



Program



Europa Deep Dive 2: Chemical Composition of Europa and State of Laboratory Data

October 9–11, 2018 • Houston, Texas

Institutional Support

Lunar and Planetary Institute
Universities Space Research Association

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Abstracts for this workshop are available via the workshop website at

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Guide to Sessions

Tuesday, October 9, 2018

8:30 a.m.	Great Room	Registration
9:30 a.m.	Lecture Hall	Terrestrial Based Observation
1:20 p.m.	Lecture Hall	Observations and Lab Work
5:00 p.m.	Great Room	Europa Deep Dive Poster Session

Wednesday, October 10, 2018

9:00 a.m.	Lecture Hall	Effects of Radiation
12:40 p.m.	Lecture Hall	Lab Work and Modeling

Thursday, October 11, 2018

9:00 a.m.	Lecture Hall	Lab Work and Analogues
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Program

Tuesday, October 9, 2018
TERRESTRIAL BASED OBSERVATION
9:30 a.m. Lecture Hall

Chair: Bryana Henderson

- 9:30 a.m. Brown M. E. * Trumbo S. K.
The Ongoing Revolution in Earth-Based Observations of Europa [#3016]
New ground-based observations are expanding and challenging our views of the composition of Europa. I will present key highlights.
- 10:10 a.m. Becker T. M. * Retherford K. D. Roth L. Hendrix A. R. Molyneux P. Raut U.
Europa's Reflectance in the Mid- and Far-UV [#3025]
We will present observations of Europa's reflectance in the UV, including new observations from the Hubble Space Telescope at mid-UV wavelengths (157–318 nm).
- 10:30 a.m. Trumbo S. K. * Brown M. E. Hand K. P. de Kleer K.
Observational Constraints on the Distribution and Temperature Dependence of H₂O₂ on the Surface of Europa [#3020]
We present observations of H₂O₂ on the surface of Europa. We map H₂O₂ across the surface and investigate its geographic variability. We also examine temperature effects on its abundance by observing the 3.5 μm band before and after eclipse.
- 10:50 a.m. Shirley J. H. *
Europa's Surface Composition: Active Icy Moons Geology with Exogenic 'Overprinting' [#3040]
Despite years of investigations, the chemical composition of Europa's endogenic non-ice materials is unknown and controversial. Nonetheless our current knowledge can provide useful insights of relevance for future remote sensing and in-situ investigations.
- 11:30 a.m. DISCUSSION
- 12:20 p.m. *Lunch*

Tuesday, October 9, 2018
OBSERVATIONS AND LAB WORK
1:20 p.m. Lecture Hall

Chair: Murthy Gudipati

- 1:20 p.m. Spencer J. R. * Grundy W. M.
Rapid Temporal Variability of Condensed Oxygen on Europa? [#3028]
New visible-wavelength spectroscopy of the 5770 Å condensed O₂ band on Europa shows apparent temporal variability in band strength on 1-week or shorter timescales. If real, this variability would imply a surprisingly dynamic surface on Europa.
- 1:40 p.m. McGrath M. A. * Sparks W. B. Spencer J. R.
New Constraints on the Abundances of Sulfur and Chlorine at Europa [#3029]
New constraints on the abundances of sulfur and chlorine are determined from deep UV spectra of Europa obtained with the Hubble Space Telescope Cosmic Origins Spectrograph.
- 2:00 p.m. DISCUSSION
- 2:20 p.m. Vance S. D. * Brown J. M. Bollengier O. Journaux B. Abramson E. H. Shaw G. Watson H.
Understanding Europa's Composition Through Geophysical Measurements: The Role of Laboratory Data [#3022]
Inferring Europa's composition, mechanical, and thermal properties requires remote sensing and geophysical measurements. Inverse solutions to those datasets can be constrained with prior knowledge from material properties obtained in the laboratory.
- 3:00 p.m. *Break*
- 3:20 p.m. Melwani Daswani M. * Vance S. D.
Melt Production, Eruption and Degassing from Europa's Interior: Effects on Composition over Time [#3032]
We couple the heat production caused by tidal dissipation to thermodynamic and chemical equilibrium models to compute compositional changes of the interior and ocean for a model Europa. Two possible eruption events will be described.
- 3:40 p.m. Howell S. M. * Leonard E. J.
Impurities in Europa's Ice Shell: Salty Tree-Rings? [#3007]
As tree rings provide an insight into the seasonal environment during wood growth, we interpret model predictions of inferred compositional complexity within the ice shell to reflect the accretion environment and tectonic history of incorporated ice.
- 4:00 p.m. DISCUSSION

Tuesday, October 9, 2018
EUROPA DEEP DIVE POSTER SESSION
5:00 p.m. Great Room

Wolfenbarger N. S. Blankenship D. D. Soderlund K. M. Young D. A. Grima C.

Leveraging Terrestrial Marine Ice Cores to Constrain the Composition of Ice on Europa [#3036]

We summarize published marine ice core data to constrain the composition of hypothesized marine ice on Europa. Sites are evaluated as potential analogs for the ice-ocean interface at Europa.

Montesi L. G. J. Howell S. M. Pappalardo R. T.

Rifting, Convection, and the Elevation of Bands on Europa [#3010]

Ice upwelling underneath bands carries heat, thinning ice. The positive elevation of bands implies either that the surrounding ice contains impurity or that the surrounding ice is convecting and upwelling shut down convection.

Chan K. Grima C. Blankenship D. D. Soderlund K. M. Young D. A.

Dielectric Brine-Ice Mixtures on Europa, and the Need for New Experiments [#3015]

We assess the ability of dielectric homogenization mixing approaches to model the complex permittivity of near-surface icy brine mixtures, and discuss additional parameters needed through future experiments.

Mishra I. Lunine J.

Investigating Detectability of Organics on Europa's Surface [#3006]

Our work deals with modelling surface reflectance spectra of Europa, considering bio-organics like amino acids and preciously deduced components like water ice, sulfuric acid hydrated and hydrated salts.

Buffo J. J. Schmidt B. E. Walker C. C. Huber C.

Not So Solid: The Multiphase Nature of Sea Ice — Lessons from Earth and What it Means for Europa's Ice Shell [#3014]

Simulating the entrainment of impurities in ice using reactive transport modeling and understanding what this means for the Europa system.

DeLuca M. Sternovsky Z. Munsat T. Ulibarri Z.

Development of a Reflectron Time-of-Flight Mass Spectrometer and Icy Dust Accelerator to Study Icy Impacts [#3005]

The effect of icy impacts on Europa's composition is being studied by shooting dust into ice. A new mass spectrometer is being built to study the ions produced in icy impacts, and a new accelerator is being developed to shoot ice particles.

Paardekooper D. M. Henderson B. L. Gudipati M. S.

Plume Profile Studies of Nanosecond Laser Induced Desorption of Water Ice — Amorphous Versus Crystalline [#3011]

The ocean worlds are of particular interest for the search of extraterrestrial life. Investigation will be required but obtaining the ice composition is a challenge, laser ablation combined with time-of-flight mass spectrometry is a promising route.

Morrison A. A. Whittington A. G. Zhong F. Mitchell K. L. Carey E. M.

Rheological Investigation of Cryovolcanic Slurries [#3012]

Subliquidus rheological experiments will be conducted for briny cryovolcanic compositions. Understanding how these materials move, deform, and evolve upon crystallizing will help constrain what morphological features can form by various compositions.

Raut U. Retherford K. D. Teolis B. D. Becker T. M. Gladstone G. R.

Europa-Relevant Laboratory Studies at the Southwest Research Institute: Far-Ultraviolet Spectroscopy and Sputtering in the Context of the Surface-Exosphere Connection [#3034]

We will discuss laboratory capabilities and perform experiments to 1) Compile FUV spectral atlas of European analogs and 2) Characterize sputtered ejecta from icy mixture to decode the surface-exosphere relation at Europa.

Hibbitts C. A.

Laboratory Spectral Measurements Needed to Better Model Europa's Surface Composition [#3030]

Laboratory spectral measurements of materials exposed to the European environment including UHV, cryogenic temperatures, and irradiation are needed to better model its surface composition.

Tremblay G. R. Kraft R. P. Bulbul E. Nulsen S. Germain G. Beegle L. Hodyss R. Vance S.

X-Ray Fluorescence Spectroscopy on the Europa Lander: Determining the Elemental Composition of the Surface and Uncovering Indicators of Habitability [#3024]

We have proposed an X-ray silicon drift detector-based instrument for the forthcoming Europa Lander mission, designed to characterize the elemental composition of Europa's surface. We discuss the instrument and the critical science it will enable.

Klima R. L. Soderblom J. Gudipati M. Europa Clipper Composition Working Group

Investigating the Surface Composition of Europa with the Europa Clipper [#3018]

The Europa Clipper mission will investigate composition of Europa's surface and exosphere, providing key constraints on the origin of surface materials. We will summarize the science addressed by the planned, synergistic composition investigations.

Hand K. P. Murray A. E. Garvin J. Hörst S. Brinkerhoff W. Edgett K. Hoehler T. Russell M. Rhoden A. Yingst R. A. German C. Schmidt B. Paranicus C. Smith D. Willis P. Hayes A. Ehlmann B. Lunine J. Templeton A. Nealson K. Christner B. Cable M. Craft K. Pappalardo R. Hofmann A. Nordheim T. Phillips C.

The Europa Lander Mission Concept and Science Goals of the 2016 Europa Lander Science Definition Team Report [#3021]

The Europa Lander SDT report recommended science requirements and a model payload consistent with the goals of searching for biosignatures, assessing Europa's habitability, and contextualizing Europa's ice shell and its relationship to the ocean below.

Wednesday, October 10, 2018
EFFECTS OF RADIATION
9:00 a.m. Lecture Hall

Chair: Jason Soderblom

- 9:00 a.m. Cooper J. F. *
Multi-Scale Radiation Environments of Europa [#3023]
Europa has multi-scale radiation environments extending from the external magnetosphere to the near-moon and surface environments, and finally into the interior. Improved moon-magnetosphere modeling, and preferably orbiter measurements are needed.
- 9:40 a.m. Nordheim T. A. * Paranicas C. Hand K. P.
Europa Radiation Environment and Implications for Surface Composition [#3039]
Jupiter's moon Europa is embedded deep within the Jovian magnetosphere and is therefore exposed to intense charged particle bombardment. Here we will discuss the effect of this weathering on the structure and chemical composition of Europa's surface.
- 10:00 a.m. Poston M. J. * Carlson R. W. Hand K. P.
Spectral Behavior of Irradiated Sodium Chloride Crystals Under Europa-Like Conditions [#3019]
Irradiation-induced color centers in sodium chloride as a tracer of exposure age of ocean materials at the surface of ocean worlds.
- 10:20 a.m. *Break*
- 10:40 a.m. Ganguly K. * Gasda P. J. Gleasner C. Mensah C. Adikari S. Quinn H. Watkins A. Love S. Misra A. Acosta-Maeda T. Sharma S. K. Wiens R. C.
Survival, Genetic Modification, and Time-Resolved Laser-Induced Fluorescence Analysis of Bacteria Exposed to High-Dose Radiation Simulating Europa's Surface [#3035]
We are developing OrganiCam, a prototype time-resolved laser-induced fluorescence instrument to detect bio-materials on Europa's surface. We analyzed the nature of radiation exposed bio-materials to simulate exposure to the Europa surface.
- 11:00 a.m. Truong N. * Glein C. Monroe A. A. Anbar A. D. Lunine J. I.
Decomposition of Amino Acids in Water with Application to Europa and Other Ocean Worlds [#3009]
Aspartic acid, threonine, isoleucine, serine, arginine are relatively sensitive to decomposition. Any of those species detected at Europa cannot be primordial, such that in situ detection would indicate recent (< 1 Myr) production of the amino acid.
- 11:20 a.m. DISCUSSION
- 12:00 p.m. *Lunch*

Wednesday, October 10, 2018
LAB WORK AND MODELING
12:40 p.m. Lecture Hall

Chair: Tracy Becker

- 12:40 p.m. Johnson R. E. * Oza A. Schmidt C. Leblanc F.
Plasma and Thermal Processing of Europa's Surface [#3041]
The effects of the intense plasma and thermal processing on the surface of Europa will be briefly reviewed as it relates to potential surface/ocean coupling.
- 1:20 p.m. Teolis B. D. * Raut U.
Quantifying the Chemical Species Radiolytically Sputtered from Europa's Complex Ices into its Exosphere Through Laboratory Experiments [#3037]
We discuss how complex ices on Europa's surface may chemically expressed in the radiolytically sputtered exosphere, and experiments in our laboratory to quantify the composition of material ejected from possible European surface materials.
- 1:40 p.m. DISCUSSION
- 2:00 p.m. Hudson R. L. *
Diving Deep into Europa's Reaction Chemistry [#3038]
This talk will cover thermally driven and radiation-induced changes in icy materials, mostly covalent and ionic compounds, studied by our NASA research group since 1998, with an emphasis on a few relatively simple molecules.
- 2:40 p.m. Singh V. * Gudipati M. S. Rhoden A. R. Henderson B. L.
ICELIB — Assessing Europa's Surface with Laboratory Ice Experiments [#3017]
In preparation for Europa Clipper, we are conducting critical laboratory studies to obtain spectroscopic data of ices in UV-VIS-NIR wavelength regions, with variations in grain size, composition, and radiation-processing at relevant temperatures.
- 3:00 p.m. *Break*
- 3:20 p.m. Gudipati M. S. *
Processes Affecting the Composition of Europa's Surface — An Overview from Laboratory Data Perspective [#3003]
Overview of processes affecting compositional equilibrium on Europa's surface.
- 3:40 p.m. Hanley J. * Becker T. Retherford K. Grundy W. Greathouse T. Tsang C. Roth L.
Chlorine Salts on Europa from Experimental Data and Recent Telescopic Observations [#3031]
We present laboratory Vis-MIR reflectance spectra of chlorine salts, as well as recent observations of Europa looking for those salts.
- 4:00 p.m. Ulibarri Z. * Munsat T. Abel B. Dee R. Gudipati M. Horanyi M. James D. Kempf S. Kupihar Z. Sternovsky Z.
On the Genesis and Detectability of Organic Chemistry in Hypervelocity Impact Ice Spectra [#3033]
The ice target at the IMPACT accelerator allows for studies of dust-ice interaction under conditions and energies relevant to the chemical evolution of ice surfaces and the detection of organics with time of flight instruments on fly-by spacecraft.
- 4:20 p.m. DISCUSSION

Thursday, October 11, 2018
LAB WORK AND ANALOGUES
9:00 a.m. Lecture Hall

Chair: Reggie Hudson

- 9:00 a.m. Henderson B. L. *
Towards a Better Understanding of Composition: Status Update on Laboratory Studies of Europa Environment Analogs [#3026]
This review will address the current state of laboratory experiments for Europa-relevant analogs and explore areas of study that would benefit from further experimentation.
- 9:40 a.m. Fox-Powell M. G. * Osinski G. R. Applin D. Stromberg J. Cloutis E. Cousins C. R.
Low-Temperature Hydrated Salts from Axel Heiberg Island as an Analog for Europa's Non-Ice Surface Material [#3013]
We present spectral analyses of natural low-temperature hydrated salts from the Canadian High Arctic, and discuss their relevance for understanding the nature of Europa's surface material.
- 10:00 a.m. Bower D. M. * Nixon C. A. Hewagama T. Aslam S. Eigenbrode J. Stern J. C. Cousins C. R. Regberg A. McAdam A. C. Knudson C. A. Young K. Achilles C.
Understanding Life Signatures Across Geothermal — Ice Gradients in Europa-Like Environments Using Raman Spectroscopy [#3008]
Ocean worlds like Europa exhibit geophysical and geochemical characteristics that are similar to terrestrial icy environments. Raman spectroscopy measurements were made on laboratory-synthesized Europa analogs and samples collected from Iceland.
- 10:20 a.m. DISCUSSION
- 11:00 a.m. *Break*
- 11:20 a.m. Clark R. N. *
Compositional Remote Sensing of Planetary Surfaces with Spectroscopy: Limits to Our Knowledge and Abilities to Interpret Data [#3027]
There are unknown absorptions in current planetary spectra. New spacecraft are being sent with more advanced instruments to answer tougher questions, but laboratory data for interpretations are lacking, limiting the scientific return from missions.
- 12:00 a.m. DISCUSSION
- 1:00 p.m. Adjourn

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Europa's Reflectance in the mid- and far-UV. T. M. Becker, K. D. Retherford¹, L. Roth², A. R. Hendrix³, P. Molyneux¹, U. Raut¹, J. Alday⁴. ¹Southwest Research Institute (6220 Culebra Rd., San Antonio, TX; tbecker@swri.edu), ²KTH Royal Institute of Technology (Stockholm, Sweden), ³Planetary Science Institute, ⁴Oxford University, Oxford, UK.

Introduction: The surface of Europa has long been known to be primarily composed of water ice from measurements in the near-IR [1, 2], but the visibly darker, reddish coloration on the trailing hemisphere [3] suggests some variation in composition. The differences are likely a combination of endogenic and exogenic processes, including emplacement from the underlying ocean, contributions from the Io plasma torus, and uneven radiolytic processing [4-8]. Ultraviolet observations of Europa probe the uppermost layers (~100 nm) of the surface, and are critical for understanding the albedo variations.

Previous Results: Using Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS) data acquired from 1999 – 2015, we measured the albedo of Europa in the far-UV from ~118 – 170 nm and found that the spectrum is dark (< 2.0%) and fairly flat [9], in agreement with previous far-UV analyses [10-11]. We also confirmed previous detections [12] that the Lyman- α reflectance is brighter on the trailing hemisphere than the leading, a reversal from the darker trailing hemisphere observed in the near-UV and visible. In Fig. 1 we plot our results as well as the results from previous HST Cosmic Origins Spectrograph (COS), STIS, and Galileo observations made in the UV.

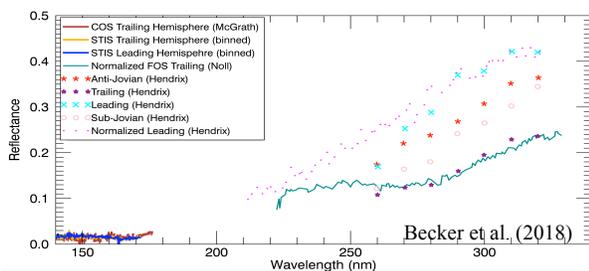


Fig. 1: Compilation of UV reflectance measurements in the UV from STIS [9], COS [13], the Faint object Spectrograph (FOS) [14], and Galileo [15]. There is a gap in published spectra from 170 nm – 210 nm.

The missing water-ice absorption edge: Spectral measurements of water ice in the laboratory and observations of the icy satellites of Saturn reveal the presence of a strong water-ice absorption edge near 165 nm. However, there is no indication of a sharp edge in the STIS data described above nor in the COS data that extends to ~175 nm [13]. This appears to be the case

for the leading, trailing, sub- and anti-Jovian hemispheres. Some initial spectral models of H₂O intimately mixed with other materials, such as sulfur or ice tholins, show that the spectral feature at 165 nm can be suppressed if the grain sizes of the water ice are an order of magnitude smaller than the grains of the contaminant material. However, such models have yet to match the observed spectra of Europa at longer wavelengths. Further, no data of Europa between the wavelengths of ~170 nm – 210 nm have been published for comparison (Fig. 1).

New Observations: In April and June of 2018, we used the HST STIS G230L mode with the 52 x 0.2 slit to acquire spatially resolved observations of Europa spanning the wavelengths 157 nm – 318 nm, filling in the spectral coverage gap. We obtained observations of the trailing, sub-, and anti-Jovian hemispheres.

We will present the new, mid-UV observations and discuss how they compare with previous observations of Europa. We will discuss potential explanations for the muted water ice feature at 165 nm, including radiation, grain sizes, and surface composition and we will show comparisons of spectral models with the HST observations. Observations at these wavelengths are critical for understanding the surface composition and processing; however, the spectral analysis of the data are limited by the lack of optical constants at UV wavelengths for many potential candidates for the surface composition.

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Understanding Life Signatures Across Geothermal - Ice Gradients in Europa-like
| Environments using Raman Spectroscopy

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Ocean worlds like Europa exhibit geophysical and geochemical characteristics that are similar to terrestrial icy environments. The interface of geothermal activity with icy terrestrial environments is a dynamic setting where microbes thrive and the composition of surface sediments is ephemeral. Icy materials that interface with geothermal activity can entrain microbes, rocks and minerals, as well as gases, and in the absence of readily identifiable biosignatures, geochemical gradients derived from biological processes can offer clues to the presence of life. Some of these geochemical gradients are distinguished by subtle variations in mineral assemblages. Deviations in mineral structure can be attributed to the incorporation of cations used in metabolic processes or from the influence of decaying organic matter on local chemistry. Raman spectroscopy is a powerful, versatile, and non-destructive tool that is well-established for in situ measurements and the detection of minerals and compounds in a wide variety of host materials like rocks and ice. To test the utility of Raman spectroscopy for supporting life detection investigations on Europa-like materials, Raman measurements were made on laboratory-synthesized Europa analogs along with rocks and ice collected near the Kverkfjöll volcano in Iceland. To increase the robustness of the Raman measurements, other techniques including reflectance spectroscopy, X-ray diffraction (XRD), X-ray fluorescence (XRF), water chemistry analyses, total organic carbon (TOC) abundances, DNA extractions, and lipid/amino acid analyses were used. Here we present our initial findings and discuss future directions in developing Raman spectroscopy instrumentation for life detection on Europa-like worlds.

THE ONGOING REVOLUTION IN EARTH-BASED OBSERVATIONS OF EUROPA. M.E. Brown and S.K. Trumbo, Division of Geological and Planetary Science, Caltech, Pasadena, CA 91107 mbrown@caltech.edu

Introduction: More the 15 years after the end of the Galileo mission, we are currently in a revolution in our ability to study the composition and surface properties of Europa from the Earth. Large telescopes with adaptive optics and modern spectrographs are able to obtain higher quality spectra than were possible from Galileo, ALMA, a giant millimeter-wave interferometry can map Europa at thermal wavelengths with more sensitivity than ever before, and observations from the Hubble Space Telescope allow access to spectra at wavelengths unavailable from Galileo. The drawback to Earth-based observations, of course, is the lack of high spatial resolution that can only be provided with *in situ* observations. Nonetheless the past decade has seen spatial resolutions approaching ~150 km over the surface of Europa with all of these techniques, allowing regional scale mapping at a wide variety of wavelengths. I will detail key results from these observations.

Infrared Adaptive-Optics Spectroscopy: Ten-meter class telescopes can obtain approximately 20 resolution elements across the disk of Europa with spectral resolution and signal-to-noise both significantly higher than that achieved from Galileo NIMS. Several critical results have emerged.

The long standing suggestions that sulfates were a dominant feature of the surface are not supported by the higher resolution spectra which show none of the spectral bands predicted by these salts. The dominant salt appears essentially featureless, which is consistent with – but by no means requires – a surface dominated instead by NaCl salts.

The spectral unit that is hypothesized to be NaCl is spatially concentrated near the leading hemisphere equator, specifically in regions that have been mapped as chaos regions (Fig 1). This realization, along with the distinct colors of the chaos regions, makes it clear that chaos regions have a surface composition distinct from other regions on Europa.

ALMA thermal mapping: In its highest spatial resolution mode, ALMA can map Europa at a spatial resolution comparable to that of adaptive optics on 10m telescopes. These provide the first full thermal mapping of the surface of Europa. Not surprisingly, thermal emission from Europa is dominated by albedo, but significant variations also point to differences in thermal inertia or in emissivity that point to regional differences in composition or texture. The region surrounding Pwyll, in particular, is seen to have an anomalously high thermal inertia, leading to the elevat-

ed nighttime temperatures previously seen in Galileo PPR observations.

Hubble Space Telescope: While Galileo provided high resolution images of much of Europa, no visible wavelength spectroscopy was available. HST fills this gap with approximately the same spatial resolution as the previous two techniques. HST observations specifically allow a search for optical absorption features known as color centers which should be present if NaCl dominates the chaos regions. The predicted color centers are indeed visible in chaos regions, though their specific distribution still requires a more thorough analysis and understanding.

While new spacecraft-based observations of Europa remain more than a decade away, Earth-based observations are continuing to quickly advance our understanding of the surface of Europa. The observations have challenged many Galileo-era assumptions and will require detailed laboratory-based work to help with interpretation in the years to come.

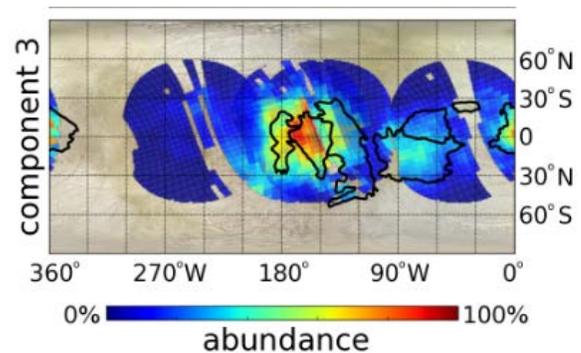


Figure 1: Distribution of salt -- possibly hydrated NaCl -- on Europa. The outlined areas of chaos regions. The salt component is seen in all leading side chaos regions, but it is particularly abundant near 0 and 180 degrees longitude.

NOT SO SOLID: THE MULTIPHASE NATURE OF SEA ICE – LESSONS FROM EARTH AND WHAT IT MEANS FOR EUROPA’S ICE SHELL. J. J. Buffo¹, B. E. Schmidt¹, C. Huber², C. C. Walker^{3,4} ¹Georgia Institute of Technology, jacob.buffo@eas.gatech.edu, ²Brown University, ³JPL, ⁴WHOI.

Introduction: The aqueous nature of terrestrial seawater leads to complex multiphase physics during its solidification [1]. The inability of salt to be adequately incorporated into the crystalline lattice of ice leads to solidification fronts characterized by a two-phase slurry of solid ice bathed in hypersaline brine. This porous layer is capable of fluid and solute transport and governs the growth rate, mechanical properties, and composition of the forming ice. The thermal and physico-chemical evolution of these multicomponent interfaces are well described by the equations of reactive transport [2], and contemporary sea ice models have proven the method's utility [3,4].

With Europa’s ice shell likely forming from, and still currently interacting with, a saline ocean [5,6], as well as evidence for ongoing intrashell hydrology [7,8], it is reasonable to assume that the thermal, mechanical, and compositional evolution of Europa’s ice shell will be dictated by these same multiphase physics. Compositional heterogeneities within the shell have been suggested as drivers of subduction [9], convection [10,11], eutectic melting [7], and putative habitability [12,13]. Additionally, the thermochemical structure of the ice shell may play a crucial role in interpreting any radar data returned from the upcoming Europa clipper mission [14,15]. Currently no models of Europa include the effects of reactive transport and estimates for the impurity content of Europa’s ice shell remains largely unconstrained.

Results: Here we present a one-dimensional reactive transport model designed to simulate the ice-ocean/brine interface dynamics of Europa’s hydrosphere. We validate the model against terrestrial sea ice (Figure 1) and apply it to a number of potential ocean/brine compositions under Europa conditions. The resulting compositional profiles and the impact they may have on ice shell properties and dynamics are discussed. An application of the model to the refreeze of basal fractures is presented. Solidification time scales produced by the multiphase model are compared to those of the typically implemented conduction solution. We discuss the models applicability to other hydrological features on Europa. Finally, past laboratory investigations of sea ice are examined as potentially beneficial methodologies for heretofore under investigated Europa environments.

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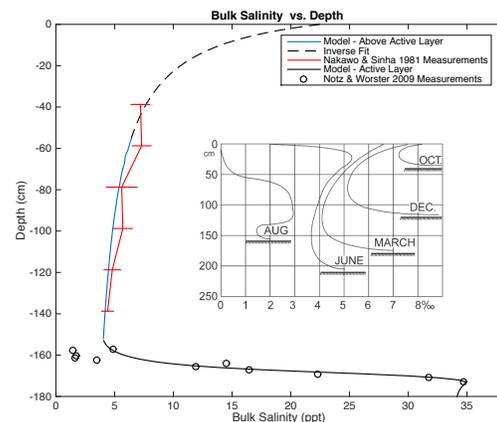


Figure 1 - Modeled (blue and black solid lines), empirical (red line [with errors reported in [16]] and black circles [17]), and interpolated (black dashed line) bulk salinity profiles of terrestrial sea ice. Inset is a graphical representation of the seasonal evolution of bulk salinity in first year sea ice (from [18]).

Dielectric Brine-Ice Mixtures on Europa, and the Need for New Experiments. K. Chan¹, C. Grima¹, D. D. Blankenship¹, K. M. Soderlund¹, D. A. Young¹, ¹Institute for Geophysics, University of Texas at Austin, J.J. Pickle Research Campus, Bldg. 196; 10100 Burnet Road (R2200), Austin TX 78758-4445 (kristian.chan@utexas.edu).

Introduction: The recent hypothesis of brine mobilization in Europa's ice regolith, ranging from hundreds of meters to kilometers thick [1-2], makes this region an intriguing target for understanding habitability on the icy moon. In addition, the Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) instrument on the Europa Clipper mission is capable of detecting near-surface brines within depths of tens of meters, while brines may be potentially located in range of in-situ sampling from a future lander mission [3]. Successful radar detection of brine-soaked firn in the McMurdo Ice Shelf of Antarctica [4] is attributed to the radar being sensitive to the dielectric constant of mixtures containing ice, brine and pore space. However, the electromagnetic properties of near-surface brines on Europa remain poorly constrained but are important for investigating physical surface properties derived from reflectometry measurements by REASON [5].

Dielectric Model: To understand REASON's sensitivity to such mixtures, we develop a three-component Debye-mixing model based on classical mixing approaches and assess its ability for constraining the permittivity of icy brine mixtures under near-surface conditions on Europa. These mixtures include a combination of ice, vacuum pores, liquid brine and/or salt hydrates. The single Debye model was used to obtain the frequency dependence of the complex permittivity for liquid and frozen brines. Experiments previously conducted with salt hydrates and liquid brine at low temperatures [6-8] provide the necessary input parameters for the Debye model. The results were then used in several dielectric homogenization mixing rules (Fig. 1) aimed to characterize a heterogeneous mixture with a bulk effective macroscopic permittivity [9, 10].

We demonstrate for mixtures containing ice, pores and modeled salt hydrates on Europa [11], the different mixing rules agree quite well with each other, predicting a mixture permittivity with a value somewhere in between the permittivities of its constituents. However, for cases containing liquid brine, the model fails to provide adequate permittivity predictions. Although suitable for modeling brine pockets in ice on Earth, the different mixing rules yield dissimilar results at relatively high liquid brine volume fractions (Fig 1.), which would be representative of a brine saturated ice regolith on Europa. The real part of the effective complex permittivity can achieve values much higher than

any of its constituents, often attributed to polarization enhancement phenomena for high-loss mixtures [12].

Experiments: Additional laboratory experiments are crucial for determining the electromagnetic characteristics of icy brine mixtures under near-surface European conditions, given the limited data available in recent literature. Factors such as composition, salinity, temperature gradients and porosity can affect the dynamics and evolution of near-surface brines. New experiments should test the effects of these parameters in order to provide better estimates of Debye model parameters, determine whether current homogenization mixing approaches are appropriate, and/or develop new empirical models needed to model mixtures of near-surface brines on Europa.

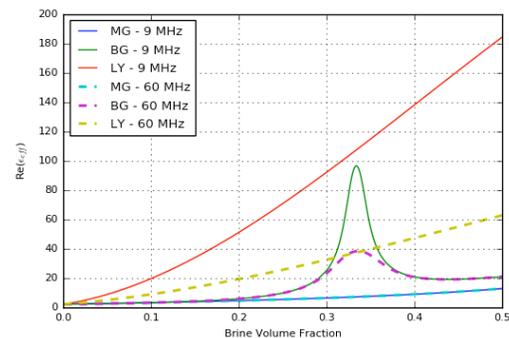


Fig 1. Real part of the complex permittivity for a mixture containing 50% ice with varying volume fractions of liquid brine and vacuum pores, using the Maxwell Garnett (MG), Polder-van Santen or Bruggeman (BG), and Looyenga (LY) mixing approaches.

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COMPOSITIONAL REMOTE SENSING OF PLANETARY SURFACES WITH SPECTROSCOPY: LIMITS TO OUR KNOWLEDGE AND ABILITIES TO INTERPRET DATA. R. N. Clark, Planetary Science Institute, Lakewood, CO, USA, rclark@psi.edu

Introduction: We are living in a golden age of planetary exploration. We are sending spacecraft to the outer reaches of the Solar System with sophisticated instruments. We also have advanced instruments on earth-orbiting telescopes and on Earth-based telescopes. Sensor technology improves each year. Compute capabilities have increased to a level where scientists can do much of their work on a simple laptop with the computing capability beyond a super computer of a couple of decades ago, and even faster machines are readily available.

The data being returned by these instruments is spectacular, often covering from the far ultraviolet to the mid and far infrared. Yet meeting after scientific meeting, we often see conflicting interpretations of the same or similar data. My assessment is that many of these conflicting interpretations are due to inadequate reference data and/or models that are too simplistic. The questions to be answered are complex.

Spectral Range and Resolution and Physical Conditions: With data from spacecraft covering UV (~0.1 micron) to mid and far infrared (20 to 100+ microns), few laboratories have the capability to measure materials over such a large range, and with spectral resolution that at least matches observational data. Spectra of gases change with both pressure and temperature. Spectra of solids change with grain size, temperature, pressure, crystallinity, and trace substitutions of elements. Planetary surfaces are subjected to bombardment by meteors large and small, as well as UV radiation, cosmic rays, energetic particles from the sun and or trapped in planetary magnetic fields. Few, if any, laboratories have the ability to study the effects of the radiation environments on materials under real-planet/satellite conditions. Even if a lab had the complete capability to measure these conditions with appropriate environment chambers and radiation sources, the time to characterize one even one sample is formidable.

Modeling: Modeling of the spectroscopic signatures of planetary surfaces is complex. Planetary scientists often use “Hapke” theory, or equivalent radiative transfer theories. Radiative transfer models require optical constants in order to model abundances and grain sizes. Classical Hapke theory is limited by geometric optics, but increasingly we are finding sub-micron and nano-particles are in enough abundance in planetary surfaces that more sophisticated models are needed [1]. Few have included coatings and layered

media in models of planetary surfaces, but that is becoming a greater need.

Optical Constants: While we have few far UV to far infrared spectra of planetary materials, we have even fewer optical constants over relevant temperature ranges. Our best case optical constants are for water ice where we have pretty good data from [2] as a function of temperature but only for the infrared. Some residual interference patterns are in the data and [1] corrected them for just one temperature. We have only one measured temperature in the UV and no idea how much the spectrum varies with temperature.

Nano-Materials: Chemical bonds at the edge of a particle are affected by different fields than those internal to a particle. As particle sizes get smaller, in the tens of nanometer range and less, the surface to volume ratio changes enough that the spectral properties change. These effects have been well demonstrated for iron oxides [3] but we have no optical constants for such conditions, nor do we have even simple spectra for many other nano-materials, including water ice that is so ubiquitous in the outer Solar System. We have no idea on how this lack of knowledge limits our interpretations.

Unknown Absorptions: We have observed absorptions in spectra of planets/satellites that remain unidentified after many years, including near-infrared absorption bands that appear to be organics, but for which no organic or combination of organics have been identified as well as unknown UV absorptions.

Measurements Needed: The list of needed spectral measurements is too long to list here, but will be discussed in the presentation. Multiple labs need to be upgraded to be able to make needed measurements and the community needs to concentrate on the most needed compounds first. This list will vary by mission and planetary surface under study. For the outer Solar System, the UV absorber is unknown with multiple contenders. For Europa, salts and acids need to be measured over the Europa Clipper instrument range. Water ice is one of the most ubiquitous compounds, yet we need measurements in the UV as a function of temperature. The ice optical constants in the visible are inadequate as they have spectral structure not seen in lab reflectance spectra.

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MULTI-SCALE RADIATION ENVIRONMENTS OF EUROPA. John F. Cooper, Heliospheric Physics Laboratory, Code 672, NASA Goddard Space Flight Center, Greenbelt, MD 20771 (e-mail: John.F.Cooper@nasa.gov).

Introduction: Europa's radiation environment should be considered in five major regions: (1) the transient local magnetospheric environment at the orbit of Europa around Jupiter, (2) the near-moon environment perturbed by the moon-magnetosphere interactions, (3) the outer surface heavily irradiated in most locations as the result of these interactions, (4) the subsurface extending through the ice crust to the water ocean, and (5) the underlying rock mantle and core of Europa. Europa's magnetospheric environment varies with location relative to the magnetospheric current sheet, tilted with the magnetic dipole axis at 9.4° (GSFC O6 Model) to the rotational plane and the orbits of the Galilean moons. The strongest plasma interaction is encountered by Europa at the center of the current sheet. Near the moon the local magnetospheric plasma and energetic particles, and UV radiation from the Sun, interact with the neutral (O_2 , O) atmosphere to produce an ionosphere and a region of perturbed magnetic field varying in magnitude and direction. The field perturbations arise from divergence of the plasma flows around the moon, and by induced magnetic fields from the ionosphere and the salty subsurface ocean. The surface ice is heavily bombarded by the magnetospheric [1,2], solar, and galactic cosmic ray irradiation but the dosage levels are strong functions of hemispheric location, local topography, and surface roughness. Potential biosignatures surviving the irradiation might be found anywhere below tens of centimeters in depth [3], in topographically shielded areas, or below a block of ice near a lander in even the most heavily irradiated areas. Roughness of the lander locality translates into a wide distribution of potential cumulative radiation dosages for organic and inorganic materials. The subsurface environment is penetrated down to hundreds of meters by secondary and higher order products of galactic cosmic ray interactions within the top ten meters, while radioisotope decays, e.g. from the ^{40}K isotope in potassium salts [4], dominate the radiation at greater depths in the ice crust, ocean, rock mantle, and core.

Moon-Magnetosphere Interaction Models: Progress on modeling the radiation in the near-moon and surface environments has been rather slow, no model yet including the spatial and temporal variance of perturbed magnetic fields from the moon-magnetosphere interaction. So far, we have relied on a first approximation [5], as later updated [3,6], that the unperturbed magnetospheric field can be used to track motions of energetic electrons to the moon surface, but this model

cannot be used for energetic ions and assumes that ion irradiation is uniform across the entire moon surface. More promising is work soon to be published [7] using the A.I.K.E.F. [8] hybrid interaction model to compute the perturbed field and plasma parameters near Callisto and improve tracking of hot ions between the upstream magnetosphere and that outer Galilean moon's surface. The same group is now adapting this approach to modeling the near-moon-perturbed environment at Europa after the first earlier hybrid simulations for that moon by another group at NASA Goddard Space Flight Center [9,10]. This author is now collaborating in a joint GaTech-GSFC effort to compare results of the previous and new simulations, and to use the computed magnetic and electric fields to model energetic radiation fluxes in the near-moon and surface environments.

Conclusions: More investment is needed in radiation applications of the more advanced moon-magnetosphere interaction models to more accurately interpret the past radiation measurements from Galileo Orbiter and support science and operations of the future Europa Clipper, JUICE, and Europa Lander missions. How can we better understand the relations between magnetospheric activity, surface radiation, and resultant outgassing that may mimic apparent cryovolcanic activity [11, 12, 13]. How could there be surface redeposition of plume material without apparent change [14] in the surface at scales of square kilometers? Could we better understand moon-magnetosphere interactions and radiation with an orbiter [15]?

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DEVELOPMENT OF A REFLECTRON TIME-OF-FLIGHT MASS SPECTROMETER AND ICY DUST ACCELERATOR TO STUDY ICY IMPACTS. M. DeLuca^{1,2}, Z. Sternovsky^{1,2}, T. Munsat³, and Z. Ulibarri^{1,3},

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Introduction: The likely presence of a liquid water ocean on Europa makes it a tantalizing location in the search for habitable locations beyond Earth. Surface ice on Europa is altered by exposure to micrometeorite impacts, which will affect the chemistry of the surface [1] and eject surface material to high altitudes. In addition, cryovolcanism on Europa is likely ejecting icy particles from Europa's subsurface ocean [2]. The subsurface and surface ice ejection processes allow the chemical composition of the ice to be probed by *in situ* dust instruments on orbiting spacecraft. Dust instruments ionize grains of material by impacting the grains at high velocities, and can then analyze the ionized fragments using time-of-flight mass spectrometry. In order to understand the chemical modification of material on Europa's surface by meteorite impacts, and to understand how icy grain impacts on dust instruments can be used to probe the composition of the ice, icy impacts need to be studied in the laboratory.

Dust Accelerator Facility: At the University of Colorado, a unique electrostatic dust accelerator facility is operated that is capable of shooting micron and submicron particles at high velocities. The facility is capable of shooting particles that cover the speed range of micrometeorite impacts and the speeds at which dust instruments on orbiting spacecraft will encounter icy particles ejected from Europa. An ice target experiment has been developed for use with the dust accelerator [3]. In the ice target, a cryogenic piece of ice is bombarded by particles shot out of the dust accelerator. Typical particles shot by the accelerator include metals and minerals. Organics and salts can be mixed into the ice to study impacts involving complex molecules embedded in the ice. A linear time-of-flight mass spectrometer is used to identify the ions produced in the impact, allowing the impact process to be studied.

Accelerator and Instrument Development: Recent developments have been made to improve the measurement capabilities to study icy impacts at the University of Colorado. First, an improved instrument setup is being designed for the ice target experiment. The improved setup consists of a new reflectron time-of-flight mass spectrometer which will improve the mass resolution of the current setup by reducing the energy spread of ions emitted by the impact. The im-

proved setup will increase the sensitivity with which dust impacts into ice can be studied. Second, an icy dust accelerator is under development. The icy dust accelerator will consist of an electrospray ionization source and a linear accelerator which will accelerate ice particles containing complex molecules to orbital velocities. The icy dust accelerator will allow the impact of ice onto a dust analyzer instrument to be directly studied in the laboratory. These improvements to the laboratory facilities at the University of Colorado will improve our understanding of how micrometeorite impacts modify icy material on Europa and how dust analyzers can be used to identify material ejected from Europa's surface ice and subsurface ocean.

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LOW-TEMPERATURE HYDRATED SALTS FROM AXEL HEIBERG ISLAND AS AN ANALOG FOR EUROPA'S NON-ICE SURFACE MATERIAL. M. G. Fox-Powell¹, G. R. Osinski², D. Applin³, J. Stromberg³, E. Cloutis³ and C. R. Cousins¹. ¹School of Earth and Environmental Sciences, University of St Andrews, Irvine Building, North Street, St Andrews, UK (mgfp@st-andrews.ac.uk), ²Centre for Planetary Science and Exploration, Dept. Earth Sciences, University of Western Ontario, London, Ontario, Canada, ³Department of Geography, University of Winnipeg, Winnipeg, Manitoba, Canada

Introduction: Jupiter's moon Europa hosts a liquid water ocean underneath a crust of water ice [1]. Non-icy material on the moon's surface has been hypothesised to originate from the underlying ocean, and thus record compositional information crucial to understanding European ocean chemistry and habitability [2]. Near-infrared spectral evidence suggests the presence of hydrated sulfate and chloride salts [2,3]. To date, insights have been provided by studying pure salts produced under controlled laboratory conditions. We investigated natural hydrated salts from cold hypersaline springs on Axel Heiberg Island (AHI), and characterized their reflectance properties at European surface temperatures. This approach enables the understanding of spectroscopic features in a natural geochemical and mineralogical context; aiding interpretation of future reflectance data from the European surface.

Field area: Axel Heiberg Island, Nunavut, Canada, hosts extensive evaporite diapirism. Associated with the diapirs is a series of anoxic, perennially cold (<0 °C) hypersaline springs, which precipitate large-scale salt 'aprons' of varying composition. Three springs were sampled in July 2017: Lost Hammer (LH), Stolz (STZ) and Colour Peak (CP). Detailed mineralogical and geochemical datasets are available for two of these (LH and CP) [4, 5], while STZ has not yet been formally described. At all springs, brines are dominated by sodium and chloride with significant concentrations of sulfate. Mineralogy includes gypsum and low-temperature calcite polymorphs at CP, and hydrated Na-sulfates and chlorides at STZ and LH. Mineral assemblages also contain minor detrital phases.

Spectral characteristics of natural salt assemblages: Visible-near-infrared (VNIR) spectra were acquired in the laboratory at three temperatures: 100 K, 253 K and 293 K (plotted in Fig. 1). The greatest spectral differences are observed between 293 K and 253 K, due to the loss of water at 293 K. STZ salts show low temperature spectral detail characteristic of hydrohalite; particularly in the ~1.5, ~1.8 and ~2.0 micron features. LH salts, which also contain hydrohalite, lack these features. It follows that a European ocean rich in sodium and chloride could form hydrohalite deposits on the surface, but not exhibit the diagnostic NIR signature observed in STZ salts. Additionally, despite containing mirabilite as a major phase, LH salts lack the spectral detail of pure mirabilite at cryogenic tem-

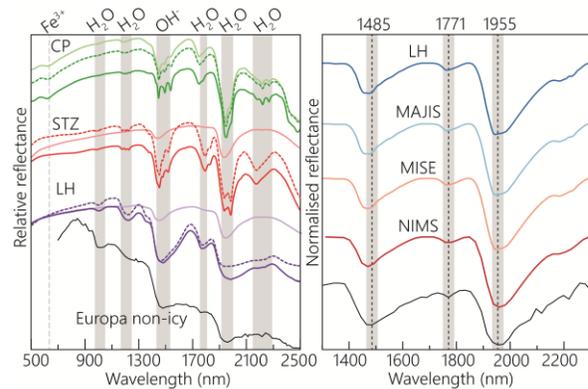


Fig. 1: Left: VNIR spectra of AHI salts, offset for clarity. Darkest lines were acquired at 100 K, dashed lines at 253 K, lightest at 293 K. Europa non-icy spectrum reproduced from [6]. Right: Continuum-removed LH spectrum, resampled to various instrument spectral resolutions. Dotted lines and gray shaded areas in right panel denote band minima and uncertainty for Europa non-icy example.

peratures. This 'smoothing' effect was achieved in previous linear mixing efforts by adding large relative abundances of sulfuric acid hydrate [7], which is not present in LH salts. At 100 K, LH spectra recreate the Galileo Near Infrared Mapping Spectrometer (NIMS) band minima for major absorptions (at NIMS spectral resolution), and approximate band asymmetry and breadth. Higher spectral resolution, such as provided by future spacecraft instruments MAJIS (JUICE; ESA) and MISE (Europa Clipper; NASA), will better represent natural mineral absorptions. Natural analogs such as these show how similar parent fluids can precipitate varied mineralogical end members. They provide natural comparisons to the numerical linear mixes presented in previous studies, and represent promising test material for the interpretation of mission data and development of future instrumentation.

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Survival, Genetic Modification, and Time-Resolved LASER-Induced Fluorescence Analysis of Bacteria Exposed to High-Dose Radiation Simulating EUROPA'S Surface. K. Ganguly¹, P. J. Gasda¹, C. Gleasner¹, C. Mensah¹, S. Adikari¹, H. Quinn¹, A. Watkins¹, S. P. Love¹, A. K. Misra², T. Acosta-Maeda², S. K. Sharma², R. C. Wiens¹, ¹Los Alamos National Laboratory, Los Alamos, NM, ²Hawai'i Institute for Geophysics and Planetology, Honolulu, HI.

Introduction: The search for life in Europa's oceans is a main goal of the proposed NASA Europa lander mission [1]. Materials from Europa's ocean may be brought to the surface at Europa's surface bands through tectonic-like processes [2], or by cryovolcanism [3]. Thus, with a lander it may be possible to sample material from the ocean, including biomaterials, if present. As surface material is subject to an extreme radiation environment, it is important to characterize radiation effects on cells and DNA and on spectral signatures of affected cells to calibrate proposed instruments for a Europa lander mission.

We are building OrganiCam, a prototype time-resolved laser-induced fluorescence instrument, designed to detect biological materials on Europa's surface [4] based on the BioFinder instrument, which can readily detect biological materials [5]. The instrument shines pulsed laser light on the ice to collect fluorescence image data with a fast-gated detector to determine bio-organic-rich areas for further analysis by lander instruments. The ns time resolution distinguished biological and organic fluorescence from that from minerals. Lab experiments with irradiated bacteria will help elucidate the spectral signatures of bacteria and the effects of radiation experienced on Europa.

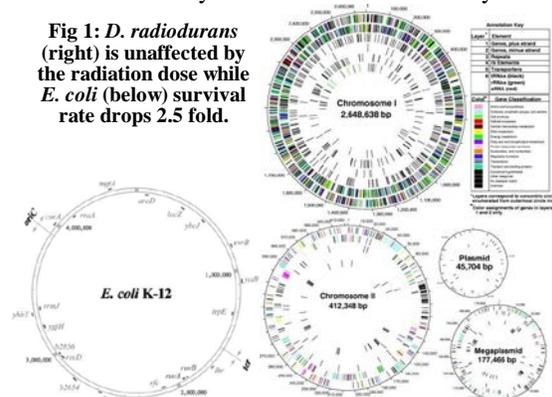
To understand the nature of radiation exposed prokaryotes or any bio-materials, we have exposed bacteria to gamma radiation. We have used two extreme varieties of prokaryotes, (i) radioresistant bacteria *D. radiodurans* and (ii) susceptible *E. coli*, to 2 and 20 Gy of gamma radiation to simulate exposure to the Europa surface and subsurface environment. We have produced survival curves for the bacteria at different exposure levels and isolated the DNA of the cells to perform deep sequencing of their genomes.

Methods: Radiation exposure Assay: Bacteria were exposed to 2 Gy (200R) and 20 Gy (2000R) by a Cs-137 γ source, JL Shepherd, Mark-1 irradiator. Exposure time: 46 s and 7 m 36 s respectively. **DNA double strand break Assay:** Cellular responses to double-strand breaks (DSB) is the phosphorylation of a histone variant, H2AX, at the sites of DNA damage. DSB assay was done with the OxiSelect™ DNA Double-Strand Break Staining Kit (CellBio Labs). **DNA deep sequencing:** gDNA were isolated from all the samples and deep sequencing was performed by Next-Gen Sequencing (NGS) at LANL Genome sequencing facility. DNA concentration was obtained using the Qubit DNA Assay Kit. Illumina libraries were prepared using NEBNext Ultra DNA II Library Prep Kit. The library mean size was determined by the Agilent

High Sensitivity DNA Kit. Library quantification determined using the Illumina/Universal Kit (KAPA Biosystems). Libraries were normalized to the same concentration based on the qPCR results. Libraries were sequenced on the Illumina NextSeq generating paired-end 151 bp reads. **Sequence Analysis:** Gene sequences are being analyzed by bio-informatics platform-EDGE (<https://bioedge.lanl.gov/>)

Results: Survival rate of *D. radiodurans* remains constant through the experiments. *E. coli*, survival rates drop to 83.3% with 2 Gy and then to 33.3% at 20 Gy.

Fig 1: *D. radiodurans* (right) is unaffected by the radiation dose while *E. coli* (below) survival rate drops 2.5 fold.



Discussion: *D. radiodurans* could be a good analog for life on Europa as any life on the surface would likely evolve to survive the radiation environment below a few cm of ice. The survivability of *D. radiodurans* during these experiments strongly suggests that biological life could survive on Europa and be sampled by a landed mission. Based on our results, we expect little change in the fluorescence signature of *D. radiodurans*, which suggests that detecting bacteria on Europa will be much the same as on Earth. Since OrganiCam is based on proven life-detecting technology [5], we can be more confident in detecting any life, if present, on Europa.

Future Work: Laser-induced fluorescence and Raman studies of the isolated DNA, intact cells, and dead cells, with and without staining exposed to ionizing and non-ionizing radiation are planned for these samples. Our time-resolved Raman microscope with similar capabilities as the OrganiCam instrument will be used to evaluate bacterial spectral signatures before and after radiation.

Acknowledgements: Funded by LANL Laboratory Directed Research and Development Exploratory Research

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PROCESSES AFFECTING THE COMPOSITION OF EUROPA'S SURFACE – AN OVERVIEW FROM LABORATORY DATA PERSPECTIVE. Murthy S. Gudipati, Science Division, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA (gudipati@jpl.nasa.gov)

Introduction: Europa's surface composition is a product of several parameters: from the rate of surface to subsurface exchange to the fluxes of photons, electrons, and ions reaching the surface of a particular geographical location. The same processes also dictate how Europa's exosphere is composed of (keeping aside the influx of exogenic materials). This contribution will summarize each of such processes and what would be the laboratory data requirements that would enable better understanding of these processes.

Chemical Composition of Europa's Surface: There is a large volume of data on the observational and laboratory modeling work on the non-ice composition of the trailing hemisphere. However, no unambiguous assignment or conclusion could yet be made. These materials could be salts such as NaCl and MgSO₄ (and their hydrates), and/or sulfuric acid hydrates (H₂SO₄ · xH₂O). Radiolysis products such as O₂, H₂O₂, and CO₂ are directly detected on Europa's surface. However, quantification of these products is still pending. Presence of organics has been inferred, but not unambiguously and positively identified.

Radiation Environment of Europa's Surface: So far the data that is available in the literature regarding Europa's near-surface radiation environment is from the Galileo mission, which is further approximated by models. Recently there is some debate on whether some of the electron, proton, and ion radiation reaching Europa's surface may be deflected away due to Europa's own magnetic field. Data from JUNO mission may give more insight into the overall radiation budget of Jupiter around Europa. Laboratory data at realistic Europa's surface radiation environment has just begun and all the previous models on surface radiation processing are driven by approximations and/or models based on other materials such as liquid water.

Near-Surface Exchange: In order to understand Europa's surface composition, we need to have a handle on near-surface geological processes on Europa. How material of about few meters (1 – 5 meters) on Europa's surface exchange.

Deep-Subsurface to Surface Exchange: Excluding plumes that could potentially connect liquid interior with surface and exosphere, other process that bring about the deep-subsurface and surface exchange contribute significantly to Europa's surface compositional diversity and material exchange highways that could potentially bring the surface radiolysis products

into the deep-subsurface and the salts from rock-water interaction on to the surface. However, our present understanding is very limited regarding the timescales and magnitudes of these process. We need to focus on what laboratory work is needed to have better constraints on the "surface to deep-subsurface highways".

Geographical and Geological Activities: Equatorial vs. high-latitude temperature gradients, surface geology, potentially shadowed regions, transport and recondensation of volatiles from warmer surface regions to the cooler regions, etc., also affect both surface and exosphere composition of Europa. These processes are also less understood and corresponding laboratory studies are not clearly identified. For example, could amorphous water-ice be used as a tracer of Europa's surface age and weathering? While some modeling and hypotheses are out there in the literature, convincing laboratory data is still missing.

This presentation will summarize and outline various processes that determine chemical compositional equilibrium on Europa's surface, which is in exchange with the interior and exosphere.

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). Funds were provided through NASA Emerging Worlds Program.

THE EUROPA LANDER MISSION CONCEPT AND SCIENCE GOALS OF THE 2016 EUROPA LANDER SCIENCE DEFINITION TEAM REPORT. K. P. Hand¹ (khand@jpl.nasa.gov), A. E. Murray², J. Garvin³, S. Horst⁴, W. Brinkerhoff³, K. Edgett⁵, T. Hoehler⁶, M. Russell¹, A. Rhoden⁷, R.A. Yingst⁸, C. German⁹, B. Schmidt¹⁰, C. Paranicas¹¹, D. Smith¹², P. Willis¹, A. Hayes¹³, B. Ehlmann^{1,14}, J. Lunine¹³, A. Templeton¹⁵, K. Nealon¹⁶, B. Christner¹⁷, M. Cable¹, K. Craft¹¹, R. Pappalardo¹, A. Hofmann¹, T. Nordheim¹, C. Phillips¹, ¹Jet Propulsion Laboratory, Caltech (khand@jpl.nasa.gov), ²Desert Research Institute & University of NV, Reno, ³Goddard Space Flight Center, ⁴Johns Hopkins University, ⁵Malin Space Science Systems, ⁶NASA Ames Research Center, ⁷Arizona State University, ⁸Planetary Science Institute, ⁹Woods Hole Oceanographic Institution, ¹⁰Georgia Tech., ¹¹Applied Physics Laboratory, Johns Hopkins, ¹²Massachusetts Institute of Technology, ¹³Cornell University, ¹⁴Caltech, ¹⁵CU Boulder, ¹⁶University of Southern California, ¹⁷University of Florida.

Introduction: In June of 2016 NASA convened a 21-person team of scientists to establish the science goals, objectives, investigations, measurement requirements, and model payload of a Europa lander mission concept. The Europa Lander Science Definition Team (SDT), following a charter from NASA HQ, refined these requirements into a viable Europa Lander mission concept, and published the Europa Lander Study 2016 report (Europa Lander, 2016). Since the completion of the SDT report, the Europa Lander mission concept team at JPL has refined the mission concept through a Mission Concept Review (MCR), and subsequently through the advice and oversight of an external advisory board. This board was active during the Summer and Fall of 2017, and a final report was presented to NASA HQ in the late Fall of 2017. The Europa Lander mission concept team is currently addressing guidance from NASA HQ in terms of technologies and mission architecture. The science of the mission concept has remained largely constant with respect to the 2016 SDT Report.

Europa Lander SDT Science Goals

The NASA HQ Europa Lander SDT Charter goals, in priority order, were as follows:

1. Search for evidence of life on Europa.
2. Assess the habitability of Europa via in situ techniques uniquely available to a lander mission.
3. Characterize surface and subsurface properties at the scale of the lander to support future exploration of Europa.

Within Goal 1, the SDT developed four Objectives for seeking signs of life (i.e., biosignatures). These include the need to: a) detect and characterize any organic indicators of past or present life, b) identify and characterize morphological, textural, and other indicators of life, c) detect and characterize any inorganic indicators of past or present life, and d) determine the provenance of Lander-sampled material. Within the Goal 1 investigations and measurement requirements there are more than seven distinct and complementary approaches for detecting potential

biosignatures within material sampled from Europa's surface and near-subsurface.

Goal 2 focuses on Europa's habitability and ensures that even in the absence of the detection of any potential biosignatures, significant ocean world science is still achieved. The objectives within Goal 2 are to: a) characterize the non-ice composition of Europa's near-surface material and determine whether there are indicators of chemical disequilibria, and b) determine the proximity to liquid water and recently erupted materials at the lander's location.

Goal 3 ensures that the landing site region is quantitatively characterized in the context needed for Goals 1 and 2, and that key measurements about Europa's ice shell are made to enable future exploration. The objectives for Goal 3 include the need to: a) observe the properties of surface materials and sub-meter-scale landing hazards at the landing site, including the sampled area (connecting local properties with those seen from precursor Europa flyby remote sensing), and b) characterize dynamic processes on Europa's surface and ice shell over the mission duration to understand exogenous and endogenous effects on the physiochemical properties of surface and shallow sub-surface materials.

The Europa Lander mission concept is capable of achieving a suite of measurements such that if potential biosignatures are present on Europa's surface they could be detected at levels comparable to those found in benchmark environments on Earth, and, further, that even if no potential biosignatures are detected, the science return of the mission will significantly advance our fundamental understanding of Europa's chemistry, geology, geophysics, and habitability.

References:

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<https://europa.nasa.gov/resources/58/europa-lander-study-2016-report/>

CHLORINE SALTS ON EUROPA FROM EXPERIMENTAL DATA AND RECENT TELESCOPIC OBSERVATIONS. J. Hanley¹, T. Becker², K. Retherford², W. Grundy¹, T. Greathouse², C. Tsang³, L. Roth⁴. ¹Lowell Observatory, Flagstaff, AZ, ²Southwest Research Institute, San Antonio, TX, ³Southwest Research Institute, Boulder, CO, ⁴KTH Royal Institute of Technology, Stockholm, Sweden; jhanley@lowell.edu.

Introduction: If found on the surface of Europa, chlorine salts would serve as a window to the interior, and support the existence of a liquid ocean beneath the icy crust. Chlorine salts lower the freezing point of water, allowing it to be liquid down to ~204 K [1].

If there is chlorine in the system, as models predict [2], chloride salts would be likely to form. Chlorides and (per)chlorates may also be produced by radiolysis of Iogenic Na, Mg and Cl. Recent studies have suggested that magnesium is originally brought to the surface as magnesium chloride [3].

Laboratory Experiments: Reference spectra of surface materials at relevant temperatures are critical for deriving abundance estimates through spectral modeling. Therefore, we measured the spectra of various chlorine-salt hydrates at 296 and 80 K, from 0.5-2.5 μm , and from 2.5-20 μm at 296 K [4, 5]. Our study alleviates the lack of data in current spectral libraries for hydrates that exist on Europa and other planetary surfaces. We suggest that it may be possible to identify chlorine salts on the surface of Europa, given the similarities of hydrated chlorine spectra to ice and other hydrated salts, such as sulfates.

We show that hydrated MgCl_2 salts exhibit many diagnostic features, especially at low temperature (Fig. 1), that aid in their detection. (Per)chlorate salts' spectra behave similarly: the main features in the NIR are due to water of hydration, and at low temps they become narrower and more well-defined [4].

Additionally, when mixed with water at eutectic concentrations, chloride salts do not significantly alter the main spectral bands seen in pure water ice [4], even though they form a hydrated phase; however, the bands do appear broader than for those of pure water ice. When comparing to the Galileo NIMS spectrum of the "dark material," the general shape is similar: most of the spectral structure arises from the water molecules, whether as ice or hydrates. Though weaker than the main H_2O bands, fine structure is apparent in the NaCl and MgCl_2 brine spectra, which could prove diagnostic.

Telescopic Observations: We obtained mid-IR spectra of Europa's leading and trailing hemispheres with the NASA IRTF/TEXES instrument. The observations span from ~10-11 μm with a resolving power of $R \sim 2500$. Few observations of Europa have been made at these wavelengths, and the high spectral resolution of the instrument enables the identification of distinguishing spectral features in this relatively unexplored bandpass. We compare the spectra from the

trailing hemisphere with those from the leading, pure-ice hemisphere and with recent laboratory measurements of chlorinated salts, which have distinct spectral signatures at these wavelengths. We find that the signal obtained from Europa's leading hemisphere is 5-10 times lower than the signal obtained from the trailing hemisphere, likely due to a temperature difference between the hemispheres. We discern several spectral features that are present in the trailing hemisphere but not in the spectra of the leading hemisphere, though the explanation for these features is not yet apparent [6].

Additionally, Ligier et al. [7] observed Europa with VLT/SINFONI and utilized our NIR laboratory spectra [4] to find that Mg-bearing chlorinated species provide better spectral fits than sulfates. "The derived global distribution of Mg-chlorinated salts (and particularly chloride) is correlated with large-scale geomorphologic units such as chaos and darker areas, thus suggesting an endogenous origin" [7].

We plan to observe Europa with Lowell's Discovery Channel Telescope and the IGRINS instrument, which is a cross-dispersed near-IR spectrograph with a resolving power $R \sim 45,000$ [8]. It can observe from 1.45-2.5 μm in a single exposure. We have several evenings in September where we hope to be able to study longitudinal variations of these salts.

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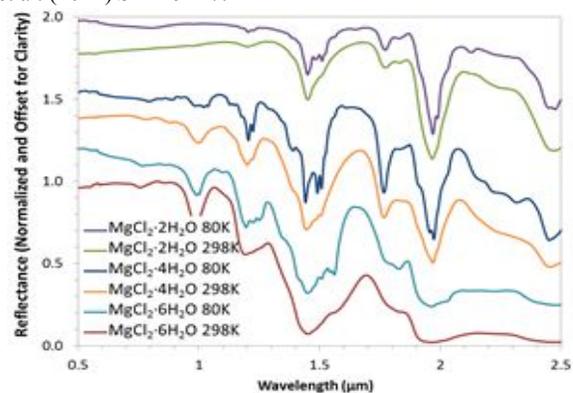


Figure 1. NIR reflectance spectra of various hydrates of MgCl_2 at 296 K and 80 K [4]. Note how spectral features become more enhanced at low temperature.

TOWARDS A BETTER UNDERSTANDING OF COMPOSITION: STATUS UPDATE ON LABORATORY STUDIES OF EUROPA ENVIRONMENT ANALOGS. B. L. Henderson, Jet Propulsion Laboratory, Caltech Institute of Technology, Pasadena, CA (Bryana.L.Henderson@jpl.nasa.gov)

Introduction: The surface of Europa, which contains both water-ice and other non-ice materials such as sulfate hydrates, is affected by both exogenic and endogenic mechanisms that have not yet been fully constrained. Over the past several decades, significant efforts have been put forth to better understand Europa's surface composition and morphology and the processes that have affected (and continue to affect) these properties.

Both physical (geologic resurfacing, ocean-surface mixing, ejection of plume material, micrometeoroid gardening) and chemical (impact-induced chemistry, thermal processing) processes can affect the observed local composition. But some of the most significant chemical changes on Europa's surface are induced by the high levels of radiation that bombards Europa's surface in the form of energetic electrons, protons, and heavy ions. This radiation can sputter surface species, and (depending on the energy of the incident particle) can affect the composition of surface and subsurface materials down to depths of tens of centimeters or more.[1,2]

Validation of laboratory studies with observational data has so far relied on spectra from ground and space-based probes such as Galileo.[3-5] While some matches of laboratory spectra to observational spectra have been made, this effort has been complicated by the fact that spectral features in the condensed state are typically broad and somewhat ambiguous. To complicate matters further, spectral signatures are affected by dehydration of hydrated minerals and textural changes such as amorphization in ice structures or mineral degradation. Even the distribution of physical grain sizes of surface materials (which are modified by radiation exposure and other processes) can markedly affect spectral signatures.[6]

Value of laboratory analog experiments: In addition to collecting spectra of candidate materials, laboratory experiments can also be used to track chemical *processes* and how these affect surface composition. For example, laboratory studies tracking effects of radiation (noting key radiation products and structural changes in the sample) can be used predictively to estimate plausible surface compositions and to search for specific spectral features. Detection of certain "indicator species" (c.f. H₂SO₄, which is very stable to radiation; or H₂S, which is very unstable [7]) can trace the history of an ice sample and its chemical "maturity" in a given environment.

This laboratory data can be interpreted in relation to data from remote sensing observations to obtain a more complete understanding of surface processes on Europa. By cataloging the effects of these processes, we may be able to distinguish between a composition that is purely the result of normal exogenic surfaces (i.e. an old surface that has reached radiolytic equilibrium) or whether it is the result of new material being freshly deposited in an endogenic process. Organics, too, tend to degrade toward a radiolytic equilibrium composition. Knowledge of how this chemistry evolves on Europa could enable us to pinpoint atypical combinations of surface species in future measurements and mark them for further study.

In this review, I will address the current state of laboratory experiments for Europa-relevant analogs and explore areas of study that would benefit from further experimentation.

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Laboratory Spectral Measurements Needed to Better Model Europa's Surface Composition. C. A. Hibbitts
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Introduction: The composition of planetary surfaces including the ocean worlds of Europa and Ceres provide insight into both endogenic and exogenous processes that have shaped them. The surface compositions can provide insights into their geologic activities and extent of subsurface evolution. For Europa, surface composition can provide insight into the habitability of the subsurface. The relatively dark 'nonice' material is a heavily hydrated material, but not water ice, and likely a combination of multiple materials including frozen brines [1,2,3]; hydrated sulfuric acid [4] and possibly chlorides or chlorates [5,6]. The relative proportions of these components in the nonice material vary spatially over Europa's surface, especially between the leading and trailing hemispheres [7,8,9,10,11,12]. Post Galileo mission, telescopic observations have subsequently refined the identity of additional components in this nonice material. A new absorption feature near 2050 nm in hyperspectral ground-based spectra of Europa primarily associated with the trailing hemisphere is ascribed to $MgSO_4$ [3].

Optical signatures are however affected by exogenous processes such as micrometeoroid, ultraviolet, and energetic particle bombardment that can degrade, modify, or induce signatures and may or not affect the bulk composition. Accurate inference of composition of surfaces that have been thus weathered must therefore consider these processes. Laboratory measurements quantifying these effects on analog materials that are to be used in spectral matching and compositional modeling are therefore needed.

Discussion: Irradiation by planetary magnetospheres and solar wind affect the spectra of these surfaces that are not protected by an atmosphere, and whose magnetic field lines, where they exist, cannot stand off the most energetic particles. *As for the Moon, where space-weathering processes must be accounted for when inferring mineralogy from reflectance measurements, the inferred composition of the surfaces of airless ocean worlds need to account for bombardment by high energy particles – especially high energy ion and electrons for Europa.* For instance, it has been proposed that particulate irradiation of the surface of Europa is responsible for its coloration [13,14].

Measurements Needed: Particulate radiation sufficiently energetic to affect the UV – Mid-IR (~10um) spectral region. This is the regions of electronic and vibrational transitions. This requires keV elec-

trons and moderately high keV protons to penetrate sufficiently to affect that portion of the spectrum (Figure 1). Additionally, sufficient fluence of the appropriate ion species need to be used to ensure the measurements made of any resulting changes can be appropriately ascribed to the correct chemical pathways.

Spectral measurements of any salt, brine, chlorate, chloride, organic or any other material analogous to Europa's surface need to be conducted at UHV, at temperature ($< \sim 130K$), ideally encompass the full ~100 nm to 5000 nm range of the spectrometers on Europa Clipper, and especially account for the particulate radiation that has certainly processed the optical surface. In addition to electrons, mass selected protons and sulfur ions are required. Particle fluences on the order of microamps are required to ensure simulating Europa surface exposure ages of even thousands of years.

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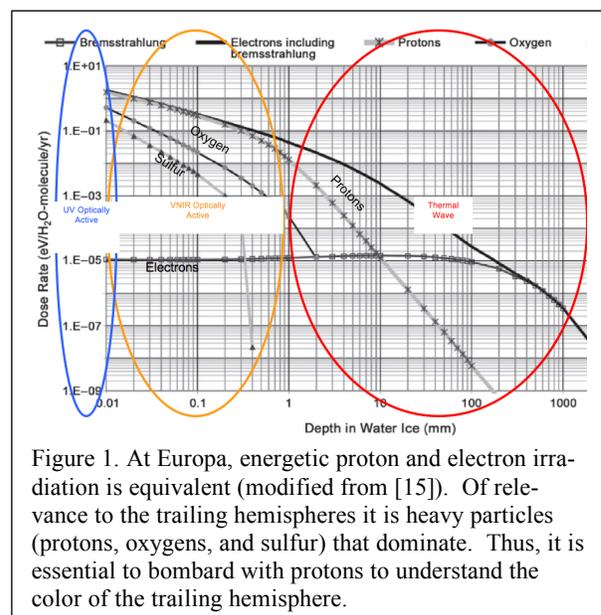


Figure 1. At Europa, energetic proton and electron irradiation is equivalent (modified from [15]). Of relevance to the trailing hemispheres it is heavy particles (protons, oxygens, and sulfur) that dominate. Thus, it is essential to bombard with protons to understand the color of the trailing hemisphere.

IMPURITIES IN EUROPA'S ICE SHELL: SALTY TREE-RINGS? S. M. Howell¹ and E. J. Leonard^{1,2}, ¹Jet Propulsion Laboratory, California Institute of Technology (samuel.m.howell@jpl.nasa.gov), ²UCLA.

Introduction: The surface of Europa records a storied history of tectonic deformation, including the exposure of new interior material at extensional bands and removal of surface material to the interior at inferred subsumption zones^{1,2}. These geologic processes are critical for transporting material through the brittle ice shell exterior^{2,3} and understanding the redox state and astrobiological potential of the interior ocean⁴. Some tectonic features are associated with the exposure of more non-ice materials than their surroundings⁵, indicating spatial or temporal variations in the distribution of impurities within the ice shell.

To explain these variations, we look to changes in ice shell thickness, which induces large stresses at low strains and has been predicted to drive tectonic activity^{2,6}, and the accretion of ocean ice to the base of the shell. The amount of non-ice material incorporated into the ice from the ocean depends to first-order on how quickly the ocean freezes⁷. Therefore, the distribution of non-ice materials may reflect the geologic evolution of the ice shell, and tectonic features may sample compositional variations or contribute to them.

We use cutting-edge computer simulations of ice shell evolution², including a mock interior ocean, to create cross-sectional maps of historical freezing rate at the time of ice incorporation to the shell. Using freezing rate as an analog for non-ice incorporation, we infer the distribution of non-ice impurities within the ice shell.

Methods: We use the finite element code SiStER (Simple Stokes solver with Exotic Rheologies)^{2,8}, extended to simulate the visco-elasto-plastic behavior of ice I above a simulated ocean [Fig. 1]. We include partial melting and freezing⁹ that affects the density and mechanical behavior of particles within the finite difference mesh. For particles transitioning from the ocean to the ice shell, we record the maximum freezing rate ever experienced as an indicator of potential impurity incorporation. Models include internal tidal heat generation and basal silicate heat flux to the ocean.

Ice Shell Evolution: We investigate 3 scenarios:

Freeze-in. An ice shell freezes in from an ocean exposed to space. In this case, we predict an impurity-rich layer a few kms thick at the surface, and a gradational decrease in non-ice abundance with depth.

Thaw-out. An initial 130 km thick shell thins. While the lithosphere retains its primitive composition, a convecting interior may permanently incorporate ocean material at moderate freezing rates.

Variable thickness. A frozen-in ice shell thickens in response to a decrease in heating. In this case, multiple non-ice horizons are recorded within the ice shell.

Tectonic Activity: We also investigate the lateral variations in composition due to extension and compression. A frozen-in ice shell will exhibit extensional bands with lower non-ice abundances. A thawed-out shell will exhibit bands with moderate non-ice abundances. A layered shell may exhibit lateral horizons in non-ice abundances. Compression tends to thicken the lithosphere, and will result in locally thicker impurity layers for a frozen-in shell.

Conclusions: We map spatial and temporal changes in the freezing rate of ocean water at the time of incorporation into Europa's ice shell. As tree rings provide an insight into the seasonal environment at the time of wood growth, we interpret these predictions of inferred global brine horizons to reflect the accretion history of incorporated ice. Non-ice distributions may record geologic history and interior heat flux, and might constrain whether the ice shell interior is convecting. Laboratory experiments quantifying the fractionation of expected non-ice materials as a function of freezing rate, within the range predicted by this study, will enable direct predictions of variations in ice shell composition on the surface and with depth.

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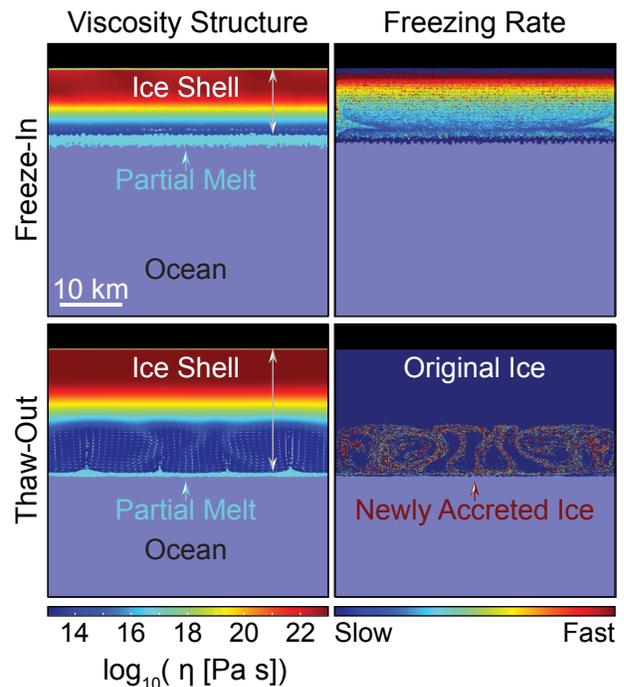


Figure 1: 2-D model predictions of (left) viscosity structure and (right) freezing rate at the time of incorporation into the ice shell for a case in which the ice shell froze in from 500 m initial thickness (top) and a case where the ice shell thawed out from 130 km initial thickness (bottom). Rates vary from 1% to 10% change in melt content per thousand years.

DIVING DEEP INTO EUROPA'S REACTION CHEMISTRY. Reggie L. Hudson¹, ¹Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771 USA .

Introduction: Since 1998, our group at the NASA Goddard Space Flight Center has carried out laboratory experiments to explore chemical changes that can occur on icy satellites such as Europa. This "Deep Dive 2" presentation will cover some of the thermally driven and radiation-induced changes expected from icy materials, primarily covalent and ionic compounds. Low-temperature conversions of a few relatively simple molecules into ions possessing distinct infrared features will be examined, with an emphasis on those that might be observed and assigned by either orbiting spacecraft or landers. The low-temperature degradation of a few bioorganic molecules, such as DNA nucleobases and some common amino acids, will serve as examples of the more complex, and potentially misleading, chemistry expected for icy moons. -- Our work has been supported by NASA's Emerging Worlds and Outer Planets Research programs, as well as the NASA Astrobiology Institute's Goddard Center for Astrobiology.

Plasma and Thermal Processing of Europa's Surface

R.E. Johnson¹, A. Oza², C. Schmidt³, F. Leblanc⁴

¹University of Virginia, ²Universität Bern, ³Boston University, ⁴University of Paris

The effects of the intense plasma and thermal processing on the surface of Europa will be briefly reviewed as it relates to potential surface/ocean coupling. Attention will be paid to the chemical processing such as production of oxygen (e.g., Teolis et al. 2017; Spencer & Calvin 2002), the ejection of Na and K (Brown et al. 2001; Leblanc et al. 2002), and the sulfur and carbon cycles (Carlson et al. 2009). The possible ejection by the heavy energetic ions of large molecules (Johnson & Sundqvist 2018) that might be suggestive of biologic activity in Europa's ocean will also be briefly reviewed. Both plasma and thermal processes affect the production of the near-surface ambient gas and plasma that have been observed, both remotely and in situ, and might eventually be directly measured by instruments on the Europa Clipper. Although ambient gas-phase O₂ observed is produced by the plasma decomposition of its icy surface, it has been suggested that the near-surface O₂ might be dominated by thermal desorption (Oza et al. 2018; Johnson et al. 2018) and the observed O₂ trapped in bubbles appears to be highly variable (Spencer & Grundy 2018). This would suggest, not surprisingly, that plasma and thermal processing are in some sense symbiotic, which is likely also the case for observed grain sizes (Cassidy et al 2013; Schaible et al. 2016) that affect the thermal inertia and the interpretation of remote sensing data (e.g., Trumbo et al. 2017)

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INVESTIGATING THE SURFACE COMPOSITION OF EUROPA WITH THE EUROPA CLIPPER. R. L. Klima¹, J. Soderblom², M. Gudipati³ and the Europa Clipper Composition Working Group. ¹Johns Hopkins University Applied Physics Laboratory, Laurel, MD (Rachel.Klima@jhuapl.edu); ²Massachusetts Institute of Technology, Cambridge, MA; ³Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

Introduction: The composition of the ice and non-ice materials on Europa's surface provides important clues for understanding habitability. A portion of the non-ice surficial material may be sourced from below the ice shell, suggesting communication between an internal ocean and the surface, but much of it may also be exogenic, accumulated on top of the icy shell [1,2]. Previous missions, including Voyager and Galileo, have provided tantalizing clues about the composition and origin of the distinctive surface materials, but many questions remain, including: (1) What is(are) the specific composition(s) of the non-ice material(s) on Europa's surface? (2) What role does Europa's radiation and plasma environment play in processing this material? (3) What are the compositional and chemical pathways in the ocean? The Europa Clipper mission will investigate these questions with a robust suite of instruments, providing answers that will aid in constraining the habitability of Europa's ocean through composition and chemistry.

The Europa Clipper: The overarching science goal of the Europa Clipper mission is to investigate Europa's habitability with the following specific science objectives: (1) Ice Shell & Ocean: Characterize the ice shell and any subsurface water, including their heterogeneity, constrain ocean properties, and the nature of surface-ice-ocean exchange; (2) Composition: Understand the habitability of Europa's ocean through composition and chemistry; (3) Geology: Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest locales, including any plumes or thermal anomalies. NASA has selected a highly capable instrument suite for this mission, including those that will directly sample fields and particles around Europa and those that will globally characterize the surface and near subsurface through remote sensing, covering wavelengths from ultraviolet through radar. These instruments include: (1) Europa Ultraviolet Spectrograph (Europa-UVS); (2) Europa Imaging System (EIS); (3) Mapping Imaging Spectrometer for Europa (MISE); (4) Europa Thermal Imaging System (E-THEMIS); (5) Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON); (6) Interior Characterization of Europa using Magnetometry (ICEMAG); (7) Plasma Instrument for Magnetic Sounding (PIMS); (8) MAss Spectrometer for Planetary EXploration (MASPEX); and (9) SURface Dust Analyzer (SUDA). Gravity science will be in-

vestigated via the spacecraft telecom system combined with REASON altimetry, while a planned radiation monitoring system will provide valuable scientific data about the environment around Europa.

Composition Investigations: Though all of the Europa Clipper investigations provide critical input for understanding the composition of Europa, MISE, Europa-UVS, MASPEX, and SUDA are explicitly designed to investigate the mineralogical and chemical composition of the surface and/or exosphere, providing key constraints on the origin of surface materials. Coupled with high-resolution EIS panchromatic and color observations, data from these instruments may be traced back to specific surface regions, and in some cases specific landforms, to understand the relative contributions of endo- and exogenic material to Europa's surface composition.

Among the data sets that will be collected by Europa Clipper are MISE global (<10 km) and regional (<500 m) scale hyperspectral image cubes. These data will reveal infrared absorption features due to hydrated salts, any organics, water ice in various phases, and radiolytic products, providing the necessary data to resolve many ambiguities in previous compositional analyses [e.g., 1]. UV observations, which were reported by [2,3] as being effective in highlighting exogenic material on the surface, will be collected at both global and regional scales by Europa-UVS. These observations will provide further constraints on the relative contributions of exo- and endogenic material. SUDA will determine the composition of particles ejected from the surface due to sputtering, tracking the trajectories of these particles to their origin on the surface, as well as distinguishing and characterizing incident exogenic dust. MASPEX will measure neutral gas composition in the exosphere, including potentially exchanged ocean-surface material, determining ocean salinity in correlated measurements with SUDA. We will present an overview of these and other synergistic compositional investigations that will be performed by the Europa Clipper mission.

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NEW CONSTRAINTS ON THE ABUNDANCES OF SULFUR AND CHLORINE AT EUROPA. M. A. McGrath¹ W. B. Sparks¹, and J. R. Spencer², ¹SETI Institute (189 Bernardo Ave., Mountain View, CA 94043, mmcgrath@seti.org and wsparks@seti.org), ²Southwest Research Institute (1050 Walnut St., Boulder, CO 80302 spencer@boulder.swri.edu).

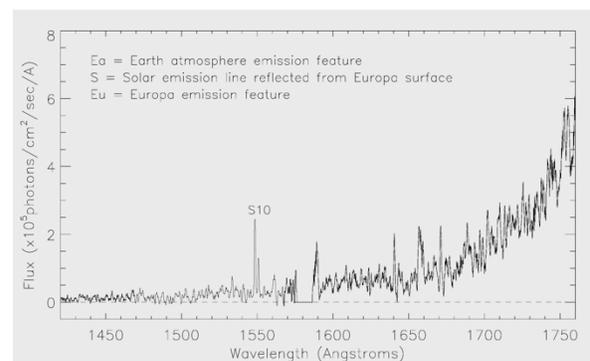
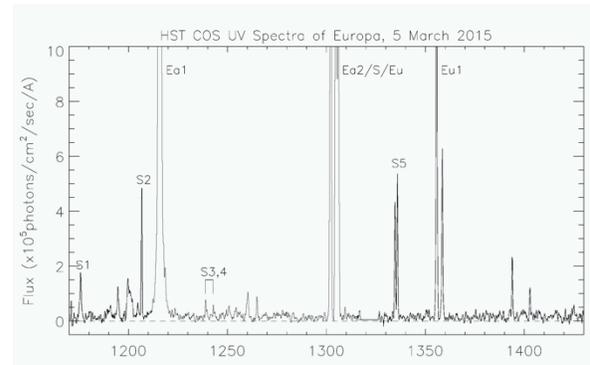
Introduction: Because Europa's atmosphere is thought to be generated primarily via charged particle sputtering of its surface, the composition of its atmosphere is therefore a proxy for its surface, and possibly subsurface, composition [1]. Furthermore, if active plumes are present, the composition of the atmosphere may also reflect the composition of Europa's subsurface water reservoir. It has long been thought that Europa's trailing hemisphere is dark at visible wavelengths due to implantation of sulfur ions transported from volcanically active Io [2]. Additionally, chlorine is predicted to be a major constituent of Europa's ocean [3], and Na and K chlorides are expected to be major constituents of the icy shell [4], [5]. Galileo plasma measurements have detected chlorine ions near Europa [6]. Thus both sulfur and chlorine are strongly suspected to be present on the surface, and therefore also present in Europa's atmosphere.

New Observations: In March 2015 we obtained 5 orbits of deep UV spectroscopy of Europa using the Hubble Space Telescope Cosmic Origins Spectrograph covering the wavelength range 1170–1760 Å. The goal of these observations was to search for several well-known emissions from sulfur and chlorine multiplets that occur in this wavelength range, as well as any other trace species that might be present. Figure 1 (right) shows the spectrum obtained. The strongest features in the spectrum are due to emissions from the Earth's atmosphere, and strong solar emission features reflected from the surface of Europa.

Results: The only emission features from Europa's atmosphere are the previously detected oxygen lines at 1304 and 1356 Å [refs.] Although none of the targeted emission multiplets were detected, the upper limits provided by these observations place useful new constraints on the surface composition of Europa. Details on the search for the sulfur and chlorine emissions, and the upper limits determined, as well as the implications of these upper limits will be provided in our presentation.

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MELT PRODUCTION, ERUPTION AND DEGASSING FROM EUROPA'S INTERIOR: EFFECTS ON COMPOSITION OVER TIME. M. Melwani Daswani¹ and S. D. Vance¹, ¹Jet Propulsion Laboratory, California Institute of Technology (mohit.melwani.daswani@jpl.nasa.gov).

Introduction: Europa's compositional evolution in time is not well constrained. Direct observations only provide approximations of the current interior structure of Europa. However, dynamic models [e.g., 1] resolve the magnitude of interior heating produced by tidal interaction over time. We couple the heat production to thermodynamic and chemical equilibrium models *Perple_X* [2], *Rcrust* [3] and *CHIM-XPT* [4] to compute compositional changes of the interior and ocean for a model Europa.

Initial composition: Assuming that neither the mantle nor core of Europa is currently molten, a Fe core could have accommodated up to 24 wt. % S during accretion, assuming chondritic (CV, CM and CI) accretion material. However, a metal-silicate segregated magma ocean was needed to allow such high S content in the core. More likely, accretion proceeded with low impact rates that allowed heat dissipation [e.g., 5]. Based on this, and experimental metal-silicate partition behavior [e.g., 6], we calculate that Europa's core contains ~1 wt. % S.

Silicate melting events: We calculated two mantle melting events corresponding to putative events in Europa's thermal-orbital evolution: a first event that melted up to 30 vol. % of the volatile-rich silicate shell, at pressures of 2.5 – 1.2 GPa \geq 4 Ga ago, and a possible melting event ~1.3 Ga ago resulting from increased dissipation as the mantle's rigidity increased [1]. Characteristic silicate melt intrusive to extrusive ratios (I/E) for Europa are unknown, but eruption to the ocean-rock interface would have been hindered by high minimum stress needed to cause fracture propagation and melt migration at depth [7]. Assuming I/E = 10, <7 wt. % melt would have erupted (Fig. 1). Even if lava erupted during the first event, limited heat transfer from, and dehydration of, the mantle may not have prevented the second event from occurring.

Considering Europa's volcanism enables us to predict the minerals likely to have influenced the ocean's composition and the mineralogy of concurrent water-rock activity. Erupted lava reacting with the ocean results in water-to-rock ratio dependent proportions of sulfides, saponite, chlorite and carbonates. We will describe implications for the ocean's composition and habitability.

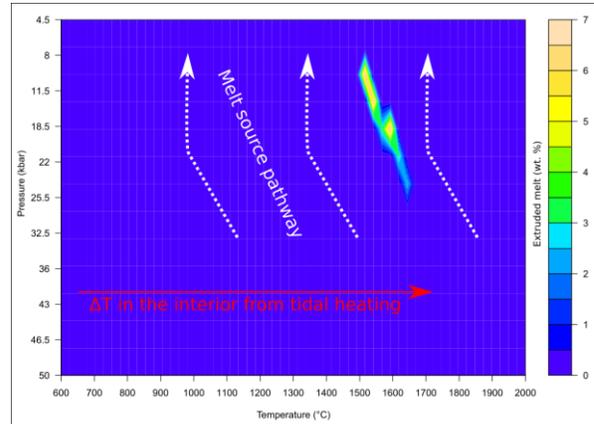


Figure 1. Melt production and migration from the melt source regions within Europa's silicate interior, for an I/E ratio = 10, and CI chondrite initial composition.

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INVESTIGATING DETECTABILITY OF ORGANICS ON EUROPA'S SURFACE. Ishan Mishra^{1,2} and Jonathan Lunine^{1,2}, ¹Department of Astronomy, Cornell University and ²Carl Sagan Institute.

Introduction:

Galileo NIMS near-infrared spectra of Europa have been used in previous studies to estimate the surface composition of the icy moon^{1,2}. Mixtures of sulfuric acid hydrates and hydrated salts along with amorphous water ice produce good matches to the spectra. The chemical composition is of interest because these materials are likely to have originated within Europa's interior and emplaced on the surface through vertical movement of warm ice or fluids that may have been in contact with the interior ocean³. From an astrobiological stand point, detection of organics on the surface, especially amino acids, will bolster the case for potential habitability of the subsurface ocean⁴. This project investigates detection of such species in light of the upcoming Europa Clipper mission that will carry the Mapping and Imaging Spectrometer for Europa or MISE. We are generating model spectra of intimate mixtures on the surface of Europa that would potentially provide benchmarks for what this instrument can detect.

Intimate mixture model: We have started with a simple, one-dimensional geometrical-optics model for spectral albedo of powdered surfaces developed by Shkuratov et. al.⁵ The model gives an equation for reflectance of a particulate surface given the optical constants (n , k), the diameter of an average particle and the porosity. It also presents a model for mixture of coarse particles, which has been used in this work. Another useful aspect of this model is that its invertible, i.e., we can get the extinction coefficient/imaginary part of the complex index of refraction (k) of any material if we have its reflectance spectra and know its average particle size.

Current Results: The water ice optical constants comes from the work done by Mastrapa et. al.⁶ Sulfuric acid octahydrate (SAO) optical constants at 77K were obtained through personal communication with the lead author of reference 2. We were not able to find optical constants of amino acids, so the current work uses reflectance spectra from the USGS Spectral Library⁷, and the invertible feature of the Shkuratov model, as mentioned above. Two example cases:

1. *Water Ice and Alanine:* At 5% concentration and below of Alanine the resultant spectrum is almost indistinguishable from pure water ice spectrum (Fig 1.a.)

2. *Water Ice, SAO and Alanine:* For similar concentration of alanine, around 5%, the reflectance values are higher for the three component mixture compared to the pure water ice spectrum. (Fig. 1.b.)

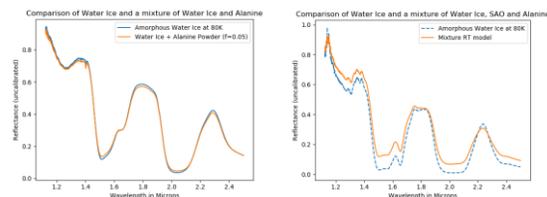


Fig 1. a) *Water Ice + Alanine* b) *Water Ice + Alanine + Sulfuric Acid Octahydrate*

Ongoing and future work: A limitation of the Shkuratov model is that all angle dependence of reflectance is ignored, so the model is not appropriate for analysis of planetary spacecraft data. Hence, currently we are working on implementing the more popular Hapke model⁸, fine-tuned to conditions on Europa's surface. Another reason to move on from Shkuratov is that we encounter numerical errors due to very high values of k for water ice around the 3 micron absorption band. The 3-5 microns spectral region is uniquely valuable for characterizing organics.⁹ We might also need to consider thermal emission, which becomes important at these longer wavelengths. Radiolytic processing of organics and its effect on the spectra also needs to be explored. Other radiolytic products like H_2O_2 , CO_2 and SO_2 can also be included in the mixture.

The biggest limitation to our preliminary work, however, has been the lack of quality laboratory data of optical constants of the end members, especially the organics, at the appropriate cryogenic temperatures. There is a similar dearth of reflectance spectra in online databases, surprisingly of water ice. The available spectra are mostly not well characterized in terms of the particle grain size distribution, temperature of the sample, etc.

Our work points out the need for additional laboratory work tuned to Europa conditions so as to maximize the utility of space and ground based spectra of this intriguing ocean world.

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RIFTING, CONVECTION, AND THE ELEVATION OF BANDS ON EUROPA. L. G. J. Montesi¹, S. M. Howell² and R. T. Pappalardo², ¹Department of Geology, University of Maryland, College Park (montesi@umd.edu) ²Jet Propulsion Laboratory, California Institute of Technology (Samuel.M.Howell@jpl.nasa.gov).

Introduction: The outer ice shell of Europa displays clear evidence for tectonic extension along tabular “bands” [Figure 1]. The margins of some bands and surrounding terrains align closely if the band itself is removed [1-3], and morphologies of the terrain inside these bands bear similarities to terrestrial mid-ocean ridges (MORs) [4]. Whether extension is passive (rift driven by plate divergence) or active (ascent of a buoyant diapir), interior ice must ascend to replace the pre-existing ice that is moving away. As warm, interior ice rises, it carries heat, thinning the overlying ice compared to the surrounding regions.

Model setup: We present here semi-analytical models of the thermal structure of passively upwelling warm ice, and we discuss the effect of upwelling velocity on ice shell thickness and topography [Figure 2]. We solve for the 1-D heat equation, including contributions from conduction, heat generation by tidal dissipation, and upward advection. Further, we manipulate scaling relations from [5] to solve for the thickness and interior temperature of a proposed layer of convecting ice beneath the conductive layer. Thermal conductivity, viscosity, and therefore tidal heat generation depend on temperature. By matching heat flux and temperature between conductive and convecting ice (assuming a viscosity contrast between the interior and the top of the convecting ice of $e^{2.23}$ [6]), we construct a temperature profile through the entire ice shell and solve for the shell thickness. Importantly, water that crystallizes at the base of the ice shell to replace the upwelling ice releases heat, so that the heat flux at the base of the shell increases when there is upwelling.

Models without convection: In the absence of convection, the upwelling due to rifting always thins the ice shell compared to neighboring ice, predicting a lower elevation inside the band than outside. Because bands stand ~ 100 m higher than their surroundings [4, 7], the ice outside the band must be denser than the freshly crystallized ice inside the band, possibly due to non-ice impurities. The band, if currently active, can open no faster than 10^{-10} m/s (~ 3 mm/yr) or the impure ice would have to be denser than water [8].

Models with convection: Models with convection exhibit a more complex behavior. For very low basal heat fluxes, the ice is conductive. For higher basal heat fluxes, convection sets in and leads to a thicker ice shell. However, if the basal heat flux is increased further, the thicknesses of both the convective and conductive shell layers decrease, until the convection cell is too thin and

the Rayleigh number, which depends on the cube of thickness, become subcritical. When convection stops due to high basal heat flow, the ice shell thickness increases, making it possible to produce a band. Surprisingly, it is possible for the increase in heat flux associated with band upwelling to shut down convection, thicken the ice locally, and produce bands that could stand a few hundred meters above their surroundings without requiring compositional variations. While unusual, this situation is predicted in our reference model.

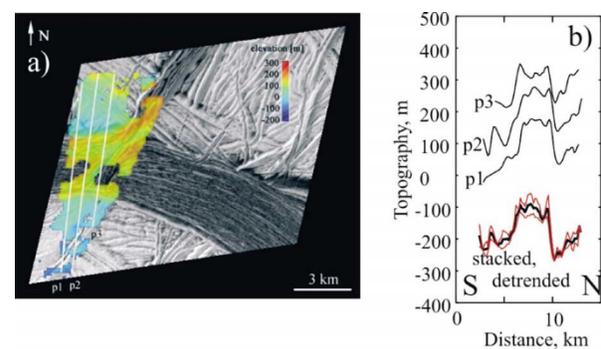


Figure 1: From [7], a) Galileo image centered at 18°S, 163°E, of a dark band, with topography derived from stereo imagery; b) topographic profiles across the band

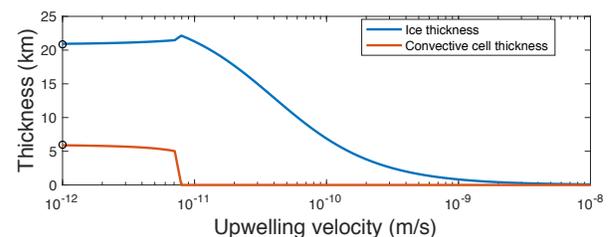


Figure 2: Change of ice thickness as upwelling velocity, and therefore basal heat flux, increases, in a convecting ice shell. When the convective cell is thin, the ice thickness increases with upwelling velocity. The band can stand as much as 400 m above the surrounding ice when convection shuts down, here at a velocity of 10^{-11} m/s (~ 0.3 mm/Myr).

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RHEOLOGICAL INVESTIGATION OF CRYOVOLCANIC SLURRIES. Aaron A. Morrison¹, Alan G. Whittington¹, Fang Zhong², Karl L. Mitchell², and Elizabeth M. Carey², ¹Department of Geological Sciences, University of Missouri, Columbia MO (aamgz8@missouri.edu), ²Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA.

Introduction: Europa is the most likely candidate for active cryovolcanism in the Jovian system. Surface compositions have been spectrally determined to be overwhelmingly water-ice with minor components of hydrated salts, carbonates, and sulfur compounds [1]. Cryolava domes may be formed by extrusion of high-viscosity briny material, and some smooth, low-albedo surfaces have been interpreted as low-viscosity flooding. These two types of features can also be explained by other non-volcanic processes, but higher resolution data are needed to test these alternatives. Cryolava dome emplacement has been modeled numerically, typically as Newtonian fluids, highlighting the need for a better understanding of how these materials behave as they extrude and become non-Newtonian during cooling and crystallization.

The rheology of these materials is fundamental in determining how cryovolcanic features are emplaced and the morphologies that result. We will attempt to address this knowledge gap by conducting a rheological investigation of briny crystal-liquid suspensions likely to be erupted on icy bodies like Europa. The few previous studies measuring subliquidus viscosity are plotted in Figure 1. Brine compositions can form due to either fractionation or melt segregation (enhanced by a very low viscosity carrier fluid) from an ammonia-water/ice source which could then be erupted creating a dome or flow feature. Potential cryogenic compositions span a similar viscosity range to that of silicate lavas. Many bodies exhibit flow features/constructs and a defined rheology will allow inferences about possible compositions based on observed morphology.

Methods: The liquid viscosity will be measured for a series of binary and ternary compositions including aqueous chlorides (Na,K,NH₄), sulfates (Mg,K,NH₄), and carbonates (Ca,Mg,Fe). The chloride and sulfate binaries are already well studied above 0 °C but very few data exist at lower temperatures relevant to outer solar system conditions. Rheological data will also be obtained in the subliquidus range of temperatures to investigate both the dependence of crystallization (size and shape distributions) and strain rate on viscosity. In addition to mechanical data, we will be able to measure thermal conductivity and diffusivity of our samples in-situ to better understand the dynamics of crystallization occurring in the samples.

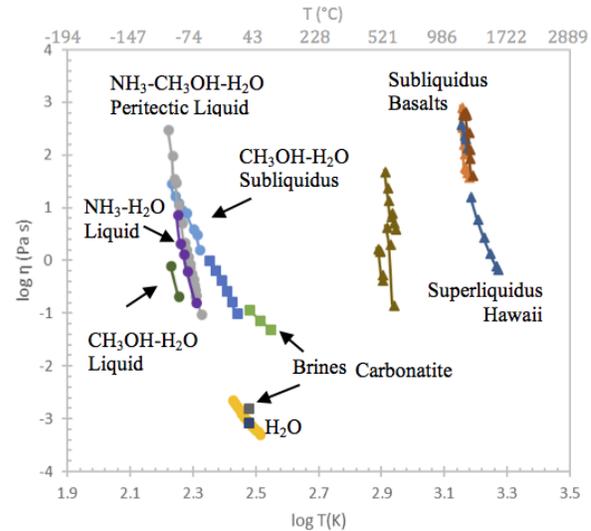


Figure 1. Viscosity data for water [2], brines [3,4], ammonia-water [5], methanol-water [5,6], ammonia-methanol-water [4], East African Rift basalts, Hawaiian basalt [7].

Implications: Understanding how these materials move, deform, and evolve upon crystallizing will help constrain what morphological features can form by various compositions. The rheological data will allow comparisons to terrestrial silicates and determinations of how similar the two materials behave. If they are, in fact, analogous to silicate systems (in terms of viscosity, flow index, yield strength, etc.), are they formed and emplaced by the same mechanisms and processes further strengthening their link? And if not, what factors are contributing to the difference? Determining rheologies of these cryogenic materials should allow us to answer these questions. Understanding these flows will also provide insight into how various bodies have evolved (or are evolving) and may suggest what the body may have looked like in the past.

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Europa's radiation environment and implications for surface composition¹T. A. Nordheim, ²C. Paranicas, ¹K. P. Hand, ¹Jet Propulsion Laboratory, California Institute of Technology, ²Applied Physics Laboratory, Johns Hopkins University

Jupiter's moon Europa is embedded deep within the Jovian magnetosphere and is therefore exposed to intense charged particle bombardment, from thermal and suprathermal plasma (eV to keV) to more energetic (keV to MeV) particles [1]. These charged particles are capable of affecting the near-surface of Europa, in some cases down to depths of several meters. Examples of radiation-induced surface alteration include sputtering, radiolysis and grain sintering; processes that can significantly alter the physical and chemical properties of surface material.

Radiolysis of surface ices containing sulfur-bearing contaminants from Io has been invoked as a possible explanation for H₂SO₄ hydrates that have been putatively detected on Europa's surface by the Galileo Near-Infrared Mapping Spectrometer (NIMS)[2][3][4] and subsequent ground-based observations[5]. However, the spatial distribution of this material, observed at low latitudes on the trailing hemisphere, does not completely correspond to the expected "bull's-eye" bombardment pattern of co-rotating plasma[6][7][8]. This could suggest that energetic particles rather than plasma is responsible, that local electromagnetic interactions are a significant factor, or possibly that some additional agent is involved in the creation of the H₂SO₄ hydrate.

Similarly, the presence of MgSO₄ hydrates on the surface of Europa has been inferred from NIMS [4] [5] and ground-based spectra and was used to argue for a sulfate-rich ocean on Europa. However, recent work [9] found that this species is spatially correlated with the trailing hemisphere and other species that are proposed radiolysis products, including H₂SO₄. On the basis of this it has been argued that the inferred MgSO₄ hydrates are themselves a radiolysis product of irradiated magnesium chloride salts present on the surface[9].

The higher abundance of amorphous H₂O ice on Europa compared to Callisto has been explained by the fact that Europa is exposed to much higher fluxes of energetic ions. Trace concentrations of radiolytically produced H₂O₂ were observed on Europa's surface by NIMS[11], and it and other radiolytically produced oxidants could serve as a source of chemical energy for life present in Europa's ocean [12][13][14].

Clearly, charged particle weathering is a major surface modification process at Europa. Therefore, a

quantitative understanding of the nature and extent of this type of radiation processing represents crucial context for both remote and in-situ observations by future Europa missions.

Here, we will present an overview of charged particle weathering as well as results from recent modelling of energetic charged particle precipitation patterns and particle physics simulations of how these particles interact with surface ice. We will discuss the implications of these results for the physical structure and chemical composition of Europa's surface, as well as implications for future landed and orbital/flyby missions.

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Plume profile studies of Nanosecond laser induced desorption of water ice - amorphous versus crystalline –
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Introduction: Recently, macromolecular organic compounds have been detected from the depths of Saturn's Moon Enceladus by NASA's Cassini.[1] The Jovian Moon Europa is soon to be subject to close investigation by both NASA's upcoming Europa Clipper and ESA's JUperer ICy moons Explorer (JUICE). The ocean worlds are of particular interest for the search of extraterrestrial life within our solar system.

Both Enceladus and Europa are covered with a presumably active ocean underneath the thick ice shell. Enceladus has cryo-volcanic plumes that actively expel material from its subsurface ocean. Active plumes are also present on Europa,[2] as has been unveiled by re-examining the data from the Galileo mission. It is likely that in the future *in situ* investigation of these highly active locations, with fresh material from the ocean is required to determine if molecules associated with life are present. However, getting detailed insights of the composition of ice is challenging. One of the possible instruments for investigation of these ices is combining laser induced desorption with time-of-flight mass spectrometry.[3,4,5]

At NASA's Jet Propulsion Laboratory, we have used the two-color Laser Ablation Ionization Mass Spectrometer system to study such ice-surface analogous.[3] The system has the capabilities to simulate relevant conditions, encountered on the ocean worlds. The structure of the ice, depends on the temperature at which this ice is deposited. IR laser desorption combined with multiphoton ionization mass spectrometry, provides insights into the desorption dynamics of amorphous and crystalline ices and their propagation in the plume. By introducing different species in low abundances into the ice structure, we can study if these molecules follow the same trend in extraction time as the water molecules. These fundamental investigations are essential for understanding the processes at play.

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Spectral Behavior of Irradiated Sodium Chloride Crystals under Europa-like Conditions.

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A key parameter when evaluating the habitability of a world is whether or not conditions exist to create chemical disequilibrium [1-4, 6]. Life tends to harness the potential energy of disequilibrium and use it to grow and multiply. In the case of Europa, it is understood that oxidants are created by irradiation of the icy surface, and reductants are expected from water-rock interactions at the base of the sub-surface ocean. However, kilometers of ice separate these two sources, leading to a second critical parameter for habitability of Europa: is there sufficient mixing between ocean and surface material to sustain a region of chemical disequilibrium?

One way to look for mixing is to look for evidence of material from the ocean at the surface. While geologic evidence does exist [5], chemical evidence would also be very useful. In this work, we choose to examine sodium chloride, the most common salt in Earth's oceans, as a tracer of exposed ocean material. Earth-based telescopic observations of Europa's surface show near-infrared features consistent with chloride salts [8-10]. However, it is known that irradiation of materials can alter their spectra; in the case of NaCl, investigation of crystal defects, often referred to as "color centers" due to their tendency to absorb light in the visible and ultraviolet spectral range, has been carried out under Earth conditions during the Nuclear Era [7]. We wanted to know: How do these materials respond in Europa-like conditions? What is the rate of color center appearance and decay in these conditions? While the literature contained valuable portions of the answers (eg. [11-13]), no systematic examination of color center formation and decay under the desired conditions was found.

We examined color center formation and decay at the Icy and Ocean Worlds Simulation Laboratory at the Jet Propulsion Laboratory [14]. Background pressure in the system was low 10^{-8} torr range, and temperature of the sample was varied from 100 to 300 K. Irradiation was 10 keV electrons, though the exact energy is not critical as secondary emissions from the material itself are understood to do most of the actual damage. Beam current was varied from 57 to 250 nA. Spectra were collected from 350-1150nm. Variations in color center dynamics were observed with differing conditions, however, relatively consistent behavior was observed when the color center formation was compared as a function of accumulated irradiation energy. Application to Europa showed that color center formation can be used to estimate the exposure age

of recent NaCl deposits less than several tens of years old [14]. This is especially useful for selecting landing sites for *in situ* surface measurements of the youngest exposed ocean materials, such as would be valuable to the Europa Lander, which is currently being studied by NASA for implementation next decade.

This work also underscores the importance of examining materials under conditions that are as representative of the application as possible. Next steps include expanding the spectral range into the far ultraviolet to examine possible contributions of irradiated salt to the 118-170 nm spectral range measured by Hubble [15]. This spectral range will also be measured by the UVS instruments on Europa Clipper and the ESA JUICE mission.

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Europa-Relevant Laboratory Studies at the Southwest Research Institute: Far-Ultraviolet Spectroscopy and Sputtering in the context of the Surface-Exosphere Connection

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Far-Ultraviolet Spectroscopy: Recent Hubble spectra of the Europa's surface in the far-ultraviolet [1] do not show a strong ice absorption edge at 165 nm (~8 eV) suggesting water ice is perhaps not the dominant constituent in the FUV sensing depth, ~100 nm. What are the other constituents present in the top layer of the icy regolith? Laboratory spectra of possible candidates – H₂O₂, SO₂, CO₂, salts and acid hydrates and organics [2] are scarce and would be valuable in the interpretation of the reflectance spectra set to be acquired by Europa-UVS. To this end, we are in the process of compiling a far-ultraviolet spectral library of icy analogs relevant to Europa's surface through laboratory work at the Southwest Ultraviolet Reflectance Chamber (SwURC). We have recently acquired far-ultraviolet spectra of Apollo soil 10084-water ice aggregates (Figure 1) and we plan to extend similar measurements to European analogs.

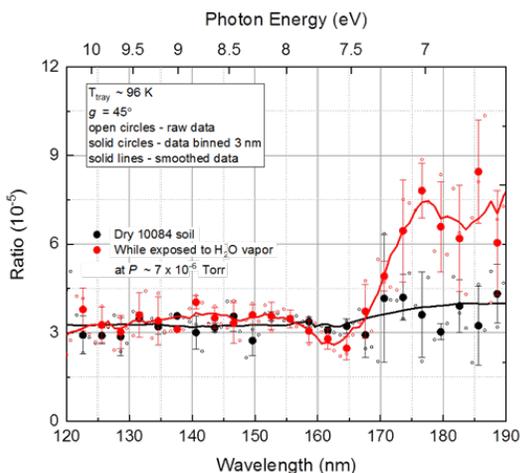


Figure 1: Far-ultraviolet spectra of dry Apollo soil 10084 (black) and with adsorbed water ice (red). The 165 nm absorption edge emerges in the spectra resulting from the uptake of water ice by the porous granular Apollo soil. We plan to extend similar measurement to European analogs in support of Europa-UVS.

Sputtering in the Context of Surface-Exosphere Connection at Europa: The presence of the less-volatile, non-ice material on the Europa's icy surface which possibly mutes the 165 nm ice absorption edge, will likely also affect sputtering and the supply rates of H₂O and O₂ into the tenuous exosphere. The estimated

O₂ source rates at Rhea and Dione were found to be ~50-300× smaller than predicted values based on laboratory studies that measured the O₂ yield from irradiation of pure water ice [3]. The very top level surfaces of these Saturnian satellites, unlike Europa, are dominated by water ice, as indicated by their far-ultraviolet spectra which show the distinct absorption edge signature at 165 nm [4] and are correspondingly less likely to have a sheen of a radiation processed lag layer. How is the sputtering rate affected by the presence of the non-ice constituent in Europa's icy grains?

To this end, we plan to irradiate relevant icy mixtures such as H₂O + CO₂ and H₂O + CH₄ with energetic particles and measure the composition and the flux of the sputtered ejecta and the composition of the evolving surface using multiple techniques like quartz crystal microgravimetry, mass spectrometry and optical spectroscopy ranging from the far-ultraviolet to the mid-infrared. We plan to execute these critical experiments to elucidate the Surface-Exosphere connection at Europa in our laboratory (Figure 2) under SwRI's new initiative: CLASS (Center for Laboratory Astrophysics and Space Science).



Figure 2: New laboratory under SwRI's CLASS Initiative to conduct experiments to characterize the sputtering from Europa relevant icy mixtures.

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Europa's Surface Composition: Active Icy Moons Geology with Exogenic 'Overprinting'

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Europa's youthful icy surface has been riven by tectonic and thermal processes, yielding a considerable diversity of geologic forms. The surface has additionally been heavily weathered by exogenic processes, including by the implantation of ions and neutrals from Jupiter's magnetosphere, with concomitant photolysis and radiolysis. Impact gardening and the sputtering and redistribution of volatiles further modify the surface properties and composition. In this review we will briefly describe the evolution of our knowledge of Europa's surface composition, from the largest scales to the smallest, and from the discovery of water ice on Europa up to the present day. As one theme we will consider the relationships to the radiation environment of Europa's inferred surface properties and composition. We will also focus on the evidence for distinctive surface compositions, of endogenic origin, corresponding to mapped geologic units on Europa's surface. Stratigraphic relationships allow 'relative' age estimates in some regions, for instance where impact ejecta have mantled exposures of greater age. In some locations, we may also detect anomalies of the percent abundance of the 'patina' of hydrated sulfuric acid, of exogenic origin, that likewise imply significant differences in the exposure ages of surface materials. Despite many years of focused investigations, the chemical composition of Europa's endogenic non-ice materials is unknown, and controversial; the results of both linear and intimate mixture modeling studies are non-unique and are thus ambiguous. Nonetheless our current knowledge can provide a number useful insights of relevance for future remote sensing and in-situ investigations.

ICELIB - ASSESSING EUROPA'S SURFACE WITH LABORATORY ICE EXPERIMENTS. V. Singh^{1, 2}, M. S. Gudipati², A. R. Rhoden³ and B. L. Henderson², ¹SESE, Arizona State University, 781 Terrace Road, Tempe, AZ 85287 (Vishaal.Singh@asu.edu), ²Jet Propulsion Laboratory, Caltech, ³Southwest Research Institute – Boulder.

Introduction: The ocean-bearing world, Europa, is one of NASA's key targets for exploration of habitable worlds [1, 2]. Europa displays unusual spectral surface properties which are likely related to the complex structure and composition of its regolith, spatially variant geological processes and radiation processing [3-5]. However, our ability to interpret our measurements is limited by a lack of "ground-truth" linking spectra to surface properties. The change in properties due to irradiation – which could modify endogenous materials and annihilate life near the surface – and mixing is still challenging to measure at relevant Europa conditions, and timescales for radiation-induced changes of icy surfaces are not well-known [6]. Europa Clipper Mission, with a suite of instruments [7-8] will image the surface, and yield critical information about its composition [9]. This wealth of data will provide great insight into the physical and compositional properties of Europa's ice shell, if we can interpret these measurements.

We present a laboratory-based pathway towards understanding Europa's surface, along with initial results of our experiments. Our goal is to obtain spectra of ices, at pressure and temperature relevant to Europa, while varying (1) grain size, (2) salt content, (3) extent of irradiation, to link spectral and surface properties. We are particularly interested in tracking co-evolution of grain size, irradiation, and colorization, as potential indicators of exposure age of surface materials.

Methods and Initial Results: The Ice Spectroscopy Laboratory (ISL) at JPL offers a state-of-the-art infrastructure for studying the spectral, optical, and compositional properties of ices analogous to materials on Europa (Fig 1a). The first objective of our investigation, which we report on here, is to characterize the effects of grain size on ice spectra and how grain size changes with radiation exposure and temperature. In

our preliminary study, we controlled grain size by (1) misting ultrapure water into a dewar filled with liquid nitrogen (LN), followed by (2) sieving in pristine N₂ environment [10-11]. Ice grains were transferred to a sample holder inside a high vacuum chamber [12], which was pumped down to 10⁻⁸ mbar and cryogenically cooled to 100 K to replicate Europa's dayside temperatures [13]. We collected VIS-NIR reflectance-absorption spectra of these ice grains, using a NICOLET 6700 FTIR spectrometer and MCT detector, and studied the variation of spectra with grain size, temperature. Our experiments include continuous microscopy observations using the Infinity K-2 DistaMax microscope to evaluate size evolution with radiation.

We have successfully produced water-ice samples, and collected preliminary reflectance spectra of pristine grains with size ranging from 25–212 μm (Fig 1b, c) – our samples display spectral signatures of crystalline water ice. Additionally, band depths of these NIR absorption signatures are sensitive to changes in sample grain size – we can use this to determine Europa's surface particle size, and surface age. We will present the findings of additional grain size experiments to quantify this sensitivity, discuss plans for delivering our measurements to the community through an ice spectral database (ICELIB), and describe upcoming experiments investigating irradiation and salt content.

Conclusions: Our objectives have been designed to answer key questions about Europa's geologic history, and to enhance our interpretation of icy surface spectra. In future years, the collected spectra will allow us to accurately model Europa NIMS/MISE datasets, which can inform site selection for in-situ sample collection.

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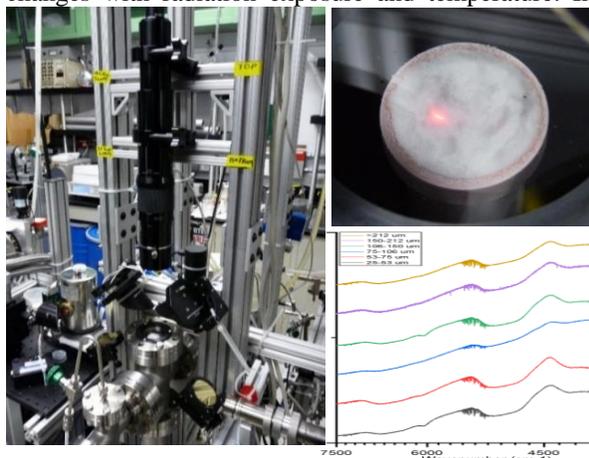


Fig 1(a) ISL is equipped to replicate Europa conditions, (b) we deposit ice, sieve, (c) collect spectra– band depths vary with size

RAPID TEMPORAL VARIABILITY OF CONDENSED O₂ ON EUROPA? John R. Spencer¹ and William M. Grundy², ¹Southwest Research Inst., Boulder, CO, spencer@boulder.swri.edu, ²Lowell Observatory, Flagstaff, AZ.

Introduction: Shallow 5773 and 6250 Å absorption bands due to condensed O₂ were detected on the icy Galilean satellites in the 1990s [1,2,3]. The band requires high density, condensed, O₂, as it results from interactions between molecules. The band is 2% deep at low latitudes on the trailing side of Ganymede, but much shallower on the poles and leading side, and only 0.3% deep on Europa and Callisto.

The O₂ is probably generated by magnetospheric sputtering of surface H₂O [4], and likely plays a key role in the complex chemical environment of icy satellite surfaces [5,6,8] and helps to support the observed O₂ atmosphere [9]. The presence of O₂ in >110 K ices on the Galilean satellites may require trapping in bubbles or clathrate cages [6]. On Europa the O₂ and related oxidants could, when introduced into the ocean by crustal cycling, provide energy to support a potential biosphere [11, 12].

New Observations: The 1990s Europa data, taken with the 1.8-meter Perkins telescope at Lowell Observatory, had insufficient SNR to usefully map longitudinal distribution, an important constraint on formation processes. We have thus obtained new higher SNR spectra using the 4-meter Discovery Channel Telescope at Lowell Observatory on 8 partial nights in June 2017, using the DeVeny CCD spectrograph, with $\lambda/\delta\lambda \cong 900$. Europa spectra were divided by contemporaneous Io spectra (which are not expected to contain condensed O₂) to remove solar Fraunhofer lines which otherwise dominate the spectra (Fig. 1).

Results: O₂ band depth is variable (Fig. 1), but is inconsistent in spectra of the same longitude taken a week apart (i.e. June 6th vs. June 13th and June 5th vs. June 12th). Fig. 2 shows the lack of correlation with longitude more clearly. There is a similar lack of correlation with Europa's Jupiter System III longitude.

Discussion: The apparent rapid temporal variability is surprising, but not easily explained as an artifact. The longitude of Io used in the ratio is the same in the pairs of observations taken 1 week apart, and the same discrepancies are seen in when each night's data is separated into two halves (Fig. 2), though uncertainties do not always overlap, which is a concern. *If real*, the variability might be due to O₂ deposition by short-lived plumes, and subsequent sublimation, or variability of production by magnetospheric sputtering. Further observations will probably be required to confirm or refute this peculiar result.

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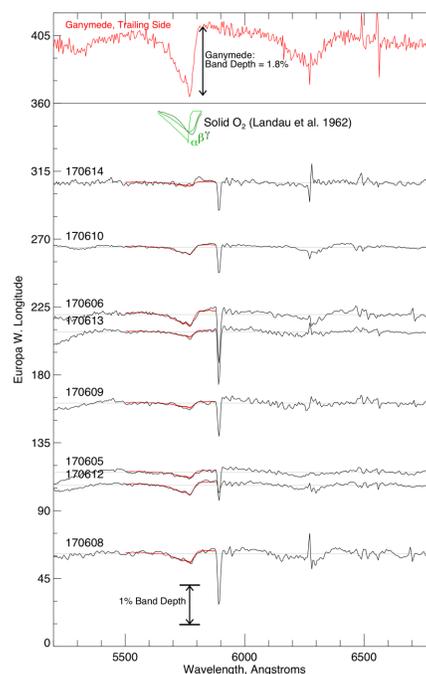


Figure 1 Europa/Io spectral ratios, arranged by longitude. Red curves show fits to a scaled Ganymede spectrum (top), used to determine band depth. The feature at 5890 Å is Na emission on Io.

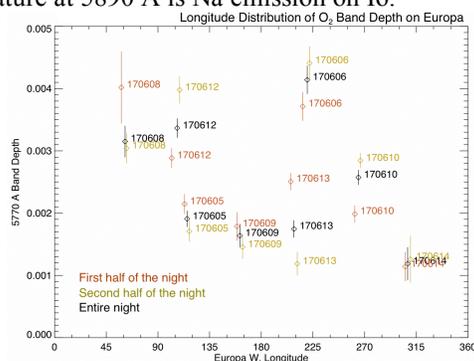


Figure 2 Band depth vs. longitude, showing the lack of correlation. Depths are shown for the full night, and also for the first and second halves of each night.

QUANTIFYING THE CHEMICAL SPECIES RADIOLYTICALLY SPUTTERED FROM EUROPA'S COMPLEX ICES INTO ITS EXOSPHERE THROUGH LABORATORY EXPERIMENTS

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Introduction: “Radiolytically sputtered” exospheres generated by magnetospheric irradiation are pervasive at massive outer solar system icy moons. As charged particles bombard the icy moons, (1) solid state radiation chemistry, or radiolysis, chemically alters the surface material, while (2) sputtering ejects the altered material into the exosphere. For this reason, exospheres dominated by radiolytic O₂ and CO₂ from reactions of surface H₂O ice with carbon-bearing ‘organic contaminants’ are common at the Saturnian (Dione and Rhea) [1-3] and Jovian (Callisto, Ganymede, Europa) icy moons [4,5]. However, ‘Ocean Worlds’ like Europa may have even more diverse surface constituents, including surface hydrated sulfate salts [6,7], and possibly complex organics erupted through the icy crust or vapor condensed cryovolcanic plume fallout. *What* exospheric molecules do these complex European surface materials ‘give off’ when sputtered by Jupiter’s magnetosphere, and in *what amounts*? What is the dependence on surface composition and irradiation parameters (ion energy, dose, mass)? Quantitative answers to these questions are essential to understanding exospheric origins at icy moons, and of rapidly escalating importance to NASA’s planned Europa Clipper mission, which will search for complex oceanic materials on Europa’s surface by measuring exospheric composition. Here we discuss the radiolytic sputtering process, and summarize experiments now being prepared in our laboratory to quantify the amount and composition ejected from possible European surface materials.

Radiolytic Sputtering at Europa: Unlike the metals and alloys which dominate the inner solar system (e.g., the moon, mercury) and tend to emit predominantly atomic species when sputtered [8], irradiated molecular ices [9] on an icy body can (1) undergo solid state radiation chemistry, and (2) emit molecular species, including radiolysis products, when sputtered. Evidence for this process on Europa can be seen on the heavily irradiated trailing hemisphere, which has a distinctively darker albedo [10] likely indicative of solid state radiolysis of both endogenous materials and implanted magnetospheric ions. Although radiolysis by high energy electrons takes place centimeters deep into the surface ice [11], the composition *sputtered* into Europa’s exosphere is sensitive to the radiolysis taking place in the topmost *angstroms* of surface material. Thus Europa’s exospheric composition, including the observed O₂ and H₂ from radiolysis of surface water ice, and SO₂, Cl, Na and K derived presumably from surface sulfate salts [12], is a function of the composition and chemistry of this thin surface layer. The following four processes, among others, may compete to determine the surface, and sputtered, composition: (1) Preferential sputtering may eject volatile molecular constituents more easily than non-volatiles, (2) Out-diffusion of radiolytic volatiles produced near the surface, (3) Gravitational fallback and re-

condensation of sputtered H₂O and other non-volatiles onto Europa’s surface, and (4) Micrometeorite gardening which may turnover and excavate “fresh” ice from below the topmost angstroms. A major unanswered question is whether preferential sputtering, together with radiolysis, may enrich the surface ices of Europa and other icy bodies with refractory material [13], and how this affects the flux and composition sputtered.

Our Laboratory: Southwest Research Institute’s new Center for Laboratory Astrophysics and Space Science (CLASS) is now pursuing a research program to advance understanding of the surface-exosphere compositional relationship at icy moons including Europa. Our Space Ice Simulation Chamber is equipped with (1) two precision gas dosers for vapor deposition of bi-component ice films, (2) a temperature-controlled quartz crystal microbalance for precise quantification of the sputtering yield (grams sputtered per incident particle), (3) a 10keV ion and 10 keV electron gun as our irradiation sources, (4) UV, visible and IR optical spectrometers to analyze the ice composition during irradiation, and (5) a mass spectrometer to measure the composition of the material sputtered. The system is therefore well equipped for measurements of both the flux and composition sputtered from “mixed” ices, *versus* irradiation dose, and allows us to observe how the sputtered composition “tracks” that of the ice during irradiation. Such experiments will reveal not only how radiolysis alters Europa’s surface composition, but will *also* allow quantification of how such changes may manifest in Europa’s exosphere. We will present an overview of our laboratory, and discuss several of our preliminary experiments.

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X-RAY FLUORESCENCE SPECTROSCOPY ON THE EUROPA LANDER: DETERMINING THE ELEMENTAL COMPOSITION OF THE SURFACE AND UNCOVERING INDICATORS OF HABITABILITY. G. R. Tremblay¹, R. P. Kraft¹, E. Bulbul¹, S. Nulsen¹, G. Germain¹, L. Beegle², R. Hodyss², & S. Vance², ¹Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge, MA 02138, USA; gtr-emblay@cfa.harvard.edu, ²Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.

Abstract: As part of the recent Instrument Concepts for Europa Exploration (ICEE2) call, we have proposed to build and test an electrical and mechanical package to operate an X-ray sensitive Silicon Drift Detector (SDD) within the technical requirements of the notional Europa Lander. X-ray fluorescence spectroscopy is a well-established technique to make direct measurements of elemental abundance, and has been used successfully on a wide variety of planetary missions. Elemental compositions were measured on Mercury using X-ray induced fluorescence generated by Solar coronal X-rays (Messenger) and will be used on Mars using an SDD and an X-ray tube to generate the characteristic X-rays (PIXL on Mars2020). Europa lies deep within the Jovian magnetosphere, and the flux of energetic (1-10 MeV) protons onto the European surface generates characteristic X-rays via particle-induced X-ray emission (PIXE).

The three primary science goals of the Europa Lander mission as defined by the 2016 SDT are Biosignatures, Habitability, and Surface Properties and Dynamics. Measurement of the elemental composition of the surface of Europa would provide *direct, unambiguous* answers to critical aspects of each of these goals. Measurements of the elemental composition of Europa's surface will enable us to understand the composition of the subsurface ocean, and thus its habitability. In addition, these measurements are critical for understanding Europa's formation, evolution, and the current roles of endogenic and exogenic surface processes. An X-ray fluorescence spectrometer complements the other notional instruments, including the vibrational spectrometer and mass spectrometer, by making a complementary measurement that can resolve confounding or degenerate measurements.

Our group has done extensive modeling of the particle environment of Europa, the X-ray emissivity of the Europa surface, and the sensitivity of our instrument in the charged-particle environment of Europa. Our instrument would be sensitive to characteristic X-ray lines from the key elements of O, Na, Mg, Si, P, S, Cl, K, Ca, and Fe, and perhaps C and N depending on entrance window (Fig. 1). It would detect the presence of trace elements on the surface of Europa to 5 parts per thousand by mass to 5σ in one day of operation. Operation for the full 20-day mission lifetime would improve the sensitivity by a factor of ~ 4.5 to approximately 1 ppt. Our instrument could be aligned to the region where the scoop will operate to provide a differential abundance measurement between the material on the surface with that at the depth of the scoop.

SDDs have a long and successful flight heritage in a large number of planetary sciences, astrophysics, and Solar mis-

sions. The technical requirements of the Europa Lander mission concept put unique constraints on the electrical, mechanical, and thermal design of the overall system. Our team has proposed to design, build, and test a complete flight-prototype system to drive a commercially-available (and radiation hard) Amptek SDD that fits within the technical envelope of the notional Lander concept. The primary technical challenges include development of an electronics package to drive the SDD that will operate within the necessary radiation tolerances, design of a sensor head that will sufficiently shield the SDD from the energetic protons and electrons that otherwise create an unacceptably large instrumental background, and model the thermal properties and power dissipation in the head to ensure successful operation in the relevant environment. We will also investigate the viability of mounting multiple SDDs with different viewing angles to sample distinct regions of the European surface (Fig. 2). Our instrument will use $<12\%$ of the power, mass, volume, and data rate of the notional lander. Our complete system will be at TRL 5 by the end of the program.

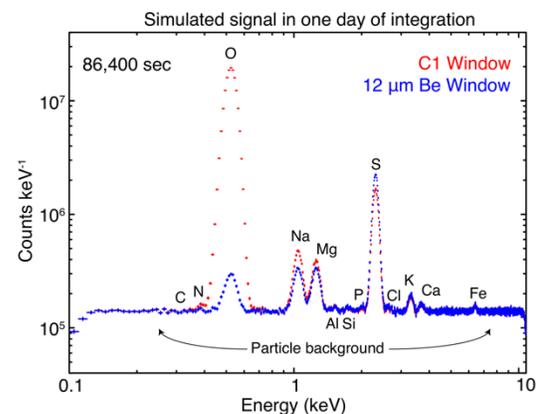


Fig. 1. Simulated signal (including incident particle background) from one day of operation of the SDD. 6σ significance is achieved for lines produced by key elements from O to Fe, enabling a robust characterization of relative abundances as well as absolute stoichiometry for other instruments, including a notional vibrational spectrometer.



Fig. 2. One of several notional form factors for our design. SDDs would be placed at each aperture. The size of the housing is roughly equivalent to a grapefruit.

OBSERVATIONAL CONSTRAINTS ON THE DISTRIBUTION AND TEMPERATURE DEPENDENCE OF H₂O₂ ON THE SURFACE OF EUROPA S. K. Trumbo¹, M. E. Brown¹, K. P. Hand², and K. de Kleer,¹ Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, 91125, USA (strumbo@caltech.edu), ² Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109, USA

Introduction: Hydrogen peroxide (H₂O₂) is part of an important radiolytic cycle on Europa. The bombardment of surface water ice by magnetospheric ions and electrons converts H₂O to H₂O₂, losing H₂ in the process and creating an oxidizing surface [1, 2, 4]. Understanding this cycle is not only important to our knowledge of the chemical composition of Europa's surface and to the study of surface-magnetosphere interactions throughout the solar system, but it is also critical for our understanding of the potential chemical energy sources to Europa's ocean [3, 6]. Water-rock interactions at the seafloor can be a source of reductants, but the energy available for redox chemistry will likely depend on the supply of oxidants, such as H₂O₂, from the radiolytically processed surface environment [3, 6].

Spectroscopic observations of potentially endogenous salts suggest that low-latitude chaos regions on the leading and anti-Jovian hemispheres may be important sites of exchange between the surface and subsurface environments [5]. However, laboratory experiments [7, 8] and disk-integrated spectroscopic observations of Europa's surface [9] suggest that the local H₂O₂ concentrations are controlled by the local temperature and availability of water ice, leading to the prediction that the highest H₂O₂ concentrations would lie at the cold, icy high-latitudes of the leading hemisphere, rather than the warm, salty equatorial regions. If these predictions are correct, such a spatial separation of H₂O₂ and the most likely locations of surface-subsurface exchange could limit the delivery of oxidants to the subsurface ocean. A definitive understanding of the distribution and controls of H₂O₂ across the surface of Europa is therefore crucial for understanding its potential habitability.

Observations and Results: We present L-band observations of Europa taken with the near-infrared spectrograph NIRSPEC and adaptive optics (AO) system (hereby combined to NIRSPA0) on the Keck II telescope, as well as with the near-infrared spectrograph SpeX of the NASA Infrared Telescope Facility (IRTF). Our NIRSPA0 observations map the 3.5 μm H₂O₂ feature across the surface of Europa at a nominal spatial resolution of ~300 km, thereby testing the expectation that H₂O₂ is concentrated in the coldest, iciest regions. Contrary to expectations, our NIRSPA0 data exhibit a depletion of H₂O₂ at the high latitudes and higher abundances near the warm equator.

Intriguingly, as demonstrated in the mapped slit of Figure 1, these data also suggest a potential concentration of H₂O₂ within the salty chaos terrains, which may imply a compositional control on abundance.

Our SpeX data examine the strength of the 3.5 μm H₂O₂ feature in disk-integrated spectra taken before and after Europa's daily eclipse and are therefore sensitive to temperature controls that are independent of local geographic location. A simple thermal model of Europa's surface [10] predicts a temperature drop of 10–20 K during eclipse. Comparison of H₂O₂ band strengths before and after this temperature change will investigate the importance of temperature in the equilibrium concentrations of H₂O₂ on Europa.

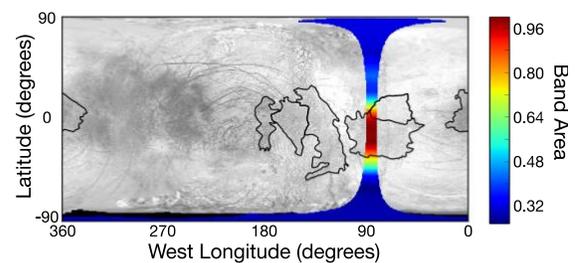


Figure 1: A NIRSPA0 N/S slit across the leading hemisphere of Europa. The H₂O₂ abundance appears to be lowest at high latitudes and most concentrated in the salty chaos region, Tara Regio. This implies a potential compositional, rather than temperature, control on H₂O₂ abundance.

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DECOMPOSITION OF AMINO ACIDS IN WATER WITH APPLICATION TO EUROPA AND OTHER OCEAN WORLDS. N. Truong^{1,2}, C. Glein³, A. A. Monroe⁴, A. D. Anbar^{4,5}, J. I. Lunine^{1,6}. ¹Cornell Center for Astrophysics and Planetary Science, Cornell University, Ithaca, NY 14850, ntruong@astro.cornell.edu, jlunine@astro.cornell.edu, ²Department of Earth and Atmospheric Sciences, Cornell University, ³Southwest Research Institute, San Antonio, TX, cglein@swri.edu, ⁴School of Earth and Space Exploration, Arizona State University, PO Box 871404, Tempe, AZ 85287, aamonroe@asu.edu, anbar@asu.edu, ⁵School of Molecular Sciences, Arizona State University, ⁶Department of Astronomy, Cornell University.

Introduction: Because proteins are indispensable components of the cell, amino acids are often considered to be one of the most important biosignatures in searching for life on other worlds [1]. However, before a biological origin can be deduced for the future potential finding of amino acids in Europa, other non-biological sources must be considered, including 1) Accretion of primordial materials or 2) Geochemical synthesis in the ocean. The first scenario was strongly suggested based on numerous findings of amino acids in primordial solar system building blocks materials, such as in carbonaceous chondrites [2] or the coma of comet 67P/Churyumov-Gerasimenko [3]. As a result, Europa as well as other ocean worlds that would be accreted from icy planetesimals might have retained an abundance of amino acids.

Therefore, the first step in using amino acids as biosignatures is to determine if amino acids were to be detected at Europa, could those species have been maintained from primordial synthesis process? Amino acids which are sensitive to destruction, unless protected or recently replaced by another process, must have been recently formed and can be identified based on their relative stabilities. Following the previous work from Monroe et al. 2017 [4], we use chemical kinetics data to estimate rates and destruction timescales of amino acids in scenarios applicable to Europa and hydrothermally active ocean worlds.

Modeling methods: Amino acid decomposition timescales are calculated by solving analytically kinetics equations with the corresponding kinetic rate constant. In order to predict rate constants at environmentally relevant temperatures, data are extrapolated using an Arrhenius relation between $\ln[k]$ vs. $1/T$. This approach also was used to estimate racemization timescales for meteoritic amino acids based on asteroid parent body temperatures [10]. As a large extrapolation may involve substantial error due to changes in reaction mechanisms, we employed a student-t distribution approach to calculating the confidence interval of the simulated rate constants.

Results and Discussion: The destruction timescale of amino acids depends strongly on the environment's temperature and the residence timescale of amino acids in elevated hydrothermal temperature. On the basis of existing laboratory data, among 16 amino acids

considered in this study, aspartic acid, threonine, isoleucine, serine, arginine are relatively sensitive to decomposition. Any of those species detected at Europa cannot be primordial, such that in situ detection would indicate recent (< 1 Myr) production of the amino acid.

Recommendation for future laboratory data: As all published data were performed at high temperature, we would recommend future experiments to obtain the kinetic rates at the lower range of temperature from 273 to 373K.

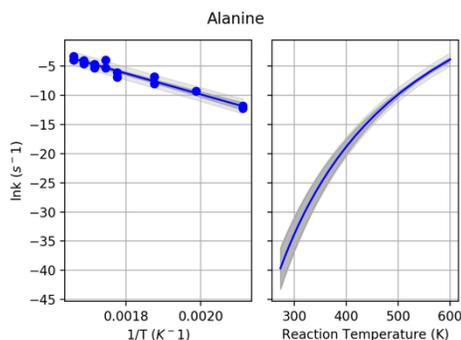


Figure 1. *Left:* Fitted rate constants vs. $1/T$. *Right:* Simulated rate constants vs. temperature (273-603K) for alanine.

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On the genesis and detectability of organic chemistry in hypervelocity impact ice spectra.

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Although ice is prevalent in the solar system and the long-term evolution of many airless icy bodies is affected by hypervelocity micrometeoroid bombardment, there has been little experimental investigation into these impact phenomena, especially at the impact speeds seen on airless icy bodies or in fly-by spacecraft. CO₂ has been observed on various moons of Jupiter, Saturn, and Uranus, and is typically thought to have been native to these bodies or brought as C atoms from exogenic sources that are later converted to CO₂ by UV or charged particle irradiation. However, carbonaceous dust particles impacting into water ice may be an important production mechanism for CO₂ on these airless bodies. Further, laser ablation and light-gas gun experiments simulating dust impacts have successfully created amino acid precursors from base components in ice surfaces, indicating that dust impacts may be an important mechanism in the chemical evolution of the surfaces of airless icy bodies, and may be capable of creating complex organic molecules necessary for life. However, this has yet to be achieved with actual dust impact. Additionally, impact ionization time of flight instruments on fly-by spacecraft provide in-situ measurements of the chemical composition of icy ocean worlds like Europa and Enceladus, but there have been no experiments to date that use actual dust impact to determine the survivability and detectability of complex organic chemicals in this type of measurement. With the creation of a cryogenically cooled ice target for the dust accelerator facility at the NASA SSERVI Institute for Modeling Plasma, Atmospheres, and Cosmic Dust (IMPACT), it is now possible to study the effects of micrometeoroid impacts in a controlled environment under conditions and at energies typically encountered by either airless icy bodies or fly-by spacecraft. Ice surfaces are prepared either by vapor deposition or by flash-freezing an aquatic solution of desired composition. Iron or carbonaceous dust is accelerated to 3-50 km/s and impacted onto the surface. Time-of-flight mass spectra of the dust impact ejecta show that amino acids and even the more fragile di-peptide amino acid chains frozen into water ice can survive impact and be detected. Future experiments will probe characteristic fragmentation patterns that can be used to identify amino acids even after breakup. Other experiments using trace amounts of CO₂ in water ice show that the CO₂ can be detected and that high velocity dust impacts convert some of this CO₂ to the volatile CO. Upcoming experiments will investigate CO₂ production rates from carbonaceous dust impactors into water ice as functions of velocity or other dust characteristics, and following experiments will probe the creation of more complex organic chemistry. Results from recent and ongoing investigations will be presented.

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UNDERSTANDING EUROPA'S COMPOSITION THROUGH GEOPHYSICAL MEASUREMENTS: THE ROLE OF LABORATORY DATA S. D. Vance¹, J. M. Brown², O. Bollengier², B. Journaux², E. H. Abramson², G. Shaw³, and H. Watson³. ¹Jet Propulsion Laboratory, California Institute of Technology (svance@jpl.nasa.gov), ²Dept. of Earth and Space Science University of Washington, Seattle, ³Union College, Schenectady.

Introduction: The workings and potential habitability Europa depends on the properties of its interior, but spacecraft missions cannot directly measure these. Inferring the compositions and mechanical and thermal properties requires a combination of remote sensing and geophysical measurements. The domain of possible solutions to the resulting inverse problem can be reduced by imposing prior knowledge in the form of structural models built from material properties obtained in the laboratory [1]. We are conducting multiple experiments at laboratories at the Mineral Physics Lab at the University of Washington, the Under Pressure Lab the Jet Propulsion Laboratory, and at labs at Union College. We provide highlights from those ongoing experiments, including detailed descriptions of the experimental apparatus, and applications to Europa.

Equations of State for Oceans in Icy Worlds: To advance the state of the art for modeling the chemistry and dynamics of very deep and cold oceans that may have exotic compositions, we are advancing the state of the art for thermodynamic equations of state for pressures up to and exceeding 1 GPa, and over a broad range of temperatures. This work has necessitated the application of geophysical inverse modeling techniques [2]. The input data are primarily sound speeds. We measure these below 1 GPa by measuring the time of flight of acoustic pulses, with an accuracy of better than 100 ppm. Above 1 GPa, we incorporate Brillouin measurements by other groups, and conduct impulsive stimulated scattering measurements in diamond anvil cells. High-pressure ice equations of state and thermodynamic properties are being extracted from newly measured in-situ single crystal synchrotron X-Ray diffraction experiments. The derived ice chemical potentials allow us to predict melting point depression due to various solutes, of all the ice phases that are predicted in icy ocean worlds and hypothetical watery super Earths (i.e. ice Ih, III, V, VI and VII). Those are also compared with newly measured melting point depression data obtained in the (Na,Cl,Mg,SO₄,NH₃)-H₂O system in diamond anvil cell high pressure apparatus.

Ices: The 30-year old data that exists on ice polymorphs is probably not precise or accurate enough for quality modeling. A recent collaboration between the Geology and Physics Departments at Union College is aimed at producing high precision data on ice polymorphs up to 700 MPa and temperatures to about -

30°C. We are currently building the pressure vessel assembly to allow these measurements using ultrasonic interferometry. While construction is in progress we are testing the ultrasonic technique using long buffer rods. We hope to begin measurements by Autumn of 2018.

In addition to the measurements in water ice, we are planning precision ultrasonic measurements on solid salts thought to be important as dissolved components of brines in the interiors of ice objects. These data should allow high precision thermodynamic analysis of complex brines in conjunction with previous (and ongoing) precision measurements on various brine solutions in progress at the University of Washington.

The equipment under development could be used for studies of clathrates and other solid phases incorporating various volatiles at elevated pressure and low temperatures.

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LEVERAGING TERRESTRIAL MARINE ICE CORES TO CONSTRAIN THE COMPOSITION OF ICE ON EUROPA. N. S. Wolfenbarger¹, D. D. Blankenship¹, K. M. Soderlund¹, D. A. Young¹, and C. Grima¹, ¹Institute for Geophysics, University of Texas at Austin, J.J. Pickle Research Campus, Bldg. 196; 10100 Burnet Road (R2200), Austin TX 78758-4445 (nwolfenb@utexas.edu).

Introduction: The origin of non-ice materials identified on Europa's surface, although debated, is either exogenic or endogenic. Exogenic fluxes have been constrained [1], but endogenic fluxes have been largely neglected despite implications for habitability.

The endogenic flux of material to Europa's ice shell is governed by the fractionation of chemical species present in the source water as it freezes [2-3]. Historically, these factors have been obtained empirically through laboratory experiments and field observations. The degree of fractionation is highly dependent on the type of ice formed as well as the rate of formation, governed by the temperature gradient.

Accreted Ices: European ice is expected to be predominantly of accreted origin, as opposed to meteoric. Accreted ices fundamentally form either through congelation growth or frazil accumulation. Congelation growth occurs when heat is lost through conduction to the overlying ice. Frazil forms in supercooled water through nucleation of individual ice crystals in the water column. Congelation growth is characteristic of sea ice and facilitates the interstitial incorporation of brine, enhancing the bulk salinity. Marine ice and platelet ice are both hypothesized to form by frazil accumulation beneath existing ice layers. Platelet ice forms below sea ice, whereas marine ice forms below ice shelves. Marine ice is thought to be distinct from platelet ice based on its total thickness (which can exceed that of platelet ice by an order of magnitude), lower temperature gradient, and reduced rate of formation. Deviatoric buoyancy stresses imparted by accumulating frazil crystals have been hypothesized to promote consolidation of marine ice. This formation mechanism is considered to contribute to the relative purity and elevated degree of fractionation of marine ice.

Implications for European Ices: European ice may be composed of both sea ice and marine ice analogs. Where conduction through the ice shell promotes thickening, sea ice may be a more appropriate analog, although additional consideration must be given to the temperature gradient. At low temperature gradients, fractionation will be elevated relative to terrestrial sea ice. Ice accreted in regions where the ice shell is relatively thinner, either due to kinetic processes or increased basal heat flux, could be more analogous to marine ice. Marine ice could play an important role in supporting the compositional diapirism hypothesized to form chaos terrain [4-6]. Moreover, diapirs could serve

as a vehicle to transport accreted oceanic material towards the surface of the ice shell.

Marine Ice Cores: Here, we summarize published marine ice core data to constrain the composition of hypothesized marine ice on Europa. Sites considered are shown in Fig. 1. Samples of marine ice from "green" icebergs are also included. Properties such as salinity, anion and cation concentration, and grain size are presented. Properties are evaluated in the context of the source water where possible to obtain an estimate for fractionation factor. The presence of biogenic material in accreted ice is noted where observed. General trends in marine ice properties between samples are identified and their implications for Europa are discussed. Sites are evaluated as potential analogs for the ice-ocean interface at Europa.

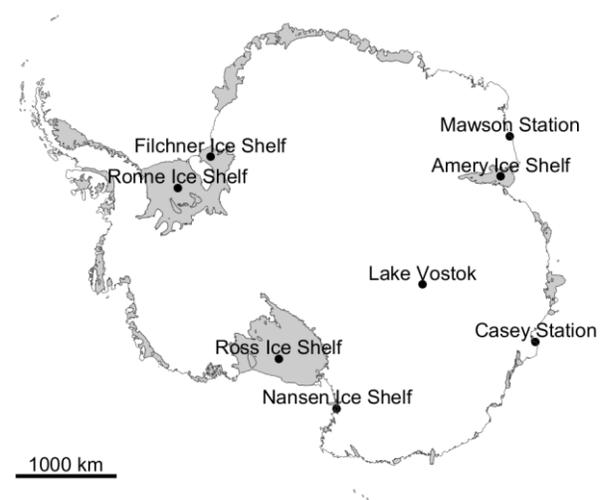


Figure 1. Published marine ice cores [3,7-13].

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