence of basaltic material at the surface of (101955) Bennu.
Fig. 2 Illustration of areal / linear mixture of basaltic and carbonaceous chondrites like compositions (dashed red line). The C taxonomic type spectrum (black line) is shown for comparison. The typical albedo of V-types and C-types are considered.

The spectrophotometric data of bright spots detected on Bennu show differences, in terms of albedo and 0.9 μm band depth, relative to the RELAB data of howardite, eucrite, diogenite meteorites. These differences are explainable by an approximation of an areal or linear mixture of basaltic and carbonaceous chondrite–like components. It involves a linear combination of the corresponding spectra. This "checkerboard" approach [15] assumes the constituent minerals are optically separated so that multiple scattering occurring between the constituents are negligible.

To exemplify this model, we considered the average spectrum of V-types asteroids (associated with basaltic howardite – eucrite – diogenite material) and the average spectrum of C-type bodies (associated with carbonaceous chondrite meteorites). To approximate the absolute reflectance, we considered a visual albedo of $p_{V} = 0.36$ for the V-type spectrum and $p_{C} = 0.05$ for the C-type one. These were combined linearly and the result is shown in Fig. 2. The result was obtained by calculating an areal ratio of 10% for the basaltic material and 90% for the carbonaceous material. This model is able to explain the spectrophotometric behavior of the brightest spots detected on Bennu [6].


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THE SHAPE OF THE 3 μm ABSORPTION BAND LINKED TO THE ALTERATION HISTORY?
LABORATORY INVESTIGATIONS ON CARBONACEOUS CHONDrites AND APPLICATIONS TO
AKARI, Hayabusa2 AND OSIRIS-REx SPECTRA

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Introduction: the two space probes Hayabusa2 and OSIRIS-REx are currently orbiting
their respective targets, the Near-Earth Asteroids (NEAs) Ryugu and Bennu. The reflectance spectra of
these small bodies are drastically different, showing a strong blue slope and well-defined 3 μm hydration
band for Bennu [1], while Ryugu presents a very low reflectance value and a tenuous 3 μm band [2]. To
explain this difference despite small bodies

Results: Fig. 1 presents the reflectance spectra before and after the heating cycles for 2 samples.

The heating experiment strongly affects the whole spectrum: the continuum become redder and darker and the absorption bands in the visible range reduce and shift towards shorter wavelengths. Focusing on the 3 μm feature, the hydration band becomes fainter and thinner, the position of the minimum shifts towards shorter wavelengths and the global shape of the band drastically changes and become much sharper.

The 3μm is due to oscillation of –OH groups, in oxidized minerals, or/and in water molecules. The feature is so a convolution of several components, that can be separated to better understand the effect of heat on the mineralogy and hydration of the sample. As an example, Fig. 2 presents the hydration feature of Orgueil (before heating) separated into 3 components, using the model and algorithm described in [5]. Two Gaussian profiles are added to model the detected stretching modes of CH2 and CH3 groups between 3400 and 3600 nm.

Figure 1: Normalized reflectance spectra of the CR1 GRO 95577 and the CI1 Orgueil before (blue) and after heating at 523 K (red). Offsets for clarity.

Figure 2: Spectral modelling of the 3μm band of Orgueil, before heating. Black: measured spectrum, Red: modeled spectrum, Green, Purple, Blue: components of the 3 μm band, Grey: organic features.

The components of the -OH absorption band have been previously described [6, 7] and are directly linked to the alteration history and relative humidity of the sample:

- the first component (green in Fig. 2) around 2750 nm is due to stretching vibrations of –OH groups in oxidized minerals, such as phyllosilicates.
Abundance and chemistry of phyllosilicates will vary with the extent of aqueous alteration. In particular, the metal-OH component will deepen and shift towards 2700 nm with increasing aqueous alteration [8]. The thermal cycle has no effect on this spectral component. This is expected as the dehydration of phyllosilicates occurs over 400°C while the heating in our experiment is at 250°C.

- the second component (blue in Fig. 2) around 3200 nm is due to –OH stretching vibrations within bulk water molecules. The amplitude and position of this component directly depends on the number of water molecules trapped between phyllosilicates sheets. With decreasing number of trapped water molecules, this component faints and shifts towards shorter wavelengths [9].

- the third component (purple in Fig. 2) around 2900 nm is due to –OH vibrations in adsorbed or mesopore water molecules, minimized thanks to acquisition under vacuum.

All studied samples showed the metal-OH and bulk water components/molecules. Half of them also presented traces of adsorbed water. The modification of the shape of the 3 μm band with temperature (see Fig. 1), from rounded to sharp, is explained by the disappearance of the adsorbed water component and the decrease and shift of the bulk water band, revealing the sharp and asymmetric shape of component related to -OH in oxidized minerals.

**Application to asteroids observations:**

reflectance spectra of 11 C-complex MBAs were selected from the AKARI AcuA survey [10]. The spectra of the two NEAs Ryugu and Bennu were digitalized from [2] and [1], respectively. Their 3 μm bands were processed similarly to those from chondrites. When comparing the position and amplitude of the different components, we found that all considered C-complex asteroids are consistent with hydrated surfaces similar to type 1 and 2 carbonaceous chondrites, as we expected. Some of the asteroidal spectra reveal the presence of bulk water molecules on the surface, other present signs of adsorbed water. Our analysis also showed that asteroids from the same type (C-, Ch-, Cgh,...) present metal-OH and water components of similar amplitudes and positions.

**Ryugu:** the reflectance spectrum of Ryugu shows a tenuous metal-OH component centered at 2720 nm, reflecting a heavy aqueous alteration of the surface. This is consistent with Ryugu being formed from an ice-covered parent body [11]. However, no water molecules, bulk or adsorbed, are detected on the spectrum. Given also the small amplitude of the metal-OH component, this would suggest a high-temperature episode (above 400°C) occurring after the heavy aqueous alteration, removing any water molecules however strongly trapped to the surface, and dehydrating the minerals.

**Bennu:** the reflectance spectrum of Bennu presents a metal-OH component consistent with strongly altered type 1 chondrites. This is in agreement with Bennu supporting affinity with CI and CM chondrites [12]. The 3 μm band also suggests traces of water molecules adsorbed to the surface of the small body. This adsorbed water could be linked to the newly discovered activity of the surface, as a cause or consequence.

**Conclusion:** Process at high temperature can strongly alter the reflectance spectra of surfaces, and drastically change the shape of the 3 μm absorption band. Laboratory measurements on meteorites under asteroid-like environment highlight the link between the different components of this feature and the aqueous alteration history of the sample. The same interpretation can be applied to asteroid telescopic observations to explain the strong difference between the 3 μm band detected on Ryugu and Bennu.

THE STRONG INFLUENCE OF VIEWING GEOMETRY AND SURFACE TEXTURE ON THE REFLECTANCE SPECTRA OF SMALL BODIES AND METEORITES

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Introduction: Reflectance spectroscopy is commonly used to analyse the composition of distant airless bodies. The spectral slope and absorption features, if detected, are characteristics of the mineralogy and structure of the surface. Several asteroids classifications are based on the shape of the reflectance spectra in the visible and near-infrared spectral range [1, 2].

It is established that the reflectance of a surface depends on the geometry under which it is measured. The first example being the photometric phase curves, presenting the general albedo as a function to the phase angle [3].

We propose to analyse the dependency of all the spectral characteristics (photometry, slope and absorption bands) with the observation geometry using bidirectional reflectance spectroscopy measurements.

Samples: Meteorites are the best accessible analogues of the Solar System small bodies. Their reflectance spectra match those of their parent bodies, and each of the different types represents a specific class of asteroids [4]. We chose several meteorites samples of different petrologies and alteration histories. All samples were manually ground but not sieved to keep a wide distribution of grain sizes. A few samples were large enough to perform a first bidirectional reflectance distribution function (BRDF) measurement on the intact rock. We also analysed a highly porous agglomerate of Ceres simulant resulting from a sublimation experiment [5].

Measurements: We used the home-made spectro-gonio radiometer SHADOWS [6] to analyse the chosen surfaces under 70 different geometrical configurations (incidence, emergence, azimuth angles). Spectra are acquired from 340 nm to 4200 nm every 20 nm, with a spectral resolution varying from 4.2 nm to 30 nm.

The measured reflectance is determined relative to measurements of calibrated Spectralon and Infragold reflectance targets.

Results: For each sample, we analyse the effect of the measurement geometry on all the characteristics of the reflectance spectra.

Photometry. The variation of photometry with the geometry is investigated through the BRDF. The BRDFs are plotted using a polar representation, where the angular position of the dot corresponds to the observation geometry of the measurement (at fixed incidence), and its distance from the center represents the measured value of the reflectance (see Fig. 1). Using this representation, the BRDF of a perfectly lambertian surface will appear as a semi-circle.

Figure 1: BRDF at 560 nm (out of any absorption feature) of an intact chip of Mukundpura compared to powdered samples of Mukundpura and Orgueil. Top panel: incidence 0°. Bottom panel: incidence 60°.

Figure 1 shows that the BRDF of a surface depends mostly on the texture of the surface, not its mineralogical composition. Two powders will present similar BRDFs behaviours with a strong backscattering, independently of its general albedo, but will differ from an intact bloc displaying a stronger forward scattering behaviour.

Spectral slope and reddening. The spectral slope is calculated as the ratio between the reflectance measured at two separated wavelengths outside of possible absorption features:

\[ \text{Slope} = \frac{R_{560\,\text{nm}}}{R_{800\,\text{nm}}} \]

A spectral slope greater than 1 suggests a rather red sample, while a slope smaller than 1 indicates a blue spectrum (see Fig. 2).

The spectral reddening represents the evolution of the slope with the geometry. It is calculated as the ratio between the slopes at a given phase angle \( g \) and at the smallest phase angle available (10° in our measurements).
In case of asteroids observation, a red slope is often linked to an irradiated surface. However, at wide phase angle, the observation geometry effect on the spectral slope can become as strong as the reddening by irradiation. When comparing textures, we found that powdered samples are typically redder than the intact chips [7].

Absorption features. The depth of the absorption bands is also geometry dependent. For each feature strong enough to be detected, the band depth is calculated as:

$$BD = 1 - \frac{R_{\text{band}}}{R_{\text{continuum}}}$$

with $R_{\text{band}}$ the reflectance of the sample at the center of the absorption feature, and $R_{\text{continuum}}$ the calculated reflectance of the continuum at the same wavelength. We considered a linear continuum between the two inflexion points of the band.

Conclusion: The bidirectional reflectance spectroscopy of a surface shows important variations with the observation geometry of the measurements. All characteristics of the spectra are impacted: the photometry changes according to the incidence and emergence angles, and with increasing phase angle, the measured spectra tend to become redder with shallower absorption features. The observation geometry strongly affects the shape of surface reflectance spectra and so has to be taken into account in the analysis of in situ or ground-based spectroscopy measurements.

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Ricochets and impulses on Asteroids. A. C. Quillen$^1$, J. South$^1$, E. Wright$^1$ and Randal Nelson$^2$. $^1$Dept of Physics and Astronomy, University of Rochester, Rochester, NY, $^2$Dept of Computer Science, University of Rochester, Rochester, NY

Abstract:
We describe laboratory experiment of impacts into dry polydisperse granular materials. In the first experiments we consider how an impact generated seismic pulse affects the surface distant from the impact site. In the second set of experiments we study non-round projectiles with low velocity encounters and at non-normal impact angles.

1. Experiments of impulses

Introduction:
Impact induced seismicity is important on small asteroids due to their low surface gravity and small volume which limits vibrational energy dispersal. Unfortunately, little is currently known about how impact generated seismic waves are excited, dispersed, attenuated and scattered in asteroids. The rapidly attenuated seismic pulse or 'jolt' model is consistent with strong attenuation in laboratory granular materials at kHz frequencies but qualitatively differs from the slowly attenuating seismic reverberation model that is sometimes assumed to account for large surface boulders on asteroids due to the Brazil nut effect.

Experiments of impulses from below:
We track the trajectories of particles ejected from the surface by a single strong upward propagating pressure pulse. High speed video images show that ejecta trajectories are independent of particle size, and collisions primarily take place upon landing. When they land, particles are ballistically sorted, leaving larger particles on the surface and smaller particles more widely dispersed. A single strong pulse can leave previously buried boulders stranded on the surface.

Summary
Boulder stranding due to an impact excited seismic pulse is an additional mechanism that could leave large boulders present on the surface of rubble asteroids such as 162173 Ryugu, 101955 Bennu and 25143 Itokawa.

2. Experiments of non-round projectiles into sand and at non-normal impact angles:

Introduction:
Spin off events and impacts can eject boulders from an asteroid surface and rubble pile asteroids can accumulate from debris following a collision between large asteroids. These processes produce a population of gravitationally bound objects in orbit that can impact an asteroid surface at low velocity, and because they are in orbit, at low or grazing angles with respect to the surface.

Experiments non-spherical projectiles at non-normal impact angles:
We carry out laboratory experiments of low velocity non-spherical projectiles (100-400 cm/s) at different impact angles into granular media. A projectile stops within its crater or rolls or bounces out of it, depending mostly on Froude number ($v^2/(gR)$). Our impact velocities have Froude numbers, 50 to 350 and this regime is relevant for 10m rocks on asteroids 101995 Bennu or 162173 Ryugu impacting the surface at velocities below the escape velocity.

We show the surface of a bowl of gravel that is hit a single time from below. Each panel shows a different time with time from impact increasing to the right. After particles are ejected off the surface, larger particles end up on top.
Fate of projectiles as a function of impact angle and impact velocity. There is a division between impactors that roll out of their impact crater and those that ricochet out of their crater. Very few remain in their crater after impact. Here the grazing angle is 90 degrees for a normal impact.

**Summary**
We find that very few low velocity projectiles stop near their site of impact. Because our lab experiments match the Froude number for 10m Boulders on Bennu, We propose that boulders perched on the surface of rubble asteroids such as Asteroid Bennu and Asteroid Ryugu could be the result of low velocity and low grazing angle impactors that ricocheted or rolled across the surface, finally coming to rest distant from their initial impact sites. The regime we study is also relevant for control of landers.
COORDINATED ANALYSIS OF A COMPACT TYPE-A CALCIUM-ALUMINUM-RICH INCLUSION IN THE NORTHWEST AFRICA (NWA) 5028 CR2 CHONDRITE: IMPLICATIONS FOR REFRACTORY INCLUSIONS TO BE RETURNED BY THE HAYBUSA2 AND OSIRIS-REx MISSIONS? T. Ramprasad1, P. Haeneecour2, T.J. Zega1,2. 1Dept. of Material Science and Engineering, University of Arizona, Tucson, AZ 86719, USA. 2Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 86721, USA. (tarunika@lpl.arizona.edu)

Introduction: Primitive asteroids are remnants of the early solar system, capable of providing insight into the various processes and environments prevalent at their time of formation. Sample-return missions such as Hayabusa2 and OSIRIS-REx (O-Rex) are dedicated to understanding the early solar system by analyzing pristine material recovered from their target asteroids Ryugu and Bennu [1,2]. Detailed understanding of the crystal structures and chemistries of the constituents of the return samples is vital to inferring the conditions prevalent in the early solar system. In order to better analyze and interpret data for samples from return missions, it is necessary to study the proxies currently available to us. One such proxy are calcium-aluminum-rich inclusions (CAIs), mm- to cm-sized objects found in primitive chondrites [3] and expected to be found in the samples returned by Hayabusa2 and O-Rex.

CAIs are composed of Ca- and Al-rich refractory materials that have been thermodynamically predicted and isotopically dated to be among the first-formed solids in the solar protoplanetary disk [4-7]. The structure and chemistry of these inclusions contain a record of the environments in which they formed and the processes to which they were subsequently exposed. Their analysis can help us better understand and constrain the early stages of solar-system formation.

While the components of CAIs are widely accepted to have initially formed via gas-phase condensation, multiple origins were proposed for the multilayer rims surrounding many of them [8-10]. Additionally, many CAIs are known to have experienced subsequent thermal and aqueous processing, resulting in changes to the morphologies, structures, and compositions of CAIs [11-13]. Here we present data on spinel and perovskite assemblages from the interior and rim of a CAI in the Northwest Africa (NWA) 5028 CR2 chondrite. Spinel and perovskite were chosen because they are materials that have been thermodynamically predicted to form at high (~1300 K) temperature [4,5], and so are probes of nebular condensation.

Sample and Analytical Techniques: A compact type-A (CTA) CAI (TR01, Fig. 1) was identified in a thin section of the NWA 5028 (Center for Meteorite Studies, Arizona State University collection #1845-5) using a Cameca SX-100 electron microprobe, located at the Lunar and Planetary Laboratory (LPL), University of Arizona. Wavelength-dispersive spectroscopy (WDS) maps and backscattered electron images (BSE) of the CAI were acquired. We identified assemblages of spinel and perovskite in both the interior and rim of TR01 for more detailed studies using transmission electron microscopy (TEM).

Four regions (Fig. 1) were extracted, and thinned to electron transparency (~100nm) using previously described methods [14] with a FEI Helios NanoLab 660 focused-ion-beam (FIB) scanning electron microscope (SEM) located at LPL. The sections from the CAI were analyzed using a 200 keV spherical-aberration-corrected Hitachi HF5000 scanning transmission electron microscope (STEM) located at LPL and the Hitachi SU9000 30kV SEM/STEM, formerly located at LPL. The HF5000 and SU9000 are both equipped with Oxford Instruments (X-max) energy dispersive X-ray spectroscopy (EDS) detectors. Selected-area electron-diffraction (SAED) patterns were acquired for determination of crystallinity and phase.

Results: The mineralogy (80 to 85 vol% melilite, 15 to 20 vol% spinel, and 1 to 2 vol% perovskite) and rounded morphology of the inclusion are consistent with previous descriptions of CTA CAIs [15]. Several spinel-perovskite assemblages were chosen to sample the heterogeneity of the CAI.

TEM reveals the detailed microstructure and composition of the CAI phases. FIB section #1 (interior) consists of a spinel grain with a silicate-perovskite inclusion and a perovskite grain. It does not show any signs of alteration [16]. FIB section #2 (rim) consists of three perovskite grains (one with a spinel inclusion and another with a hibonite inclusion) embedded in a large spinel grain, and contains veins and rims around the grains of material with compositions consistent with Fe-rich silicates [16]. The Fe-silicates have needle-like morphologies and occur in crosslinked patterns. FIB section #3 (interior) consists of two spinel grains and a perovskite grain partially surrounded by a
Ca-Al silicate phase with regions rich in Cl, as seen from the high-angle annular-dark-field (HAADF) image and energy-dispersive spectroscopy (EDS) maps (Fig. 2) [17]. FIB section #4 (rim) consists of a perovskite grain between two spinel grains.

Discussion: The condensates in CTA CAIs are thought to have experienced some amount of thermal processing. The evidence for such processing includes: their rounded morphology, inward zoning of Åkermanite content, lathic melilite, and symplectite morphology [18]. Except for the rounded morphology of the CAI, TR01 lacks these characteristics, suggesting that the interior of TR01 was not significantly affected by thermal processing. Below we explore signatures of nebular condensation and secondary alteration.

According to equilibrium thermodynamic calculation that model a cooling gas of solar composition, perovskite condenses at 1593 K, whereas spinel forms at 1397 K [2]. Therefore, the presence of the perovskite inclusion within the spinel grain in section #1 (interior) is consistent with these predictions. In comparison, the spinel inclusion within the perovskite grain in section #2 (rim) is not consistent with these predictions. The hypotheses for rim formation include condensation [8], melt solidification [9], and evaporative residues [10]. The sequence of minerals seen in the rim is consistent with that listed in [9] as being evidence of melt solidification. Further, recrystallization experiments conducted on CAI melts show that spinel solidifies before perovskite [19]. The microstructure that we observe in section #2 (rim) is consistent with a formation through melt solidification.

NWA 5028 is a CR2 chondrite and it contains evidence of aqueous alteration, in the form of secondary phases such as hydrated minerals in the matrix and CAIs [20,21]. TR01 also shows clear signs of fluid flow [22]. Moreover, their morphology and Ferich composition are similar to Fe-rich phyllosilicates previously described as products of aqueous alteration [13]. In comparison, section #4 (rim) shows no signs of alteration. Section #3 (interior) contains Cl-rich silicate regions. Chlorine is a highly volatile element and its incorporation into the inclusion is consistent with low-temperature processing, e.g. [23]. Thus, we hypothesize that these Cl-rich regions are remnants of low-temperature iron-alkali-halogen metasomatism such as those described by [13,22]. The data point towards a complex history involving equilibrium condensations and non-uniform secondary processing.

Studies have shown that the spectral properties of Bennu and Ryugu are similar to CM chondrites [24,25]. CM chondrites have experienced alteration and the CAIs found in them contain mineral phases consistent with aqueous processing [3,22]. Therefore it is possible that any CAIs found in samples from Hayabusa2 and O-Rex missions experienced alteration. Consequently, understanding of the evolution of meteoritic samples will aid in the interpretation of asteroid evolutions through the study of samples from Hayabusa2 and O-Rex.

Fig 2. TEM data on FIB section #3. HAADF image (top); EDS maps(bottom).


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OVERVIEW OF CM CHONDrites IN THE US ANtarctic METEORITE COLLECTION:
IMPLICATIONS FOR UNDERStANDING BENNU AND RYUGU. K. Righter, NASA-JSC, Mailcode XI2, 2101 NASA Pkwy, Houston, TX 77058; kevin.righter-1@nasa.gov; D. S. Lauretta, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

Introduction: Spectral and remotely sensed data from Bennu and Ryugu share some common properties with CM chondrites. First, they contain evidence for the presence of magnetite. Second, they contain ample evidence for hydration features such as the 2.7 micron feature. Finally, the asteroids and the CM chondrites all have very low reflectance typical of dark and volatile-bearing material [1-3]. Spectral studies of the target asteroids of the OSIRIS-REx and Hayabusa2 missions - Bennu and Ryugu - have included comparisons to several samples from the US Antarctic meteorite collection including MET 00639 (CM2), MET 01072 (CM2), ALH 83100 (CM1/2), and LAP 02277 (CM1) [1-3]. The fact that these four samples provide insight into understanding these asteroids leads one to wonder what carbonaceous chondrites (CCs) are represented in the US collection and if there are others that might also be helpful for comparison? Here we focus on the CM chondrites which may serve as an important resource to the missions.

CM chondrites: There are 344 CM chondrites in the US Antarctic meteorite collection (Figure 1), including large pairing groups from the ALH, EET, LEW, LAP, MET, MIL, and QUE dense collection areas. The mineralogy of CM2 chondrites is fine grained and difficult to study using standard optical microscopy, but x-ray diffraction studies indicate their major mineralogy is cronstedtite, olivine, pyroxene, calcite, magnetite, and sulfide [4-5]. CM1 chondrites are more rare in the collection, typically of small size (<10 g), and have Mg-rich serpentinite forming at higher degrees of aqueous alteration. The transitional CM1/2 represent intermediate degrees of aqueous alteration. There are some intriguing correlations among some mineralogic, chemical, and isotopic indicators. For example, the most altered CMs should have higher water contents and they do [6]. If a common water source is causing aqueous alteration, then there should be O and H isotopic correlations with alteration; these trends are less clear [6], but also suffer from a small number of analyses compared to the number of samples available. Linking sample measurements with spectral features being measured at Bennu and Ryugu is possible and has led to correlations [7].

Despite the lack of clear trends for all samples, a subset of samples in the US collection helps to define general and overall trends indicative of the processes leading to mineralogic and compositional diversity within the CM chondrites. However, such assign-ments are tentative and incomplete due to several key issues such as uncertain pairing relations, sample heterogeneity, brecciation, and small sample size and friability (especially given the evidence for brecciation on Bennu), and the recognition of anomalous CMs that might represent additional processes at work on the CM parent body (see below). In general, both sample measurements and spectral studies must acknowledge and recognize these challenges and work to overcome them to make progress in understanding CMs and potential links to Bennu and Ryugu. This might also lead to resolution of the debate between open and closed processes on the CM parent asteroid(s) [8,9].

CM or ungrouped carbonaceous chondrites: CM anomalous or ungrouped chondrites share spectral features with Ryugu, which has a small hydration peak arguably due to hydrated minerals left after either impact heating or shock in carbonaceous chondrites [3]. PCA 91008, PCA 02012, GRO 95566, and LEW 85311 are all CMs that have experienced heating or metamorphism that may be due to impacts, solar radiation, or radiogenic decay [10]. These samples may hold clues to understanding the mineralogy of Ryugu, or interpretations of its spectral properties. On the other hand, WIS 91600 appears to be related to several other highly altered CM [10]; an understanding of this grouplet will also aid in the interpretation of Bennu samples which have a strong hydration features.

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Figure 1: Carbonaceous chondrites in the US collection.
ANALYSES OF BRIGHT CLUSTERS DETECTED AT THE SURFACE OF RYUGU. L. Riu\textsuperscript{1}, T. Nakamura\textsuperscript{2}, E. Tatsumi\textsuperscript{3}, C. Sugimoto\textsuperscript{3}, S. Sugita\textsuperscript{3}, K. Kitazato\textsuperscript{4}. \textsuperscript{1}ISAS/JAXA, Sagamihara, Japan (riu.lucie@jaxa.jp), \textsuperscript{2}Tohoku University, Sendai, Japan, \textsuperscript{3}University of Tokyo, Tokyo, Japan, \textsuperscript{4}Aizu University, xx, Japan.

Introduction: The Hayabusa2 spacecraft has been hovering close to asteroid (162173) Ryugu for more than a year [1]. Numerous information has been gathered from orbit and \textit{in situ} regarding the asteroid surface properties. Namely, the NIRS3 instrument, which operates between 1.8 and 3.2 µm, showed that the spectral properties in this range and as seen from orbit, are very homogeneous. Ryugu surface presents a low albedo (~1.4% on average) and a sharp 2.72 µm absorption feature, that is detected globally at the surface [2]. The visible camera ONC-T onboard Hayabusa2 reported the several spots extraordinary brighter than the average [3]. It is expected that NIRS3 can find bright regions with closer, higher resolution, and multiple time observations even if it seems homogeneous from the one global observation by [2]. Here we report the bright regions observed by NIRS3.

Dataset: We propose here to do a systematic analysis of the NIRS3 spectra that displayed high albedo value in order to characterize, from orbit, large bright areas at the surface of Ryugu. We use thermally and photometrically corrected NIRS3 near infrared spectra. The photometry correction is still subjected to change due to refinement on the spacecraft geometry information. The uncertainties on albedo based on the improvement in incidence and emergence angles values are under study. However, first order analysis comparing different sets of photometrically corrected data showed that the bright areas on Ryugu are consistently located on the equatorial ridge (see previous map in [4]). The methodology for our study is as follows, we extract for each day of observation the 10 brightest spectra (based on the albedo value at 2 µm), corresponding to a total of 420 “bright” spectra associated to the 42 observations campaigns from the end of June 2018 to end of February 2019, which include the resolution from ~40 m to ~10s cm/pixel. The data acquired after February 2019 still needs geometrical information before being added to this analysis. In order to ensure that the detected bright spots correspond to actual brighter areas consistently, we regrouped the bright spectra into clusters of spectra. We defined a cluster if more than 10 spectra, of at least 2 different days of observation, falls within the same area within a 8° x 8° grid on the asteroid surface. The majority of NIRS3 observations are acquired with a resolution of 40 m per pixel which roughly corresponds to 8° at the equator.

Figure 1 - Preliminary map of bright clusters on the surface of Ryugu. Each color is associated to one day of observation. The approximate size of the NIRS3 spot size, based on spacecraft altitude, corresponds to the size of the boxes on the map.
Results: We found a total 7 clusters, all located on the equatorial ridge (see Figure 1). The clusters are composed of 11 at minimum (cluster #1) and 39 at maximum (cluster #5) spectra. Note that among the 42 observations used for this analysis, 31 of them only covers the equatorial ridge regions. Observing the bright clusters gathered on the equatorial ridge may thus be a biased from the observation campaigns. Only two of the clusters have an “average” resolution < 30 m and include high resolution spectra (clusters #2 and #6). All other clusters are low resolution spectra, which would mean that they represent a rather big area on Ryugu’s surface (on average ~ 40 m x 40 m). The clusters are relatively concentrated on the western bulge. This is consistent with slightly brighter nature observed by ONC-T [5].

For each cluster, we evaluate the spectral variations, albedo, band depth characteristic (at 2.72 μm), slope (between 2.0 and 2.2 μm) and resolution of observation. We also evaluate the variation of these values amongst each cluster by calculated the standard deviation on all spectra within a cluster (represented as error bars on Figure 2). The highest albedo found in a cluster is ~2.2% (cluster #2). The cluster #2 is located at the rim of the largest crater Urashima. The fluffiness and less porosity of the crater rim may explain the brightness on this region.

All clusters present average albedo greater than 2% (Figure 2b), although the latest photometry correction provides an average albedo at standard condition on the overall surface > 1.9% in comparison with older dataset that provided an average albedo < 1.7 %. We observe a possible correlation between the slope and the band depth at 2.72 μm (Figure 1a), which seems to show a decrease in the band depth (i.e. less hydrated spectra) with increasing slope (i.e. redder spectra), with the exception of the cluster #1. No clear correlation is observe between the average albedo and the average slope (Figure 2b), which is observed in visible wavelength by ONC-T [5].

The next step of this study will be to combined those results with the ONC visible camera images [4] to access the geomorphological features at the defined clusters locations and understand the spectral variations observed with NIRS3 and to combine and compare the spectral variations observed in the near-infrared with the variations observed in the visible to be able to contribute to the story of Ryugu’s formation and evolution.

THE MULTI-ASTEROID ENCOUNTER TOUR WITH IMAGING AND SPECTROSCOPY (MANTIS).
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The Multi-Asteroid eNcounter Tour with Imaging and Spectroscopy (MANTIS), proposed to the 2019 Discovery mission competition offered by NASA, is a flyby grand tour encountering 14 asteroids covering a wide range of types and masses, and obtaining remote sensing and in-situ data with a powerful multi-instrument payload.

Introduction and Motivation: The asteroids preserve information from the earliest times in solar system history, with compositions in the population reflecting the material in the solar nebula that experienced a wide range of temperatures. Today they experience ongoing processes, some of which are shared with larger bodies but some of which are unique to their size regime. They are critical to humanity’s future as potential threats, resource sites, and targets for human visitation. However, over 25 years since the first spacecraft encounters with asteroids, they remain poorly understood and seldom visited.

A flyby tour of asteroids is an effective means of quickly sampling many members of this population of objects, providing discovery science on a large number of small worlds in the inner solar system and also returning data that is complementary and contextual to past, present, and future missions. While the overwhelming numbers of small bodies makes the prospects of visiting a representative sample of asteroids daunting, recent work suggests that the vast majority of objects in the asteroid belt may be derived from a small number of 100-km-scale parent bodies [1, 2], which then collisionally evolved to created today’s population. Focusing on family members makes it possible to effectively visit the objects responsible for most of the impactors in the inner solar system and the meteorites that fall to Earth, and providing ground truth for extensive observations conducted from Earth.

Targets: The MANTIS tour, as noted, visits 14 asteroids. The largest of these is 50 Virginia, an 85-km Ch-class asteroid that is consistent with an intact planetesimal in the “born big” scenario [3]. The smallest is the Mars Trojan 2011 UB256 which is ~300 m in diameter. Other objects of especially notable individual interest are the multiple system 1993 QO and a member of the Gersuind family, whose members tend to be in the unusual L spectral class [4].

In addition to these objects of particular interest, the MANTIS tour is designed to focus on members of asteroid families. The trajectory goes past members of eight known collisional families (including objects already mentioned) of different spectral classes and in different parts of the asteroid belt. This allows robust comparisons of surface properties and active processes among objects within families, between families thought to have similar compositions, and between families with dissimilar compositions. It also provides for a test of the homogeneity of family members via remote sensing, how objects change between their original parent bodies and arrival at Earth as meteorites, and how representative family members are of their parent bodies.

Payload: MANTIS has a payload of four instruments, allowing comprehensive characterization of the objects it encounters. In contrast to all previous asteroid flybys to date, which encountered asteroids en route to other objects, the MANTIS payload is optimized for asteroid flybys. These instruments include a powerful narrow-angle camera similar to that onboard the New Horizons spacecraft and planned for inclusion on the Double Asteroid Redirection Test (DART) and Lucy spacecraft, a near-infrared imaging spectrometer similar to the CRISM instrument onboard the Mars Reconnaissance Orbiter, a mass spectrometer analyzing microsamples shed by asteroids and interplanetary dust particles encountered during cruise, and a mid-infrared camera measuring thermal emission and built by colleagues in the United Kingdom.

Summary: The mission we present, the Multi-Asteroid eNcounter Tour with Imaging and Spectroscopy, explores the diversity of asteroids to understand our solar system’s past history, its present processes, and future opportunities and hazards. The MANTIS tour visits 14 unexplored asteroids, including an intact planetesimal, a Mars Trojan asteroid, a low-albedo multiple-asteroid system, and members of 8 collisional families. MANTIS addresses many of NASA’s highest priorities as laid out in its 2014 Science Plan and provides additional benefit to the Planetary Defense and Human Exploration communities via a low-risk, cost-effective tour of the inner asteroid belt. MANTIS would revolutionize our understanding of asteroids through its state-of-the-art payload of com-
plementary instruments. MANTIS obtains datasets at each target that can be readily intercompared with one another, effectively doubling the current sample of asteroids visited by spacecraft.

We will discuss the MANTIS concept as proposed to the 2019 Discovery competition.


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THE FREQUENCY OF PUTATIVE FALBACK PARTICLES ATOP BENNU’S FIELDS OF BRECCIATED BOULDERS. B. Rizk⁰¹, M. Pajola⁰², K.J. Walsh⁰³, E.B. Bierhaus⁰⁴, D.N. DellaGiustina⁰¹, C. Y. Drouet d’Aubigny⁰¹, D.R. Golish⁰¹, E.R. Jawin⁰⁴, M. Delbo⁰⁶, R.-L. Ballouz⁰¹, J.L. Molaro⁰¹, C.A. Bennett⁰¹, K.N. Burke⁰¹, P. Michel⁰⁶, L. Lim⁰⁸, J.P. Dworkin⁰⁹, H. Campins¹⁰, H.C. Connolly, Jr.¹⁰,¹¹, T.J. McCoy³, M.G. Daly¹¹, M.C. Nolan¹, D.S. Lauretta¹, ¹Lunar and Planetary Laboratory, 1415 N. Sixth Ave., University of Arizona, Tucson, AZ, USA 85705, (bashar@LPL.arizona.edu), ²INAF-Astronomical Observatory of Padova, Vic. Osservatorio 5, 35122 Padova, Italy, ³Southwest Research Institute, Boulder, CO, USA, ⁴Lockheed-Martin Space Systems, Littleton, CO, USA, ⁵Smithsonian Institution, National Museum of Natural History, Washington, DC, USA, ⁶Observatoire de la Côte d’Azur, Nice, France, ⁷Planetary Science Institute, Tucson, AZ, USA, ⁸NASA Goddard Space Flight Center, Greenbelt, MD, USA, ⁹University of Central Florida, Orlando, FL, US, ¹⁰Department of Geology, Rowan University, Glassboro, NJ, USA, ¹¹York University, Toronto, Canada

Introduction: Cobbles and pebbles perched on boulder surfaces that exhibit orientations and albedos divergent from the underlying boulder’s texture and brightness is a novel feature of Bennu’s boulder diversity. This phenomenon, dubbed ‘rocks-on-rocks’ by the mission team, has been recorded by the OSIRIS-REx Camera Suite (OCAMS) PolyCam and MapCam imagers since high-resolution imaging began in early 2019 [1][2][3][4]. Here, we interpret their origin as either (a) inclusions revealed by weathering or (b) externally sourced material that has landed on the boulder surface as particulate fallback. Bennu’s surface geology supports both possibilities (Figure 1, A and B). The two phenomena may be related if ejection of particles from one boulder provides the source material for another boulder’s fallback. The latter interpretation is recently motivated after particles ejected from Bennu’s surface were observed to fall back to the asteroid’s surface [5]. Here, we report a preliminary census and salient observations about putative fallback particles relative to exhumed inclusions with a goal of constraining both particle ejection and exhumation mechanisms.

Classification: Based on our counts, roughly two-thirds of boulders on Bennu are dark, brecciated, seemingly friable, and host inclusions. Many of these boulders are strongly weathered and exhibit clast shedding at various stages of completion (Figure 2, A-H). The texture of these cauliflower-like boulders appears to amalgamate brighter, angular, harder clasts within a darker, softer matrix. A set of several thousand high-resolution images—gathered mostly during the Orbital A and Orbital B global campaigns—has captured this process at various stages of its life cycle. Paradoxically, such extensive fragmentation makes it challenging to positively identify potential fallback particles.

We employed 8 criteria, [6], that analyzed weathering, reflectance, shadowing, alignment, morphology, discoloration, clustering and proliferation in order to...
divide candidate fallback and inclusions into either category. We estimated that in a sampling of almost 5000 meter-to-several meter–sized boulders some 5%, or almost 250 boulders, host pebbles and cobbles that could be classified as fallback particles. The rest—or 95%—host evident inclusions, i.e., clasts that began life embedded within the underlying boulder matrix and are now mechanically separated.

**Figure 2:** High-resolution high-phase-angle PolyCam images displayed in order of decreasing exhumation, clast shedding and textural weathering CCW starting from upper left. Image information (name, phase angle, scale (cm/pix), lon, lat & CW angle to North direction (°)): A) 20190711T092848S026_pol, 90.6, 0.9, 221, -82, 278, B) 20190718T081041S737_pol, 90.7, 0.9, 108, 69, 83, C) 20190802T095005S980_pol, 84, 0.9, 212, 23, 269, D) 20190713T101830S351_pol, 88, 0.9, 122, -47, 85, E) 20190225T200127S887_pol, 92, 2.4, 120, 52, 286, F) 20190715T002243S946_pol, 91, 1.0, 130, -46, 271, H) 20190711T124030S145_pol, 88, 0.9, 122, -47, 85

**An Active Asteroid:** One of the most exciting discoveries at Bennu, in its status as both a carbonaceous and a microgravity body, has been its evidently still active geology [5]. Several physical mechanisms seem plausible enough to be considered as capable of ejection of particles from Bennu’s surface: micrometeoroid impacts, thermal cracking and abrupt pressure release from phyllosilicate dehydration ([7][8][9][10][11]). Images of evident micrometeoroid impacts are recorded in smooth boulder faces all over Bennu [7]. Images of cracking, both linear and network-like, abound [8]. And many of the darker boulders show pits that match the shape of nearby cobbles and grains that may have started out as clasts within these same boulders. These observed morphologies support the above mechanisms—micrometeoroid impact, thermal cracking and abrupt bound-water-driven release—respectively. The signature of electrostatic lofting has not been observed, despite searches during the Detailed Survey Equatorial Station campaigns of May 2-3 & 30, 2019, but the observation is a difficult one, and there is yet no observational reason to discount this mechanism.

In addition, all of these mechanisms may act in concert. For example, thermal stress may prepare a boulder to explosively release its clasts when struck by a micrometeoroid or may lower the pressure required to abruptly decompose a boulder [5]. Decomposing boulders could be more likely to retain fallback particles because their pitted, cracked surface provides more mechanical purchase for the particles to cling. In addition, the presence of externally-sourced clusters of particles may indicate that the process of impact (or ejection) fragments the external particles.

We hope to provide support for one or more of these, or any other, mechanisms in the observations of the morphologies of the putative fallback particles.


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SHAPE, SPIN, STRENGTH, AND STABILITY OF BENNU. J.H. Roberts¹, O.S. Barnouin¹, G.A. Neumann², M.C. Nolan³, M.E Perry⁴, R.T. Daly⁵, C.L. Johnson⁶, M.M. Al Asad⁷, M.G. Daly⁸, E.E. Palmer⁹, J.R. Weirich², K.J. Walsh⁵, D.J. Scheeres⁶, J.W. McMahon⁶, D.S. Lauretta¹, ¹The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA; ²NASA Goddard Space Flight Center, Greenbelt, MD, USA; ³Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA; ⁴Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, Canada; ⁵Planetary Science Institute, Tucson, AZ, USA; ⁶The Centre for Research in Earth and Space Science, York University, Toronto, Ontario, Canada; ⁷Southwest Research Institute, Boulder, CO, USA; ⁸Colorado Center for Astrodynamics Research, University of Colorado, Boulder, CO, USA.

Introduction: Images of asteroid (101955) Bennu acquired by the OSIRIS-REx mission [1,2] reveal a rocky world covered in rubble, including numerous boulders with diameters up to tens of meters. The geologic evolution of Bennu is driven in large part by downslope migration of surface material [3] and rubble, which may be dislodged from an initial state by a number of processes, such as YORP-induced spin-up [4,5], re-accumulation [6,7], impact-induced seismic shaking, thermal stresses, or tidal disruption by close encounters with larger bodies.

Shape: Shape models of Bennu have been developed from images using stereophotoclinometry (SPC) [8] and from lidar data collected by the OSIRIS-REx Laser Altimeter (OLA) [9,10]. A SPCOLA shape model derived from a combination of both datasets is shown in Figure 1. A spherical harmonic decomposition of the shape (Figure 2) reveals a number of interesting features, which can be used to interpret the geological significance of the shape. The zonal terms show a sharp dichotomy between the odd and even terms, which is indicative of symmetry about the equator. These zonal terms also are particularly strong at degrees 2 and 4. Figure 3a,b shows a reconstruction of the SPcola shape model from the spherical harmonics, truncated at degree 4. The zonal component at degree-4 is largely due to the equatorial ridge typical of top-shaped asteroids, and the strong sectoral component reflecting high-standing longitudinal ridges, which are most obvious as a “squarish” outline as viewed from the poles [10].

Figure 2: Spherical Harmonic decomposition of Bennu’s global topography.

Figure 3c,d extends the reconstruction out to degree-8, to show the next level of detail. The next pair of spikes shown in the zonal terms at degrees 6 and 8 in Figure 2, are indicative of the terraces (Barnouin et al., 2019). The larger craters are noticeable in the degree-8 shape model as well. We also note that the tesselar terms decay much more slowly than the Vening-Meinesz style power law [11] would predict, suggesting the fractal nature of the size distribution of the surface of the rubble.

Internal properties: The large-scale surface topography may also provide insight as to the strength of the interior. Although Bennu appears to be an unconsolidated rubble-pile asteroid, it cannot be completely strengthless because the shape deviates from a hydrostatic surface. Indeed, there is no hydrostatic shape that is consistent with Bennu’s observed rotation rate and density, and it must be supported either by internal friction or cohesion. In the absence of cohesion, an angle of internal friction of 18° is necessary to maintain the current shape against large-scale failure, flattening, and potential disruption (Figure 4) [10]. This could also be achieved by ~ 1 Pa of cohesion [12].

Stability: Previous analysis of the shapes and spins of small bodies indicate that these properties will gradually evolve towards a condition of maximum topographic stability; that is, a state of low topographic variation, low slopes, and low surface erosion (mass-
wasting) rates. However, Bennu is already rotating faster than the optimum rate for this stability condition, and the YORP effect is further increasing the rotation rate. Rotational stability analysis demonstrates that an internal friction angle of at least 18° is necessary to prevent Bennu from failure via mass wasting in the absence of cohesion. However, if the observed increase in rotation rate [12] persists, in less than 0.6 Myr, no amount of internal friction would be sufficient to prevent failure, and significant cohesion (>15 Pa) would be required. We note that catastrophic disruption due to YORP spin-up is extremely unlikely. As the asteroid begins to deform, the increased oblateness results in a higher moment of inertia, and would cause the asteroid to spin down, potentially moving it into a stable regime. Moreover, YORP can change on short timescales, and is very sensitive to the precise shape of the body. Thus, the deformation of the asteroid may be halted after a small episode of failure. A more comprehensive evolution of the deformation and spin rate [13] is under investigation.

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THERMAL INERTIA AND SURFACE ROUGHNESS MAPS OF (101955) BENNU FROM OSIRIS-REX INFRARED OBSERVATIONS. B. Rozitis1, J. P. Emery2,3, A. Ryan4, P. R. Christensen5, V. E. Hamilton6, A. A. Simon7, D. C. Reuter7, B. E. Clark8, M. Delbo9, E. S. Howell4, L. F. Lim10, M. C. Nolan4, H. C. M. Susorney10, K. J. Walsh10, and D. S. Lauretta4. 1Open University, Milton Keynes, UK (benjamin.rozitis@open.ac.uk); 2Northern Arizona University, Flagstaff, AZ, USA; 3University of Tennessee, Knoxville, TN, USA; 4Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA; 5Arizona State University, Tempe, AZ, USA; 6Southwest Research Institute, Boulder, CO, USA; 7NASA Goddard Spaceflight Center, Greenbelt, MD, USA; 8Ithaca College, Ithaca, NY, USA; 9Observatoire de la Côte d’Azur, Nice, France; 10University of British Columbia, Vancouver, Canada.

Introduction: Asteroid (101955) Bennu is the target of NASA’s OSIRIS-REx mission, which will return a sample of ≥60 grams of regolith from its surface [1]. Before picking up the sample from the surface, OSIRIS-REx will have spent more than a year characterising the surface with cameras, spectrometers, and the laser altimeter that are onboard the spacecraft. The primary data set used for thermophysical analyses are thermal spectra from the OSIRIS-REx Thermal Emission Spectrometer (OTES) [2]. Additionally, the long-wavelength end of spectra obtained by the OSIRIS-REx Visible and Infrared Spectrometer (OVIRS) is also dominated by thermal emission [3].

From the Approach phase of the mission, disk-integrated data returned by OTES and OVIRS confirmed the previous Spitzer-based thermal inertia measurement of Bennu [4]. In particular, a thermal inertia of 350 ± 20 J m⁻² K⁻¹ s⁻¹/² and a surface roughness RMS slope of 43 ± 1° were derived from OSIRIS-REx thermal emission lightcurves and the updated shape model of Bennu [5]. These observations also found no significant variations in thermal inertia, or surface roughness, with rotational phase.

While the Approach-phase observations rule out large hemispheric differences in thermal inertia, they do not rule out smaller-scale variations. During the Detailed Survey phase of the mission, OTES and OVIRS measured the infrared radiation from the surface at ~20- to ~40-m spatial scales, enabling us to produce detailed maps of thermal inertia and roughness for the entire surface of Bennu. Such maps will aid in the interpretation of local variations seen in the geology and/or composition on the surface of Bennu, and also in generating detailed Yarkovsky and YORP effect predictions for Bennu.

Observations and Methods: During the Detailed Survey phase, OTES and OVIRS observed the surface of Bennu at seven different local times of day (see [6] for more details). We carried out thermophysical analysis of this data by using a custom thermal model that is based on the Advanced Thermophysical Model of Rozitis and Green [7,8,9]. See Figure 1 for an example comparison between observed and fitted brightness temperatures for the Nightingale candidate sample site.

Results: An analysis of OTES data collected from all seven local times of day finds definitive spatial variations in thermal inertia and surface roughness (see Figure 2). In particular, local thermal inertia values range from ~200 to ~400 J m⁻² K⁻¹ s⁻¹/² with a global average thermal inertia value of ~300 J m⁻² K⁻¹ s⁻¹/². Similarly, local surface roughness values range from ~30° to ~50° RMS slope with a global average surface roughness value of ~40° RMS slope. These results and spatial variations were checked for consistency by per-
forming an independent analysis using the OVIRS data, and we found an excellent agreement between the OTES- and OVIRS-derived results.

**Discussion:** Unexpectedly, the lowest thermal inertia values are associated with the largest boulders on Bennu, and the highest thermal inertia values are found in association with regions lacking large boulders (see Figure 2a). This unexpected result prompts a re-evaluation of the interpretation of thermal inertia for small rubble-pile asteroids, and provides insight into the nature of the unusual boulders found on the surface of Bennu [10]. Interestingly, we find a strong trend of increasing thermal inertia with increasing Bond albedo [11], which suggests that the brighter boulders have different physical and/or compositional properties to the darker boulders found on Bennu.

Spatial variations in surface roughness appear to correlate with the spatial density of large boulders resting on the surface of Bennu (see Figure 2b). Similar to thermal inertia, we also find a strong trend of decreasing surface roughness with increasing Bond albedo, which might be explained by the different textures expressed on the surfaces of the bright and dark boulders.

The excellent agreement between the model (i.e. which assumed a constant thermal inertia value with depth) and the brightness temperature data (see Figure 1) suggests the lack of a substantial global dust layer, which is consistent with independent analysis of spectral data of Bennu [12]. In particular, dust layers as thin as 10-100 μm would significantly affect the shape of diurnal temperature curves [13] but we do not see any signatures of this in the temperature data of Bennu. However, very thin layers and/or mono-layers of dust cannot yet be ruled out until more sophisticated 3D heat conduction models are applied to the temperature data of Bennu [14].

Finally, we used the thermal inertia and surface roughness maps to produce a detailed estimate of the Yarkovsky accelerations acting on Bennu throughout its orbit. By comparing to the observed Yarkovsky semi-major axis drift rate [15], we were able to estimate the bulk density of Bennu to be within ~1% of that determined by radio science [16]. This Yarkovsky result demonstrates the high accuracy to which we have measured, and subsequently modeled, the thermal emission from Bennu.

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**References:**
THE FALL AND TERRESTRIAL ALTERATION OF THE IVUNA (CI1) METEORITE: UNDERLINING THE IMPORTANCE OF WELL-CURATED SAMPLE RETURN. S. S. Russell1, N. V. Almeida1 and A. J. King1 1Department of Earth Sciences, The Natural History Museum, Cromwell Road, London, SW7 5BD, UK (sarr@nhm.ac.uk)

Introduction: The most chemically-pristine group of meteorites are the CI carbonaceous chondrites. There are five CI meteorite falls (Alais, Orgueil, Tonk Ivuna and Revelstoke), plus our Antarctic finds which are listed in the Meteoritical Bulletin as CI [1], but likely form a separate group, coined the CYs [2]. Of the falls, the type specimen Ivuna is the most recent that is of significant mass (> 10g).

The detection of magnetite on Bennu [3] suggests a possible association with CI chondrites, as these meteorites contain up to 10% magnetite, more than any other meteorite group [4] (although this mineral may also be from space weathering of CMs[3]). Therefore the CI chondrites may be used as an analogue for the OSIRIS-REx returned sample, for curation preparation purposes.

In this abstract we summarize details of the fall of Ivuna and describe how it has changed while it has been on the Earth’s surface, with the aim of providing lessons learned for the curation of carbonaceous chondritic material returned from space. There has been previous work on the terrestrial alteration of Orgueil, demonstrating that this meteorite is highly susceptible to terrestrial oxidation [5, 6] but no similar studies have been reported on Ivuna, for which we have multiple pieces of the same stone at the Natural History Museum (NHM), London, with separate and distinct curation histories. As the most recent fall of significant size, we postulate that Ivuna is likely to be less severely affected by terrestrial processing than other available CI. A more detailed account of this project, including new bulk element data for Ivuna, is currently under review [7].

The Fall of Ivuna and appearance post-fall:

Ivuna fell at 5:30pm on 16th December 1938 on the western shore of Lake Rukwa, near the Ivuna salt pans in Tanzania. One stone of 704.5g was recovered at the time, with reports that two other stones fell into nearby sandy soil but were not reported recovered. The recovered mass fell into the branches of a tree, from where it was collected the following day [8].

The first description of Ivuna was by Oates in 1941 [8] who states: “The stone has a bituminous or coaly appearance but micro-slides do not reveal any notable structure. The stone contains sporadic blebs of nickel-iron”. A sketch of the meteorite soon after its fall is shown in Fig. 1.
conditions. A subsampling of this stone was conducted in 2012, to separate pieces for allocation to research requests without needing to repeatedly expose the main mass. The fragments removed have been kept in microenvironments since; they are stored in glass vials, aluminium foil or polyethylene (depending on their size and friability), heat-sealed in an Escal barrier film enclosure, with oxygen, corrosive gas and moisture scavengers (Mitsubishi RP-A system). The other samples of Ivuna are stored as is typical for carbonaceous chondrites of our collection: double-bagged in polyethylene within in acid-free cardboard trays, in glass-topped drawers, in wooden cabinets. This all serves to prevent contamination, but also to buffer the temperature and relative humidity against changes in the local environment. All materials have been approved for long-term curation use by our conservation team, i.e. have been tested for off-gassing and subjected to accelerated degradation experiments.

**Petrology and Present-day alteration of Ivuna:**
The main mass of Ivuna currently at the NHM is a rounded friable stone approximately 7cm in maximum dimension. A black fusion crust is present over around 50% of the surface. The interior is also black in colour; in parts it is completely black and in other sections, especially closest to the fusion crust, is covered in white millimetre-sized flecks of sulphate (Fig 2). We undertook an SEM comparison of thin sections of Ivuna of different curation history – BM2008, M1 and BM1996, M4. Both sections show Ivuna consists of rounded ~mm clasts of different Fe and K content. The clasts are predominantly composed of phyllosilicates, a mix of serpentine and saponite. Embedded in this matrix are irregularly shaped grains of carbonates and euhedral or anhedral crystals of pyrrhotite. Magnetite is abundant and present as isolated grains or in clusters.

Sections from both specimens of Ivuna contain abundant sulphate grains; sulphates are Fe-bearing, and in the case of one section where silver dag was used as a conductant, Ag-bearing. Sulphates grow out of the plane of the thin section, showing that they postdate the polishing of the section. They are approximately equally abundant in both specimens and must have grown in less than 6 years, from the time of section preparation. BM2008, M1 also contains an enrichment in Na and S in the cracks in the meteorite, which are likely to be terrestrially-formed Mg- and/or Na-bearing sulphates such as epsomite or bloedite. These are not observed in BM1996, M4.

**Conclusions and Implications for curation of carbonaceous sample return samples:** We find that, like the case for Orgueil [5], the appearance of Ivuna has changed significantly from the time of its fall, from a black, bituminous-like stone to one with a heterogeneous but obvious growth of white sulphates on its surface. The sulphates likely formed either by dissolution and reprecipitation of primary sulphates and/or oxidation of sulphide grains on reaction with water in air. The original description of Ivuna reported abundant Fe-Ni blebs [8], but we assume these were actually sulphide grains rather than metal that has reacted over time, since no metal is reported in any CI.

Although curated under Museum conditions in different ways designed to halt terrestrial interactions, this has failed to prevent the stones of Ivuna from oxidizing in air. The mobilization of S and Na in some samples is of particular concern.

We conclude that sample return material that is composed of porous and volatile-rich carbonaceous chondrite type materials are likely to be very quick to react on exposure to terrestrial atmosphere, as previously shown by studies of Orgueil [5]. We would recommend that they are stored in an inert atmosphere (e.g., N2) with absolute minimal exposure to air with consistent conditions, and preferably in a cold (~10°C) environment [9]. This applies both to rock chips and to prepared thin sections, because these are also highly susceptible to alteration.

**Figure 2.** The present day appearance of the main mass of Ivuna (BM 2008 M1), stored in N2. Note the white sulphate grains across the surface, but only on some lithological units, others remaining relatively pristine. The stone is approximately 7cm across.

**References:**
Introduction: In order to properly interpret thermal observations of the surfaces of airless bodies, it is necessary to have an understanding of the thermal properties of the materials that cover the surface. In the case of particulate regolith, the thermal conductivity varies primarily as a function of particle size and porosity and to a lesser extent material composition. Several theoretical, numerical, and experimental studies have been conducted to improve our understanding of heat flow through particulates in a vacuum with the ultimate goal of developing a broadly applicable model for regolith thermal conductivity (e.g. [1,2]). Theoretical models are often validated by experimental data, which of course limits the types of regoliths that can be studied. For example, high-porosity regoliths (>60% void fraction) are nearly impossible to create under Earth’s gravity, except with very fine powders. However, 3D numerical simulations are not limited in this sense and thus can be used in lieu of a laboratory experiment to study the relationship between thermal conductivity and porosity. Thus, the objective of this work is to use a numerical model to study the thermal conductivity properties of regolith in configurations that would be difficult or impossible to study in a laboratory.

The first target for study in this work is the relationship between conductivity and porosity. Two widely utilized models for regolith conductivity (Sakatani et al., 2017 and Gundlach and Blum, 2012/2013) predict significantly different thermal conductivity as a function of porosity.

The second objective of this work is to investigate what we will refer to as the skin-depth problem (Figure 1). To explain the problem, we must first provide some background. Regolith composed of particles that are “small” compared to the diurnal skin depth (i.e. e-folding depth of the thermal wave) can be treated in thermal models as a continuous material with bulk material properties. In this case, the apparent thermal inertia is equivalent to the bulk thermal inertia of the particulates as a whole. Conversely, when regolith is composed of particles that are “large” compared to the skin depth (e.g. cobbles, boulders), that regolith is assumed to have an apparent thermal inertia that is equivalent to a bedrock or boulder of infinite size with the bulk rock material properties [3]. Until now, the definition of particles being “small” and “large” has only been vaguely defined as occurring somewhere around the diurnal skin depth. On Bennu, the diurnal skin depth is approximately 1–3 cm, which falls directly across the cutoff for sampleability by TAGSAM, the OSIRIS-REx sample acquisition mechanism. As such, it is essential to study how the apparent thermal inertia of a regolith varies when the particles are within this size range (Figure 1).

Methods: Regolith particles are rendered as spheres in a 3D finite element modeling mesh framework [4]. Heat transfer is accomplished by heat diffusion within the spheres themselves and by radiative heat transfer between the surface mesh elements of the spheres. All simulations and geometries are periodic in the x-y direction to minimize the size and computation time of the simulations.

Sphere packings are generated with several different methods to achieve different porosities. The lowest possible porosities (0.26 and 0.32) are achieved with ordered face-centered and body-centered packings. The optimized dropping and rolling algorithm [5] generates dense random packings with porosities of approximately 0.39. A simple cubic
packing provides a porosity of 0.48. For higher porosities (>0.60), two methods are utilized: random ballistic deposition and random sequential packing (e.g. [6]). For the ballistic deposition method, particles or small clusters of particles move in linear trajectories from random directions and stick to each other upon first contact (Figure 2). For the sequential packing, individual spheres are placed randomly into a 3D space and are kept only if they are not intersecting any pre-existing spheres.

The porosity studies are conducted in a steady-state configuration, where a constant temperature is applied to one side of the geometry and a constant flux is applied to the other side. The bulk conductivity is determined simply from the temperature differential across the geometry once steady-state is achieved (Figure 2).

The skin-depth problem study is conducted in a diurnal heating configuration, where a periodic packing of spheres is heated from above with a solar source that varies in magnitude and direction based on specified target body latitude, longitude, and date. The particle size, porosity, and material properties of the regolith is varied iteratively to explore how the diurnal brightness temperature curves are affected. The resulting diurnal brightness temperatures from the simulation are then compared to a simple, 1-dimensional model for diurnal heat flow in order to determine the apparent thermal inertia.

**Figure 2.** Example steady-state heat flow simulation temperature results. This bed of spheres was generated by random ballistic particle-to-particle deposition (porosity=0.62). The periodicity of the packing is apparent between the left and right sides of the packing.


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THERMAL MODELING TO DETERMINE THE EXISTENCE AND NATURE OF LAYERED MATERIAL ON BENNU. A. J. Ryan¹, D. Pino-Muñoz², J. P. Emery³, M. Delbo¹, B. Rozitis³, R.-L. Ballouz¹, J. L. Molaro⁶, M. Bernacki², J. Bandfield³, C. Elder³, M. Siegler³, and D. S. Lauretta¹. ¹Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA (ajryan@orex.lpl.arizona.edu), ²MINES ParisTech, PSL Research University, Centre de mise en forme des matériaux (CEMEF), CNRS UMR 7635, Sophia Antipolis, France, ³Northern Arizona University, Flagstaff, AZ, USA, ⁴Observatoire de la Côte d’Azur and Université Côte d’Azur, Nice, France, ⁵Open University, Milton Keynes, UK, ⁶Planetary Science Institute, Tucson, AZ, USA, ⁷Space Science Institute, Boulder, CO, USA, ⁸Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA.

Introduction: The detection of layered material on Bennu, such as dust/sand/pebble coatings on the surface of rocks is of interest for geologic investigations and from a perspective of sampleability. The presence of a layer of cm-scale pebbles on a rock surface could for example be indicative of thermally driven exfoliation [1] or some other weathering or fallback process. The presence of layered material could also significantly bias our estimates of rock thermal inertia from data acquired by the OTES and OVIRS spectrometers onboard the OSIRIS-REx spacecraft, and as such could at least in part explain unexpectedly low thermal inertia values for Bennu and Ryugu [2,3,4,5].

Thermal analyses of Bennu and Ryugu so far have predominantly been performed with single-component thermophysical models with hemispherical craters to represent roughness [4,5]. Some work has, however, been done to study the effects of dust coatings. [5,6] showed that layers of dust as thin as 10–100 µm would significantly and noticeably affect the shape and phase of diurnal brightness temperature curves. However, neither study found compelling evidence for appreciable dust layers on Ryugu [5,6]. We seek to build upon the layered modeling work conducted by [5,6] by testing for the presence of thin layers of coarser, mm-to-cm-scale particles.

Methods: In order to model diurnal heating with very thin layers of particulate material, the individual particles must be treated explicitly in the model. We utilize a 3D finite element model for heat conduction and radiation [7]. Spheres are randomly dropped onto a smooth or rough surface to create a layer of particulates. The rough surface model geometry consists of a single hemispherical crater which is analogous to the craters utilized in global Bennu thermal inertia modeling [5]. Spheres are randomly dropped into the crater where they adhere to the walls and floor upon first contact. The crater is made sufficiently large compared to the sphere diameters so that the addition of the spheres does not significantly diminish the bowl-shaped nature of the crater.

The substrate rock in both the smooth- and rough-surface model is approximated as a continuum material to a depth of 20 diurnal skin depths. Heat flow through the solid materials is accomplished by means of an explicit heat diffusion solver, whereas surface-to-surface radiation between surface mesh elements is calculated using the Stefan-Boltzmann equation and added as an explicit term. The simulations are run through diurnal heating cycles until the maximum and minimum diurnal surface temperatures change by less than a defined threshold (currently -0.05 K). All smooth-surface models are periodic in the x and y directions (where z is the direction of the surface normal) to minimize the size of the geometry and the computation time.

Figure 1. Temperature snapshot of diurnal heating of a loosely periodic monolayer of loosely distributed 1 cm diameter spheres on a smooth surface. The local time here is mid-morning when the solar source is positioned near the upper-right corner of the image. Note the visibility of thermal shadows to the left of the particles.

The smooth- and rough-surface models are run iteratively for different particle sizes (~0.1–5 cm diameter) with different layer thickness (monolayer and bilayer). The material properties, which are at present assumed to be the same for the rock substrate.
and for the sphere material, are varied iteratively for each model geometry. Finally, diurnal brightness temperature curves produced from the layered model simulations are compared to diurnal curves created using the global Bennu thermal model [5] in order to determine which physical scenarios could possibly be present on the surface of Bennu.


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FINE-GRAINED REGION WITH LOW THERMAL INERTIA IN CRATERS ON RYUGU. N. Sakatani1, S. Tanaka1, T. Okada1, H. Senshu2, T. Arai2, H. Demura3, K. Suku4, Y. Shimaki1, T. Sekiguchi2, J. Takita5, T. Fuhuhrara1, M. Taguchi1, T. Müller6, A. Hagermann7, J. Biele8, M. Grott9, M. Hammi10, M. Delbo11, S. Sugita12, R. Honda13, T. Morota12, M. Yamada13, S. Kameda12, E. Tatsumi14, Y. Yokota1, T. Kouyama15, H. Suzuki16, C. Honda4, K. Ogawa17, M. Hayakawa1, K. Yoshioka13, M. Matsuoka1, Y. Cho12, H. Sawada1, and A. Miura1. 1Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (3-1-1 Yoshino-dai, Chuo-ku, Sagamihara, Kanagawa, Japan, sakatani@plaenta.sci.isas.jaxa.jp). 2Chiba Institute of Technology, Japan. 3Ashikaga University, Japan. 4University of Aizu, Japan. 5Hokkaido University of Education, Education, Japan. 6Hokkaido Kitami Hokuto High School, Japan. 7Rikkyo University, Japan. 8Max-Planck Institute for Extraterrestrial Physics, Germany. 9University of Stirling, UK. 10German Aerospace Center, Germany. 11Observatoire de la Côte d'Azur, CNRS, France. 12University of Tokyo, Japan. 13Kochi University, Japan. 14Instituto de Astrofísica de Canarias, Tenerife, Spain. 15National Institute of Advanced Industrial Science and Technology, Japan. 16Meiji University, Japan. 17Kobe University, Japan.

Introduction: The Hayabusa2 spacecraft is surveying asteroid Ryugu from June 2018. Global observation by thermal infrared imager TIR revealed low thermal inertia around 200-300 J m² K⁻¹ s⁰·⁵ [1]. The expected grain size from this thermal inertia was several centimeters [2]. However, the surface of Ryugu is globally filled with larger boulders [3]. These observational results indicate highly porous nature of the surface boulders with low thermal inertia, unexpectedly different from the carbonaceous meteorites we have. Local observations by MARA radiometer onboard MASCOT lander supported it [4, 5].

In addition to the global observation, close-up imaging by TIR during descending operations, including MINERVA and MASCOT releases, touch-down operations and their rehearsals, were conducted. The high resolution TIR images revealed local temperature anomaly related to the boulders [6] and craters, which showed local variation in thermophysical properties.

In this study, we show survey of thermally-unusual craters on Ryugu using these close-up images. The unique feature were found as hot spot around the center of some small craters.

Observation: We checked all TIR images acquired below 250 m altitude during the descending operations. TIR took the images every 256 seconds during the descending sequence. The spatial resolution of TIR is 0.051⁰/pix, so that it is about 8.9 cm/pix at 100 m altitude, for example [7]. The surface area of this survey is only 5% of the total area of Ryugu, due to spacecraft trajectory of the descending sequence.

Hot spot in craters: We have found three craters with anomalously higher temperature region near the center. Figure 1A and B shows TIR and ONC images for the most remarkable one, observed during MINERVA rover release operation at 21st Sep. 2018. The diameter of this crater is about 14 m, and the size of the hot spot region is about 5 m. For comparison, Figure 1C and D shows the images of a crater without hot spot.

To understand the nature of this hot spot, we carried out thermal calculation using a global shape model at the observation epoch, with various thermal inertia. Comparison with the simulated data and observed data revealed that the temperature of the hot spot is consistent with the calculation with thermal inertia of 50 J m² K⁻¹ s⁰·⁵, while the other region including the inner wall of the crater and the outside seems to have thermal inertia from 200 to 400 J m² K⁻¹ s⁰·⁵.

Although the detailed nature of the hot spot region cannot resolved from ONC-T image in Fig. 1B, it seems smooth, and the low thermal inertia implies presence of fine-grained deposit, like lunar regolith. The thermal inertia of 50 J m² K⁻¹ s⁰·⁵ corresponds to grain size of several hundred micrometers or smaller [2]. The other hypothesis of the material of the hot spot is super-porous rock with low thermal conductivity. According to a model of thermal conductivity of rock [4, 8], the porosity of the rock is estimated to be around 58%.

![Figure 1](https://example.com/figure1.png)

Figure 1. (A) A TIR image of a crater with central hot spot. (B) An ONC-T image of the same crater. (C) A TIR image of a crater without hot spot. (D) ONC-T image of the same crater.
The other two craters are smaller than this crater. Size of the hot spot does not relate to the diameter of the parent crater.

Discussions: If formation of the hot spot, or fine-grained deposit, is a universal process in the crater formation, the fact that only small craters have the hot spots would indicate that these craters are fleshier than the other similar-sized craters. At the same time, the erasure process of the fine-grained deposit from the bottom of crater would be required. A probable way is collapse of pebbles from inner wall of the crater into the center, and/or lift-up of the large pebbles from the underground activated by seismic shaking, which masks the fine-grained layer. The required size of the pebbles is larger than the diurnal thermal skin depth (several centimeters). The resurfacing timescale of top 1 meter layer on Ryugu is less than 1 Myr [3]. The timescale of the hot spot erasure process should be much shorter than this, because change of the surface temperature is sensitive to the top several centimeters layer.

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**CRACKS OF BOULDERS ON RYUGU: POSSIBILITY OF THERMALLY INDUCED ORIGIN.**  
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iscampus - 2 spacecrafte of Hayabusa 2 spacecrafte revealed that a small carbonaceous asteroid 162173 Ryugu is a rubble pile with low overall density [1] The surface of Ryugu is covered with various sizes of boulders. On Ryugu, 4400 boulders larger than 5m are observed. A relative surface abundance of large boulders (>20m) is about twice as that of Itokawa or Bennu [2,3]. Each boulder can be considered as an impact fragment from aspect ratio study [3]. On the surface of Itokawa, several cracked boulders are observed and compared with fragments from impact experiments, where some fragments have cracks [4]. Impacts on Itokawa would form cracks on boulders. Recently, thermal fatigue is advocated for the disintegration process of surface rocks [5], where diurnal (and annual) thermal cycle may promote crack growth in the rocks on regolith over various spatial and temporal scales [6].  

In preliminary data analysis, we noticed that cracks on Ryugu boulders have preferred orientation. Cracks/fractures with meridional (north-south) direction are frequently observed [7]. Desert rocks of the Earth and Mars have preferred orientation of cracks [8,9]. This would be explained by thermal process, including freezing. Here in this study, we analyzed more than 500 cracks on Ryugu boulders and checked their directions.

**Cracked Boulders on Ryugu:** We analyzed 124 images (taken from 50-4000m height at proximity operation phase such as rover deployment and touchdown sampling, or their rehearsals) by Hayabusa-2 ONC-T. Image resolution is 3mm/pixel at best. Image size is 1024 x 1024 pixels. We confirm the image position and resolution from shape model matching (SPC) and/or altimetry data by LIDAR. Hayabusa 2 usually observes the surface from the direction of the sun, which provide high phase angle data with short shadow width. We carefully check images so that we do not pick up the shadowed surface structure as a crack.  

To check if a rock has a crack or not, 15-20 pixels are necessary. At the highest resolution, we may check a rock smaller than 10cm. Assuming the same range size, about 2-5% of boulders have cracks. So far, we do not observe changes of the abundance ratio of cracked rocks on the Ryugu surface. Western bulge region (160E-70W) would have fewer abundance of the rocks both with and without cracks. In general, mid to high latitude data, more cracked rocks are observed.

We classified cracks into four categories.  
(a) Straight cracks: Some cracks are running linearly without bending or kinking (Fig.1(a)). Some straight cracks are associated with open fracture.  
(b) Sinuous cracks: Some cracks have bowing, bending, and/or wavy structure (Fig.1(b)).  
(c) Incomplete cracks: We observed many rocks have a crack which does not go through (Fig.1(c)). It looks like growing crack.  
(d) Complex (typically branched) cracks: Sometimes a boulder would have been broken into several pieces.

It seems that the crack might be controlled by pre-existing structure which would be visible at higher resolution data. Most of boulders on Ryugu are brecciated conglomerates (e.g., Fig.1(b)), which contain pre-existing structure reflecting parent body processes such as layering (due to thermal evolution) and impact mixing.

**Crack Direction:** We separated the strike of cracks into 6 directions with 30deg bin. We analyzed 500 boulders (after removing complex type with multiple directions) and found 60% of them have the meridional direction (+/-15deg from N-S) (Fig. 2) This trend is not changed among crack types as well as rock size. (We considered that large boulders would have less preferred crack orientation.)  

As in the case of Itokawa, we should discuss where and when the cracks are formed. If a surface boulder is a fragment of accreting rubble piles, the crack could be formed either before Ryugu formation at the parent body (including its disruption) or after Ryugu formation. Meteoroid impact on the boulder is a possible process. And dynamic stress induced through large mass movement [1] along the change of rotation speed,
and thermally-induced stress is also a candidate process.

If those cracks on Ryugu are formed by impact processes, whether impacts occur before or after formation of Ryugu, the direction of cracks should distribute more random. There would be discussed boulder distribution and direction of the long axis, according to sorting through mass movement toward mid latitude [3]. However, it is difficult to control the direction of a crack in the boulder.

So far, thermally-induced stress by diurnal rotation and annual revolution of Ryugu might be a possible process for the growth of cracks in meridional direction, as discussed for preferred crack orientation on desert rocks of the Earth and Mars [6,8,9]. It is reported that preferred direction of cracks is also observed on boulders of Bennu [10]; they would be driven by solar-induced thermal stress.

OSIRIS-REX GRAVITY FIELD ESTIMATES FOR BENNU USING SPACECRAFT AND NATURAL PARTICLE TRACKING DATA


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Summary

The current best estimates of Bennu’s gravity field will be presented, based on the independent solutions from four different teams involved on the OSIRIS-REx mission. The discovery of ejected particles about Bennu that may remain in orbit for several days or more provide a unique opportunity to probe the gravity field to higher degree and order than possible by using conventional spacecraft tracking. However, the non-gravitational forces acting on these particles must also be characterized, and their impact on solution accuracy must be assessed. This talk will present the latest results from the mission, incorporating spacecraft tracking from the lowest orbit in which the satellite will be during the mission.

Introduction

Current estimates of the Bennu gravity field coefficients will be presented, based on spacecraft tracking data and the tracking of the orbits of particle ejected from the asteroid surface. This talk summarizes the estimates from four teams on the OSIRIS-REx mission that are independently processing these results, using unique combinations of data and models. The gravity field information is key for understanding and constraining the interior mass distribution of the asteroid. Based on the Approach data published in [1] it is already evident that density inhomogeneities exist within Bennu. Thus, it is expected that the analysis of higher degree and order gravity field coefficients will provide additional insight into the interior structure of the body [2].

The teams producing independent assessments of the gravity field are from the University of Colorado, which leads the Radio Science Working Group, the Jet Propulsion Laboratory, KinetX Aerospace, and NASA’s Goddard Space Flight Center. These different teams are applying different methodologies to fit and model the relevant spacecraft dynamics and ejected particle trajectories. We will present a synthesis and comparison of these results, which will allow for a more precise characterization of the uncertainties in the higher degree and order gravity field coefficients.

Expected Results

Due to the particle ejection events encountered at Bennu, with multiple particles being lofted into low-radius trajectories that may persist over several orbits, there is a possibility for insight into gravity field components at much higher degree and order than was nominally planned for. However, the uncertainty in these higher order gravity coefficients may be large, because they are based on tracking natural particles with unknown properties and mass loss characteristics.

The prime radio science data collection period for the OSIRIS-REx spacecraft was during its Orbital B phase, an extended period of time when the spacecraft was in a Sun-terminator orbit with a radius less than 1 km. During this orbit phase, the spacecraft was in its closest sustained orbit about Bennu, and hence experienced the strongest perturbations from the nonuniform mass distribution within Bennu. Prior to the observed particle ejection events, this orbit period was thought...
to be the best opportunity to gain insight into the gravity field coefficients of this body, with expectations being that the spacecraft would experience sensitivity to select gravity coefficients up to degree and order 4 [3]. The gravity field coefficients estimated during this time are still of high importance, as they will serve as a ground-truth for comparisons with gravity coefficients inferred by tracking the ejected particles.

The natural particles are highly sensitive to the Bennu gravity field, as they emanate from the surface and can have repeated close approaches to the surface. Initial analysis shows that the particle trajectories can be sensitive to gravity coefficients beyond degree and order 4. Estimation of coefficients up to these higher orders would provide unprecedented insight into the interior of a rubble-pile asteroid. However, the motion of these particles is affected by significant non-gravitational forces, due to solar radiation pressure and thermal emission from the asteroid surface. Further complicating the situation is possible mass loss from the ejected particles, which would corrupt the information on these gravity terms. If the particle trajectories can be accurately fit, however, they will allow for considerable leverage in understanding density inhomogeneities.

Analysis of Uncertainties

A key component of this work is the identification of systematic modeling and measurement uncertainties in the estimated gravity field. This will be done using several different approaches. First, a classical covariance analysis of the expected uncertainties in the determined gravity field coefficients will be carried out. A key element of this analysis will be to characterize the effect of unmodeled non-gravitational forces on the ejected particles. The non-gravitational forces acting on the ejected particles will likely not be well modeled and could lead to systematic errors and uncertainties in the determined gravity field coefficients. These objects may have complex shapes and be tumbling due to torques imparted on the particles during ejection from the surface. This will lead to non-constant solar radiation pressure forces acting on these particles over time. As the shapes of the ejected particles cannot be observed, it is not possible to uniquely account for these effects. Even more dramatic, the particles may be outgassing once separated from the asteroid surface environment. Should this occur the particles will also be subject to “jetting” that would mask or alter the estimated effect of gravity coefficients. A covariance analysis is able to estimate the induced uncertainties in the estimated gravity field coefficients accounting for these effects, and thus provide estimates of confidence in these solutions.

Another approach to assess the systematic uncertainties in these gravity coefficients is to directly compare independent estimates, and estimates generated using different combinations of data. In this area it will be crucial to compare the gravity field coefficients that can be estimated using the spacecraft tracking data with the coefficients estimated from the ejected particles. The spacecraft-based gravity field estimates are expected to have very low levels of uncertainty in non-gravitational perturbations, and thus can serve as a “truth” estimate, even though the statistically significant estimates will not extend to high degree and order. Where they overlap with the particle-based estimates will be important, however, as ideally they should have the same value. The talk will present current progress on these activities as well.

Summary and Conclusions

The possibility of combining tracking data from the spacecraft and from natural particle trajectories can yield unprecedented insight into the gravity field coefficients of the asteroid Bennu. This talk will present current estimates of Bennu’s gravity field following the planned lowest extended orbit period.

Acknowledgements

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References


COMPARING THE ESTIMATED DYNAMICAL ENVIRONMENTS AND MASS DISTRIBUTIONS OF BENNU AND RYUGU

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Summary

A direct comparison of the dynamical environments and mass measurements of asteroids (101955) Bennu and (162173) Ryugu are made, leveraging recently published data for both bodies as well as the latest results. The comparisons are of interest both for the design of close proximity operations and for the geophysical analysis of these bodies. The motivation for this discussion is to provide better insight into the diversity of small, primitive small bodies. Even though these two asteroids share many similarities, they are also individual worlds to be explored, with their own unique attributes.

Introduction

The year 2018 was a banner year for asteroid exploration, with the Hayabusa2 [1] and OSIRIS-REx [2] missions achieving rendezvous with their target asteroids, (162173) Ryugu and (101955) Bennu, respectively. Both missions will stay in rendezvous with their respective asteroids for an extended period of time, characterizing the environment before making descents to the surface to sample the regolith. Ultimately, both spacecraft will bring their samples back to Earth.

In this paper we combine published information on these bodies to outline the similarities and differences between their dynamical and geophysical environments. Such a comparison is especially relevant given their similar spectral types. Several papers and presentations have already given the basic computations about these individual bodies. This presentation is an opportunity to make direct comparisons of the dynamical quantities that can be directly computed given their mass, shape, spin state and heliocentric orbit. The information we use for the asteroid Bennu was published in several papers, specifically an overview paper [3], a paper on the mass of the asteroid [4], a paper on the asteroid shape [5], and one that covers the spin state and other observations [6]. The information for the asteroid Ryugu was presented in two main papers [7,8]. The presentation will also take advantage of updates to these published values. All of these results have also been shown in special sessions at the 2018 DPS, 2018 AGU, 2019 LPSC and 2019 EPSC/DPS conferences.

This abstract presents the basic parameters for both of the bodies. The presentation will compare these and describe the orbital environments about both bodies, ranging from near-surface motion out to their respective Hill spheres. The presentation will also focus on their surface environments, including surface slopes, accelerations, escape speeds, and geopotentials. Even though the two bodies have qualitatively similar shapes, we find substantial differences which will lead to different dynamical environments about these bodies. These are mostly driven by the bodies having spin rates that differ by a factor of 2 and sizes that differ by a factor of 2.

Properties of Bennu and Ryugu

Table 1 presents the main properties of these two bodies, as extracted from the indicated papers. Some important points of comparison can be made. First, the estimated densities of the bodies are the same, within published error bars (not shown in these tables). While this may be expected as Bennu and Ryugu have been classified as similar types, it is still a remarkable fact given the many differences between these bodies as studied in [9,10]. Another point of comparison can be made with the gravity field coefficients predicted from the shape and assuming constant density. These non-dimensional numbers are also remarkably consistent, showing that the bodies have a clearly similar oblate shape. Ryugu has more asymmetry in its north-south shape, as correlated with its larger $C_{30}$ coefficient.
Table 1: Bennu Parameters [3] (left) and Ryugu Parameters [7] (right). Gravity coefficients are computed from the published shape model using a constant density assumption.

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### Discussion

The presentation will focus on these above basic parameters of the system and use them to discuss the relative equilibria and their manifolds, the Roche Lobes of both bodies and other dynamical phenomenon of interest.

### Acknowledgements

This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program. We are grateful to the entire OSIRIS-REx Team for making the encounter with Bennu possible.

### References

THE FE/S RATIO OF PYRRHOTITE IN CHONDrites: A UNIVERSAL RELATIONSHIP WITH THE DEGREE OF PARENT ASTEROID AQUOUS AND THERMAL ALTERATION? D. L. Schrader, J. Davidson, T. J. Zega, and T. J. McCoy. 1Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-1404, USA (devin.schrader@asu.edu; jdavidson@asu.edu), 2Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721, USA (tzega@lpl.arizona.edu), 3Dept. of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC USA (mccoyt@si.edu).

Introduction: Fe-sulfides are present in many types of meteorites [e.g., 1,2] and are sensitive indicators of formation and alteration conditions in the Solar System. The compositions and textures of sulfides can be used to constrain the oxygen and sulfur fugacities, and the histories of aqueous alteration, thermal metamorphism, shock-impact processing, and cooling of the host rock [e.g., 2–7]. The most abundant sulfides in astromaterials are the pyrrhotite group (ideally Fe1–xS where 0≤x≤0.125), which can occur with pentlandite (FeNi)xS8 and pyrite FeS2 [e.g., 2,6,8–13]. The compositions of pyrrhotite in carbonaceous chondrites vary with the degree of aqueous alteration experienced; the at.% Fe/S ratio of pyrrhotite decreases with increasing degrees of aqueous alteration (i.e., Fe/S of pyrrhotite in CI < CM1 < CM2 [10,11,14]). However, [14] found troilite (FeS, Fe/S = 1) in aqueously altered and heated CM/CI-like chondrites, and proposed it formed by S loss during heating and decomposition of pyrrhotite into troilite and Ni-poor metal.

Here we determine the Fe/S ratio of pyrrhotite in chondrites that cover a wide range of aqueous and thermal histories, to evaluate its usefulness as an indicator of parent body processes. Minimally altered samples and those that have experienced varying types/degrees of secondary processing are included as: (1) asteroid Bennu is most like CM or CI chondrites [e.g., 15]; (2) asteroid Ryugu is most like heated CI, CM [16,17], or CY chondrites [18]; and (3) both asteroids likely include impact-delivered xenoliths.

Samples and Analytical Procedure: We analyzed the compositions of sulfides in CI, C1-ungrouped, CR1, CR-an, CR2, shock-heated CR2, CM1/2, CM2, CM-like, CO3.00, CV3OAX, CV3OAXB, CV3Rab, CK4 to CK6, LL3 to LL6, L3.05, and R3 to R6 chondrites. Some Fe/S ratios were determined from sulfide compositions that we previously published; R and CK [2], LL [2,7], CR2 [12,19,20,23,24], and CO3 [21] chondrites. We also obtained high-resolution images and chemical compositions with the Arizona State University JEOL-8530F Hyperprobe electron microprobe analyzer (EPMA) and the University of Arizona Cameca SX-100 EPMA, respectively, following procedures described in [7].

Samples. We studied samples of CI (Alais), C1-ungrouped (Miller Range [MIL] 090292), CR1 (Grosvenor Mountains [GRO] 95577), CR-an (Al Rais), CR2 (16 different meteorites), shock-heated CR2 (Graves Nunataks [GRA] 06100 and GRO 03116 [19]), CM1/2 (Allan Hills [ALH] 83100), CM2 (Mighei), CM-like (Sutter’s Mill), CO3.00 (DOM 08006), CV3OXA (Allende), CV3OXB (Bali), CV3Rab (Vigarano), CK4 (ALH 85002 and Karoonda), CK5 (Larkman Nunatak [LAR] 06868), CK6 (Lewis Cliff [LEW] 87009), LL3 (Semarkona and Vicência), LL4 (Hamlet and Soko-Banja), LL5 (Chelyabinsk and Siena), LL6 (Appleby Bridge and Saint-Séverin), L3.05 (Queen Alexandra Range [QUE] 97008), R3 (Meteorite Hills [MET] 01149), R4 (LaPaz Icefield [LAP] 03639), R5 (LAP 031275), and R6 (LAP 04840 and MIL 11207) chondrites.

Results: Pyrrhotite and/or troilite were identified in almost all samples studied. In some cases where pyrrhotite was present, pure pyrrhotite analyses were not possible to obtain due to submicron-sized grains of pentlandite intergrown with pyrrhotite at scales below the interaction volume of the EPMA (e.g., the R6 LAP 04840). To avoid analyses that could contain overlaps with submicron-sized grains of pentlandite, we define Ni-poor pyrrhotite as pyrrhotite containing less than 1 wt.% Ni [7]; these analyses were used to determine the at.% Fe/S ratios. No pyrrhotite was found in the CK chondrites; the Fe-sulfides found in these samples were pentlandite and pyrite. The compositions and implications of Ni-rich pyrrhotite (1 to 16 wt.% Ni), pentlandite (Ni > 16 wt.%), and pyrite have been [2,7] and will be discussed in other works.

Troilite (FeS, Fe/S = 1) was found in all LL chondrites, the L3.05, the CO3.00, all CV3s, the CR1, all CR2s, the CM2 Mighei, the CM-like chondrite Sutter’s Mill, and the R3 and R5 chondrites. Sulfides in the CR2 chondrites are dominantly troilite, however no troilite was found in the highly aqueously altered CR chondrite [e.g., 19] Al Rais.

Pyrrhotite (Fe1−xS; Fe/S from <1 to 0.875) was found in the CI Alais, the C1-ung MIL 090292, the CR-an Al Rais, some sulfides within CR2 and shock-heated CR2 chondrites, the CM2 Mighei, the CM-like Sutter’s Mill, and R3 to R6 chondrites.

Discussion: The average Fe/S ratio of pyrrhotite varies between meteorite group and petrographic types within meteorite groups. The average Fe/S ratio of
pyrrhotite generally trends with the degree of aqueous alteration in carbonaceous chondrites (those most relevant for samples to be returned from Bennu and Ryugu), for example: CI < CM1/2 < CM2 < CR2 ≅ CV3_{OAa} < CV3_{OAb} < CV3_{red} < CO3.00. Overall, the trend in average Fe/S ratio is significantly more complicated: CI < R6 < CM1/2 < CR-an < CI-ung < R5 < R4 < CM-like < R3 < CM2 < CR2-shocked < CR2 ⩾ CR1 = CV3_{OAa} < LL3 to LL6 ⩾ L3.05 < CV3_{OAb} < CV3_{Red} < CO3.00. Internal sample heterogeneities, internal group variations, thermal metamorphism, differences in sulfur and oxygen fugacities (perhaps for the R chondrites) may be responsible for this complex order of Fe/S ratios.

For some meteorite groups the average Fe/S ratio of pyrrhotite decreases with increasing aqueous alteration (e.g., CM chondrites), consistent with [10,11,14,22], and troilite is present in all minimally altered (e.g., CR2s, LL3s, CO3.00) and some thermally metamorphosed samples (e.g., LL4 to LL6). However, this is not always the case, for example: (1) MIL 11207 (R6) has an Fe/S ratio nearly the same as Alais (CI); (2) unlike that seen in the LL3 to LL6 chondrites (all contain troilite), the average Fe/S ratio of pyrrhotite in the R chondrites decreases with increasing degree of thermal metamorphism; (3) despite the CV3_{OAa}, CV3_{OAb} and CV3_{Red} chondrites having significant differences in their aqueous and thermal histories [e.g., 1,23], all contain troilite; and (4) the CR chondrites do not follow an overall trend between pyrrhotite Fe/S ratio and aqueous alteration due to GRO 95577 (CR1).

The CM and the CR chondrites provide a way to test how the Fe/S ratio of pyrrhotite varies with increasing degree of aqueous alteration within individual groups. Pyrrhotite in the more aqueously altered CM1/2 has a lower Fe/S ratio than in the CM2 Mighei. Al Rais is recognized as the most aqueously altered CR chondrite, with the exception of the CR1 GRO 95577 [e.g., 24,25]. There is a trend in the average Fe/S ratio of pyrrhotite between the CR2 chondrites and Al Rais; Al Rais does not contain troilite and its average Fe/S is lower than that of all CR2 chondrites. There is also a range within individual CR2 chondrites; individual grains of pyrrhotite in the CR2s Shişir 033 and North West Africa (NWA) 801 have Fe/S ratios as low as that seen in Al Rais, indicating either heterogeneity in the degree of aqueous alteration or post-aqueous alteration mixing of lithologies via brecciation.

Unexpectedly, the CR1 GRO 95577 does not contain pyrrhotite with low Fe/S ratios, but instead contains troilite intergrown with pentlandite and as independent grains, neither of which are associated with Fe,Ni-metal. This is unlike that observed by [14] for heated CM/CI-like chondrites. This may indicate that (1) GRO 95577 was heated and the lack of Fe,Ni-metal is either a sampling artifact or due to metal loss during terrestrial weathering (GRO 95577 is a grade B) or (2) the troilite in GRO 95577 did not form from the decomposition and S-loss from Fe-deficient pyrrhotite during heating. The bulk δD of GRO 95577 [26] is significantly lower than CR chondrites except for the shock-heated CR chondrites, which may strengthen the case for GRO 95577 being mildly heated.

**Summary:** The average Fe/S ratio of pyrrhotite is a useful parameter to understand both the aqueous and thermal history of meteorites. However, the relationship between the pyrrhotite Fe/S ratio and the degree of aqueous/thermal alteration that a sample has experienced varies between different meteorite groups and is likely complicated by numerous factors (distinct thermal/aqueous histories, and oxygen and sulfur fugacities). This finding has important implications for the analysis of sulfides in chondrites and returned samples.

**References:**

**Acknowledgements:** We thank the Smithsonian Institution, NASA, JSC, NSF, and ASU for the samples used in this study, and NASA grant NNX17AE53G (DLS PI, TJZ Co-I) for funding this research.
IMAGING INCLUSION SPECTRAL DIVERSITY IN CARBONACEOUS CHONDrites WITH MASCAM. S. E. Schröder¹, K. Otto¹, N. Schmitz¹, H. Scharf¹, A. Greshake², F. Scholten¹, F. Trauthan¹, and R. Jaumann¹, ¹Deutsches Zentrum für Luft- und Raumfahrt (DLR), 12489 Berlin, Germany (stefanus.schroeder@dlr.de), ²Museum für Naturkunde, 10115 Berlin, Germany.

Introduction: In October 2018, MASCOT successfully completed its 17-hour mission on the surface of Cg-type asteroid Ryugu. The bulk composition of Ryugu is thought to be best represented by thermally metamorphosed carbonaceous chondrites, mostly because of their low albedo over the visible wavelength range [1]. Close-up images of a small rock in front of the lander made by the MASCOT camera (MASCam) reveal small inclusions set in a dark matrix, confirming the link between C-type asteroids and carbonaceous chondrites [2]. However, MASCOT also found the rock to be highly porous [3]. Rocks such as these may not survive entry into the Earth atmosphere, and representative carbonaceous chondrites may not actually exist. We address the issue of representativeness by imaging several carbonaceous chondrites with a MASCam spare in an experiment performed at the Natural History Museum in Berlin, Germany, and compare the results with images from the surface of Ryugu.

![Figure 1. A color (RGB) composite of the Ryugu rock in front of MASCOT. The inclusions are shown at their full brightness range, in natural colors at the top and saturated colors at the bottom.](image1)

Ryugu images: Images of a Ryugu rock acquired by MASCam show abundant, predominantly bright, inclusions (Fig. 1). Most of these feature either a blue or red spectral slope in the visible wavelength range [2]. The colors of the inclusions are barely perceived in the natural color view (top), but after strongly saturating the image (in the HSL color space) they appear more distinctly blue and red (bottom). The smallest inclusions are sub-mm sized, whereas the largest are several millimeters large.

Meteorite imaging campaign: The meteorites that we imaged are listed in Table 1 and were selected from the collection of the Natural History Museum. We included mostly known meteorite falls to limit and better assess terrestrial contamination of the meteorite surface. The surface of the meteorites in our sample was often rough (fractured), and sometimes smooth (cut). We imaged the meteorites with the MASCam engineering model (EM), which is fully functional and partly calibrated, using LED illumination in four colors: blue, green, red, and IR (effective wavelengths: 471, 532, 633, and 809 nm [4]). As an example of the data that were collected, Figure 2 shows a color composite of one of the meteorites, displayed in similar fashion as the Ryugu rock in Fig. 1 (top). In this paper we analyze the spectral properties of the inclusions and compare their color variation and abundance with those in the Ryugu rock. A companion paper [5] will focus on analyzing the size distribution and morphology of the inclusions in the meteorites in Table 1.

![Figure 2. A natural color (RGB) composite of a piece of the Orgueil meteorite, as imaged in the experiment, displayed at the full brightness range of the inclusions.](image2)

Outlook: The experiment was performed in August 2019, and we are currently analyzing the data. By quantifying the spectral diversity of the inclusions, we will identify which of the carbonaceous chondrite in our sample matches the Ryugu rock best. We hope to present the first results at the workshop.

**Table 1.** Carbonaceous chondrites selected for imaging.

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Sp. type</th>
<th>Type</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allende</td>
<td>CV3</td>
<td>Fall</td>
<td>1969</td>
</tr>
<tr>
<td>Colony</td>
<td>CO3.0</td>
<td>Find</td>
<td>1975</td>
</tr>
<tr>
<td>El-Quss Abu Said</td>
<td>CM2</td>
<td>Find</td>
<td>1999</td>
</tr>
<tr>
<td>Karoonda</td>
<td>CK4</td>
<td>Fall</td>
<td>1930</td>
</tr>
<tr>
<td>Lancé</td>
<td>CO3.5</td>
<td>Fall</td>
<td>1872</td>
</tr>
<tr>
<td>Mighei</td>
<td>CM2</td>
<td>Fall</td>
<td>1889</td>
</tr>
<tr>
<td>Murchison</td>
<td>CM2</td>
<td>Fall</td>
<td>1969</td>
</tr>
<tr>
<td>Murray</td>
<td>CM2</td>
<td>Fall</td>
<td>1950</td>
</tr>
<tr>
<td>Ningqiang</td>
<td>C3-ung</td>
<td>Fall</td>
<td>1983</td>
</tr>
<tr>
<td>Nogoya</td>
<td>CM2</td>
<td>Fall</td>
<td>1879</td>
</tr>
<tr>
<td>NWA 11118</td>
<td>CM2</td>
<td>Find</td>
<td>2016</td>
</tr>
<tr>
<td>Orgueil</td>
<td>C1</td>
<td>Fall</td>
<td>1864</td>
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<tr>
<td>Ornans</td>
<td>CO3.4</td>
<td>Fall</td>
<td>1868</td>
</tr>
<tr>
<td>Warrenton</td>
<td>CO3.7</td>
<td>Fall</td>
<td>1877</td>
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INVESTIGATION OF THE EVOLUTION OF HYDRATION IN CARBONACEOUS ASTEROID REGOLITH SIMULANT. C. D. Schultz¹, Z. A. Landsman², A. S. Rivkin¹, D. T. Britt³, K. R. Stockstill-Cahill³
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Introduction: Water has been found to be prevalent throughout the solar system from as far out as distant KBOs [1] to the inner solar system in the permanently shadowed craters on Mercury [2 find citation]. The role of water in a geologic context has been intensely studied and it is suggested that aqueous alteration due to the presence of water may be one of the most widespread mechanisms that affects primitive solar system materials [3]. Of particular interest is the discovery of water in various forms as found on primitive asteroids [4]. More recently, NASA’s OSIRIS REx spacecraft discovered spectral evidence suggestive of the presence of hydrated minerals on the near-Earth asteroid (101955) Bennu [5].

Water and hydroxyl both have strong absorptions in the 3 µm spectral region, making that region particularly diagnostic. The 2.7 – 2.8 µm band minimum associated with the presence of hydroxyl [6] has been shown to be diagnostic of phyllosilicates and the degree of aqueous alteration in carbonaceous chondrites [7-10]. Understanding the hydration state of primitive bodies in the solar system via the study of the 3 µm spectral feature may help us understand the degree of aqueous alteration, thermal evolution, and potential of bodies for future resource utilization.

Table 1: Mineralogical composition of the CI-2 asteroid regolith simulant.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Wt.%</th>
</tr>
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<td>Mg-serpentine</td>
<td>48.0</td>
</tr>
<tr>
<td>Magnetite</td>
<td>13.5</td>
</tr>
<tr>
<td>Vermiculite</td>
<td>9.0</td>
</tr>
<tr>
<td>Olivine</td>
<td>7.5</td>
</tr>
<tr>
<td>Pyrite</td>
<td>6.5</td>
</tr>
<tr>
<td>Epsomite</td>
<td>6.0</td>
</tr>
<tr>
<td>Sub-bituminous coal</td>
<td>5.0</td>
</tr>
<tr>
<td>Attapulgite</td>
<td>5.0</td>
</tr>
</tbody>
</table>

The Exolith Lab at the Center for Lunar and Asteroid Surface Science at the University of Central Florida (UCF) has developed and produced a series of high-fidelity asteroid regolith simulants [11,12]. Among the types developed is a carbonaceous asteroid-like regolith simulant named CI-2 based on the compositional analysis of the Orgueil meteorite [13]. The composition of the CI-2 simulant is shown in Table 1. Having a high-fidelity material analog with a finely controlled mineral composition has provided us the unique opportunity to explore the evolution of the 3 µm spectral feature as we exposed the sample to a variety of asteroidal conditions via infrared spectroscopy.

We also performed thermogravimetric analysis (TGA) on the sample to measure the temperatures at which the volatile loss and mineral phase transitions might occur.

Experiment: The CI carbonaceous asteroid regolith simulant (CI-2) was prepared for us at the Exolith Lab at UCF. Infrared spectra were taken at the Laboratory for Spectroscopy under Planetary Environmental Conditions (LabSPEC) at the Johns Hopkins University Applied Physics Lab (JHU APL) with a Bruker 70 FTIR spectrometer. Once secured the CI-2 regolith simulant within the sample holder, the apparatus was placed within the Ultra-High-Vacuum (UHV) Chamber, which was pumped down to 10⁻⁶ – 10⁻⁷ Torr. The sample was then gradually heated to 474 Kelvin over the course of several hours. After allowing the sample to cool overnight, it was then cooled to approximately 147 Kelvin. IR spectral measurements were taken throughout both the heating and cooling process at 25 Kelvin intervals.

To measure band parameters, we fit a linear continuum across the 3 µm absorption feature from ~ 2670 nm to ~ 3260 nm. After dividing by the continuum we then measured the band center, band depth, and band area.

TGA was performed at the Advanced Materials Processing and Analysis Center at UCF using an SDT Q600 from TA Instruments. The samples mass was constantly measured while being heated via nitrogen flow at a rate of 20° C/min to 1200° C.

IR Spectra: Shown in Figure 1 is the IR spectra (shifted for comparison) of the CI-2 simulant at various stages in the heating and cooling cycled.
**Figure 1:** Evolution of the 3 µm absorption feature as captured at various stages in heating and cooling.

**TGA:** Shown in Figure 3 are the results from the TGA experiment showing the change in mass and heat flow as the CI-2 sample is slowly heated to 1200º C.

**Figure 2:** TGA data shows two key episodes of mass loss were observed between 20º and 200º C and between ~500º and ~1000º C.

**Discussion:** Throughout the heating profile we observed a slight longward shift in the band center of the 3 µm absorption feature along with a gradual shallowing and decrease in band depth and band area. This can be attributed to the desiccation of the sample and the loss of absorbed molecular water. Cooling the sample to cryogenic temperature resulted in no significant shift or change in either band parameters. We measured the band shape of the feature following the procedure by Takir and Emery [14] and ascribe a “sharp” classification, consistent with their interpretation of the feature due to hydrated minerals and phyllosilicates.

In the TGA data we observed two episodes of mass loss between ambient and 200º C, consistent with the release of absorbed water, and between 500º C and 1000º C. This suggests that we should expect no significant change to the band feature due to mineral evolution of Mg-rich serpentes at the temperatures in which we took spectral measurements.

**References:**

THE ORIENTATIONS OF BOULDERS ON (101955) BENNU’S SURFACE. S.R. Schwartz1,2,*, R.-L. Balouz1, E. Asphaug3, O.S. Barnouin3, C. Bennett4, K.N. Burke1, H.C. Connolly, Jr.4,1, C.Y. Drouet d’Aubigny1, M. Delbo6, D.N. DellaGiustina1, E.R. Jawin2, M. Jutzi8, P. Michel2, H. Miyamoto1, J.L. Molaro5, M. Pajola9, A.C. Quillen9, B. Rizk1, D.J. Scheeres11, S. Sandford12, K.J. Walsh13, D.L. Lauretta1, 1Lunar and Planetary Laboratory, University of Arizona (1629 University Blvd., Tucson, AZ 85721, srs@lpl.arizona.edu), 2UCA-CNRS-Observatoire de la Côte d’Azur, 3The Johns Hopkins University Applied Physics Laboratory, 4Rowan University, 5Smithsonian Institution, 6University of Bern, 7University of Tokyo, 8Planetary Science Institute, 9INAF-Astronomical Observatory of Padova, 10University of Rochester, 11University of Colorado, Boulder, 12NASA Ames Research Center, 13Southwest Research Institute.

Introduction: Small energy inputs to the surfaces of rubble-pile asteroids help to orient rocks and boulders in such a way as to minimize their potential energies, namely along lines of local slope. The largest of boulders require greater energy inputs to move toward their optimal energy-minimizing orientations. However, large-scale events may have the effect of pushing small rocks to a more randomized configuration, depending on their granular mechanical properties.

This points to a way, using the global-coverage, high-resolution images from the OSIRIS-REx spacecraft [1,2], to attempt to glean insight into the types and frequencies of processes experienced by (101955) Bennu. Here, we report on global distributions in the orientations of surface rocks, which may relate to the seismic efficiency of the subsurface and to the history of energetic events on Bennu.

Method: Using resolved image data from the Preliminary Survey mission phase [3], we have examined boulder orientation patterns as potential signatures of small-scale events [4,5]. For a region that spans 20° of longitude and about 100° of latitude (around 5% of the surface), we counted boulders by fitting ellipses [6,7] using the Small Body Mapping Tool [8]. This region was chosen to include some specific features of interest and may or may not be representative of the surface as a whole.

The preliminary dataset shown in this abstract suggests a trend for boulders to be oriented with their long ends along the north-south direction (Fig. 1, cyan), which corresponds to the global sloping direction that points towards the equator (a trend also supported by [9]). Further, this figure shows that if we weight the “value” of each boulder by its elongation, the case for this preferential boulder orientation becomes stronger (Fig. 1, purple). Going further still, and using the local dynamical slopes from the OSIRIS-REx Radio Science Working Group based upon shape models from the Altimetry Working Group [10,11], we showed how boulders align themselves in relation to the local dynamical slope.

We will present on results using this and other data, including counts that span most of the surface, and discuss implications.

Figure 1: Boulder orientations relative to the local dynamic slope from several hundred counts within a certain 20° longitudinal slice on (101955) Bennu. Orientation angle is defined as the clockwise offset from perfect alignment with local slope (0°).

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ANALYSIS OF A SUPERNOVA OLIVINE AGGREGATE IN THE CO CHONDRITE DOMINION RANGE 08006: IMPLICATIONS FOR THE MEASUREMENT OF PRESOLAR GRAINS IN SAMPLES OF ASTEROIDS BENNU AND RYUGU.

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Introduction: Primitive asteroids offer a glimpse into the early solar system and provide insight into its formation and evolution. The laboratory analyses of samples returned from missions such as OSIRIS-REx and Hayabusa2 could provide ground truth to astronomical datasets. One key area of interest in sample-return missions are primitive materials such as circumstellar dust grains, which formed around ancient stars and in the ejecta of stellar explosions. The analysis of these important materials is one of the main science goals of the OSIRIS-REx and Hayabusa2 missions [1-2] and requires the development of successful coordinated analytical protocols and techniques to maximize the information that we will be able to gain from them.

Previous studies have shown that core-collapse supernovae (SNe) are the second largest contributor of circumstellar dust grains to the solar system [3]. A supernova occurs when a massive star falls out of hydrostatic equilibrium and its stellar core contracts, rebounds, and sends a shock wave propagating through the circumstellar envelope. The propagation of the shock wave triggers rapid nucleosynthesis and results in a radial explosion away from the star. Solids condense in this ejected material, and some of these circumstellar grains are transported through the interstellar medium (ISM). A fraction of such grains are preserved in asteroid parent bodies and transported to Earth via meteorites [4].

Information on the structure and chemistry of silicate grains derived from SNe is severely limited. To date, only eight supernova silicates were analyzed for detailed structure and chemistry using transmission electron microscopy (TEM) [5-9]. Nonetheless, these studies reveal diverse structures and morphologies, including single crystals, aggregates and amorphous phases, highlighting the varied chemical and physical conditions in the ejecta of SNe. Here we report on a supernova (SN) silicate grain identified in the Dominion Range (DOM) 08006 CO3.0 chondrite. We expect to find similar materials in returned samples and therefore sample-preparation and analytical protocols developed here will be important for the Hayabusa2 and OSIRIS-REx missions.

Methods: Local isotopic enrichments were identified via NanoSIMS raster-ion-imaging of C and O isotopes in a thin section of DOM 08006 and elemental compositions were provided by Auger spectroscopy [10]. We chose one anomalous region, DOM-35, thought to originate in SN ejecta for detailed chemical and structural analysis using TEM.

A cross-section of DOM-35 was prepared using well-established focused-ion beam scanning-electron microscopy (FIB-SEM) techniques [11] with the Thermo Fischer Scientific Helios G3 FIB located at the Lunar and Planetary Laboratory (LPL). The section was then analyzed with LPL’s 200 keV aberration-corrected Hitachi HF5000 scanning transmission electron microscope (S/TEM). The HF5000 is equipped with secondary electron (SE) detectors, STEM-based bright-field (BF) and dark-field (DF) imaging detectors, as well as an Oxford Instruments X-MaxN 100 TLE EDS system with dual 100 nm2 windowless silicon-drift detectors with large (2.0 sr) solid angle.

Results: NanoSIMS analysis of DOM 08006 revealed an O-anomalous region with enrichments in both 16O and 18O relative to solar-system values, with 17O/16O= 4.0E-4 ± 2.0E-5 and 18O/16O= 3.34E-3 ± 7.0E-5 [10], which is consistent with a supernova origin [12]. The O-anomaly has an oblate shape (Fig. 1), measuring roughly 235 × 235 nm, as confirmed by TEM data.

Figure 1: (A) SE image of hotspot (red circle) within DOM 08006 matrix. (B) NanoSIMS δ18O image with arrow indicating the oblate hotspot and enrichment in 18O.

TEM-EDS mapping of the overall FIB section reveals a matrix containing Si, O, Mg, Ca, Fe and large grains containing Fe and S. DOM-35 contains O, Mg, and Si, with localized enrichments in (Fig. 2).

Selected-area electron-diffraction (SAED) patterns were acquired across the hotspot and reveal DOM-35 is an olivine aggregate. The left portion of the aggregate is a single crystal of forsterite (Fo30) and the right portion is a polycrystalline assemblage. Measurements of the polycrystalline region, together with EDS spectroscopy indicates an Fe-rich olivine (Fo65).

Discussion: Conditions within SNe are not well understood due to their highly energetic environments. It is therefore challenging to constrain the conditions of such environments via comparison of grain data
with thermodynamic models. However, a few studies are available in the literature. For example, Fedkin et al. [13] used model compositions of thin layers of ejecta within the main burning zones of type-II SNe, computed by [14], to construct the chemical compositions of minerals condensed by equilibrium processes in 15-, 21- and 25-Mo SNe. The resulting minerals, compositions, sequences of condensation and temperatures of condensation are similar for all three masses [13]. Olivine is a predicted condensate in the H, He/N, O/C, O/Ni and O/Si SN layers [13]. The compositions of the H and He/N layers are reducing because they are close to solar composition, therefore, forsterite is the favorable condensate, and \( X_{Fe} \) cannot exceed 0.002 above 1000 K. In the deeper, more O-rich zones forsterite is favorable between 1500 and 1600 K, and the fayalite content is between 0 < \( X_{Fe} \) < 0.03 due to the low atomic \( Fe/Mg \) ratio. Below these zones, temperatures are too low for the formation of silicates. In order to produce a more fayalitic composition, mixing between SN layers is required. Alternatively, Nozawa et al. [15] demonstrated that forsterite is a predicted condensate in both unmixed and mixed SN ejecta through non-steady-state nucleation and grain growth.

We can place constraints on the progenitor SNe of DOM-35 via comparison of the grain data to these models. In comparison to [13], the \(^{16}O/^{18}O \) ratio of DOM-35 is most consistent with a 15 Mo SN, and the stoichiometric single-crystal forsterite (Fo$_{85}$) is consistent with equilibrium condensation in a 15 to 25Mo SN between 1063-1575 K. We note that Nozawa et al. [15] developed a model in which forsterite could condense in unmixed SN ejecta through non-steady-state nucleation and grain growth. However, mixing between SN layers is required to produce the Fe-rich composition of the polycrystalline region of DOM-35 (Fo$_{55}$). Moreover, astronomical observations of SNe remnants show that the ejecta are heterogeneous, clumpy, and large scale mixing is occurring, e.g. [16]. Thus, while we cannot completely rule out forsterite condensation in an unmixed zone of the progenitor star to DOM-35, it seems unlikely that both a single-crystal forsterite grain and Fe-rich polycrystalline olivine aggregate could otherwise accrete together without significant transport occurring within or between zones.

We note that, to our knowledge, only two other stoichiometric SN silicates, B10A [5] and 2-4 [8], were previously identified in meteoritic samples. The data from both of these grains are consistent with equilibrium condensation, the former at 1560 K in a solar-metallicity star with a mass 15 M$_{\odot}$, but mixing was required to produce its Fo$_{55}$ composition [5]. The single-crystal forsterite in DOM-35 is similar in crystal structure and chemical composition to SN grain B10A [5], but its isotopic composition is significantly different. Thus, while it is conceivable that the single-crystal forsterite in DOM-35 formed under similar thermodynamic conditions as B10A, the data imply different nucleosynthetic origins.

Spectroscopic characterization of asteroids Bennu and Ryugu indicate a CM-chondrite-like petrology [17-18]. CM chondrites show evidence of aqueous alteration [19], and have also been shown to contain SN grains [e.g. 20], therefore SN grains from returned samples may show signs of processing. Applying the analytical techniques, of the kind we report here, to similar grains in returned samples from OSIRIS-REx and Hayabusa2 will aid in deciphering characteristics consistent with condensation in the host circumstellar envelope compared to those that resulted from secondary processing on asteroids Bennu and Ryugu.


Acknowledgements: We gratefully acknowledge the late Professor Christine Floss for her contributions to the identification of DOM-35 through NASA grants NNX14AG25G and NNX12AN77H. We also acknowledge NASA grants NNX12AL47G, NNX15AJ22G and NSF grant 1531243 for funding instrumentation in the Kuiper Materials Imaging and Characterization Facility at LPL. Research supported by NASA grant NNX15AJ22G and 80NSSC19K0509.

Figure 2: EDS maps of DOM-35 with HAAADF image showing anomalous region with red circle for comparison.
Summary of results from LIDAR on board Hayabusa2. H. Senshu1, N. Namiki2,3, H. Noda3,4, K. Matsumoto3,4, T. Mizuno5, R. Yamada6, Y. Ishihara7, H. Hirata8, K. Yamamoto2, T. Osubo8, A. Higuchi9, H. Araki10, S. Abe10, F. Yoshida1, S. Sasaki10, S. Oshigami3, S. Tsuruta9, K. Asari1, and M. Shizugami2, 1Planetary Exploration Research Center, Chiba Institute of Technology (2-16-1, Tsudanuma, Narashino, Chiba, 275-0016, Japan, senshu@perc.it-chiba.ac.jp), 2National Astronomical Observatory of Japan (2-21-1 Osawa, Mitaka, Tokyo, 181-8588, Japan), 3SOKENDAI (The graduate University for Advanced Studies, Shonan Village, Hayama, Kanagawa, 240-0193, Japan), 4National Astronomical Observatory of Japan (15-2 Hoshigaoka, Mizusawa, Oshu, Iwate, 023-0861, Japan), 5Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (3-1-1 Yoshinodai, Chuou, Sagamihara, Kanagawa, 252-5210, Japan), 6The University of Aizu (Tsuruga, Iki, Aizu-wakamatsu, Fukushima, 965-8580, Japan), 7National Institute for Environmental Studies (16-2 Onogawa, Tsukuba, Ibaraki, 305-8506, Japan), 8Hitotsubashi University (2-1 Naka, Kunitachi, Tokyo, 186-8601, Japan), 9Nihon University (7-24-1 Narashinodai, Funabashi, Chiba, 274-8501, Japan), 10Osaka University (1-Machikaneyama, Toyonaka, Osaka, 560-0043, Japan).

Introduction: Hayabusa2 is the second Japanese asteroid mission launched on 3rd Dec. 2018 by H-IIA Launch Vehicle No. 26 [1]. One of the main purposes of Hayabusa2 is to retrieve samples from its target body 1999JU3 (lately named as “Ryugu”). The first and second touchdown onto the surface of Ryugu to sample material were conducted successfully and Hayabusa2 is now ready to return to the Earth.

The Light Detection And Ranging (LIDAR) on board Hayabusa2 (hereafter we call this instrument “the LIDAR”) is a laser altimeter and one of the bus instruments of Hayabusa2 [2]. This means the main task of the LIDAR is to measure the altitude to navigate Hayabusa2 safely. Usually Hayabusa2 keeps its position on the line between Ryugu and the Earth and the altitude of about 20 km (“Home position”), and sometimes leaves the Home position to get closer to Ryugu for precise observation, separation of rovers or lander, sampling, and rehearsal of sampling [1]. As a result, the LIDAR is required to measure the distance from 25 km to as low as 30 m, corresponding to 6 orders of magnitude range in terms of energy. The LIDAR equips two optical systems, one is for short range and another is for long range, and two gains with one orders of magnitude separation of sensitivity for each optical systems to cover the required range. Table 1 compiles the main specifications of the LIDAR [2].

<table>
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<td>Resolution</td>
<td>0.5 m</td>
<td>300 MHz</td>
</tr>
<tr>
<td>Accuracy</td>
<td>1 m @ 30m</td>
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<td>external trig.</td>
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<td>1.5 mrad</td>
<td>FAR optics</td>
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<td>YAG</td>
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</tr>
<tr>
<td>Power consump.</td>
<td>18 W</td>
<td>w/o heater</td>
</tr>
</tbody>
</table>

Table 1: Main specification of the LIDAR [2]

Based on the rough estimation, the alignment of the LIDAR is determined more precisely through in-situ observation. Even if the satellite remains a fixed position in the inertial system, the footprint of the LIDAR constantly moves westward on the surface of Ryugu because of Ryugu’s spin. Thus the alignment of the LIDAR is determined from the matching of the distribution of boulders obtained by camera images and the time series ranging data of the LIDAR [4].

Orbit reevaluation: Once the alignment of the LIDAR is precisely determined, the orbit of the satellite can be reevaluated from the matching of the footprint position and the shape model of Ryugu [5]. The precision of the initially predicted orbit can be as large as several-hundred-meters and in some cases the position of LIDAR footprint is calculated to be inside or outside Ryugu. After reevaluation of the orbit of Haya-
busa2, almost all of footprint is settled to the surface of Ryugu, resulting a new shape model based on the LIDAR data [5].

**Local shape model of Ryugu:** The new shape model based on the LIDAR data (the LIDAR shape model) is, of course, almost the same with the original shape model used in the reevaluation procedure. However, the LIDAR should be more sensitive in terms of vertical position than camera images. So we can discuss the vertical morphology by using the LIDAR shape model. The vertical sections of big craters on the equatorial region from the LIDAR shape model show that these craters are conical shape and the slope of each walls is almost the same [6]. This might mean these craters are deformed and relaxed during or after their formation to achieve the angle of repose. These tendency is not confirmed for smaller craters because of the limitation of spatial resolution of the LIDAR shape model.

**Dust Detection by using the LIDAR:** Addition to the normal ranging mode, the LIDAR equips an operational mode called “Dust Counting mode” in which the LIDAR attempts to detect a faint signal from dust grains on the line of sight. In this operational mode the LIDAR does not measure the distance to a hard target, instead the LIDAR checks whether a signal is detected from a 1-km-wide observational range. The position of the observational range on the line of sight can be set by a command. The 1-km-wide observational range is divided into 50 small areas and the comparison of the received signal to a threshold is conducted for each small areas, resulting 50 sets of 1 (detected) and 0 (not detected). The threshold value can be changed by a command so that we can know the time-series shape of received light if signals are detected at the same position with multiple threshold values [7].

Although the attempt to detect dust grains above the surface of Ryugu and around the satellite have been conducted after arrival to Ryugu, we have not obtained obvious signal of dust grains yet. We will check the obtained data more carefully.

**Summary:** The LIght Detection And Ranging (LIDAR) on board Hayabusa2 is one of the bus instruments to measure the altitude of the satellite. Its data are also used for science purposes. We have found its effectiveness to evaluate the orbit of Hayabusa2. The combination of accurate orbit and attitude with LIDAR’s ranging data gives a new shape model which unveil the vertical cross section of the surface morphologies of Ryugu. LIDAR was also used to detect dust grains on the line of sight, however, we have not obtained concrete result yet.


**Acknowledgement:** This study was partly supported by Japan Society for the Promotion of Science (JSPS) Core-to-Core Program ”International Network of Planetary Sciences”.
**THERMODYNAMIC ANALYSIS OF WATER-ROCK REACTIONS IN THE PARENT BODY OF RYUGU.** T. Shibuya\(^1\), Y. Sekine\(^2\), S. Kikuchi\(^1\), H. Kurokawa\(^3\), K. Fukushima\(^1\), T. Nakamura\(^4\) and S. Watanabe\(^5\), \(^1\)JAMSTEC (takazos@jamstec.go.jp), \(^2\)ELSI, Tokyo Tech., \(^3\)Kanazawa Univ., \(^4\)Tohoku Univ., \(^5\)Nagoya Univ.

**Introduction:** The recent remote-sensing observation by Hayabusa2 provided a large amount of data to unravel the origin of Ryugu [1–3]. The Near Infrared Spectrometer (NIRS3) onboard Hayabusa2 revealed that the IR reflectance of the global surface of Ryugu is extremely low (~0.02) and the spectra include small but clear absorption at 2.72 μm. The findings indicate the great abundance of dark materials and the subordinate amount of hydrous minerals in the surface, respectively [3]. These materials are important clues to constrain the conditions of aqueous alteration such as the temperature experienced by the parent body and the original volatile compositions during accretion stage. In this work, we conducted thermodynamic modeling of chondrite-water reactions under various conditions to establish a model explaining the aqueous alteration of the parent body.

**Modeling Methods:** In the thermodynamic calculations, a mean composition of CV chondrites was assumed for the initial bulk rock (minor amount of carbon, nitrogen and chlorine are also included) [4, 5]. For the initial fluid, four cases were assumed; CO\(_2\) concentration is 0, 1, 3 and 10 mol% (Cases 1–4, respectively) relative to water while the latter three cases also include NH\(_3\) (0.5%) and H\(_2\)S (0.5%) additionally [6]. The equilibrium temperature and pressure were assumed to be 0, 100, 200, 300 and 350 °C, and vapor pressure of water. In the calculations, pyrene was considered as a representative of polycyclic aromatic hydrocarbon while C1 compounds except CH\(_4\) were included as soluble species [7].

In the water-chondrite reactions, molecular hydrogen is generated through reduction of water by metal iron and FeO in chondrite, which elevate \(fH_2\) of fluid to H\(_2\) saturation level in some cases. Therefore, it was assumed that \(fH_2\) of fluid does not exceed water pressure (P\(_{H_2O}\)). Considering that the ice melting and subsequent water-chondrite reactions of the parent body starts from its center, the water-chondrite reactions that \(fH_2\) reaches P\(_{H_2O}\) potentially supply excess H\(_2\) to outer part of the parent body as ice melting proceeds outward. Therefore, water-chondrite reactions likely start under H\(_2\)-rich conditions in the outer part of the parent body. Thus, two initial \(fH_2\) conditions were assumed; \(fH_2\) (initial) = 0 and \(fH_2\) (initial) = P\(_{H_2O}\). These two \(fH_2\) (initial) conditions qualitatively reflect the inner and outer parts of the parent body, respectively.

The thermodynamic calculations of water-chondrite reactions were conducted with EQ3/6 computer code [8]. The thermodynamic database required for the calculations was generated by SUPCRT92 [9] with thermodynamic data for mineral, aqueous species and complexes [10–16]. Thermodynamic parameters for a series of smectites were estimated by using the procedure of Wilson et al. [17].

**Results and discussion:** The calculations showed that stabilities of hydrous/anhydrous minerals, carbonate, pyrene change with temperature and water/rock mass ratio (W/R). In Case 1 (CO\(_2\)-free), the altered chondrite consists of serpentine, troilite and subordinate amount of hydrous/anhydrous minerals (e.g., magnetite, saponite, gibbsite and chlorite) at 0–300 °C. However, with increasing temperature above 300 °C, olivine and clinopyroxene become major phases as the amounts of serpentine, chlorite and magnetite decrease. At 350 °C, olivine becomes the most abundant minerals in conjunction with decrease in the amount of serpentine.

![Fig. 1. Abundance of alteration minerals under the condition of \(fH_2\) (initial) = 0 at (a) 100 °C and (b) 350 °C in Case 3 (CO\(_2\) = 3%).](image-url)
Similar temperature dependencies of hydrous mineral stabilities were also shown at low W/R in Cases 2–4 (CO₂ = 1–10%) whereas carbonate is predominant at high W/R (Fig. 1). Although the abundance of hydrous minerals in the surface of Ryugu is still unconfirmed, the calculation results suggest that the temperature of hydrothermal reactions experienced by Ryugu is lower than approximately 300 °C if a certain amount of hydrous minerals are present in the surface rocks. In contrast, if the amount of hydrous minerals is relatively small, higher temperatures (>350 °C) may account for the observed IR spectra, which is consistent with the model that the parent body underwent instantaneous high-temperature events such as impacts after the aqueous alteration [2].

![Fig. 2. Abundance of alteration minerals under (a) \( f_{H_2}^{\text{initial}} = 0 \) and (b) \( f_{H_2}^{\text{initial}} = P_{H_2O} \) conditions at 0 °C in Case 4 (CO₂ = 10 %).](image)

Among the predicted alteration minerals, abundance of pyrene and/or magnetite should be much higher than other minerals to account for the darkness of Ryugu (pyrene is not dark by itself but can be altered to dark organic matter through thermal maturaion). Especially, pyrene can be consolidated through reduction of CO₂ in Cases 2–4 even under the condition of \( f_{H_2}^{\text{initial}} = 0 \). These solid phases are minor or absent at high W/R where carbonate is predominant but the sum of them exceeds several % at low W/R because water-chondrite reactions at low W/R generate abundant hydrogen. Therefore, the results indicate that the altered chondrites broadly become darker with decreasing W/R. However, if the water-chondrite reactions start under H₂-rich condition (e.g., \( f_{H_2}^{\text{initial}} = P_{H_2O} \), the CO₂ in the fluid would be effectively reduced to form organic materials (Cases 2–4) even at high W/R (Fig. 2), which also potentially contribute the low reflectance of Ryugu.

Although it is still uncertain if NH₄-bearing minerals are present on the surface of Ryugu, the results of calculations showed that NH₄-bearing smectites (NH₄-saponite and NH₄-beidellite) appear at 0 °C under both \( f_{H_2} \) conditions in Cases 2–4 but are unstable at 100–350 °C. The calculations of temperature dependence of the stability of NH₄-bearing minerals indicate that NH₄-saponite change to Fe-saponite at around 70–80 °C due to decrease in pH and increase in Fe concentration of fluid with increasing temperature. If NH₄-bearing minerals are included in the samples collected by Hayabusa2, the temperature of water-chondrite reactions should be lower than 100 °C.

A series of our thermodynamic calculations revealed that large redox gradient could occur due to transportation and condensation of H₂ generated by water-chondrite reactions within the parent body. As a result, secondary mineral assemblages and organic contents could greatly change depending on not only temperature and initial volatile composition but also redox gradient. The direct analysis of collected samples will provide constraints on the alteration temperature, redox state, initial volatile composition and the original distance from the sun of the parent body.

GLOBAL THERMAL INERTIA AND SURFACE ROUGHNESS OF ASTEROID 162173 RYUGU BY TIR ON HAYABUSA2. Y. Shimakib, H. Senshuc, N. Sakatind, T. Okadae, T. Fukuharae, S. Tanaka, T. Arai, H. Demura, K. Suko, T. Sekiguchie, T. Kouyama, J. Takitae, M. Taguchie, and S. Hasegawai. 1Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa 252-5210, Japan, shimaki@plaenta.sci.isas.jaxa.jp). 2Chiba Institute of Technology, Japan. 3Rikkyo University, Japan. 4Ashikaga University, Japan. 5University of Aizu, Japan. 6Hokkaido University of Education, Japan. 7National Institute of Advanced Industrial Science and Technology, Japan. 8Hokkaido Kitami Hokuto High School, Japan.

Introduction: The thermal infrared imager TIR has been acquired thermal images of the C-type near-Earth asteroid 162173 Ryugu since June 2018. Observations for one asteroid rotation from a spacecraft position, such as the Home Position located at the 20 km altitude of sub-Earth point, enable us to trace apparent diurnal temperature change of a surface of Ryugu. The temperature profiles of Ryugu show flat pattern ubiquitously, which indicates strong effects of surface roughness, and the global thermal inertia is estimated to be around 200-300 J m^-2 K^-1 s^0.5 (=tiu) [1,2]. The value is consistent with the ground observations [3] and the in-situ measurements by MARA on MASCOT [4] but is less than the value of Bennu [5]. In this study, we examined global thermal properties including surface roughness of Ryugu by comparing TIR observations and thermophysical model (TPM) calculations.

Methods: TIR observations. TIR is based on a two-dimensional uncooled bolometer array inherited from the Akatsuki Venus Orbiter [6]. The thermal images are converted to the brightness temperature images via the calibration curves based on the pre-flight ground tests, and those brightness temperature images are projected onto a shape model of Ryugu using SPICE kernels [7]. A shape model of Ryugu composed of 200k polygon with a spatial resolution of ~2 m/polygon (SHAPE_SFM_200k_v20180804) was used [8]. With an observation for one-asteroid rotation, a diurnal temperature profile of a facet of the shape model was obtained. We used 112 out of 120 thermal images obtained at the Mid altitude operation on August 1, 2018, with one of the highest resolution (~4.5 m/pixel). During the observation, the solar-spacecraft-earth angle was ~20°, the sub-solar latitude was -8.4°, and the heliocentric distance of Ryugu was 1.06 AU. We assumed the emissivity of 0.95 instead of nominal value of 1.0.

TPM calculations. Two TPMs are used to evaluate results of TIR. One is a TPM using a shape model of Ryugu (TPM1) based on [9] and the other is one using a fractal rough surface (TPM2) based on [10]. We applied similar parameters, such as rotation axis and heliocentric distance, for both calculations. Emissivity of 0.95 was assumed. Albedo of 0.045 (bond albedo [11]) for TPM1 and 0.0146 (geometric albedo [2]) for TPM2 were assumed. For TPM1, we varied the thermal inertia γ from 20 to 800 tiu. For TPM2, we varied the latitude of the fractal rough surface from -88°N to 88°N, the thermal inertia from 10 to 800 tiu, and the surface roughness from 0 (flat) to 0.5 (rough).

Estimation of thermal inertia. The thermal inertia of a position of Ryugu is estimated from the maximum temperature by TPM1 and from the pattern of diurnal temperature profile by TPM2. The method using TPM1 is a similar one used in the landing site selection (LSS) for the first touchdown [12]. On TPM2, we used 4-order function to characterize diurnal temperature profiles at local time from 10 to 16 hour. From the regression analysis of the fitting coefficients of temperature profiles by TPM2, we obtained empirical equations to estimate thermal inertia and surface roughness from the fitting coefficients. We applied surface tilt angle correction in ±15° both in longitude and latitude, since a shape model reduces surface slope due to limitation of resolution. We regulate analysis on the dataset with the solar incident angle <35°.

Results and Discussions: Thermal inertia of Ryugu using TPM1. TPM1 provides a temperature profile of a surface of a shape model of Ryugu [7,13] and the temperatures reached maximum at low latitudes, since the solar incident angle defines input solar flux. As a result, the thermal inertia of Ryugu estimated by TPM1 shows latitudinal variation with a peak at the equatorial ridge with ~400 tiu, with the global mean of 280±140 tiu. No thermal inertia was obtained at high latitudes, because no TPM1 calculation reproduced observed maximum temperature. Although the global thermal inertia is in the range of the values by the ground and the in-situ observations [3,4], no geologic variation in latitude was observed by the optical navigation camera (ONC) [2]. Thus, we consider that this global thermal inertia is useful only for a prediction of maximum temperature for given epoch required in the LSS.

Thermal inertia of Ryugu using TPM2. TPM2 gives flat temperature profile as a function of a thermal inertia, a surface roughness, and a latitude of rough surface. Regression equations for thermal inertia and surface roughness for each latitude were obtained. Using the 4-order fitting coefficients of an observed
temperature profile of a facet, the thermal inertia and the surface roughness of the facet was obtained.

Figure 1 shows the map of the thermal inertia with variations in the longitude and the latitude. Locations of natural craters are shown by circles. The thermal inertia of Ryugu shows homogeneous distribution both in the longitude and latitude, with the global thermal inertia of $210 \pm 50$ tui. We could not determine the thermal inertia at high latitudes.

The surface roughness map of Ryugu by TPM2 is shown in Figure 2. Similar to the thermal inertia map, the surface roughness shows homogeneous distribution with the mean value of $0.42 \pm 0.02$, corresponds to moderately rough surface. The relatively low thermal inertia and the high surface roughness suggests that the surface of Ryugu is covered by numerous boulders with low thermal inertia.

We investigated the thermal inertia of natural craters and found no dependence of the thermal inertia on crater size, suggesting that there is no compaction craters. Besides inside of the craters, ejecta depositions surrounding these craters were not observed in the thermal inertia map. The lower global thermal inertia of Ryugu might be results from porous and probably fragile nature of C-type asteroid as an ancestor of carbonaceous chondrites.

![Figure 2. Surface roughness (sigma) map with latitudinal and longitudinal variations.](image)

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**References:**


![Figure 1. Thermal inertia map with latitudinal and longitudinal variations. Natural craters are shown by circles.](image)
Introduction: Global observations of the near-Earth asteroid Ryugu with the telescopic Optical Navigation Camera (ONC-T) onboard Hayabusa2 revealed that the color of Ryugu surface is very uniform and extremely dark (4.5% of albedo, one of the most darkest material in the Solar System [1]). Thus, anomalous materials deviated from the average color on Ryugu are expected to stand out as bright spots. In fact, Hayabusa2’s initial observations have revealed the presence of bright spots (Fig.1) [1]. Because of their small size, however, no spectral characterizations have been conducted.

After the global observations, higher resolution images were taken during the low-altitude observations, such as MINERVAII and MASCOT deployments, the touch down rehearsals, and the touch down operations. These observations revealed the abundance of bright spots in smaller scale (Fig.2). In this study, we define objects with peak reflectance \( \geq 1.5 \) times more than the global average reflectance of Ryugu as bright spots and investigate their spectral properties.

Spectral classification: Using the 7 color band filters (ul: 0.40 \( \mu \)m, b: 0.48 \( \mu \)m, v: 0.55 \( \mu \)m, Na: 0.59 \( \mu \)m, w: 0.70 \( \mu \)m, x: 0.86 \( \mu \)m, p: 0.95 \( \mu \)m), we evaluated the visible spectra of surface of Ryugu. Note that objects smaller than the diameter of 2 pix cannot be evaluated because of the point spread function (FWHM~1.7 pix [2]). We extracted the visible spectra of bright spots observed during hovering operation after MASCOT deployment at \( \approx 3 \) km of the altitude (\( \approx 0.3 \) m/pix). The spatial distribution of 21 bright spots (M1 - M21) is shown in Fig.3.

Data processing, such as removal of stray light, bias, and read-out smear, flat fielding and I/F conversion have been conducted based on the calibration method described by [3]. Note that we employed the updated flat files based on the close encounter images of the asteroid, which is reported by [4]. The spectra of bright spots were photometrically corrected to incidence, emission, phase angles of \( (i,e,\alpha) = (30^\circ,0^\circ,30^\circ) \) in the same way as [1].

The spectra of these bright spots are classified into two groups depending on the absorption near 1 \( \mu \)m, indicative of mafic minerals. Six out of 21 bright spots have relatively strong 1-\( \mu \)m absorption (S-type bright spots) and others are featureless at around 1 \( \mu \)m (C- or X-type bright spots) as shown in Fig. 4.

S-type bright spots: The six S-type bright spots range from \( \approx 0.5 \) to \( \approx 2 \) m in diameter. Absorption band around 2 \( \mu \)m, which is covered by NIRS3 [5], is useful for characterizing anhydrous silicates. However, because the footprint of NIRS3 is much larger than that of ONC-T, measuring the spectra of small bright spots are much more challenging. Nevertheless, the spectra of largest bright spots (\( \approx 2 \) m in diameter) can be measured with NIRS3, indicating rather shallow absorption of this bright spot. This observation result implies that these bright spots are similar to S-type asteroids or ordinary chondrites.

Because Ryugu spectra are uniformly Cb-spectra [1], such S-type spectra are difficult to come from the same parent body. Thus, these materials should be exogenic. Ryugu is most likely from inner asteroid main belt through the \( \nu_6 \) resonance [6]. Exogenic origin of S-type bright spots is consistent with the abundance of S-type asteroids in inner main belt. There are two hypotheses for mixing of S-type materials: 1) They are emplaced on the Ryugu surface as a result of low-velocity collision of small S-type asteroids. Such soft landing without major impact comminution of projectiles would require \( \approx 0.2 \) km/s of impact velocity. 2) They were mixed during the catastrophic disruption of Ryugu’s parent body caused by a large S-type asteroid. Considering the collisional velocity in the inner main belt [7], soft landing of several exogenous material is less possible compared with the probability of catastrophic disruption of Ryugu by a larger impactor. This suggests that mixing during catastrophic disruption is much more likely.

C- or X-type bright spots: C- or X-type bright spots show featureless spectra. Compared with the spectra of boulders on the Ryugu, however, they have greater variety of spectral slope and absorption in ultraviolet (UV) wavelengths. Although these bright spots are much brighter than the average of Ryugu, the similarity of spectral shape, suggests that the bright spots are possibly intrinsic materials.

Because carbonaceous chondrites are known to change its color by heat-induced devolatilization [8,9], the observed color variation of C-type bright spots may reflect differences in thermal metamorphism. Thus, we compared spectra between bright spots and heated chondrites. For example, heating experiments on CM chondrites suggests that UV absorption strength continues to decrease until 700 or 800 °C and then in-
increases again thereafter with flattering (bluing) of spectral slope [8]. C-type bright spots with bluer spectral slope have a trend that bluer ones have stronger ultraviolet absorption. This trend is similar to the spectral change seen in heating experiments with CM chondrite above 700 – 800 °C. These similarity in color variation between C-type bright spots and CM chondrite heating experiments suggests that the C-type bright spots may have experienced partial dehydration to degrees different from the average Ryugu materials.

Fig. 1. S-type bright spots images obtained during high-resolution observations. Scale bars are 5 m. M13 and M7 is first and second largest bright spots with S-complex spectra.

Fig. 3. Location map of bright spots. Note that the apparent concentration of bright spots in the equatorial region is due to the fact that high-resolution observations are highly concentrated near the equator.

Fig. 2. Bright spots observed during touch-down rehearsal operation on 15th Oct. 2018 at 241 m of the altitude. Scale bar is 5 m.

Fig. 4. V-band-normalized reflectance spectra of two types of bright spots. (a) An S-type bright spot with strong 1 μm absorption. (b) A C-type bright spot with spectra similar to Ryugu surface average. Thin grey line indicates the average of Ryugu surface.

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NUMERICAL SIMULATIONS OF THE DEFORMATION OF RAPID-ROTATING ASTEROIDS AND THE FORMATION OF SPINNING TOP SHAPES. K. Sugiura, S. Watanabe, H. Kobayashi, H. Genda, R. Hyodo, S. Inutsuka. 1Earth-Life Science Institute, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo, 152-8550, Japan. 2Department of Earth and Environmental Sciences, Nagoya University, Furo-cho, Chikusa-ku, Aichi, 464-8601, Japan. 3Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Aichi, 464-8601, Japan. (sugiura@elsi.jp)

Introduction: The asteroids Ryugu and Bennu now explored by the spacecraft Hayabusa2 and OSIRIS-Rex, respectively, are rubble piles and have so-called “spinning top” shapes [1], [2]. The top-shaped asteroids are mostly axisymmetric around their axes of rotations, and they have cone-like surfaces from low latitudes to mid latitudes. Many top-shaped asteroids, such as the asteroid 1999 KW4 [3], rapidly rotate with the rotation period of about 3 hours. The axisymmetric shapes and the rapid rotations of the top-shaped asteroids suggest that spinning top shapes are formed through the deformation due to rapid rotations caused by the Yarkovsky-O’Keefe-Radzievskii-Paddack (YORP) effect.

Rapidly rotating fluid bodies deform into oblate spheroids (i.e., the Maclaurin spheroids). Thus, the formation of top shapes is not natural outcomes of the deformation due to the rotational spin-up and requires some conditions such as high friction angles or internal structures of rubble pile bodies. The conditions required for the formation of top shapes may constrain physical properties and evolution of the top-shaped asteroids.

How rubble piles are deformed through the spin-up is mainly investigated through numerical simulations using discrete element methods (DEMs). Although the simulations with a hard sphere DEM [4] successfully show that the spin-up of rubble pile bodies produces top shapes, detailed conditions for the formation of top shapes are still unknown partly because the hard sphere DEM does not explicitly treat the friction between DEM particles. A soft sphere DEM [5] explicitly treats the friction and cohesion between DEM particles, but the formation of top shapes is not observed in the simulations with the soft sphere DEM although they conduct many simulations with various values of the angle of friction and cohesion.

In this study, we investigate the deformation of rubble pile bodies due to the spin-up using the other simulation method: a smoothed particle hydrodynamics (SPH) method. We use the version of a SPH code [6], [7] that includes the friction model for granular material [8]. DEMs calculate the friction between particle pairs. In contrast, the SPH code directly treats the friction of the bulk of rubble pile bodies, i.e., the aggregation of granular particles.

Simulation Setup: We simulate the rotational deformation of a spherical body with the radius of 500 m and the uniform density of 1.19 g/cm³. The number of SPH particles comprising the body is about 25,000. Although the friction angle obtained from lunar soil is at most 50 degrees [9], we vary the friction angle of the body from 20 to 80 degrees because the cohesion may increase the “effective” friction angle.

The initial rotation periods of the body are determined so that the spherical shapes with given friction angles are stable [10]. Then we accelerate the rotations such that 0.5 h decrease of the rotation periods occurs in 1.0 × 10⁵ s. We stop the acceleration after 1% of the total mass are ejected.

Results:

Fig. 1: Cross sections of the deforming body through the spin-up. Vectors and those colors show velocity fields. Times presented at the top of the panels show elapsed times after the starts of the simulations. Panels (a), (b), and (c) show the results of the simulations with the friction angles of 40, 60, and 80 degrees, respectively.

Figure 1 shows the cross sections of the body when the deformation of the body is the most noticeable. Note that the body axisymmetrically deform. Fig. 1a shows that the deformation speed with the friction angle of 40 degrees is slow. The timescale of the deformation is about 1.0 × 10⁵ s, which is similar to the timescale of the spin-up, i.e., quasi-static deformation occurs. Fig. 1b shows that the deformation speed with the friction angle of 60 degrees is fast. The timescale of the deformation
is about $1.0 \times 10^4$ s. We also notice that not only the outer parts but also the innermost parts of the body deform, i.e., dynamical and internal deformation occurs. Fig. 1c shows that, in the case with the higher friction angle of 80 degrees, inner parts of the body do not deform but the surfaces move to equatorial region, i.e., landslide occurs.

![Image](70x522 to 177x625)

Our numerical simulations of the friction angle of 80 degrees produces top shapes. Our results suggest that the spin-up of rubble piles with the friction angle of 80 degrees can produce top shapes.

How reasonable the very high friction angle of 80 degrees is? The friction coefficient is the ratio of shear strengths to confining pressures, and the friction angle is the arctangent of the friction coefficient. The cohesion plays as shear strengths, and the cohesion of lunar soil is at most 1 kPa [9]. The confining pressure at the center of an asteroid with the radius 500 m is about 50 Pa. The shear strength of 1 kPa and the confining pressure of 50 Pa result in the effective friction angle of about 87 degrees. Thus, the existence of the cohesion may realize the high friction angle of 80 degrees.

The acceleration rate of the rotation examined in this study is of course much faster than the actual spin-up rate caused by the YORP effect. Shapes of asteroids before the deformation due to the spin-up may not be complete spheres and they may initially have surface roughness or complex shapes. In our future works, we will investigate how the spin-up rate and initial shapes affect shapes produced through the deformation caused by the spin-up.

**References:**


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**Fig. 2:** Cross sections of the body after the deformation shown in Fig. 1 occurs. The red lines show the surfaces of the body for the latitudes of 0 – 20, 20 – 40, 40 – 60 degrees. The red numbers near the red lines represent surface slope in degrees, i.e., the angles between the rotation axes and the surfaces. Panels (a), (b), and (c) show the results of the simulations with the friction angles of 40, 60, and 80 degrees, respectively.

Figure 2 shows the cross sections of the body after the deformation shown in Fig. 1 occurs. Fig. 2a and b show that the internal deformation produces the rounded and flat shapes. The shapes do not have straight surfaces and the differences of the surface slopes between low latitudes and mid latitudes are large. In contrast, Fig. 2c shows that the landslide produces straight surface with the small difference of the surface slopes between low latitude and mid latitude. This shape is axisymmetric and thus have the cone-like surface, i.e., the top shape. Our results suggest that the spin-up of rubble piles with the friction angle of 80 degrees produces top shapes.

**Summary and Future Prospects:** We conduct the numerical simulations of the spin-up of the rubble pile body using the SPH code and investigate how they deform. We find that the quasi-static and internal deformation occurs for the body with the friction angle of 40 degrees, the dynamical and internal deformation occurs for the friction angle of 60 degrees, and the landslide occurs for the friction angle of 80 degrees. The landslide produces the axisymmetric straight surfaces from low latitude to mid latitude, i.e., the top shape. Therefore, our results suggest that the spin-up of rubble piles with the friction angle of 80 degrees can produce top shapes.
MODELLING THE PARTICLE AND PHYSICAL MAKEUP OF METEOROIDS. B. Szutu¹,² and P. Jenniskens²,¹Research Experience for Undergraduates Program. ²SETI Institute, Mountain View, CA

Introduction: Every night, the Cameras for All-sky Meteor Surveillance (CAMS) project detects hundreds of meteors and calculates their trajectory and orbit to map our meteor showers. Each meteors’ light curves is recorded along with other parameters such as height, velocity, and deceleration. That data is saved into the CAMS database.

In this SETI Institute Research Experience for Undergraduates program study, we worked to implement into the CAMS data processing pipeline a numerical meteoroid model that fits the meteor lightcurves as a function of height and that outputs relevant parameters on particle size distribution and thermal and physical properties of the meteoroids.

Methodology: In order to create this model, three objectives needed to be considered: Firstly, the model should be able to simulate a lightcurve and velocity profile closely matching the observations in a reasonable amount of time. Secondly, the model should extract meaningful physically parameters. Thirdly, the model’s output should be written to an output text file that integrates to the CAMS data processing pipeline.

Our starting point was an existing MATLAB code that had implemented the meteoroid ablation model of Campbell-Brown et al. [1]. The model assumes that a meteoroid will start breaking up once the melting temperature of the “glue” of the meteoroid is reached. Once this glue temperature is reached, the glue melts and solid grains of the meteoroid are released. Those solid grains then ablate according to classical meteor ablation theory.

This code was translated into Python. The code was further improved by implementing the grain erosion model by Borovička, Spurný, and Koten [2]. It assumes a more continuous fragmentation of the meteoroid, resulting in smoother light curves.

Further improvements were made. For the atmospheric density and temperature in the upper atmosphere, for example, we fitted $7^{th}$ and $9^{th}$ degree polynomials to the respective logarithmized outputs of the MSISE-90 atmospheric model. The logarithmized temperature versus height was specifically fit with two $9^{th}$ degree polynomials since the MSISE-90 model outputted a sharp rise in temperature starting at 100 km in altitude.

Results: An example of the height versus magnitude output of the model with manually inputted free parameters is shown in Fig. 1. An improved fit could perhaps be obtained when exploring the parameter space, but that required a long run time.

Discussion: One way to solve the long run-time problem is to limit the parameter space. For example, the lightcurve's f-parameter, the measure of how lopsided the light curve is, could estimate the size distribution index. Another method in optimizing the run time is to utilize one of the many available mathematical optimization algorithms available.

Overall, the new software tool is a good starting point towards implementing a pipeline tool to extract the various physical parameters of detected meteors.

Conclusion: In order to obtain the physical parameters of detected meteoroids, a model was created in order to produce a best-fitting light curve for each meteoroid. This model was then implemented into the pipeline of the SETI CAMS project. While the model has a qualitatively good fit for sample meteor, more work needs to be done in order to for it to run through the many detected meteors efficiently.

HAYABUSA2 SAMPLE COLLECTION AT RYUGU.  S. Tachibana1,2, H. Sawada2, R. Okazaki3, Y. N. Miura4, Y. Takano5, K. Sakamoto1, and H. Yano2, 1UTokyo Organization for Planetary and Space Science (UTOPS), University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan. tachi@eps.s.u-tokyo.ac.jp. 2 Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (JAXA). 3Department of Earth and Planetary Sciences, Kyushu University. 4Earthquake Research Institute, University of Tokyo. 5Biogeochemistry Program, Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

Hayabusa2 at Ryugu: Hayabusa2, JAXA’s asteroidal explorer, arrived at a near-Earth C-type asteroid (162173) Ryugu on June 27, 2018. Ryugu is expected to record a long evolutionary history of the Solar System from the beginning to the present. Since its arrival, Hayabusa2 has been investigating the asteroid [1-3] with a telescopic optical camera with 7 band filters (ONC-T), a near-infrared spectrometer (NIRS3), a thermal infrared imager (TIR), and a laser altimeter (LIDAR), two rovers (MINERVA-II1; HIBOU and OWL), and a MASCOT lander [4, 5].

It has been found that Ryugu has a top shape with an equatorial ridge (mean radius of 448 ± 2 m), having a retrograde rotation with a period of 7.6326 hours and an obliquity of 172° [1]. Its bulk density is estimated to be 1.19 ± 0.03 g/cm³, suggesting that the asteroid has a large macro-porosity of ~50-60% [1]. One of the striking surface geological features is the presence of many large (>20 m) boulders with a number density twice as large as that of Itokawa, and there is no smooth terrain as seen in Itokawa [2]. These observations (low bulk density and boulder-rich surface) lead to the conclusion that Ryugu is a rubble-pile body [1]. It has been also found that the surface has a very low geometric albedo, darker than most of meteorite samples [2], and that the surface has uniformity in visible and near infrared spectra with a weak 2.72-μm absorption feature [2, 3]. The 2.72-μm absorption feature suggests the ubiquitous presence of hydrous phases [3].

The MASCOT lander found that the surface is not covered with fine grained dust, and that the surface rock with inclusions could be similar to carbonaceous chondrites [4] but with a lower thermal conductivity [5].

Sample collection at Ryugu: The basic concept and design of the Hayabusa2 sampler are the same as the original Hayabusa [6-8] (Fig. 1). In order to collect sufficient amount of samples (100 mg) compliant with both monolithic bedrock and regolith targets, a 5-g Tungsten projectile is shot at an impact velocity 300 m s⁻¹ at the timing of touchdown. The ejecta are put into a sample catcher through an extendable sampler horn and a conical horn under a microgravity condition (1.5 x 10⁻⁴ m s⁻² [1]). One-gravity laboratory experiments using the 1:1 scale of the sampling system with 1 mm glass spherules at one gravity shows that 150-250 mg of samples can be collected with a projectile shooting, which is expected to be increased under microgravity because eject with low velocities can be collected. Three projectiles are equipped for sampling at three different surface locations.

The sample catcher of the Hayabusa2, located at the top-end of conical horn, has three chambers to store samples obtained at three locations separately [7] (Fig. 2). An inlet to the sample catcher is rotatable to select a chamber to store samples at each location. The size of sample catcher is almost the same as that of the original Hayabusa with two chambers, and the total volume is ~45 cm³. The sample catcher has a design that is easier to be taken apart during curation at ISAS/JAXA than that of the original Hayabusa.

A back-up sampling method is also prepared [7]; The tip of the sampler horn is turned up like the teeth of a comb (Fig. 1), and surface pebbles will be lifted up by the turn-up part during touch down. The lifted pebbles will be put into the sample catcher by deceleration of the spacecraft.

On February 22, Hayabusa2 landed at a location on the equatorial ridge, and the projectile was successfully shot to the Ryugu surface. After the SCI impactor experiment in April, the spacecraft made another successful landing nearby the artificial impact crater to collect sub-surface material excavated by the impact. There is no way to monitor the amount of collected samples, but the images taken during the landing operations (Fig. 3) imply that samples were collected at two locations.

After the sampling operations, the sample catcher that stored samples at two locations separately was transported into the sample container inside the Earth re-entry capsule and sealed on August 26 (Fig. 4). The aluminum metal sealing system [8] will avoid the terrestrial air contamination (Fig. 2), which was designed to allow only a leak of 1 Pa air for 100 hours at atmospheric pressure. To avoid further potential contamination, volatile components released from the samples will be extracted prior to the opening of the container. The container will be attached to a vacuum line, and the bottom of the container, a part of which is thinned, will be pierced with a needle to extract volatiles (Fig. 2).
This study was supported by Japan Society for the Promotion of Science (JSPS) Core-to-Core Program "International Network of Planetary Sciences".


Fig. 1. Photograph of the Hayabusa2 sampler horn and schematic illustration of the Hayabusa2 sampler [7].

Fig. 2. Schematic illustration of the Hayabusa2 sample catcher and container [7].

Fig. 3. The images of the sampler horn after the first and second touchdown operations.

Fig. 4. Transfer of the sample catcher to the sample container inside the Earth re-entry capsule [7].
**RESURFACING PROCESS ON RYUGU CONSTRAINED BY CRATER DISTRIBUTION**

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**Introduction:** Hayabusa2 observations have revealed various geomorphological features, such as impact craters and flow features on Ryugu [1]. An important finding on impact craters on Ryugu is deflation of small craters [1]. This suggests that resurfacing is very active in surface layers. Similar deflation in small craters has been observed on Eros, Itokawa, and Bennu [2,3,4]. Seismic shaking induced by impacts, regolith flow induced by the YORP effect, and granular convection have been proposed as resurfacing processes on these asteroids. In particular, seismic shaking has been modeled and shown to reproduce crater size frequency distributions on Eros and Itokawa [5,6].

However, unknown parameters, such as quality factor and diffusion constant, were assumed in the seismic shaking model. For example, strong cohesive force was assumed in the model, but Small Carry-on Impactor (SCI) experiment revealed that cohesive strength of subsurface layer on Ryugu is very small [7]. In this study, we estimate the crater retention age of Ryugu, Itokawa, Eros, and Bennu based on crater counting and crater production function. Then, we compare resurfacing processes among four asteroids.

**Method:** Crater retention ages can be estimated by using the crater size frequency distribution (CSFD) and the crater production function (CPF). The CPF consists of impactor distribution model and crater scaling relation. We used the main-belt impactor distribution calculated by [8] (BAL model) and a scaling law incorporating the armoring effect [9] for Ryugu, Itokawa, and Bennu. We assumed that cohesion strength on small asteroids is zero. For analysis, we produced crater production functions of a variety of ages. Reading an intersection of the CPFs with CSFDs constructed from actual observations yields the age required to form the number of observed craters. The age corresponds to lifetime (retention age) of craters. Thus, we derived the crater retention age \( t \) as a power-law function of crater diameter \( d \), \( t \sim d^a \). Then, we calculated the power-law indices \( a \) by using the least squares method.

**Dataset:** The CSFD of Eros is given by [2]. Crater candidates on Itokawa are counted and classified based on confidence levels (CL) by [3]. We counted crater candidates on Ryugu and classified in a similar fashion as Itokawa. We used CL1-2 crater candidates of Itokawa and Ryugu for our analysis. Crater candidates on Bennu are classified as distinct or less distinct [4], and we used distinct crater candidates.

**Results:** The power-law indices \( a \) were 2.8 ± 0.1 on Ryugu, 2.9 ± 0.3 on Itokawa, 2.5 ± 0.2 on Eros, and 2.9 ± 0.3 on Bennu, respectively (Fig. 1). Since different physical processes should yield different power-law indices, the similar \( a \) values suggest that a similar resurfacing process is dominant on these asteroids. Vertical intersects are controlled by resurfacing efficiency. The vertical intersect for Eros is larger than that for Ryugu, Itokawa, and Bennu, suggesting that resurfacing rate on Eros is smaller than other three asteroids.

![Fig. 1. Relation between crater retention age and crater diameter. Circles are data calculated from R-plot. Solid lines are linear fitting for the data points. Green dashed line shows power-law with index \( a=2 \) (i.e., diffusion process).](image)

**Discussion:** If crater degradation is controlled by diffusion processes (e.g., seismic shaking), the crater retention age is proportional to the square of crater diameter, i.e., \( t \sim d^2 \). However, the power-law indices of the four asteroids are significantly larger than 2.

Here we note that the power-law indices can vary depending on the models, such as the impactor size.
distribution and cohesion condition. Nevertheless, we found that the power-law indices of crater retention age are consistently larger than 2 despite the uncertainty in impactor size distribution. If we use a different impactor distribution model, such as [10] (OOG model), the power-law indices become even larger than the BAL model.

If we use a stronger cohesion condition, on the other hand, the power-law indices of the four asteroids become approximately 2 and are consistent with that of diffusion process. However, the small cohesion on Ryugu revealed by the SCI experiment [7] is inconsistent with this interpretation. Because the morphologies (e.g., raised rim and bowl shaped cavity) of craters on Bennu are similar to those on Ryugu [4], the cohesion on Bennu could be as small as that of Ryugu. The small cohesion may be true for Itokawa as well because Itokawa’s crater retention age calculated under gravity-dominant condition is consistent with cosmic ray exposure ages and boulder distribution age [9]. Thus, small cohesion condition may be valid for Itokawa. On Eros, loose regolith layer thickness is estimated to be the order of tens of meters from the NEAR observations [11]. Cohesion on Eros is supposed to be small.

Here we focus on Ryugu’s crater retention age plot. The Ryugu’s plot (Fig.2) shows a transition at diameter \( d \sim 30 \) m. The retention age of craters 30 m in diameter at the near-Earth orbits is estimated to be about 3.5 Myr by using the method described in the method section. Craters on Ryugu can be classified as “red” or “blue” based on spectral slope of the inside craters [12] and the retention age of blue (fresh) craters on Ryugu is estimated to be about 8 Myr, suggesting that Ryugu has been in the near-Earth orbit at least for 8 Myr. This result implies that most of the craters smaller than about 30 m were produced at the near-Earth orbit and may be erased by resurfacing process at the near-Earth orbit.

The power-law index for the Ryugu data is significantly larger than 2. One interpretation for this is that the crater distribution on Ryugu reflects diffusion processes at different orbits. The size distribution of large craters (\( \geq 53 \) m) on Ryugu may reflect diffusion processes in the main asteroid belt, and that for small craters (\( \leq 13 \) m) may reflect those at the near-Earth orbit. That for mid-size craters may reflect transition from the main belt to the near-Earth orbit (Fig.2).

Acknowledgment: This study was supported by Japan Society for the Promotion of Science (JSPS) Core-to-Core Program “International Network of Planetary Sciences”.


Fig. 2. Relation between crater retention age and crater diameter for Ryugu. The power-law indices of red lines are 2 (i.e., diffusion process). The upper red line is diffusion process in the main asteroid belt, and the lower red line is theoretical prediction for diffusion process at the near-Earth orbit. Blue line might record the transition from the main asteroid belt to the near-Earth orbit.
Nature of Roughness of Ryugu Revealed by Thermal Simulation of High Resolution Digital Elevation Model.


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Introduction:

One of the main science objectives of the observations made by the thermal infrared camera (TIR) on board the Hayabusa2 spacecraft[1] is to deduce the thermal structure of the surface of asteroid Ryugu. So far, we found that the thermal inertia (TI) on a global scale with 5-20m resolution is widely uniform but strongly affected by surface roughness. In order to fit the temperature profile from dawn to dusk, an artificial roughness model was applied [2].

On the other hand, digital elevation models (DEM) with different resolution were constructed based on observations of the optical navigation camera (ONC) by the Hayabusa2 Shape Modeling Team. Higher resolution of the DEM reflects real surface roughness, and then, it is of our interest to investigate the relationship between observed TIR data and characteristic of roughness.

In this study, we performed thermal simulations using DEMs with different resolutions, and compared these with the observation data.

TIR Observation:

TIR has been collecting images of Ryugu since June, 2018 and more than 10000 images have been taken to date. Basically, three different types of observations have been conducted such as, (1) stationtal observation at 20km altitude (so called “home position”), (2) mid-altitude at 5km altitude, and (3) close-up observation for off-nominal descent operations such as touch down, lander deployments, and gravity measurement and so on. In order to analyze global thermal behavior, mid-altitude observation is suitable because the target subject was included within a image frame. This observation was conducted on Aug. 1, 2018, and then we used this data as reference.

Digital Elevation Model (DEM):

The Digital Elevation Model was constructed by the Hayabusa2 Shape Modeling Team. Representative global shape models consist of 3M and 200K polygons whose characteristic length (one side of triangle) is about 1m, and 5m respectively. In addition to these models, partial DEMs for special purposes were made in order to survey the safety of touch down operations. In this study, we used the L08B local DEM model which was made for the first touchdown, carried out on Feb. 21, 2019. The length of each polygon is about 10cm, one order finer than the 3M polygon model.

Thermal Simulation:

Temperature simulations were carried out using our original coded program which involves secondary radiation effects on the surficial polygon, and one dimensional thermal conduction from the surface[3]. We also simulated the expected images that will be obtained by TIR from orbital information. We applied a parallel projection in the rendering process from a 3D to a 2D image[3]. In this study, we assumed bond albedo of 0.014, and an emissivity of 1.0 uniformly for all models.

Results and discussion:

Figure 1 shows an example of numerical simulation and observation image taken on Aug.1, 2018.

Fig.1 TIR image at 5km altitude taken on Aug 1, 2018 (left) and result of thermal simulation (right). The center area of Ryugu is approximately in a sub-solar position. The global shape model is the 200K polygon model and a thermal inertia of 300 J m\(^{-2}\) K\(^{-1}\) s\(^{0.5}\) was assumed.
The thermal inertia of the simulation was assumed to be 300 J m\(^{-2}\) K\(^{-1}\) s\(^{0.5}\) which is an averaged global value \[2\]. We found a large difference between observation and model. In particular, the simulated temperature at noon (around the center of the object) is higher, and more than 20K lower in the dusk and dawn region. That is, the temperature distribution of the real image is more uniform throughout dawn to dusk than that of the numerical simulation using this shape model. This phenomena should be a characteristic thermal behavior of rough surface\[2\] and 200k model could not reflect its thermal response.

Figure 2 shows a diurnal temperature profile at the first touchdown area at where the finest DEM was produced. The figure also shows the fitted curve obtained using the artificial roughness model\[2\]. There is little difference between the 3M and the 200K model. However, the result of the L08B model was drastically different and matches the observation data well. We note that this is the first time a good match of the diurnal temperature change between observation data and simulation data based on the “real topographic model” has been obtained.

Acknowledgments: The authors would express thanks to the Hayabusa2 team members for their technical and operational supports and for helpful scientific discussions.

References:

In order to investigate the validity of the result, Figure 3 shows one of the closest images of TIR taken at an altitude of 8.5m when the final touch down operation sequence was conducted. We found that the surface is predominantly covered by boulders tens of cm to several tens of cm in size. In this sense, the thermal behavior of Ryugu seems can be explained as depicted by the finest DEM, dominated by roughness on scales of tens of cm.
COMPARISON OF RYUGU AND BENNU BASED ON CROSS CALIBRATION BETWEEN ONC-T AND MAPCAM. E. Tatsumi,1,2,3, T. Koyama4, D. R. Golish5, S. Kameda6, H. Sato7, B. Rizk8, D. N. DellaGiustina9, Y. Yokota9,8, H. Suzuki9, J. de León10, H. Campins10, J. Licandro1,2, M. Popescu1,2, J. L. Rizos1,2, R. Honda1, M. Yamada1, T. Morota1, N. Sakatani1, Y. Cho1, C. Honda12, M. Matsuo12, M. Hayakawa7, H. Sawada7, K. Oga- wa12, Y. Yamamoto7, S. Sugita3, D. S. Lauretta5, 1Instituto de Astrofisica de Canarias, Tenerife, Spain (etatsumi@iac.es), 2Dept. of Astrophysics, Univ. La Laguna, Tenerife, Spain, 3Univ. of Tokyo, Tokyo, Japan, 4National Inst. of Adv. Ind. Sci. and Tech., Ibaragi, Japan, 5Lunar and Planetary Laboratory, Univ. of Arizona, AZ, USA, 6Rikkyo Univ., Tokyo, Japan, 7Inst. of Space and Astron. Sci., Japan Aerospace Exploration Agency, Kanagawa, Japan, 8Koigi Univ., Koigi, Japan, 9Meiji Univ., Kanagawa Japan, 10Univ. of Central Florida, FL, USA, 11Planetary Exploration Research Center, Chiba Inst. of Tech., Chiba, Japan, 12Univ. of Aizu, Fukushima, Japan, 11Kobe Univ., Hyogo, Japan.

Introduction: The Hayabusa2 spacecraft by JAXA and the OSIRIS-REx spacecraft by NASA both aim to sample from the primitive asteroids, Ryugu and Bennu, respectively. They have both similarities and differences. For example, both asteroids are top-shaped, have similar density, and are considered to be rubble-pile asteroids [1,2]. Moreover, they are suggested to come from the inner main belt region [3,4]. However, the near infrared spectrometers, NIR3 and OVIRS, showed great difference in 2.7-µm band absorption [5,6]. It is very important to compare directly both objects and discuss compositional and evolutionary similarity and difference between two objects.

In this study, we conduct cross calibration between multi-band cameras for both spacecraft, the telescopic Optical Navigation Camera (ONC-T) onboard Hayabusa2 and MapCam onboard OSIRIS-REx. Although independent calibrations have been done by [7,8], they used different light sources for absolute calibrations; the stellar observations for ONC-T and the lunar observations for MapCam. Spectra are sensitive to the reference light source. Especially since the two asteroids do not have much variation over the surface, we need careful calibration when we compare directly. We conducted cross calibration based on the lunar models, SP/SELENE [9,10] and WAC/LROC [11], as the common reference.

Instruments: Both ONC-T and MapCam are equipped the multiple bandpass filters based on the Eight-Color Asteroid Survey (ECAS, [12]). ONC-T has 7 bandpass filters centered at 398, 480, 549, 590, 700, 857, and 945 nm, while MapCam has 4 bandpass filters centered at 473, 550, 698, and 847 nm.

Datasets: The lunar images were taken during the flyby near the Earth by both cameras. Table 1 shows a summary for the lunar observations. As references, we simulated the moon images for all filters based on the observational geometry with the WAC/LROC model for shorter wavelengths (<700 nm) range and the SP/SELENE model for longer wavelengths (>500 nm) range (Fig. 1). It should be noted that the WAC/LROC model does not cover pole regions due to lack of data and that the SP/SELENE model is less accurate at high emission and incidence angles [10].

Table 1 The observation of the Moon.

<table>
<thead>
<tr>
<th>Date</th>
<th>ONC-T</th>
<th>MapCam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>2015-12-05</td>
<td>2017-09-25</td>
</tr>
<tr>
<td>Time</td>
<td>11:49:08</td>
<td>02:50:06</td>
</tr>
<tr>
<td>Distance</td>
<td>763,969</td>
<td>1,226,706</td>
</tr>
<tr>
<td>iFOV (°)</td>
<td>0.00615</td>
<td>0.00388</td>
</tr>
<tr>
<td>Phase angle(°)</td>
<td>59.3</td>
<td>42.8</td>
</tr>
</tbody>
</table>

Figure 1 Observed radiance images based on the current calibrations and simulated radiance [W/sr/m²] images based on the SP/SELENE model. (top left) ONC-T observed image. (top right) ONC-T simulated image. (bottom left) MapCam observed image. (bottom right) MapCam simulated image.

Boost factors: Comparison between observed and simulated images gives us a factor to boost the simulated image to fit the observed image. After we aligned the observed and simulated images, the radi-
ance images are compared pixel-by-pixel where the incidence angle >60˚ and the emission angle >45˚. The boost factor is acquired as the slope of the least square linear regression of pixels. Figure 2 shows the example of fitting. The boost factors are summarized in Table 2 and Fig. 3. Although the absolute values for the simulated Moon image has up to 10% error, the relative brightness between wavelength is as accurate as 3%. Assuming that the calibration of ONC-T based on stellar observations are more reliable than the lunar model in terms of absolute brightness, it can be seen that the generally the current calibration of MapCam underestimates the brightness by ~18% at 550 nm.

**Figure 2** Comparison between the observed and simulated images pixel-by-pixel for ONC-T. The boost factors are derived as the slope of linear fitting.

**Figure 3** Boost factors for both instruments. (right) The absolute boost factors based on the Lunar models, showing the MapCam underestimates the brightness for all wavelengths compared with ONC-T. (left) The normalized boost factors shows the deviation between two instruments. This can cause the spectral shape difference even when both observe the same object.

**Comparison between Ryugu and Bennu:** Utilizing these boost factors, albedos and spectra can be compared directly. Previously the geometric albedos of Ryugu and Bennu were reported as 4.5 ± 0.2%[13] and 4.4 ± 0.2%[14], respectively. However after applying the boost factors, Bennu could be 5.1% – 5.2%, suggesting ~15 - 18% brighter than Ryugu.

It is interesting to note that the Otohime boulder on the south pole of Ryugu has normal albedo ~5% significantly higher than the Ryugu average and similar to the cross-calibrated average albedo of Bennu. This boulder is also known as one of the bluest parts on Ryugu [13], and the blue color (i.e., spectral slope) is comparable to the Bennu average. This suggests similarity between Otohime and Bennu spectra. However, the surface of Otohime was possibly dehydrated by solar heat in the past. These findings suggest that the Otohime boulder can be a key for understanding the relationship between two bodies.

**Acknowledgment:** We are grateful to the entire Hayabusa2 and OSIRIS-REx Team for making the encounter with Ryugu and Bennu possible. This study is supported by JSPS Core-to-Core program “International Network of Planetary Sciences”. This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program.


Introduction: The Hayabusa2 spacecraft has been investigating the C-type asteroid (162173) Ryugu for more than one year. Global observations at the home position (alt. of ~20 km) by the telescopcial optical navigation camera (ONC-T) revealed the presence of blue material distributed on both poles of Ryugu [1]. Based on their correlation with topological features, the blue material is expected to be fresher (less processed) material. Moreover, the largest boulder, Otohime on the south pole has different spectral and morphological faces, being very distinct from other boulders on Ryugu’s surface. In particular, the similarity between the blue material spectra to Bennu’s visible spectra is especially a great topic to discuss regarding the relationship between the two bodies. Thus, we have conducted close (alt. of ~5 km) observations of the poles on 28 February to 1 March and from 26 to 27 July 2019. Especially, in July, the ONC-T and the spectrometer NIR3 performed simultaneous observations to obtain both visible and near infrared wavelength information. In this study, we are focusing on the presence of 0.7-µm band which indicates an Fe2+ to Fe3+ charge-transfer transition in oxidized iron, associated with phyllosilicates [2]. The presence of 0.7-µm absorption is also important to constrain the composition of Ryugu’s material. The distribution of the 0.7-µm band absorption is discussed in comparison with the solar wind flux and solar heating of Ryugu’s surface.

Observations: The visible camera (ONC-T) onboard Hayabusa2 is equipped with 7-color band filters: ul: 0.40 µm, b: 0.48 µm, v: 0.55 µm, Na: 0.59 µm, w: 0.70 µm, x: 0.86 µm, p:0.95 µm [3]. Both north and south poles were observed with 7 bands at every 30° longitudinally. The phase angle was 16° – 17° for February and March and 38° – 39° for July.

Data reduction: Radiance factors (I/F) were calculated using the calibration described in [3]. Note that we used the updated flat-fields [4] to reduce the fringe pattern in the original flat-fields. Moreover, we also implemented the radiator stray-light reduction described in [3]. The detectability of 0.7-µm band absorption was tested on-ground using the ONC-T flight model and CM2 chondrites [5]. We measured the degree of the 0.7-µm band absorption using the relationship

\[ d_{0.7} = 1 - \frac{3.1R_w}{1.6R_x + 1.5R_o}, \]

where \( R_w, R_x \), and \( R_o \) indicate the radiance factor at v-, w-, and x-bands, respectively. After conducting the calculation at a pixel-by-pixel resolution, we took the median value of 8 x 8 pixel boxes in order to reduce statistical noise, because the ONC-T has SNR~100 without binning and this is not enough to distinguish subtle differences in the 0.7-µm band absorption. We also measured the b-to-x spectral slope using the same methods as [1].

Results: Figure 1 shows the 0.7-µm band absorption (left column) and b-to-x spectral slope (right column) for both the north and south poles. The pole regions have bluer spectra, i.e., negative spectral slope, than other low latitudinal regions. At the same time, some of the bluer regions show a deeper absorption at 0.7 µm. Specifically, some boulders on the north pole and the Otohime boulder on the south pole exhibit stronger absorption of ~2% compared with adjacent regions. Although there are still random noise and shadows to be carefully removed, the positive identification of the absorption on the polar boulders is considered real. This 0.7-µm band absorption could indicate the presence of more hydrated minerals at the pole regions.

Discussions: The 0.7-µm band is very important to distinguish between CM or CI chondrites; CM with the 0.7-µm band absorption and CI with absence of it. Thus, the discovery of a 0.7-µm band absorption suggests that Ryugu might have been processed from CM-like material with more Fe-rich phyllosilicates. The 0.7-µm band absorption is easily lost by heating and/or space
weathering [6,7]. The 0.7-µm band absorption in the pole regions can be related to solar irradiation of the surface. Calculations of the solar wind flux to the entire surface of Ryugu shows that the irradiation rate of the pole regions is ~5 times less than that of the equatorial ridge in the asteroid’s current orbit and pole position. On the other hand, the temperature of the surface was observed by the thermal infrared imager (TIR)[1]. Initial analysis of TIR data showed that thermal inertia of the surface is around 300 J m²K⁻¹s²⁻⁰·⁵ [8]. Figure 2 shows the modeled maximum temperature map of Ryugu at perihelion, using the shape model of SHAPE_SFM_200k_v20180804 [9] with a uniform thermal inertia of 300 J m²K⁻¹s⁻0·⁵. The temperature map also suggests that a part of the north pole is among the coldest <100K on Ryugu’s surface even at perihelion. It should be noted that Otohime’s sharp cliff-like face is even hotter than average. Thus, the absorption at Otohime needs further explanation regarding the presence of the hydrated mineral. Although the current orbital distance from the Sun cannot explain the heating up to the temperature of dehydration ~600°C [10], Ryugu could have experienced a closer encounter to the Sun in the past given its chaotic orbital motion[11]. The 0.7-µm band absorption could be weakened and the spectral slope could become redder due to the solar wind and/or the solar heat. If this is the case, there would be more hydrated material inside of Ryugu than it currently appears on the surface. The NIRS3 spectra of those regions which show the 0.7-µm band absorption and the sub-surface by the Small Carry-on Impactor experiments are under analysis. The integration of information about the relative strengths of the 0.7-µm and 2.7-µm band absorptions may provide stronger constraints to distinguish between those two scenarios.

Moreover, the bluer regions are spectrally similar in the visible range to the near-earth asteroid Bennu, which is the target asteroid of OSIRIS-REx [12]. More hydration and blueness of the spectra for less irradiated boulders suggest that Ryugu and Bennu could be siblings that had different orbital histories or different creation times.

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Figure 1. The 0.7-µm band absorption maps (left) and b-to-x spectral slope maps (right) for the north pole (top) and the south pole (bottom).

Figure 2. Maximum temperature map at perihelion calculated using the shape model. Some areas on the north pole suggest low surface temperatures. The lowest temperature can be found around (lat, lon) ~ (60°, 300°).

Advancing Asteroid Science and Technology Using Student Built CubeSat Centrifuge Laboratories

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Asteroid science, technology, and exploration is an important and exciting research and education theme at the UA that encompasses the College of Science and College of Engineering. For example, the UA’s Catalina Sky Survey has been instrumental in discovering a large fraction of known Near-Earth Asteroids. In addition, the UA leads the OSIRIS-Rex mission (PI: Dante Lauretta)—a sample-return mission to the Near-Earth Asteroid, Bennu. These ongoing achievements make the UA an ideal institution to lead an effort in STEM education that creates excitement and instills a sense of adventure and discovery to a diverse community of minority students in the local community. UA is planning to develop a research and education center called ASTEROID (Asteroid Science, Technology and Exploration Research Organized by Inclusive eDucation (ASTEROID) funded by NASA.

This proposed program envisions project-centric, hands-on education that would place UA students and transfer students from the nearby Pima Community College and the University of Puerto Rico, Humacao in cutting-edge research labs at the UA and in direct collaboration with a NASA Center. UA, Pima, and Univ. of Puerto Rico students would be tasked with developing an exciting series of CubeSat missions particularly CubeSat centrifuge laboratories AOSAT 2 through 4. They will use the student-built AOSAT-1 as the template. On AOSAT-1 minority students made-up 50% of the team and was representative of local demographics. These on-orbit labs will be built and operated by students and they will simulate asteroid surface conditions and will be used to advance the science and technology of asteroids.

The students will use AOSAT 2 through 4 to test their hypothesis. These on-orbit centrifuge laboratories will be on the frontlines to advance asteroid science and technology. AOSAT 2 will perform hypothesis testing of impact studies on a simulated asteroid surface. This will result in the formation of artificial craters and their characterization over accelerated time. In AOSAT 3, the focus will be on manipulation of the simulated asteroid surface through excavation, grappling, and anchoring activities. AOSAT 4 will be used to demonstrate excavation and processing on a simulated asteroid and to extract water for production of rocket propellant. The water may be heated into steam or electrolyzed into hydrogen and oxygen and combusted. The on-orbit centrifuge platform will enable accelerated development and testing of critical In-situ Resource Utilization technology to extract water on asteroids and turn them into propellant for transiting spacecraft.

The longterm strategic vision of the center is to facilitate the development of low-cost, UA-led small-satellite and CubeSat exploration missions to Near-Earth Asteroids, planetary moons, and comets. This is being led by an interdisciplinary team of graduate Master’s students, Ph.D. students, and postdocs at UA’s College of Engineering and College of Science. In pursuit of this long term effort, rapid advancements are being made using automated missions design tools to design whole new missions including single and multiple (swarms) of spacecraft to perform tours of asteroids and Kuiper Belt Objects (KBOs). The capability is being replicated with robotics to enable end to end multidisciplinary design and control optimization for extreme environment exploration tasks. Another focus area is on unconventional spacecraft architectures including hybrid orbiter/landers such as SPIKE, inflatable spacecraft, and landers to perform multiple surface examinations and seismic readings of small bodies. A third focus area has been the development of a diverse ‘toolbox’ of
miniature landers, hoppers, and impactors scaled to tackle varying high-risk/high-reward exploration goals. These landers are meant to be dropped off from passing spacecraft to perform short-duration missions to characterize the small body surface and layers beneath covered due to weathering. Impactors are being designed both to clear a surface and remain as a beacon for secondary science missions. A fourth focus area has been to advance the Cislunar economy and to find ways to utilize the natural resources on nearby asteroids and moons and their strategic locations for assembly of next-generation telescopes, fuel depots, critical communication relays and deep space spacecraft repair/servicing and assembly centers. System architecture development is complemented with basic research in new forms of solar and laser-based additive manufacturing and robotic assembly.

These factors make asteroid science, technology, and exploration an exciting vehicle for hands-on education of minority students. Our past efforts have shown that involving new students in front-line research projects helps bring out student creativity, new and diverse ideas, and instill drive, purpose, and ambition. Working with UA, Pima and Univ. of Puerto Rico undergraduate students, in turn, helps graduate student mentors advance their leadership skills, get teaching experience, and sharpen their research efforts. Importantly, the proposed program educates students through hands-on, motivational skills and experience—an experience that will enable them to open doors to opportunities in the high-tech science and technology sectors and meet NASA education goals by strengthening the future workforce for NASA and the nation.
THE EFFECTS OF SPACE WEATHERING ON THE ORGANIC AND INORGANIC COMPONENTS OF A CARBONACEOUS CHONDRITE: IMPLICATIONS FOR RETURNED SAMPLES FROM HAYABUSA2 AND OSIRIS-REx


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Introduction: Space weathering, driven by micrometeoroid impacts and solar wind irradiation, modifies the microstructure, chemical composition, and reflectance properties of surface material on airless bodies [1]. Our understanding of space weathering processes has largely been derived from studies of lunar and ordinary chondritic materials e.g., [2,3]. However, there are fewer constraints on how hydrated, organic-rich materials respond to these processes. With the OSIRIS-REx and Hayabusa2 missions already reporting results from their carbonaceous targets, Bennu and Ryugu, respectively, it is important to understand how space weathering affects the surfaces of these asteroids e.g., [4]. In advance of sample return, we can investigate the microstructural, chemical, and spectral effects of space weathering on carbonaceous chondrites by performing laboratory experiments, e.g., [5,6]. Here we report results of coordinated analyses of samples of a carbonaceous chondrite which independently underwent pulsed laser irradiation to simulate micrometeoroid bombardment and ion irradiation to simulate solar wind exposure.

Samples and Methods: We dry-cut four rock chips of the CM2 Murchison meteorite for laser and ion irradiation experiments. For three of the chips, we rastered an Nd-YAG pulsed laser (λ=1064 nm, ~6 ns pulse duration, energy 48 mJ/pulse) over their surfaces 1x, 3x, and 5x, respectively. For the fourth chip we irradiated two distinct areas; one region with 2 keV H$_2$ ions for a total fluence of 8.1x10$^{17}$ ions/cm$^2$ and the second region with 4 keV He$^+$ ions to a total fluence of 1.1x10$^{18}$ ions/cm$^2$. The ion flux for both irradiations was 1.1x10$^{13}$ ions/cm$^2$/s.

After irradiation, we collected reflectance spectra over the wavelength range of 0.35-2.5 μm from the fresh, laser- and ion-irradiated regions of the samples respectively using an ASD FieldSpec 3 Spectrometer. We used the µL$^2$MS instrument at JSC to investigate changes in the concentration and functional group chemistry of organics in the samples after both laser- and ion-irradiation. We also prepared electron-transparent thin sections from the heterogeneous meteorite matrix and from select olivine, pyroxene, and sulfide phases using the FEI Quanta 3D focused ion beam (FIB) for each of the laser- and ion-irradiated samples. We performed microstructural and chemical analysis of these samples in a JEOL 2500 transmission electron microscope (TEM). Finally, we used a radiative transfer model to interrogate the spectral effects of the nanoparticle population observed via TEM in the laser-irradiated samples in order to correlate microstructural and chemical features with measured reflectance data.

Spectral Analyses: The VIS-NIR spectra show that the laser-irradiated regions of the samples are all darker than the unirradiated material, although there is increased brightening with progressive laser irradiation. In contrast the ion-irradiated regions appear brighter, with a more significant increase in reflectance for the He-irradiated region of the sample (Fig. 1). There is an attenuation of the 0.7 μm band (associated with Fe$^{2+}$ to Fe$^{3+}$ charge transfer in phyllosilicates) in each of the irradiated samples. There is an observed initial increase in the strength of the 0.48 μm band between the 1x and 3x laser-irradiated samples, and an overall increase in the band depth for both H- and He-irradiated sections of the sample.

![Figure 1: Absolute reflectance spectra of the raw (black), 1x laser-irradiated (purple), 5x laser-irradiated (green), H-irradiated (red), and He-irradiated (blue) samples.](image-url)

Organic Analyses: µL$^2$MS spectral maps of the laser-irradiated samples consistently show similar (5x) or increased (1x) concentration and distribution of organics in the lasered regions compared to the raw surface and also show an increase in the abundance of aromatic/conjugated organic material in lasered regions. In contrast, analyses of the ion-irradiated regions show a
significant decrease in the distribution of organics, by up to 40%, in the He-irradiated region, with aromatic species being preferentially retained.

**TEM Analysis:** Results from the TEM reveal complex microstructural and chemical features in both the laser- and ion-irradiated samples.

**Laser Irradiated Samples:** For each of the matrix samples, there is a surface melt layer, increasing from 500 nm to ~1 μm in thickness from the 1x to the 5x laser irradiated sections. These melts contain abundant nanoparticles, ranging from <10-100 nm in diameter. High-resolution TEM (HRTEM) data and energy-dispersive X-ray spectroscopy (EDS) maps indicate the nanoparticles include Fe (possibly metal, may contain O), Fe-oxide (magnetite), Fe-S (troilite), and Fe-Ni-sulfides (pentlandite). The nanoparticles are dominated by Fe-Ni-sulfides in the 5x lasered sample (Fig. 2). HRTEM images indicate the degree of amorphization of phyllosilicates increases with continued laser irradiation.

**Figure 2:** TEM data of the 5x lasered matrix. a) Bright field STEM, and EDS maps of b) S, c) Fe, and d) Ni.

**Ion-Irradiated Samples:** The He-irradiated matrix section shows a continuous vesiculated layer greater than 100 nm in thickness. It is characterized by large vesicles up to 50 nm in width. HRTEM shows amorphization of the matrix material up to depths between 125 – 175 nm, consistent with results from [7]. Small (<2 nm) nanoparticles are present below the vesiculated layer and are distributed heterogeneously throughout the sample. The H-irradiated matrix sample also has a continuous vesiculated layer, however it is thinner (<100 nm) than in the He-irradiated matrix. Here, phyllosilicates are amorphized up to a depth of ~95 nm from the surface. Finally, the H-irradiated enstatite FIB-section is characterized by a 100 nm-thick vesiculated (Fig. 3). Nanoparticles between 3-5 nm in diameter are located within this vesiculated layer. Diffraction patterns suggest these nanoparticles are likely Fe-bearing.

**Spectral Modeling:** We used a radiative transfer model to investigate the spectral characteristics of quartz grains hosting nanoparticles varying in size and composition. Nanophase (<40 nm) and microphase (>40 nm) magnetite particles cause an overall darkening and bluing of the spectrum. Similarly, both nano- and microphase inclusions of troilite show darkening. However, nano-phase troilite causes strong reddening of the spectrum, whereas microphase particles cause bluing.

**Figure 3:** HRTEM image of a H-irradiated enstatite grain showing the thickness of the vesiculated layer to be 100 nm. The lattice fringes indicate the grain maintains crystallinity up to the boundary with the vesiculated layer.

**Implications for Primitive Asteroids:** The results presented here provide further evidence that the space weathering of carbonaceous surfaces is likely to be a complex process. Laser- and ion-irradiation produce seemingly conflicting spectral trends resulting in darkening and bluing vs. reddening and brightening, respectively. Similarly, the size and composition of nanoparticles produced in the experiments is highly variable, with larger, Fe-oxide and Fe-Ni-sulfides present in the laser-irradiated samples and smaller, heterogeneously distributed Fe-nanoparticles identified in isolated phases in the ion-irradiated samples. Radiative transfer modeling indicates that the size and composition of the nanoparticles plays a significant role in the resulting spectral characteristics of the sample. As such, differences in nanoparticle production mechanisms and/or evolving populations of nanoparticles could result in the inconsistent spectral trends observed here. Additionally, analyses of the organic abundance and functional group chemistry also indicates divergent trends between the laser- and ion-irradiated experiments. In both experiments, however, aromatic molecules appear resistant to simulated space weathering, providing clues as to the types of organic species we might expect in returned samples.

Together, these results suggest that carbonaceous-style space weathering is unique and that micrometeoroid bombardment and solar wind irradiation may induce competing spectral trends driven by unique microstructural and chemical characteristics specific to each constituent process.

SPACE WEATHERING MAPS OF (101955) BENNU USING A RADIATIVE TRANSFER MODEL. D. Trang\textsuperscript{1}, B. E. Clark\textsuperscript{2}, H. H. Kaplan\textsuperscript{3}, M. S. Thompson\textsuperscript{4}, S. Ferrone\textsuperscript{5}, A. A. Simon\textsuperscript{5}, L. P. Keller\textsuperscript{6}, H. C. Connolly Jr.\textsuperscript{7,8}, K. J. Walsh\textsuperscript{5}, and D. S. Lauretta\textsuperscript{8}.\textsuperscript{1}Hawai‘i Institute of Geophysics and Planetology, University of Hawai‘i, \textsuperscript{2}Ithaca College, \textsuperscript{3}Southwest Research Institute, \textsuperscript{4}Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, \textsuperscript{5}NASA Goddard Space Flight Center, \textsuperscript{6}NASA Johnson Space Center, \textsuperscript{7}Rowan University, School of Earth and Environment, \textsuperscript{8}Lunar and Planetary Laboratory, University of Arizona

Introduction: Space weathering is an important process that affects the surfaces of airless bodies, such as (101955) Bennu. The consequences of this process include physical and chemical changes to materials on the surface, which in turn change spectral characteristics, especially in the visible to near infrared wavelengths [1–5]. These spectral changes are not the same across airless bodies because the changes are dependent on the composition and mineralogy of the surface and even location within the Solar System [e.g., 5, 6]. The main space weathering products responsible for these spectral changes are submicroscopic particles, which consist of two types, nanophase and microphase particles, and affect visible to near-infrared reflectance spectra differently [7–8]. Nanophase particles are particles <33 nm in size and occur in agglutinates and within glassy patinas around regolith particles [9]. In contrast, microphase particles are >33 nm in size and are present only within agglutinates. These spectral differences are best illustrated by lunar samples. In lunar soils, the nanophase and microphase particles consist of metallic iron [e.g., 5]. With increasing abundance of nanophase iron particles in a regolith, its spectrum exhibits a lower overall reflectance in the visible to near infrared, weakened absorption bands, and a reddened continuum slope [7]. In contrast, an increasing abundance of microphase iron only causes decreases in reflectance and not reddening. Because of the spectral differences introduced by these two types of particles, it is possible to model the nanophase and microphase particle abundances of a surface through the radiative transfer technique.

Beyond the Moon, the composition of the nanophase and microphase particles can include other phases because the mineralogy of the surfaces of other planetary bodies is different. For example, the nanophase and microphase particles may consist of amorphous carbon (Mercury) and sulfides (Itokawa) [6, 10]. The mineralogy of Bennu is consistent with carbonaceous chondrites [11,12]. From a number of space weathering experiments on CM chondrites [11, 12], the likely nanophase and microphase mineral phases on Bennu includes iron, magnetite, and sulfides (i.e., pentlandite and troilite) [13].

The goal of this work is to input the predicted nanophase and microphase compositions for Bennu into the radiative transfer technique. Next, we use this technique to model the OSIRIS-REx Visible Infrared Spectrometer (OVIRS) so that we can model the nanophase and microphase particle abundances across the surface. This will result in space weathering maps of the surface of Bennu, which are useful for understanding the degree of space weathering across the surface and its relationship to various regions and geological features.

Methods: We implement a radiative transfer model that was developed by [5] and improved by [8] to model the OVIRS spectra. Although boulders dominantly cover the surface of Bennu [14], to use this model, we needed to assume that the surface of Bennu is covered with a regolith consisting of 45 μm particles, which we call the host particle. This host particle consists of silicates with a constant reflectance of ~3% to keep the nanophase and microphase abundances to realistic values similar to the Moon (~<2 wt%). We will be applying this model to the photometrically-corrected OVIRS data obtained during the 12:30pm Equatorial Station of the Detailed Survey mission phase, and therefore used an emission and incidence angle of 0° and 30°, respectively, in our model. Our model uses three different compositions for the nanophase and microphase particles (total of six different particle types), metallic iron, magnetite, and troilite as we do not have optical constants for pentlandite.

Results: We find that we can consistently model the visible to near-infrared reflectance of OVIRS spectra of Bennu (Fig. 1). Furthermore, our model shows that space weathering can produce the “bluing”, which could explain in part or in full Bennu’s global blue visible to near-infrared spectral slope [11]. In our model, we used host particle sizes ranging from 30–50 μm, which increase or decrease the overall reflectance. We observe that using different particle sizes result in similar relative abundances between different nanophase particle compositions. However, the microphase iron abundance and to a lesser extent the microphase troilite abundance increase with smaller host particle sizes and decrease with larger host particle sizes. This is due to the model using the microphase iron particle abundance (which darkens a spectrum) to decrease the overall model reflectance to match the OVIRS spectra. Therefore, although our model does
not properly account for host particle grain size, the nanophase abundances can be considered in terms of abundance relative to other nanophase particle abundances. The microphase iron abundance and to a lesser degree, the microphase troilite abundance, are dependent on the host particle size.

Using these submicroscopic particle abundances, we produced nine global maps, three nanophase, three microphase, and three submicroscopic particle abundance maps of each of the three mineral phases, iron, magnetite, and troilite. *According to our model, the primary phases present on Bennu that are due to space weathering are the submicroscopic magnetite and troilite particles.*

**Future Work:** With these new space weathering maps, we will search for correlations with other Bennu-referenced geospatial quantities to determine how these relative abundances of submicroscopic particles vary with composition, geology, surface features (e.g., craters), and latitude and longitude position.

![Figure 1](image_url)

**Fig 1:** An example of a best-fit model spectrum (red dashed) to an observed OVIRS spectrum (black line) over an area centered at 204.6°E and 8.7°N.

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DEHYDRATION PROCESS OF C-COMPLEX ASTEROIDS REVEALED THROUGH NEAR-INFRARED SPECTROSCOPY. F. Usui1, S. Hasegawa2, T. Ootsubo3, K. Amano3, and T. Nakamura3. 1Center for Planetary Science, Graduate School of Science, Kobe University, 7-1-48 Minatojima-Minamimachi, Chuo-Ku, Kobe, Hyogo 650-0047, Japan (usui@cps-jp.org), 2Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan, 3Division of Earth and Planetary Materials Science, Graduate School of Science, Tohoku University, Sendai, Miyagi 980-8578, Japan.

Introduction: Knowledge of hydrated minerals among asteroids is important for understandings of solar system formation, evolutionary processes, and thermal history. Hydrated minerals are formed in environments where anhydrous rock and liquid water exist together with a certain pressure and temperature, resulting from aqueous alteration. Because hydrated minerals are stable even above the sublimation temperature of water ice, they become an important reservoir to trace the water present in the history of the solar system. Hydrated minerals exhibit diagnostic absorption features in the near-infrared wavelength at around 2.7 µm (e.g., [1]); however, not many studies have been done to compare asteroids with meteorites in this wavelength. Many spectroscopic surveys of asteroids have been conducted in near-infrared wavelengths using ground-based telescopes (e.g., [2]), which are severely affected by atmospheric absorption especially in 2.5-2.85 µm. Besides, spectral measurements of meteorites in the laboratories are severely suffered from contamination of atmospheric water that is absorbed in and rehydrated to samples under ambient terrestrial conditions.

Recently this situation has been drastically improved by (a) the infrared astronomical satellite AKARI covered spectroscopically in 2.5-5 µm [3], (b) in-situ measurements of asteroids with the spacecrafts Hayabusa2 [4] and OSIRIS-REx [5], and (c) the heating experiments in the laboratory to remove effects of adsorbed/rehydrated water [6-7]. Here we provide a comparative study of spectral characteristics of asteroids and meteorites in the 2.7-µm band.

Data Set: Figure 1 shows examples of the obtained spectra in this work; C-complex asteroids observed with the AKARI satellite [3], the in-situ measurements of asteroid 162173 Ryugu with Hayabusa2 [4] and 101955 Bennu with OSIRIS-REx [5], and the results of the heating experiments of the Murchison meteorite in the laboratory [6-7].

Results and Discussion: As seen in figure 1, the peak wavelengths of significant absorption features are concentrated at around 2.75 µm. In particular, C-complex asteroids observed with AKARI have a trend between the peak wavelength and the band depth [3]. Figure 2 shows this trend for 17 C-complex asteroids. Except for four outliers, there is a clear correlation between the peak wavelength and the band depth among 13 C-complex asteroids. The characteristics of Ryugu and Bennu can also be interpreted in the context of this trend found by the AKARI observations. This can be understood in terms of the process where hydrated minerals are being heated up and gradually losing water, that is, the dehydration process. Based on the laboratory experiments, it is reported that a peak-wavelength in the 2.7 µm band of hydrated minerals shifts toward shorter wavelength because of the dehydration process [6-7]. The band depth indicates an abundance of phyllosilicate which means an amount of water, and the peak wavelength indicates the Mg/Fe ratio in phyllosilicate. During the dehydration process by heating, the amount of water decreases and the Mg/Fe ratio of phyllosilicate simultaneously increases. The heating energy of the dehydration could be supplied by solar wind plasma, mutual collisions of asteroids, or decay heat from radioactive isotopes in the rocks. Interestingly, the size range of the dehydration process in figure 2 has three orders of magnitude (from 1000 km to < 1 km). This dehydration process can be considered as a universal phenomenon among C-complex asteroids, although there is no clear correlation found between band depths and the sizes of asteroids or the heliocentric distances.

Nowadays, telescopic observations and spacecraft explorations are complementary to each other. Ground-based and space-borne telescopes obtain a large number of data for studying a wide range of compositional distribution of asteroids. In-situ spacecraft observations provide detailed physical, chemical, and geological information of targeted asteroids. In addition, sample analyses and experiments in laboratories determine mineralogical characteristics of asteroidal materials. This is one of the first attempts for full-scale interdisciplinary research in the study of C-complex asteroids.

Figure 1: Reflectance spectra normalized at 2.6 µm of (red) C-complex asteroids observed with AKARI [3], (blue) in-situ measurements of asteroid 162173 Ryugu with Hayabusa2 [4] and 101955 Bennu with OSIRIS-REx [5], and (orange) the Murchison meteorite heated in the laboratory (unheated, 300, 400, and 500°C heated) [6-7]. The gray dashed line indicates the position of 2.75 µm.

Figure 2: The relationship between the band depths at 2.7 µm against the peak wavelength for the obtained spectra in this work. The red dots denote C-complex asteroids observed with AKARI [3]; the different marks show differences of subgroups in the types of C-complex based on the Bus-DeMeo taxonomy [8]. The solid gray line indicates the fitted linear line of the correlation coefficient of 0.88. The thin red dots denote the asteroid treated as outliers for fitting (details are given in [3]). The blue filled circle and open circle denote Ryugu [4] and Bennu [5] observed with Hayabusa2 and OSIRIS-REx, respectively. The orange dots denote the Murchison meteorite heated in the laboratory [6-7], as unheated, 300, 400, and 500°C heated samples, connected by arrows in this order. The trend of data points located from top right to bottom left indicated by the gray line can be understood in terms of the dehydration process.

MARTIAN MOONS EXPLORATION: PHOBOS SAMPLE RETURN FOR UNDERSTANDING THE MARS-MOON SYSTEM. T. Usui1, K. Bajo2, W. Fujiya3, Y. Furukawa4, M. Koike1, Y. N. Miura2, H. Sugahara1, S. Tachibana1,6, Y. Takano3, M. Zolenski5, K. Kuramoto1,4, 1Institute of Space and Astronautical Science, JAXA, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 252-5210, Japan (usui.tomohiro@jaxa.jp), 2Dept Earth Planet Sci, Hokkaido University, 3Faculty of Science, Ibaraki University, 4Dept Earth Sci, Tohoku University, 5ERI, University of Tokyo, 6UTOPS, University of Tokyo, 7Biogeochem. Program, JAMSTEC, 8ARES, JSC/NASA.

Introduction: Japan Aerospace Exploration Agency (JAXA) plans a Martian moon’s sample return mission (MMX: Martian Moons eXploration) [1]. The origin(s) of the Martian moons (Phobos and Deimos) is still a matter of significant debate: i) capture of asteroids [e.g., 2] or ii) in-situ formation by co-accretion [3] or a giant impact [e.g., 4] on Mars (Table 1). In either case, samples from a Martian moon returned by MMX will provide the necessary ground truth to test these theories and to offer an opportunity to directly explore the building blocks or juvenile crust/mantle components of Mars. This new knowledge of Phobos/Deimos and Mars will be further leveraged by constraining the initial condition of the Mars-moon system and have the potential for offering vital insights regarding the sources and delivery process of volatiles including water and organics into the inner rocky planets. This paper summarizes the recent update on our study [5] for the expected characteristics of the returned samples and the prospective scientific outcomes from their laboratory analyses (Table 1).

Sampling System: The MMX spacecraft is scheduled to be launched in 2024, orbit Phobos and Deimos (performing multiple flybys), and retrieve and return >10 g of Phobos regolith back to Earth in 2029. To fulfill the mission goals [6], MMX should collect both endogenous and exogenous samples from the regolith covering the Phobos surface. The former represents Phobos building blocks that record information of the moon’s origin, while the latter is expected to contain solar system projectiles and ejecta derived from Mars and Deimos [7, 8]. Although the depth profile of Phobos regolith regarding material distribution is unknown, a ratio of [exogenous /endogenous] abundances is expected to be highest at the top-most regolith layer which is where sampling will occur.

MMX plans to employ a double sampling approach: (C) coring and (P) pneumatic. The C-sampler, a core soil tube deployed by a robotic arm, would provide access to Phobos’ building blocks beneath the surface (>2 cm), but would collect a mixture of surface and sub-surface materials. The P-sampler, on the other hand, selectively samples the surface veneer and provides a reference of surface component for the C-sampler. The P-sampler will also increase the chance of retrieving invaluable Martian and Deimos materials. Thus, the C- and P-samplers would provide a complementary approach to addressing the MMX mission goals [6].

The double sampling system not only enhances the scientific merits of MMX, but also reduces risks associated with the coring system. The nominal landing operation will execute both C- and P-sampling at each landing site. However, lacking knowledge of physical and chemical properties and conditions of the surface of Phobos (e.g., compositions, temperature gradient/variation, porosity, grain size distribution), we will prepare for scenarios in which the C-sampler cannot penetrate deep enough into a thin regolith layer covering a rigid basement and/or that it cannot be extracted once it penetrates. Under any conceivable surface conditions, the P-sampler will work effectively and independently to collect fine-grained regolith particles.

Expected Characteristics of Returned Samples: The characteristics of the returned endogenous samples depend on Phobos’ origin (Table 1). In the case of the captured asteroid origin [e.g., 2], the returned samples would be analogous to a certain type of chondrites, IDPs (interplanetary dust particles), or even comets, depending on where these moons originally formed in the early solar system. If they formed in the outer solar system (beyond the snow line), they could potentially contain abundant hydrous secondary phases and organic molecules. Such phases could have formed by water-rock-organic interaction under low-temperature conditions in the parent asteroid of Phobos, resulting in H-, C-, and N-rich bulk chemistry [9]. Alternatively, outer solar system formation could be indicated by unreacted ice and crystalline/amorphous silicate dust mixtures, as found with the comet Wild-2 samples returned by the Stardust Spacecraft [10]. On the other hand, if the Martian moons formed in the inner solar system (inside of the snow line), they probably consist mostly of anhydrous phases with lower bulk volatile contents and characteristic isotopic differences. These two extreme cases for the captured model may be tested on the basis of the heliocentric gradients of volatile isotopes and abundances (e.g., CO/H2O, D/H, 15N/14N and noble gases) and the isotopes of rock-forming elements of O, Cr, Ti in the solar system [11-13].

In contrast to the captured asteroid scenario, if Phobos and Deimos formed in-situ by a giant impact
(like the Earth’s moon) [e.g., 4, 14], the returned samples would be characterized by high-$T$ and possibly high-$P$ glassy or recrystallized igneous phases. Due to the high-$T$ impact process (e.g., $>$2000 K)[14], endogenous organic materials would be unlikely to be present to a significant degree in the regolith. The bulk chemistry could range from a mafic to ultramafic composition with high abundances of highly siderophile elements, representing a mixture of Martian silicate portions (crust/mantle) and the impactor [14]. The bulk-silicate Mars is characterized by elevated volatile (e.g., Na and K) and siderophile (e.g., Mn, Cr, and W) elements and depletions in chalcophile elements (e.g., Cu), relative to the bulk silicate Earth. Such a volatile-rich nature relative to the Earth and Moon is evident in ratios of $K/Th$ and $K/U$ (volatile/refractory incompatible element); the $K/Th$ ratio of Phobos surface will be measured by MEGANE [15].

Under the condition that the representativeness of the sampling site(s) is guaranteed by remote sensing observations in the geologic context of Phobos, laboratory analysis (e.g., mineralogy, bulk composition, O-Cr-Ti isotopic systematics, and radiometric dating) of the returned sample will provide definitive information about the moon’s origin. Stable isotopic systematics of O, Cr, Ti, and Mo clearly differentiate the carbonaceous and non-carbonaceous reservoirs, which are currently proposed to have been spatially separated by Jupiter [e.g., 13, 16, 17]. A suite of these isotope analyses, except for Mo, can be carried out using a $<100$ mg fraction of the returned samples. These comprehensive isotopic data will be carefully examined petrographic and mineralogical observations to help discriminate the exogenous materials. For example, major element mineral chemistry of olivine and pyroxene, phases that are common in planetary materials, is distinct between asteroids (chondrite/achondrite parent bodies) and Mars. Other lines of evidence for Phobos’ origin would also come from the presence/lack of refractory inclusions, amorphous silicates, presolar grains, organic materials with anomalous H, C, and N isotopic compositions.


Table 1: Expected characteristics of endogenous returned samples

<table>
<thead>
<tr>
<th>capture of asteroid</th>
<th>Moon origin</th>
<th>In-situ formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analogous to carbonaceous chondrite, IDP, or cometary material</td>
<td>Analogous to ordinary chondrite</td>
<td>Co-accretion</td>
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<tr>
<td>Mineralogy</td>
<td>Rich in oxidized and hydrous alteration phases (e.g. phyllosilicate, carbonates), amorphous silicate</td>
<td>Reduced and mostly anhydrous phases (e.g., pyroxene, olivine, metal, sulfides)</td>
</tr>
<tr>
<td>Bulk chemistry</td>
<td>Chondritic, volatile-rich (e.g. high C and high H)</td>
<td>Chondritic, volatile poor</td>
</tr>
<tr>
<td>Isotopes</td>
<td>Carbonaceous chondrite signature (e.g., $\Delta$17O, $\delta^{13}$C, $\delta^{15}$O, $\delta^{15}$N), primitive solar-system volatile signature (e.g., D/H, 15N/14N)</td>
<td>Non-carbonaceous chondrite signature (e.g., $\Delta$17O, $\delta^{13}$C, $\delta^{15}$O, $\delta^{15}$N), primitive solar-system volatile signature (e.g., chondritic D/H, 15N/14N)?</td>
</tr>
<tr>
<td>Organics</td>
<td>Primitive organic matter, volatile &amp; semi-volatile organics, soluble organics?</td>
<td>Non-carbonaceous signature?</td>
</tr>
</tbody>
</table>

References:
THERMOPHYSICAL MODELING OF (3200) PHAETHON USING A RADAR/LIGHTCURVE SHAPE AND CONSTRAINED BY INFRARED OBSERVATIONS WITH SPEX AT NASA/IRTF. R. J. Vervack, Jr.1, E. S. Howell2, Y. R. Fernández3, C. Magri4, S. E. Marshall5, M. L. Hinkle1, A. S. Rivkin6, J. P. Emery7, D. Takir7, and L. McGraw6. 1Johns Hopkins Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723-6099 (ron.vervack@jhuapl.edu), 2Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 3Department of Physics, University of Central Florida, Orlando, FL, 4University of Maine at Farmington, Farmington, ME, 5Arecibo Observatory, Arecibo, PR, 6Northern Arizona University, Flagstaff, AZ, 7Jacobs/ARES, NASA Johnson Space Center, Houston, TX.

Introduction: The Apollo asteroid (3200) Phaethon is notable for several reasons. It approaches closer to the Sun than any other named asteroid, and it is considered the parent body of the Geminids meteor shower in December. Phaethon is a B-type asteroid with an orbit that is more comet-like than most asteroids, and it has been observed at times to have a dust tail [1] as well as unexpected brightening [2]. Phaethon is categorized as a potentially hazardous asteroid and is the target of the JAXA DESTINY+ mission [3].

Given wide interest in Phaethon, we carried out a series of observations with the SpeX instrument [4] at NASA’s Infrared Telescope Facility in order to measure the asteroid’s near-infrared spectrum on several dates. The spectra from these observations are being used as constraints in thermal models of Phaethon that utilize a shape model based on Arecibo radar observations, allowing us to investigate the physical properties of Phaethon’s surface. Any one asteroid spectrum can be fit equally well with simple thermal models with many combinations of parameters. However, when multiple observations, particularly at a wide range of wavelengths, and a detailed shape are available, more robust solutions can be derived.

Shape Model: Our preliminary shape model of Phaethon is shown in Figure 1 and is based on both radar and lightcurve data [5,6]. The pole is near ecliptic coordinates (316,-47) degrees, which is close to the pole of (318,-47) degrees found by [7]. The rotation is retrograde, and Earth was facing the northern hemisphere (facing south in direction of spin vector). The images are the principal axis views (positive on top, negative on bottom). The axis dimensions are 6.64×6.38×5.42 km.

Infrared Observations: We observed Phaethon on four nights: December 6, 8, 12, and 15, 2017. We utilized both prism (0.7-2.5 µm) and LXD-long (1.9-5.3 µm) modes of the SpeX instrument at the IRTF, so we covered the entire range from 0.7-5.3 µm. This wavelength coverage is particularly important as it spans the regime from being wholly reflected sunlight to dominated by thermal emission, allowing us to model both the reflected and thermal emission components self-consistently. Example spectra are shown in Figure 2.

Thermophysical Model: For our project, we have developed a detailed thermophysical model known as SHERMAN. SHERMAN uses the detailed shape provided by the radar data to explain multiple observations of an asteroid at different viewing geometries. Using SHERMAN, we compute the local surface temperature for each facet on the asteroid model at the time of each thermal observation by following reflection and absorption during 10 previous rotations (more if the model has not converged), including self-shadowing, multiple scattering, and sub-scale roughness (following [8-10]) that affect the surface temperatures and thus the thermal emission.

Preliminary Results: Figure 2 shows spectra for three dates and compares them to a simple NEATM-like thermal model (described in [11]) utilizing the thermal parameters determined by [12] using spectra from 0.4-2.5 µm. As can be seen, the models do not match the spectra, generally being too hot at the longer wavelengths and particularly so for the earlier dates. Equally important, the difference in the December 6 and 8 models is much smaller than the difference in the spectra for those two dates.

Although a different set of parameters could be determined for each date, with small near-Earth asteroids such as Phaethon, the detailed shape, thermal inertia and surface roughness play increasingly important roles and simple relationships with effective diameter and albedo break down. The sub-Earth latitude was about 35° on December 8 and 8° degrees by December 15. This is consistent with the thermal measurements showing the December 6 and 8 spectra cooler than the models as on those dates we viewed more of the morning side. In contrast, the data used to infer the simple model parameters viewed closer to the equator and nearer local noon, so the observations were of an overall hotter surface. Including surface roughness as SHERMAN does will probably increase the relative difference between the model December 6 and 8 spectra, and will also give a better albedo value consistent with all of the available data.

By utilizing the detailed shape and modeling the full spectral range from 0.7-5.3 µm, we can investigate the physical parameters more consistently and account for some of the variations that are “rolled up” in the

Thermophysical Model: For our project, we have
beaming parameter and geometry assumptions of the simpler models. Across the four nights there are differences in observational geometry and illumination across the surface that SHERMAN can handle appropriately. By considering all of these factors, the resulting thermophysical model will provide a detailed picture of the surface properties of Phaethon and allow for investigation of the surface properties of this highly interesting object. We will present the thermophysical modeling results during the meeting.

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**Figure 1.** Preliminary shape model of (3200) Phaethon based on radar and lightcurve data [5,6].

**Figure 2.** Simple, NEATM-like models utilizing the parameters determined by [12] (Tl=0, η=1.7, p_v=0.08) compared to SpeX data from three nights in December 2017. The models are a poor match to the spectra at longer wavelengths.

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The Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx, [1]) mission is currently studying the surface of near-Earth asteroid (101955) Bennu [2]. Radar observations had previously revealed that Bennu has a top-like shape—an oblate spheroid with an equatorial ridge—with at least one large boulder on its surface having a diameter between 10 and 20 m [3]. Images obtained by OSIRIS-REx after arrival at Bennu confirmed the top shape [4] and also revealed additional large boulders and candidate impact craters [5, 6].

There is an abundance of candidate impact craters on the surface of Bennu, which suggests an old surface that should have experienced between 100 and 1000 Myr of bombardment in the main asteroid belt [6]. Some of the largest candidate craters, those over 100 m in diameter, are found in equatorial latitudes (see Figure 1). These candidate craters stratigraphically younger than the equatorial ridge, suggesting that the ridge is likely one of the oldest features on the surface of Bennu [6].

Many near-Earth asteroids (NEAs) appear to have equatorial ridges based on radar observations. The ridges have been hypothesized to be related to rotational spin-up by the thermal YORP effect, as these features are commonly found among some of the most rapidly rotating NEAs [7]. On Bennu, with an old ridge that likely was present during its time in the main asteroid belt, either YORP spin-up acted to form the ridge long ago, or a different process was responsible [8].

We aim to constrain the history of the equatorial ridge. Some of the large equatorial craters have experienced alteration since their formation. In particular, a large landslide has overtopped the rim of an equatorial candidate crater and left a ~5-m layer of material over the rim and into the floor of the crater [6]. Although such large-scale mass movement could plausibly erase small craters, there are still several ~20-m candidate craters found near the equator [2,6]. Therefore, such large mass movement events are spatially isolated or have only been active since the ejection of Bennu from the main belt [9].

The equatorial regions also are being characterized in terms of their chemistry, mineralogy, and

Figure 1: A mosaic of images of Bennu that were taken by the PolyCam instrument on OSIRIS-REx on 2 December 2018. One of the largest candidate craters, with a diameter ~160 m, is visible on the equator.
thermophysical properties with data acquired by the OSIRIS-REx Visible and InfraRed (OVIRS) and Thermal Emission (OTES) spectrometers [10, 11, 12]. These data have been used to produce resolved spectral maps of the surface over a wide range of wavelengths from ~0.4 to 100 µm. The combined analysis of the spatial distribution of geologic features, spectral characteristics, and thermophysical properties will constrain the timing and mechanism of the formation of Bennu’s equatorial ridge.

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**References**

The Role of Electrostatic Dust Lofting in Shaping the Surface Properties of Asteroids, X. Wang1,2, N. Hood1,2, A. Carroll1,2, H.-W. Hsu1,2 and M. Horányi1,2. Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder CO, 80303, 2NASA SSERVI’s Institute for Modeling Plasma, Atmospheres and Cosmic Dust, University of Colorado, Boulder CO, 80303. The first author’s email: xu.wang@colorado.edu.

Introduction: Electrostatic dust lofting and transport, as a long-standing problem, has been suggested to explain a number of observations on airless bodies throughout the solar system, such as the lunar horizon glow [1] and the ‘spokes’ in Saturn’s rings [2]. The electrostatic mechanism is expected to play a bigger role in shaping the surface properties of asteroids due to their smaller gravity. Dust ponds formed on asteroid Eros have been suggested to be caused by the depression of electrostatically transported dust into the bottom of the craters [3]. Recent Hayabusa-2 mission found the absence of fine dust on Ryugu’s surface [4] and the OSIRIS-REx mission also observed a rocky surface of Bennu, rougher than expected [5], indicating a lack of regolith. Electrostatic dust lofting and escaping may be responsible for these observations. Here we present the recent advancement on the dust charging and lofting studies and their implications to the previous and new observations on asteroids.

Patch Charged Model: As shown in Fig. 1, the model [6] explains that emitted photoelectrons and/or secondary electrons can be re-absorbed inside microcavities between dust particles, resulting in large negative charges on the surrounding particles that repel each other to become lofted. Computer simulations have also shown largely enhanced dust charges and strong grain-scale electric fields in the regolith [7].

Fig. 1 Schematic diagram of the patched charge model [6]. The negative charges on dust particles forming microcavities can be estimated using the following equation [6]

\[ Q \approx -0.5C(\eta T_{e}/e) \]  

where \( C = 4\pi \varepsilon_0 r^2 \) is the capacitance of a dust particle with radius \( r \), \( \eta \) is an empirical factor between 4 and 8, \( T_{e} \) is the emitted electron temperature in eV. \( \eta T_{e}/e \) indicates the surface potential of the dust particle with respect to the ambient plasma.

Characteristics of Dust Lofting: Several key characteristics of electrostatic dust lofting, including the initial charge, size, initial launch velocity and rate of lofted dust, have been measured in the laboratory [6, 8-10]. Micron-sized dust particles were charged under exposure to UV (7.2 eV) or beam electrons (up to 120 eV). The measured dust characteristics are critical for fully understanding the dynamics of electrostatic lofting and its effects on shaping the surface properties of asteroids. The results are shown below.

Charge. All lofted dust particles are charged negatively, even under UV radiation [8]. This result is contrary to generally expected positive charges on dust particles due to photoemission; however, it is in agreement with the patched charge model, as described above. The magnitude of the measured charges is on the order of \( 3 \times 10^{-14} \) C for 20 \( \mu \)m radius particles, also in agreement with the patched charge model prediction [8].

Fig. 2 Size distributions of lofted dust particles in the plasma and electron beam, and the UV conditions [6].

Size. The lofted dust shows a wide size range from 5 to 70 \( \mu \)m in radius (Fig. 2, [6]). In addition to single-sized particles, large aggregates due to the inter-particle cohesive forces were lofted with the size up to 70 \( \mu \)m in radius. In contrast, single sized particles 35 \( \mu \)m in radius remained at rest under the same charging conditions. This indicates that the total charge can be enhanced on high-porosity dust, as expected from the patched charge model.
**Velocity.** The results from our recent experiment [9] show that the vertical launch velocity is inversely proportional to the radius of lofted dust and is on the order of ~0.5 m/s for 12.5 μm radius particles (Fig. 3). It is found that the vertical velocity spreads over a wide range for similar-sized particles due to large variations in the inter-particle cohesive forces. Based on the lab results, dust particles as large as 15 μm in radius are expected to escape from Ryugu. This may be a cause for the absence of small dust particles on the rocky surface of Ryugu [4].

![Fig. 3 Vertical launch velocity as a function of the radius of dust particles. The red and blue curves are the theoretical expectation and its corrected version [9].](image)

**Rate.** It is shown from our recent experiment [10] that the lofting process is time-dependent. It goes relatively fast at the beginning and then slows down as time progresses. The slow-down is likely because the refilling or removal of microcavities as a result of dust movement reduces the microcavity charging effects. The lofting rate is found to be as high as ~5 particles cm² s⁻¹ at 1AU for the dust size between 5 and 20 μm in radius.

**Implications to the asteroid observations:** Both lab and simulation studies described above have shown that dust particles can gain significant charges due to the microcavity charging effect and become lofted by repulsive forces. Based on the initial launch velocity measurements [9], micron-sized particles can travel a long distance (on the order of 100m for 8 μm radius particles) across the surface of Eros-sized asteroids. It is possible that these long-shot particles are depressed in the bottom of the craters to form the dust ponds on Eros [3]. For smaller asteroids like Ryugu and Bennu, large amount of fine dust particles would be expected to escape to space, leaving their surfaces to be likely regolith free as observed from Hayabusa-2 mission [4] and likely the OSIRIS-REx mission [5].

**Conclusion:** The understanding of the fundamental charging and lofting mechanisms of regolith dust has been greatly advanced through recent laboratory experiments and computer simulation work. Several key characteristics, including the initial charge, size, launch velocity and rate of lofted dust, have been measured in the laboratory, which are critical for fully understanding the dynamics of charged dust particles on asteroids and their effects on shaping their surface properties. The results of these lab studies provide more insight into the observations of the surface properties on asteroids Eros, Ryugu and Bennu.

AN OVERVIEW OF HAYABUSA2 MISSION AND ASTEROID 162173 RYUGU. S. Watanabe1,2, M. Hirabayashi3, N. Hirata3, N. Hirata3, M. Yoshikawa4, S. Tanaka2, S. Sugita6, K. Kitazato4, T. Okada2, N. Namiki2, S. Tachibana5, M. Arakawa3, H. Ikeda4, T. Morota6, K. Sugiu6,1, H. Kobayashi7, T. Saiki2, Y. Tsuda2, and Hayabusa2 Joint Science Team10. 1Nagoya University, Nagoya 464-8601, Japan (seicoro@eps.nagoya-u.ac.jp), 2Institute of Space and Astronautical Science, JAXA, Japan, 3Auburn University, U.S.A., 4University of Aizu, Japan, 5Kobe University, Japan, 6University of Tokyo, Japan, 7National Astronomical Observatory of Japan, Japan, 8Research and Development Directorate, JAXA, Japan, 9Tokyo Institute of Technology, Japan, 10Hayabusa2 Project

Summary: The Hayabusa2 mission reveals the nature of a carbonaceous asteroid through a combination of remote-sensing observations, in situ surface measurements by rovers and a lander, an active impact experiment, and analyses of samples returned to Earth.

Introduction: Asteroids are fossils of planetesimals, building blocks of planetary formation. In particular, carbonaceous asteroids (or C-complex asteroids) are expected to have keys identifying the material mixing in the early Solar System and deciphering the origin of water and organic materials on Earth [1]. Before 2018, the only carbonaceous asteroid that spacecraft visited was (253) Mathilde; NEAR Shoemaker spacecraft flew by the ~50 km sized C-type asteroid in June 1997. More than 20 years later, the great leap has come; Hayabusa2 and OSIRIS-REx encountered (162173) Ryugu and (101955) Bennu in 2018 and try to return asteroid surface samples to Earth [2,3].

Mission profile: Hayabusa2 spacecraft arrived at C-type near-Earth asteroid Ryugu on June 27, 2018 [2]. The spacecraft did not enter into circum-asteroid orbit but hovered around the “Home Position”, located at an altitude of ~20 km. The remote sensing instruments suite onboard Hayabusa2 are the Optical Navigation Camera-Telescopic (ONC-T) with seven narrowband filters, a Thermal Infrared Imager (TIR), a Near-Infrared Spectrometer (NIRS3), and a laser Light Detection and Ranging (LIDAR) system.

Combined with the rotational motion of the asteroid, global surveys of Ryugu were conducted several times from ~20 km above the sub-Earth point (SEP), including global mapping from ONC-T (Fig. 1) and TIR, and scan mapping from NIRS3 and LIDAR. Descent observations covering the equatorial zone were performed from 3~7 km altitudes above SEP. Off-SEP observations of the polar regions were also conducted. Based on these observations, we constructed two types of the global shape models (using the Structure-from-Motion and SPC techniques) [2] and selected target sites for sampling touchdown and lander/rover deployments.

On September 21, 2018, rovers MINERVAII-1A, B were landed in a northern midlatitude region on Ryugu [4] and sent rocky surface images (Fig. 2). On October 3, lander MASCOT landed in a southern midlatitude region and perform in situ measurements[5, 6]. One of the MASCam image shows a cauliflower-like rock consisting of a dark matrix with small, bright inclusions [5]. During multiple low-altitude (40~60 m) descent maneuvers for the rover/lander deployments and touchdown rehearsals, we conducted high-resolution (<1 cm) observations of specific regions.

On February 21, 2019, the Hayabusa2 spacecraft conducted its first touchdown on the equatorial ridge of Ryugu, shooting a projectile within a sampler horn and collecting surface materials. The operation of a Small Carry-on Impactor (SCI) was carried out on April 5, 2019, and an artificial impact crater with a diameter of >10 m was formed (Fig. 3) [7]. A Deployable Camera

Figure 1. ONC-T image of Ryugu taken from 20 km altitude on July 10, 2018. Hemisphere centered at 5°S, 11°E. White arrow represents the spin axis [2].

Figure 2. Surface of Ryugu taken from a hopping rover MINERVAII-1B (Owl) on September 23. Credit: JAXA.
3 (DCAM3) recorded live images of the evolving ejecta curtain generated by the SCI impact [7]. To obtain deposited subsurface materials ejected from the SCI crater, the second touchdown site was selected at ~20 m north of the center of the SCI crater. The second touchdown was conducted on the target site on July 11, 2019, collecting ejecta from the SCI crater (Fig. 4).

Real face of Ryugu: The physical parameters of Ryugu were determined from Hayabusa2’s observations [2]. Ryugu is a retrograde rotator (the obliquity is 171.6°) with a spin period of 7.63262 hours. In spite of the slow rotation rate, Ryugu has a spinning-top shape with an almost perfect circular equatorial ridge, suggesting rotation-induced deformation of Ryugu during a period of rapid rotation [2, 8]. The equatorial radius is 502 ± 2 m and polar-to-equatorial axis ratio is 0.872 ± 0.007. The mass estimated from gravity measurement operation is (4.50 ± 0.06) × 10^{11} kg. The bulk density is derived to be (1.19 ± 0.02) × 10^{3} kg m^{-3}, which falls within the range of bulk densities measured for BCG-types. The total porosity is >50% if the constituent grain density is similar to those of carbonaceous chondrites [2, 9]. The porosity is even higher than that of the rubble-pile asteroid Itokawa (44 ± 4%), the target S-type asteroid of Hayabusa mission [10], suggesting that Ryugu is also a rubble pile. Ryugu’s high porosity could be ascribed to loss of volatile components.

NIRS3 observations indicate that OH-bearing minerals are ubiquitous on Ryugu [11]. The central wavelength (2.72 µm) and depth (10%) of Ryugu’s 3-µm absorption band falls on the correlation line found from the spectral survey of asteroids in the 3-µm band using the infrared astronomical satellite Akari [12].

The spectral data obtained with ONC-T and NIRS3 indicated that Ryugu is a Cb-type asteroid with a low geometric albedo of 4.5 ± 0.2% at 0.55 µm [11, 13]. The regional variation in visible and NIR reflectance data is less than 15%. Coupled with the fact that the deficient of small craters on Ryugu [13], this suggests efficient mixing processes in the surface layer. However, there are few evidence of large-scale grain-size segregation, unlike Itokawa [10], suggesting lower degree of global surface activity. The only known exception may be fewer spatial densities of boulders in small (D < 30 m) craters, indicating possible vertical grain-size segregation in the surface layer.

The SCI impact experiment establishes a scaling law connecting impact energy and the diameter of the generated crater on Ryugu, showing cohesive forces in the surface layer of Ryugu should be very weak [7]. For a cohesionless surface, the surface age of Ryugu is estimated to be 9×10^{6} years based on collision frequency models for the main belt [13, 7]. The younger surface age is interpreted, not necessarily as the formation age of the rubble pile, but as the age of the top shape formation due to Ryugu’s spin-up probably by the YORP effect. Comparative studies between Ryugu and Bennu would be key to understanding not only the origin and structure of top-shaped asteroids, but also the properties and evolution of carbonaceous asteroids.

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FIB TOMOGRAPHY OF WARK-LOVERING RIMS IN THE ALLENDE METEORITE  
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Introduction: Calcium-aluminum-rich inclusions (CAIs) are significant objects occurring within chondritic meteorites. Based on radiometric dating and thermodynamic modelling they are considered to be some of the first solids to condense from a cooling gas of solar composition [1-4]. Therefore, they provide a window into the early solar system’s chemistry.

Many CAIs are surrounded by multi-layered, thin mineral sequences, called Wark-Lovering Rims (WLR)[5]. Different formation mechanisms have been discussed for these rims, among them condensation, metasomatic exchange and flash heating [6-11].

The electron and ion microprobes have been extensively used to study CAIs [12-14]. Information on the three-dimensional structure of CAIs, such as that offered by FIB tomography [15-18], could provide new insights into their origins. Initial work demonstrated the potential of FIB tomography toward understanding CAI origins [19] however, detailed method development for planetary materials has not to our knowledge been performed. Here, we present 3D reconstruction of the internal structure of different locations of WLR from a CAI within the Allende meteorite.

Material & Methods: We studied a CAI in a section of the Allende CV3 chondrite, from the University of Arizona collection (UoA 28-4). The Cameca SX-100 electron microprobe (EMP) at the Kuiper Materials Imaging and Characterization Facility (KMICF) at the University of Arizona (https://kmicf.lpl.arizona.edu) were used to obtain backscattered electron (BSE) images to identify a suitable location for FIB tomography. EMP analysis of the CAI rim was done using 1µm beam size at 20nA current and 15kV voltage. The wavelength-dispersive spectrometers were calibrated using well-characterized natural minerals and materials. 3D Tomography datasets and EDS maps were obtained using ThermoFisher Helios 660 G3 dualbeam FIB equipped with an integrated EDAX EDS detector also at KMICF. Data was analyzed using Avizo 19.2.

Results & Discussion: In this study, we selected a specific region of the WLR surrounding the CAI identified by microprobe analysis (Fig. 1 a+b).

![FIB data on the section of the Allende CAI](image)

Figure 1. Microprobe and FIB data on the section of the Allende CAI. (a) BSE overview showing region of interest for FIB tomography (white box). (b) False-color WDS map of the section showing Ca (green channel), Al (blue channel) and Mg (red channel). (c) Higher magnification BSE of the ROI in which tomography was performed (white box).

The following mineral phases were identified in this region via WDS spectra analyses: spinel, olivine, nepheline and hibonite. Illustrative stoichiometry includes spinel, Mg$_{0.72}$Fe$_{0.28}$Al$_{1.96}$O$_4$ and olivine, Mg$_{1.22}$Fe$_{0.78}$Si$_{0.99}$O$_4$ and Mg$_{1.2}$Fe$_{0.76}$Si$_{0.99}$O$_4$. To enable the visualization of the interface in FIB tomography, it was oriented perpendicular to the direction of FIB slicing (Fig. 1 c). A total of 247 slices with 20 nm thickness were collected (representative images in Figure 2). A complex microstructure of grain boundaries, macropores and nanopores concentrated along grain boundaries were observed.
Summary: In this study, we demonstrate successful FIB tomography characterization of WLR in the KMICF. Further refinement of both measurement conditions and data analyses are required to maximize scientific output of these analyses. We will combine FIB tomography analyses with FIB lift out for transmission electron microscopy sample preparation. The method development demonstrated here will enable the 3D FIB-tomography of samples to be returned from the Hayabusa 2 and OSIRIS-REx missions.


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FROM POINT SOURCE TO PARTICLE: A GIS TO MAP A SAMPLE TO AN OBJECT MILLIONS OF KILOMETERS FROM EARTH. M. M. Westermann, C. A. Bennett, D. N. DellaGiustina, H. C. Connolly, and D. S. Lauretta; 1University of Arizona, Tucson, Arizona, USA. 2Rowan University, Glassboro, NJ, USA.

Introduction: After the OSIRIS-REx sample return in September 2023 an unprecedently comprehensive dataset will exist for asteroid (101955) Bennu [1]. This dataset will include point-source observations from Earth-based telescopes [2], high resolution, in-situ global and local maps generated from observations during OSIRIS-REx proximity operations, and finally detailed sample analysis conducted in the world’s best laboratories. The data will be co-registered and integrated into a single Geographic Information System (GIS), allowing one to view Bennu from point source through a global dataset at a variety of resolutions.

Figure 1: A closeup of the global map of Bennu created from Approach data showing image footprints from the Detailed Survey phase (blue) and two potential sample sites (orange) where the returned particles could originate from.

Geographic Information Systems: GIS is well established in Earth and planetary science to organize, analyze, and visualize geographic data. These data include, but are not limited to, images, terrain feature maps, and spectral and thermal data, that are presented within the framework of a single, spatially aware set of software applications. We expand on these capabilities to utilize commercially available GIS tools to spatially map data to the scale of a returned sample.

Traditionally, when a terrestrial or meteorite sample is analyzed through microscopy and other lab-based methods, the acquired information is manually mapped to scanned photos of thin sections. These images and data are organized and stored without an industry-wide set of standards or best practices. Here, we use standard GIS tools and established methods to store and process the sample data. We do this by assigning thin sections, slabs, and other sample types a unique coordinate reference system (CRS). All data subsequently collected from that sample can be spatially linked to the sample’s CRS [3]. These data, in turn, can also be linked to the remotely sensed global and local data of asteroid Bennu. By using a GIS, data in a wide variety of formats and at vastly varying resolutions can be analyzed and visualized within the same system.

Tools: The entirety of the Bennu-resolved OSIRIS-REx OCAMS dataset is stored in a Postgres geospatial database [4]. The same database will be used to store digitized images, rasters, shapefiles (standard vector files), and tabular output from sample analysis. Additionally, the database will store data from other OSIRIS-REx payloads such as the OVIRS and OTES spectrometers. All data within the database are spatially connected to each other via geo-referencing and/or table keys. Using standard SQL commands, the data are easily queried to perform simple and complicated spatial data analysis. Data within a Postgres geospatial database is also easily accessible through most commercial and open-source GIS software, such as ArcMap and QGIS, where all data can be visualized, layered, and further queried and manipulated to produce insightful rasters, shapefiles, and ultimately maps. The outputs of data manipulation will also be stored within the database for future reference and use. The final system will enable the end-to-end mapping of sample data—from a thin section to an image, global spectral map, shape model or other datasets—enabling data querying and manipulation in unified environment.

Conclusion: Using the same GIS for remotely-sensed and sample datasets allows the returned material to be studied in the global context of asteroid Bennu. Additionally, by utilizing a GIS the analysis performed will be reproducible and available in an industry
standard format opening research capabilities up to the wider scientific community and seamlessly incorporating new analysis in the future. As sample return missions like OSIRIS-REx and Hayabusa2 become more common, a standard method to organize the sample information alongside other datasets acquired throughout the mission will be extremely valuable in advancing asteroid and planetary science.


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Chemical History of Organic Macromolecules in the Early Solar System: Scientific Strategy and Expected Insights from Asteroid Ryugu. H. Yabuta¹ and Organic macromolecules initial analysis sub-team². ¹Department of Earth and Planetary Systems Science, Hiroshima University (1-3-1 Kagamiyama, Higashi-Hiroshima, 739-8526 Hiroshima, Japan. E-mail: hyabuta@hiroshima-u.ac.jp)

Introduction: Since the arrival of the JAXA’s Hayabusa2 spacecraft at asteroid Ryugu on June 27, 2018, observations by onboard remote-sensing instruments, MASCOT and MINERVA landers have provided interesting insights into the features of asteroid Ryugu [1-4]. The two-times of successful touchdowns have enabled collections of both surface and interior samples of the asteroid, which is an advantage to investigate origin and evolution of the Solar System as well as the surface processes of the asteroid. After the sample return in the end of 2020, curatorial work on the Ryugu sample will be conducted at JAXA for the first 6 months. Afterward, initial sample analysis will be performed during the following 12 months.

The presence of organic compounds is unknown at this stage, although the low albedo at 0.55 μm may be related to the presence of organic carbon [5]. Thus, the initial sample analysis will be the first opportunity to unveil the distributions and compositions of organic molecules on a C-type asteroid, which lead to our understanding of the Solar System formation and volatile delivery to the Earth.

Significance of investigating organic macromolecules in solar system small bodies: Organic macromolecules have been identified from various types of small body materials, such as chondritic meteorites, interplanetary dust particles (IDPs), cometary dusts, and Antarctic micrometeorites (AMMs), indicating that they enable our comprehensive understanding of chemical history of the early Solar System. Organic macromolecules from chondritic meteorites have been often characterized as an acid-insoluble organic matter (IOM). The intact chemical structure of IOM in primitive carbonaceous chondrites (CCs) is still unknown, while a number of previous studies have suggested that it is composed of aromatic network crosslinking with short-branched aliphatic chains and various O-bearing functional groups [6, 7]. Elemental, molecular and isotopic variations of IOM within and across meteorite groups and petrologic types sensitively record the chemical history of the meteorite parent bodies [6, 7]. Distributions of IOM are often related to those of phyllosilicates in primitive CCs, implying that meteoritic IOM could have been a product from parent body aqueous alteration of precursor molecules.

On the other hand, organic macromolecules in IDPs, cometary dusts, and AMMs, may not be necessarily “insoluble”, according to their diverse compositions. In particular, comet 81P/Wild2 dust particles collected by Stardust as well as anhydrous IDPs and AMMs which are thought to be cometary origin, contain high abundances of organic macromolecules consisting of N- and/or O-bearing functional groups, and/or aliphatic carbon compared to chondrites [8]. These chemical features are also comparable with those of comet 67P/Churyumov Gerasimenko observed by Rosetta [8]. The organic macromolecules often coexist with GEMS, implying that they could have been formed prior to parent body aqueous processes [8].

Deuterium and ¹⁵N enrichments have been commonly observed from organic macromolecules in meteorites, IDPs, cometary dusts and AMMs. The isotopic features indicate that their precursors may have a common origin in extremely cold environments, such as outer solar nebula and interstellar clouds [6], while there have been also other hypotheses that organic macromolecules may have been formed from inner nebula gas or during parent body processes [6].

Comparison of organic chemistry in association with mineralogy between meteorites and cometary materials have revealed a blurred boundary between carbonaceous chondrites and comets, as observed in an ultracarbonaceous AMM [9] and a ultracarbonaceous microxenolith of primitive CC [10]. The findings imply the material mixing in the early Solar System (e.g. [11, 12]). Investigation of organic macromolecules in asteroid Ryugu samples will verify the hypothesis and constrain the origin and chemical evolution of building blocks of planets and life as well as the formation of asteroid Ryugu.

NORMAL ALBEDO MAP OF RYUGU AT VISIBLE WAVELENGTH. Y. Yokota$^{1,2}$, R. Honda$^2$, E. Tatsumii$^{1,3,5}$, D. Domingue$^6$, S. E. Schröder$^1$, M. Matsuoka$^1$, S. Sugita$^3$, T. Morotaa$^5$, N. Sakatani$^1$, S. Kameda$^2$, T. Koyama$^{10}$, H. Suzuki$^{11}$, M. Yamada$^{12}$, C. Honda$^{13}$, M. Hayakawa$^1$, K. Yoshioka$^5$, Y. Cho$^5$, and H. Sawada$^1$, $^1$ISAS/JAXA, (3-1-1 Yoshino-dai, Chuo-ku, Sagamihara, Kanagawa, Japan, yokota@planetasci.isas.jaxa.jp), $^2$Kochi Univ., Japan, $^3$Instituto de Astrofísica de Canarias, Spain, $^4$Univ. of La Laguna, Spain, $^5$Univ. of Tokyo, Japan, $^6$Planetary Science Institute, USA, $^7$DLR, Germany, $^8$Nagoya Univ., Japan, $^9$Rikkyo Univ., Japan, $^{10}$AIST, Japan, $^{11}$Meiji Univ., Japan, $^{12}$Chiba Inst. Tech, Japan, $^{13}$Univ. of Aizu, Japan.

Introduction: Since June 2018, the Optical Navigation Camera (ONC) onboard Hayabusa2 has observed Ryugu at a distance below 20 km [1]. ONC consists of three cameras: ONC-T, -W1 and -W2, [2–4]. ONC-T has 7 broadband filters ranging in wavelength from 0.40–0.95 μm [2]. We report on the derivation of the normal albedo map of Ryugu from the opposition observations by the ONC-T.

Data: On 8 January 2019, Hayabusa2 moved to the sub-solar position, and ONC-T observed the asteroid at the opposition geometry from ~20 km distance, during one rotation period. A 7-band image set was obtained every 30° rotation phase. Local solar phase angle ranged from 0.0° to ~1.7°. Therefore, if we have a phase curve for this narrow phase angle range, we can convert each pixel’s observed I/F (radiance factor) to the ideal I/F at phase angle zero, which is the normal albedo [5].

Method: The data number of the image pixels are converted to I/F with the calibration parameters described in [4]. Observation geometry of each pixel is calculated using the Ryugu shape model [6] produced by the Hayabusa2 shape model team.

Fitting. To average the data density bias in the geometry space, the data was binned every 1° in incidence and emission angle, and every 0.1° in phase angle. To avoid the effect of the solar disk size, data within the phase angle range 0.0°–0.25° were omitted from the data set. Then, we fit a linear formula to the data set as

$$r = a_0 + a_1 \alpha,$$  \hspace{1cm} (1)

where $r$ is I/F, and $a_0$ and $a_1$ are fitting parameters. Fig. 1 shows the data set and the fitted line. The derived parameters are $a_0 = 0.0404$ and $a_1 = 0.0019$. Therefore, we estimate the average normal albedo of Ryugu is ~0.0404.

Mapping. We assume that this phase curve shape (a straight line for this case) is approximately the same for phase angles <1.7° for all Ryugu’s surface and all ONC-T bands. Then, the observed I/F at near opposition can be converted to the I/F at phase angle zero, by

$$r(0) = r_{\text{obs.}}(\alpha) \frac{a_0}{a_0 + a_1 \alpha},$$  \hspace{1cm} (2)
Acknowledgment: We thank the entire Hayabusa2 team to achieve the observation and analysis. This study was supported by Japan Society for the Promotion of Science (JSPS) Core-to-Core Program “International Network of Planetary Sciences”, NASA’s Hayabusa2 participating scientist program (grant number NNX16AL34G), and NASA’s Solar System Exploration Research Virtual Institute 2016 (SSERVI16) Cooperative Agreement (NNH16ZDA001N) for TREX (Toolbox for Research and Exploration).


Fig. 2. Normal albedo (I/F at phase angle zero) map of Ryugu at v-band (0.55 μm). (a) Grey scale. (b) Color scale.

Fig. 3. Normal albedo ratio of b-band (0.48 μm) / x-band (0.86 μm) is shown as a function of b-band normal albedo. Global data of ~8x8 m (1 deg at equator) size bin is plotted.
Volatiles-Driven Cryovolcanic Eruption on Asteroid Ceres as a Probe to Its Interior. K. Yumoto\(^1\), Y. Cho\(^1\), and S. Sugita\(^1\), \(^1\)Department of Earth and Planetary Science, Graduate School of Science, University of Tokyo (yumoto@eps.s.u-tokyo.ac.jp).

**Introduction:** Observation of morphological properties of bright deposits (or faculæ) on asteroid (1) Ceres revealed that Ceres was active in the geologic recent past [1]. Crater model ages suggest that deposition of bright material at the central pit of the Occator crater occurred as recent as \(\sim 4\) Ma [1]. These materials could be evidence of cryovolcanic activities from the subsurface reservoir. Model calculation by [2] showed that overpressure caused by the gradually freezing magma chamber could have induced its ascent. Assuming a common initial condition of reservoirs, overpressure could facilitate the ascent for \(< a\) few hundred Myr timescales; activities on Ceres could be a recent but temporal event. However, the large population of rim/wall faculæ could be relics of geologically older cryovolcanic eruptions [3]; the oldest faculæ remaining to date could be as old as \(< 1300\) Ma [5].

Morphologies of scattered patches of bright materials near the rim of Cerealia and Vinalia faculæ suggest ballistic emplacement from explosive venting. Thus, volatile exsolution may have enabled the ascent of cryomagma for a wide time range. In this study, we explore the possibility of “volatile-driven” cryovolcanism on Ceres by phase equilibria and model calculations. This study also aims to validate this hypothesis to see if faculæ could be a probe to peer into the volatile composition of the putative internal ocean of Ceres at the time of its formation.

**Model:** Properties of the cryomagma. Reflectance spectra of faculæ material in Occator suggest that 45-80 vol\% consists of carbonate with Na\(_2\)CO\(_3\) as the most likely constituent [6]. The presence of salt material implies that the liquid phase cryomagma are brines together with volatile species dissolved within. The pervasive amount of carbonate and ammoniated phyllosilicates on the surface of Ceres [7] implies CO\(_2\) and/or NH\(_3\) as the dissolved volatile specie [8]. This study assumes the cryomagma to be a NaCl-H\(_2\)O-CO\(_2\) ternary system. However, model calculation of the viscous relaxing dome at the center of Cerealia facula indicates a viscosity of \(10^5-10^7\) Pa s at the time of its emplacement [2]. Thus, inclusion of solid phase in the cryomagma should be needed to achieve this slurry-like viscosity. Its most likely constituent is ice/clathrates, but may also include precipitated salts and entrained silicates. Assuming that explosive eruptions occurred at a point in time close to the formation of the dome [4], the cryomagma deposited from explosive eruptions should have similar properties.

**Fig. 1:** \((P, T)\) Phase diagram of NaCl-H\(_2\)O-CO\(_2\) ternary system (<25 wt\% salinity). Phase that occurs in each P-T region are shown in the figure; Cla: Clathrate, HH: Hydrohalites, L\(_{\text{aq}}\): Liquid CO\(_2\), V: Gas CO\(_2\), L\(_{\text{aq}}\): Liquid phase with dissolved gas and salts (Modified from [9]).

This slurry-like property of cryomagma constrains the \((T: \text{Temperature}, x: \text{salinity})\) condition to be within the solidus and liquidus curves along decompression during its ascent in the \((P, T)\) phase diagram of NaCl-H\(_2\)O-CO\(_2\) ternary system (<25 wt\% salinity) (Fig. 1). Also, its ascent should be nearly isothermal for ascending velocities \(> 10^3\) m/s [2]. Once the \((T, x)\) condition is constrained, the Henry coefficient, which governs the solubility of CO\(_2\), could be estimated (Fig. 2). Henry’s law shows that solubility of CO\(_2\) increases linearly with increasing depth. However, it must be noted that the solubility remains constant below the CO\(_2\) gas-liquid transition depth. For \((T, x) = (-8^\circ\text{C}, 10\text{ wt\%})\), the solubility of CO\(_2\) becomes \(~ 7\text{ wt\%}\) at depth of \(8\) km and would not increase with greater depth where liquid CO\(_2\) becomes stable.

**Model description.** One dimensional, steady state, two-phase conduit ascent of cryomagma with volatile exsolution and bubble segregation was modelled by modifying the Henry’s law in [10]. The pressure at the reservoir top was set to be lithostatic and the magma
flow rate was iteratively computed to satisfy the choked flow condition at the Ceres surface. Conduit radii \( r_c \) (1-100 m [4]), conduit length \( L \) (<45 km [11]), viscosity \( \mu \) \((10^{-2}-10^8 \text{ Pa s})\), and initial dissolved volatile \( n_0 \) (<7 wt\%) were chosen as free parameters.

To evaluate the hypothesis that cryovolcanism on Ceres is “volatile-driven”, the calculated eruption velocities were compared with its estimated value. These were estimated from the typical emplacement radii of explosive deposits of Cerealia and Vinalia faculae. The estimated eruption velocities lies within 17-68 m/s depending on the difference in emplacement radii between faculae and uncertainty in eruption angles.

Fig. 2: Henry coefficient of CO\(_2\) in the NaCl-H\(_2\)O-CO\(_2\) ternary system shown in the \((T, x)\) plane. The shaded area shows \((T, x)\) conditions where ascent from >10 km is possible (i.e. the isothermal decompression curve lies within the solidus and liquidus). The starred coordinate shows the \((T, x)\) value used in the model calculation.

**Results and Discussion:** Our calculation showed that the eruption velocities have limited sensitivities to the conduit length (e.g. Fig. 3). However, eruption velocities were highly sensitive to the conduit radii, viscosity, and volatile content (Fig. 4).

**Fig. 3:** The \((L, n_0)\) parameter space with fixed \((\mu, r_c)=(10^5 \text{ Pa s}, 10 \text{ m})\). Coordinates shown in + show the calculated points and its colors the calculated eruption velocity.

**Fig. 4:** \((r_c, n_0)\) Parameter space. The four figures correspond to a fixed viscosity of \(\mu=(A) 10^5, (B) 10^6, (C) 10^7, (D) 10^8\text{ Pa s}\) respectively.

The calculated result shows that estimated eruption velocities are consistent within a reasonable range of free parameters \((r_c, \mu, n_0)\) and supports the “volatile-driven” hypothesis. Also, the constraints in parameters are obtained. For instance, large conduit radii of >100 m is needed to match the eruption velocities for viscosities >10^7 Pa s, and thus should be improbable.

Furthermore, Fig. 4 shows that eruption velocities become sensitive to conduit radius for high volatile content and sensitive to volatile content for large conduit radii. Assuming that the faculae with different emplacement radii (and thus different eruption velocities) occurred from a common reservoir, its difference should be explained by difference in conduit radii alone. This constrains the volatile content to be >2wt%, which is consistent with mineralogy calculations [8].

**Conclusion:** This study shows that cryovolcanism on Ceres could be “volatile-driven” and may have promoted its ascent during a wide time range in Ceres history. The inferred abundance of dissolved CO\(_2\) supports the formation of Ceres in the outer solar system given a CO\(_2\) ice origin.


Introduction: The primary objective of the Hayabusa 2 and OSIRIS-REx Missions is the return and analysis of pristine carbonaceous regolith to study the nature and history of asteroids Ryugu and Bennu [1,2]. Successful completion of that objective requires laboratory techniques capable of providing information on composition and structure of the sample over a range of spatial scales. Such information includes chemical composition, isotopic composition, spatial relationships, texture, microstructure, crystal chemistry, crystal structure, and local atomic order. Here we describe a new laboratory facility for electron and ion microscopy at the Lunar and Planetary Laboratory (LPL), University of Arizona (UA), newly constructed and motivated by the need for state-of-the-art instrumentation in support of planetary materials research programs and sample-return missions.

The Kuiper Materials Imaging and Characterization Facility (KMICF) is located in the sub-basement of the Gerard P. Kuiper building for Space Sciences, which was constructed in 1966 with funds provided by NASA. Located approximately 30 ft. below ground and slab-on-grade, the basement was renovated and repurposed to house electron and ion microscopes. The KMICF serves the research needs of planetary-science investigations and is open to the UA community, including regional private- and public-sector users, as well as other NASA planetary-science investigators. For planetary science, materials investigated at KMICF include but are not limited to: meteorites, lunar samples, interplanetary dust particles, micrometeorites, samples returned from the first Hayabusa Mission, circumstellar dust grains from ancient stars, organic compounds in meteorites, chondritic sulfides, and refractory inclusions in meteorites, e.g. [3-7].

The costs of facility operation are shared among LPL, the UA College of Science, and the UA Office of the Vice President for Research. The KMICF is staffed by professional scientists who manage daily operations and train users. The Scientific and Technical Oversight Committee, composed of faculty users, provides oversight and scientific direction. Additional information can be found at https://kmicf.lpl.arizona.edu.

Layout and Instrumentation: The facility consists of parallel instrument bays and includes space for sample preparation, meeting and workshops, and offices for laboratory scientists and visitors (Fig. 1). A utility corridor was constructed behind several labs to house service equipment, e.g., roughing pumps, chillers, and uninterruptible power supplies for the instruments. We describe the various laboratories below.

The Scanning Electron Microscope (SEM) suite currently houses two microscopes as well as a room designed for a next-generation nanoscale secondary ion mass spectrometer (NanoSIMS). The Hitachi S-4800 cold-field emission gun (cold FEG) can operate between 0.5 keV and 30 keV. It is equipped with a Thermo-Noran Si(Li) energy dispersive X-ray spectrometer (EDS) running Noran SystemSix (NSS) software. The Hitachi S-3400 is a W thermal emitter with a variable-pressure chamber. It is equipped with a Renishaw InVia confocal Raman system (514 nm and 785 nm lasers) and automated stage for mapping and spectral scans as well as a Structural and Chemical Analyser (SCA) interface and Reflex microscope that can be run stand alone. It is further equipped with secondary-electron and backscattered-electron detectors and a Thermo-Noran SDD EDS system operating NSS software. The SEM suite also has laboratory benchtop space for sample-preparation, including a broad-beam Ar-ion mill and plasma cleaner for TEM samples, and includes a chemical fume hood. See Fig. 2a,b.

The focused-ion-beam scanning electron microscope (FIB-SEM) lab houses a ThermoScientific Helios NanoLab 660 G3. The Helios is equipped with an Elstar electron gun and monochromator, and is capable of electron beam resolution down to 0.6 nm from 15 kV to 2 kV. Its Tomahawk Ga+ ion column can be operated between 65 nA and 500 V for, respectively, removal of large volumes of material and final sample polishing. Under standard operating conditions, an ion beam resolution of 2.5 nm at 30 kV is achievable. The Helios is equipped with in situ micromanipulation for creation and transfer of lamellae for transmission electron
microscope (TEM) analysis. It is also equipped with an EDAX EDS system and electron backscatter diffraction (EBSD) analysis system for compositional and crystallographic analysis in two and three dimensions. Furthermore, FIB tomography via slice-and-view software is available and can be coupled with EDS and EBSD for 3-D volume reconstructions. Multiple polygons are supported for device patterning as well as the ability to directly import customized shapes for patterning or deposition. The Helios is equipped with C and Pt gas-injection systems. See Fig. 2c.

The Transmission Electron Microscope (TEM) lab houses a newly installed Hitachi HF5000. The HF5000 is equipped with a cold FEG and optical alignments at 200 keV and 60 keV. It is equipped with a Hitachi 3rd-order spherical aberration corrector for the scanning TEM (STEM) probe. Spectroscopic capabilities include: (1) Oxford Instruments twin silicon-drift detectors (SDD) for EDS providing a total solid angle approaching 2.0 sr; and (2) a Gatan Quantum Imaging Filter (GIF) for electron energy-loss spectroscopy (EELS). The HF5000 is capable of ≤0.4 eV energy resolution for EELS under full emission and 78 pm point-to-point resolution in STEM mode for atomic-resolution imaging. The HF5000 is also equipped with a full array of sample holders including single- and double-tilt analytical (low background) for EDS analysis as well as a heating holder (Hitachi Blaze) for in situ thermal studies inside the TEM [3]. See Fig. 2d and Fig. 3a-d.

The Electron Microprobe (EMPA) lab houses Cameca SX-50 and Cameca SX-100 Ultra instruments. The SX-50 was installed in 1991 and has been in continuous service for 26 years. It is equipped with a 30 keV W thermal emission gun, four wavelength dispersive X-ray spectrometers (WDS), 12 diffracting crystals, and a Princeton-Gamma Tech Si(Li) EDS system, allowing analysis of elements with Z≥4. The SX-100 Ultra was installed in 2011 and has been in service for nearly eight years. It is equipped with a 30 keV LaB6 filament, five WDS, 14 diffracting crystals, and an SDD-EDS system, allowing analysis of elements with Z≥5. See Fig. 2e.


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Figure 2. Photographs of KMICF laboratories. (a) Hitachi 4800 SEM. (b) Hitachi 3400 SEM. (c) ThermoScientific Helios FIB-SEM. (d) Hitachi HF5000 S/TEM. (e) Cameca SX-100 microprobe.

Figure 3. Example data acquired using KMICF instrumentation. (a) Secondary electron image of lunar soil grain heated in situ in the TEM using the Hitachi Blaze heating holder from [3]. (b) False-color EDS map of a presolar graphite spherule from a CO Nova from [4]. (c) Bright-field TEM image of synthetic 3C SiC subjected to in situ heating and irradiation from [5]. (d) Atomic-resolution HAADF image of Si showing 78 pm spacing between columns of Si atoms in the [112] orientation.
FORMATION OF EXTREMELY ELONGATED BODIES BY TIDES: APPLICATION TO THE INTERSTELLAR OBJECT 1I/‘OUMUAUMA. Y. Zhang1, P. Michel1 and D. C. Richardson2, 1Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Laboratoire Lagrange, Nice, France, 2University of Maryland, College Park, MD 20742, United States.

Introduction: Astronomical surveys, such as Pan-STARRS, LONEOS, WISE, and Catalina, etc., reveal a considerable amount of extremely elongated small bodies with a short-to-long axis ratio $c/a < 1/3$ in the Solar System [1,2]. The first and only discovered interstellar interloper, ‘Oumuamua (11/2017 U1) exhibits a more unusual axis ratio $c/a < 1/5$. Among the possibilities, collisional events are unlikely to produce an object with an axis ratio $c/a < 1/3$ [3], as are thermal YORP-induced rotational deformations [4], which leaves tidal disruption as the most probable mechanism to form such an extraordinary shape [5]. Here we numerically investigate the fragmentation outcomes of tidal disruption events and discuss the range of shapes produced with different material strengths.

Methodology: We use a high-efficiency SSDEM code, pkdgrav, to investigate the dynamical behaviors of self-gravitating rubble piles during close planetary encounters. A soft-sphere discrete element model including 4 dissipation/friction components in the normal, tangential, rolling, and twisting directions is applied for computing particle contact forces [6,7]. These quantities determine the magnitude of the material shear strength.

Simulation setup: We physically simulate the disintegration of self-gravitating rubble piles that approach an Earth-type planet on a parabolic orbit with various perigee distances. The rubble-pile object is modelled as a spherical granular assembly consisting of ~20,000 particles with a –3-index power-law particle size distribution. The initial bulk density is set to 2 g/cc and radius to 100 m. The mass of the planet is assumed to be $1M_E = 5.97 \times 10^{24}$ kg with radius $1R_E = 6378$ km, for which the theoretical tidal failure limit for a cohesionless rubble pile with a friction angle of 30° and a bulk density of 2 g/cc is about $1.9R_E$ [8]. As the tidal failure limit $d_{\text{limit}}$ is proportional to the bulk density $\rho_p$ of the object and the planetary or stellar bulk density $\rho$ and size $R$ as $d_{\text{limit}} \propto e^{-\rho/\rho_p}1/3$, the simulation results can be scaled to different rubble-pile bodies and planet or star types. Additional simulations of the tidal disruption of a rubble pile approaching a star give similar fragmentation results when the bulk density and size is set to the right scale.

Results: The simulation results show the same behavior of the rubble-pile body in response to tidal forces as found in previous studies [5]. Due to the intrinsic material shear strength, the rubble-pile object can only be tidally disrupted at a distance notably lower than the theoretical tidal failure limit (i.e., $1.9R_E$ in this case). For weak encounters, where the perigee distance is close to the tidal failure limit, the rubble pile is slightly distorted to a prolate shape when passing by the planet. The distortion of the object becomes more severe with a smaller perigee distance. When the perigee distance is smaller than $1.5R_E$, the parent body is spun up, heavily distorted and then disrupted by planetary tides. Since tidal forces increase dramatically with decreasing perigee distance, the parent body is subject to more intense disruption and is split into many more fragments for a closer orbit.

![Figure 1 Effective spin period and axis ratio distributions of fragments for different material friction angles φ. The symbol size denotes the semimajor axis a, and color denotes the rotation state, where $\lambda = 1, 0$, and $-1$ indicate the short-, intermediate-, and long-axis rotation states, respectively, and values in between indicate non-principal-axis rotation states. We run the simulations until all the fragments have settled down to stable configurations. The resulting fragments have shapes that are typically much more elongated than in previous studies that did not include frictional forces [9]. Many fragments are produced during the strong encounter cases. Figure 1 presents the shape and rotation state of the resulting fragments for tidal disruption at a perigee distance of $1.05R_E$, and...](image-url)
Figure 2 shows an example of an elongated fragment. Generally, larger fragments have more extreme axis ratios and longer rotation periods, and almost all of the fragments are tumbling rotators. More elongated fragments can be formed when using a higher friction angle $\phi$, as shown in Fig. 1 (elongation increases to the left). Extreme elongated fragments with $c/a \sim 0.3$ can form even for a friction angle as low as 27$^\circ$. This indicates that production of elongated fragments by strong tides is robust.

![Figure 2](image.png)

**Figure 2** Example of an elongated fragment (size: 265 $\times$ 89 $\times$ 55 m) formed by tidal disruption. The colors show the bulk rotation, about 16.2 h in this example.

**Conclusion:** Our study provides a possible formation scenario for the observed extremely elongated small bodies. The fragments produced by tidal disruption primarily have prolate shape. This is consistent with the shape distribution of small Solar System bodies, among which none of the oblate bodies is observed to have an axis ratio $c/a < 0.4$ while some prolate bodies have an axis ratio $c/a \sim 0.2$ [10].

The interstellar object ‘Oumuamua can also be formed through tidal disruption. The energy injected into the resulting fragments by the tidal forces can lead to ejection from their original planetary system if a rubble-pile object closely passes by its host star on a nearly parabolic orbit. The close encounter with the host star would cause sublimation of volatiles, producing interstellar objects resembling ‘Oumuamua’s spectroscopic properties [11].

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**References:**
PHYSICAL REGOLITH PROCESSES REVEALED BY CM AND CI CHONDRITES. Michael Zolensky, ARES, NASA Johnson Space Center Houston, TX 77058, USA (michael.e.zolensky@nasa.gov).

Introduction: C-complex asteroids frequently exhibit reflectance spectra consistent with thermally metamorphosed or shocked carbonaceous chondrites [1], and brecciation [2], including Ryugu [1,3], and probably Bennu. Petrographic evidence of impact shock melting and brecciation has been presented for CM and CI chondrites [4], which we review here as a reminder of what we expect in the returned Ryugu and Bennu samples.

Agglutinates: We located in several CI and CM chondrites apparent agglutinate grains containing melted matrix grading into desiccated phyllosilicates (Figure 1). The melt partially devitrified into normally-zoned olivine crystals (Figure 1c) which sit in mesostasis glass. These glasses have partially devitrified to olivine, in contrast to the situation for lunar agglutinates, possibly due to a higher olivine normative composition, and the difficulty of quenching a liquid with an almost pure olivine composition (Gary Lofgren personal communication, 1999). Agglutinate grains are rare in C chondrites, but should be more abundant in unconsolidated regolith samples.

Figure 1. BSE images of a probable agglutinate in Orgueil. (a) Image of the entire agglutinate grain. (b) Close-up of partially dehydrated (heated) matrix at the edge of the agglutinate. Arrows indicate dehydration cracks in the matrix phyllosilicates. (c) Close-up of the center of the agglutinate grain, where complete melting has occurred, and cooling has produced normally-zoned olivine crystals (forsterite cores – F) in mesostasis glass. (d) Close-up of the gradation between melted and unmelted material at the agglutinate edge

Shock Melt Vein Material: We have previously reported on shock melted C2 chondrite materials in the Kaidun meteorite breccia lithologies (mainly C and E chondrites), some of which have experienced post-shock aqueous alteration which severely masks the evidence for shock [5,6]. Two examples are shown in Figure 2, both from a C1/2 lithologies in Kaidun. In these melt vein samples zoned acicular olivine and plagioclase crystals have nucleated into pyroxene-composition mesostasis. In Figures 2a and b the entire assemblage has been altered to phyllosilicates, which preserve most aspects of the compositions and even the zoning. These veins are apparently identical to shock melt veins in shergottites and terrestrial samples [7].

Figure 2. BSE images of shock melt vein materials in Kaidun. (a) & (b) From the CM1 lithology, serpentine faithfully pseudomorphs a vein originally consisting of zoned, acicular olivine crystals nucleating into pyroxene composition mesostasis. (c) & (d) Vein fragment, still fresh, consisting of acicular plagioclase nucleating into augite mesostasis. After [5].

Glassy Beads: In every carbonaceous chondrite (even CI chondrites) where we carefully searched we encounter 10-100µm-sized beads of glass or phyllosilicates which could arguably be microchondrules, but when obviously vesicular are more likely a product of impact. Two typical examples are shown in Figure 3, one (rom Orgueil which is still non-crystalline, and the other from the Nogoya CM2 chondrite which we suggest has been altered from glass to serpentine. Again, unless the original glassy state has been preserved, it is perhaps impossible to ascribe these particular objects to impacts. Fortunately a few survivors are present for further work.
Melted Sulfides: In some C2s masses of melted sulfides record a flash heating event. Figure 4 illustrates one of many troilite masses in the Jbilet Winselwan CM2 chondrite which have obviously been melted, and matrix silicate grains injected inward. For the sulfur to have not completely evaporated requires rather rapid cooling. This particular meteorite exhibits additional evidence of a heating event [8,9], containing partially equilibrated olivine aggregates and chondrules, matrix phyllosilicates transformed into olivine, and areas of finely comminuted, size-sorted olivine grains. A study of shock-melted sulfides in an LL6 chondrite indicated that they produced reflectance spectra that differed significantly from samples with unmelted sulfides [10].

![BSE image of melted troilite](image)

**Figure 3.** Beads. (Left) Vesicular glassy bead from Orgueil. (Right) Serpentine bead in Nogoya. Note the mottling, resembling the vesicular glassy Orgueil bead.

**Figure 4:** BSE image of melted troilite (white — on the right) in the Jbilet Winselwan CM chondrite. Embedded matrix silicates (grey) in the troilite include olivine and low-Ca pyroxene. Note the area of well-sorted olivine grains in the center of the image, adjacent to the troilite, probably resulting from asteroid shaking.

Breciation in Regoliths

The plot in Figure 5 shows Cosmic Ray Exposure (CRE) ages for CMs vs. number of lithologies identified in each meteorite [11, unpublished CRE data from K. Nishizumi and M. Caffee]. The lithologic heterogeneity vs. exposure-age relationship in Fig. 5 could indicate different responses of homogeneous and heterogeneous meteoroids to the space environment between their on-set of exposure (exhumation and ejection from the parent body) and arrival at Earth. Breccias have more internal surfaces of lithologic discontinuity, resulting in weaker meteoroids that disintegrate more readily than their more homogeneous counterparts. The implication of this relation is that samples at the asteroid surface (extrapolating to zero CRE age) will generally consist of very numerous, different lithologies (but possibly still predominantly the same meteorite class), with varying degree of heating/metamorphism. This view appears to be supported by recent imaging of the regoliths of Ryugu and Bennu.

![CRE age vs. number of lithologies](image)

**Figure 5.** There is an anti-correlation between CRE age and the number of distinct CM lithologies within individual CM chondrites. After [5].

**Implications:** Regolith returned from Ryugu and Bennu will be diverse breccias sampling varying degrees of aqueous alteration, impact shock, thermal metamorphism and asteroid shaking.

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