Program
Pluto System After New Horizons

July 14–18, 2019 • Laurel, Maryland

Institutional Support

Lunar and Planetary Institute
Universities Space Research Association
Johns Hopkins Applied Physics Laboratory

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Johns Hopkins Applied Physics Laboratory

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Southwest Research Institute
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Johns Hopkins Applied Physics Laboratory
Alan Stern
Southwest Research Institute
Cindy Conrad
Southwest Research Institute
Abstracts for this meeting are available via the meeting website at

www.hou.usra.edu/meetings/plutosystem2019/

Abstracts can be cited as

## Guide to Sessions

### Pluto System After New Horizons
**July 14–18, 2019**
**Laurel, Maryland**

**Sunday, July 14, 2019**

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<tr>
<td>5:00 p.m.</td>
<td>Kossiakoff Center</td>
<td>Registration and Opening Reception</td>
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**Monday, July 15, 2019**

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<tr>
<td>8:30 a.m.</td>
<td>Auditorium</td>
<td>Discovery of Pluto and the Kuiper Belt: The Imperative for Exploration</td>
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<tr>
<td>10:15 a.m.</td>
<td>Auditorium</td>
<td>Pluto Geology and Surface Features</td>
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<tr>
<td>1:30 p.m.</td>
<td>Auditorium</td>
<td>Pluto Geology, Colors, and Composition</td>
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<td>6:00 p.m.</td>
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<td>End of Day 1</td>
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**Tuesday, July 16, 2019**

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<tr>
<td>8:30 a.m.</td>
<td>Auditorium</td>
<td>Charon</td>
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<tr>
<td>1:00 p.m.</td>
<td>Auditorium</td>
<td>Small Satellites and Orbital Dynamics of the Pluto System</td>
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<tr>
<td>3:00 p.m.</td>
<td>Auditorium</td>
<td>Pluto’s Got Atmosphere — Kickoff</td>
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<tr>
<td>4:00 p.m.</td>
<td>North Dining Room</td>
<td>Poster Session</td>
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<td>6:00 p.m.</td>
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<td>End of Day 2</td>
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**Wednesday, July 17, 2019**

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<thead>
<tr>
<th>Time</th>
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<tbody>
<tr>
<td>8:30 a.m.</td>
<td>Auditorium</td>
<td>Pluto’s Got Atmosphere I</td>
</tr>
<tr>
<td>1:30 p.m.</td>
<td>Auditorium</td>
<td>Pluto’s Got Atmosphere II</td>
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<tr>
<td>3:00 p.m.</td>
<td>Auditorium</td>
<td>Pluto’s Climate and Redistribution of Volatiles</td>
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<tr>
<td>5:45 p.m.</td>
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<td>End of Day 3</td>
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**Thursday, July 18, 2019**

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<tr>
<th>Time</th>
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<th>Event</th>
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<tbody>
<tr>
<td>8:30 a.m.</td>
<td>Auditorium</td>
<td>Beyond Pluto: 2014 MU69 and the Kuiper Belt Environment</td>
</tr>
<tr>
<td>10:30 a.m.</td>
<td>Auditorium</td>
<td>Future Investigations of the Pluto System and Kuiper Belt</td>
</tr>
<tr>
<td>1:00 p.m.</td>
<td>Auditorium</td>
<td>Origin and Dynamics of the Pluto System</td>
</tr>
<tr>
<td>3:45 p.m.</td>
<td>Auditorium</td>
<td>Closing Announcements</td>
</tr>
<tr>
<td>4:00 p.m.</td>
<td></td>
<td>End of Conference</td>
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### Program

**Monday, July 15, 2019**

**DISCOVERY OF PLUTO AND THE KUIPER BELT: THE IMPERATIVE FOR EXPLORATION**

**8:30 a.m.  Auditorium**

**Chairs:** Harold Weaver and Leslie Young

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<th>Times</th>
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<tr>
<td>8:30 a.m.</td>
<td></td>
<td>Welcome and Opening Remarks</td>
</tr>
<tr>
<td>8:45 a.m.</td>
<td>[INVITED] Schindler K. S. *</td>
<td>Pluto, the Moon, and the Case for Multi-stage Space Exploration [#7059]</td>
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<tr>
<td></td>
<td></td>
<td>This program explores the value of multi-stage space exploration, comparing the classic</td>
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<td>case of Moon research--from naked eye observing to manned missions--to the discovery of</td>
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<td></td>
<td></td>
<td>Pluto, ensuing research of that planet, and potential future efforts.</td>
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<tr>
<td>9:15 a.m.</td>
<td>Binzel R. Cruikshank D.</td>
<td>GUIDED DISCUSSION: Historical Recollections and the Ongoing Imperative for Exploring the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Third Zone of Our Solar System</td>
</tr>
<tr>
<td>9:45 a.m.</td>
<td></td>
<td>Break</td>
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**Monday, July 15, 2019**

**PLUTO GEOLOGY AND SURFACE FEATURES**

**10:15 a.m.  Auditorium**

**Chairs:** Bryan Butler and Anne Verbiscer

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<th>Times</th>
<th>Authors (*Denotes Presenter)</th>
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<tr>
<td>10:15 a.m.</td>
<td>[INVITED] Singer K. N. *</td>
<td>The Geology of Pluto [#7005]</td>
</tr>
<tr>
<td></td>
<td>White O. L. Moore J. M.</td>
<td>New Horizons revealed surprising geologic diversity across Pluto. We give an overview of</td>
</tr>
<tr>
<td></td>
<td>Howard A. D. Schenk P. M.</td>
<td>the varied processes sculpting Pluto’s landscapes, including sublimation and redeposition</td>
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<td></td>
<td>Williams D. A. Lopes R. M. C.</td>
<td>of ices, tectonics, glaciers, cratering, and possible cryovolcanism.</td>
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<tr>
<td></td>
<td>Stern S. A. Ennico K. Olkin</td>
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<td></td>
<td>B. Weaver H. A. Young L. A.</td>
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<tr>
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<td>New Horizons Geology and</td>
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<td></td>
<td>Geophysics Team</td>
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<tr>
<td>10:45 a.m.</td>
<td>[INVITED] Buratti B. J. *</td>
<td>Photometry and Albedo Maps of Pluto and Charon [#7023]</td>
</tr>
<tr>
<td></td>
<td>Hofgartner J. Hilier J. H.</td>
<td>Photometric properties of Charon are similar to those of the icy moons of the outer</td>
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<tr>
<td></td>
<td>Hicks M. D. Verbiscer A. J.</td>
<td>planets, but Pluto’s huge differences in albedo — second only to Iapetus — show it is</td>
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<tr>
<td></td>
<td>Stern S. A. Weaver H. A.</td>
<td>a unique, geologically active planet.</td>
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<tr>
<td></td>
<td>Howett C. J. A. Young L. A.</td>
<td></td>
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<tr>
<td></td>
<td>Cheng A. Ennico K. Olkin C.</td>
<td></td>
</tr>
<tr>
<td>11:15 a.m.</td>
<td>[INVITED] Schenk P. * Singer</td>
<td>Impact Craters on Pluto: Size-Frequency Distributions, Morphologies, Terrain Ages [#7043]</td>
</tr>
<tr>
<td></td>
<td>K. Greenstreet S. Robbins S.</td>
<td>Big rocks fall from sky, go boom. After that the fun begins. Crater scars left behind tell</td>
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<td></td>
<td>Bray V. McKinnon W. White O.</td>
<td>tales of Pluto and the Kuiper Belt.</td>
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<tr>
<td></td>
<td>Spencer J. Weaver H. Lauer T.</td>
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<tr>
<td></td>
<td>Moore J. Stern S. A. Beyer R.</td>
<td></td>
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<tr>
<td></td>
<td>Young L. Olkin C.</td>
<td></td>
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<tr>
<td>Time</td>
<td>Authors (*Denotes Presenter)</td>
<td>Abstract Title and Summary</td>
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<tr>
<td>11:45 a.m.</td>
<td>McGovern P. J. * White O. L. Schenk P. M.</td>
<td><em>Tectonism Across Pluto: Mapping and Interpretations</em> [7063] We present structural mapping of Pluto’s encounter hemisphere and assign mapped tectonic features into orientational classes. We consider the implications of our results in terms of what factors control tectonism across Pluto.</td>
</tr>
<tr>
<td>12:00 p.m.</td>
<td>Radebaugh J. * Telfer M. W. Parteli E. J. R. Beyer R. A. Kirk R. L.</td>
<td><em>The Shapes and Distributions of Dunes on Pluto</em> [7069] The dunes of Pluto have forms that vary in size and shape across Sputnik Planitia. They display shapes, spacings, and heights consistent with shapes of dunes seen on other planets, especially elementary forms and snow dunes on Earth.</td>
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<tr>
<td>12:15 p.m.</td>
<td>Lunch Break</td>
<td></td>
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Monday, July 15, 2019  
PLUTO GEOLOGY, COLORS, AND COMPOSITION  
1:30 p.m. Auditorium  
Chairs: Jani Radebaugh and Patrick McGovern  

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<tr>
<td>1:30 p.m.</td>
<td>[INVITED] Olkin C. B. * Howett C. J. A. Protopapa S. Grundy W. M. Buie M. W. Verbiscer A. Stern S. A. Weaver H. A. Young L. A. Ennico K.</td>
<td><em>The Colors and Photometric Properties of Pluto</em> [7045] This paper will focus on our new understanding of the color of Pluto’s surface from the New Horizons mission results. Different terrain units will be discussed. Also an overview of the photometric properties of Pluto’s surface will be presented.</td>
</tr>
<tr>
<td>2:00 p.m.</td>
<td>[INVITED] Grundy W. M. * Cruikshank D. P. Protopapa S. Schmitt B.</td>
<td><em>Pluto’s Surface Composition</em> [7051] Pluto’s surface composition is regionally heterogeneous. Volatile ices of N₂, CO, and CH₄ are mobile on seasonal timescales, interacting with and even sculpting more inert materials such as H₂O, NH₃, CH₃OH, and complex organics.</td>
</tr>
<tr>
<td>2:30 p.m.</td>
<td>Stern S. A. * Weaver H. A. Young L. A. Olkin C. B. Moore J. M. Grundy W. M. McKinnon W. B. Lauer T. R. Cruikshank D. P. Spencer J. R. Gladstone G. R. Ennico K. New Horizons Science Team</td>
<td><em>Pluto’s Far Side</em> [7024] This session will review all we know about the “far side” of Pluto based on the datasets obtained by New Horizons. We will also review future opportunities to advance the study of the far side over the next few decades.</td>
</tr>
<tr>
<td>3:00 p.m.</td>
<td>Umurhan O. M. * Cruikshank D. P.</td>
<td><strong>Cryovolcanism on Pluto: Various Theoretical Considerations</strong>[^7066] Cryovolcanism has been suggested as the culprit responsible for several observed surface features on both Pluto and Charon. We theoretically examine how this might look under conditions appropriate to these bodies.</td>
</tr>
<tr>
<td>3:15 p.m.</td>
<td>Break</td>
<td></td>
</tr>
<tr>
<td>3:45 p.m.</td>
<td>[INVITED] Ahrens C. J. * Umurhan O. M. Chevrier V.</td>
<td><strong>Overview of Thermal and Rheological Properties of Ices on Pluto and Other Bodies of the Outer Solar System</strong>[^7033] Surfaces processes on Pluto and other icy bodies of the outer solar system require detailed knowledge of ice thermophysical and rheological properties. We present a comprehensive compilation of these quantities based on the published literature.</td>
</tr>
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<td>4:15 p.m.</td>
<td>Butler B. J. * Grundy W. M. Gurwell M. A. Lellouch E. Moreno R. Moulet A. Young L. A.</td>
<td><strong>Observations of Pluto’s Surface with ALMA</strong>[^7058] We will describe long-wavelength (~1mm) observations of Pluto with ALMA. Observations were carried out at three longitudes, with enough resolution to easily resolve Pluto. At least one brightness temperature enhancement is seen, near Piri Planitia.</td>
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<tr>
<td>4:30 p.m.</td>
<td>Protopapa S. * Olkin C. Grundy W. Li J. Y. Verbișer A. Cruikshank D. P. Howett C. J. A. Stern A. Weaver H. A. Young L. A.</td>
<td><strong>Photometric Properties of Pluto’s Main Surface Units</strong>[^7054] We present a multi-wavelength, regionally dependent photometric analysis of Pluto’s surface. We will use these properties to quantitively infer the composition of Pluto’s different terrains.</td>
</tr>
<tr>
<td>4:45 p.m.</td>
<td>Schmitt B. * Gabasova L. Bertrand T. Grundy W. Stansberry J. Lewis B. Protopapa S. Young L. Olkin C. Reuter D. Stern A. Weaver H.</td>
<td><strong>Methane Stratification on Pluto Inferred from New Horizons LEISA Data</strong>[^7004] We show that the relative intensity of the CH$_4$ band depth reflect a stratification of CH$_4$. The stratification of CH$_4$ is shown to result from the differential sublimation between N$_2$ and CH$_4$ which tends to concentrate CH$_4$ in N$_2$ ice grains.</td>
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<td>Time</td>
<td>Name &amp; Affiliation</td>
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<tr>
<td>5:00 p.m.</td>
<td>Fayolle M.  Quirico E.  Schmitt B.  Jovanovic L.  Gautier T.  Carrasco N.  Grundy W.  Vuitton V.  Poch O.  Gabasova L.  Protopapa S.  Young L.</td>
<td>Testing Tholins as Analogs of the Dark Reddish Material Covering the Cthulhu Region [#7075]</td>
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<td>Optical properties of dust tholins have been determined in the laboratory and used to feed Hapke models. Fitting MVIC/LEISA data of the Cthulhu region reveals that the dark reddish material is likely highly porous, or may have been processed by GCR.</td>
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<td>We investigate the dark refractory constituent that distinguishes Cthulhu and compare and contrast its signature as the H2O component varies. Our goal is to trace the origin of the material and constrain its mechanisms of formation.</td>
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<td>5:30 p.m.</td>
<td>Keane J. T.  Moore J.</td>
<td>GUIDED DISCUSSION: New Insights on Pluto’s Geology, Colors, Composition and Their Correlations</td>
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<td>6:00 p.m.</td>
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### CHARON

#### 8:30 a.m.  Auditorium

**Chairs:** Lynnae Quick and Benjamin Teolis

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Charon is a geologically complex world, different in character from Pluto. Charon shows signs of tectonic disruption and large scale resurfacing, consistent with an ancient global ocean, now frozen. |
| 9:00 a.m.  | Quick L. C. *                                                                                                                                             | A New Analysis of the Rheology of Cryolava Flows in Vulcan Planitia [#7081]                             |
This paper is an overview of Charon’s global and regional colors, and its photometric properties. |
| 9:45 a.m.  | [INVITED] Cook J. C. * Protopapa S. Cruikshank D. P. Dalle Ore C. M. Grundy W. M.                                                                        | Charon's Surface Composition [#7049]  
This is an invited talk to give a review of what is known about the surface composition of Charon. |
We present combined exospheric modeling and laboratory measurements to quantify the contribution of solid methane photolysis to the surface composition and color of Charon’s red polar cap. |
| 10:30 a.m. | Robbins S. Protopapa S.                                                                                                                                    | GUIDED DISCUSSION: New Insights into Charon as a Large Satellite and Member of the Kuiper Belt |
| 11:00 a.m. |                                                                                                                                                        | Lunch Break                                                                                                 |

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### SMALL SATELLITES AND ORBITAL DYNAMICS OF THE PLUTO SYSTEM

#### 1:00 p.m.  Auditorium

**Chairs:** Kathy Mandt and Ted Stryk

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In this invited talk, we review the properties of the small satellites and how they inform our understanding of the origin of the Pluto system. |

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**Tuesday, July 16, 2019**

**CHARON**  
8:30 a.m. Auditorium

**Chairs:** Lynnae Quick and Benjamin Teolis

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**Tuesday, July 16, 2019**

**SMALL SATELLITES AND ORBITAL DYNAMICS OF THE PLUTO SYSTEM**  
1:00 p.m. Auditorium

**Chairs:** Kathy Mandt and Ted Stryk
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<td>1:30 p.m.</td>
<td>Lauer T. R. * Throop H. B. Showalter M. R. Weaver H. A. Stern S. A. Spencer J. R. Buie M. W. Hamilton D. P. Porter S. B. Verbiscer A. J. Young L. A. Olkin C. B. Ennico K.</td>
<td><em>The New Horizons and Hubble Space Telescope Search for Rings, Dust, and Debris in the Pluto/Charon System</em> [#7041] We searched for rings and dust/debris features during the New Horizons exploration of the Pluto/Charon system. No features were discovered at I/F limits comparable to those at which faint rings had been detected around other solar system objects.</td>
</tr>
<tr>
<td>2:00 p.m.</td>
<td>Showalter M. R. * Porter S. B. Verbiscer A. J. Buie M. W. Helfenstein P.</td>
<td><em>Rotation States of Pluto’s Small Moons and the Search for Spin-Orbit Resonances</em> [#7052] Lightcurves from Hubble data 2010–2019 provide the precise rotation rates and polar precession rates of the Pluto’s small moons. We will compare these results with new models for spin-orbit resonances that allow for the moons’ polar precession.</td>
</tr>
<tr>
<td>2:15 p.m.</td>
<td>Hamilton D. P. * De Santana T.</td>
<td><em>Three-Body and Spin-Orbit Resonances in the Pluto System</em> [#7072] We investigate the history of Pluto’s small satellites numerically, paying particular attention to likely important three-body and spin-orbit resonances.</td>
</tr>
<tr>
<td>2:30 p.m.</td>
<td>Showalter M. Canup R.</td>
<td><em>GUIDED DISCUSSION: New Insights into the Pluto Satellites and the Orbital Dynamics of the Pluto System</em></td>
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**Tuesday, July 16, 2019**

**PLUTO’S GOT ATMOSPHERE — KICKOFF**

3:00 p.m. Auditorium

Chairs: Kathy Mandt and Ted Stryk

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<tr>
<td>3:00 p.m.</td>
<td>[INVITED] Summers M. E. * Young L. A. Gladstone G. R. Strobel D. F. Person M. J.</td>
<td><em>The Composition of Pluto’s Atmosphere</em> [#7077] The Observations obtained by the New Horizons flyby of Pluto have provided a watershed for our understanding of the composition of Pluto’s atmosphere from its surface to near ~1500 km altitude.</td>
</tr>
<tr>
<td>3:30 p.m.</td>
<td></td>
<td><em>Break</em></td>
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The document contains several abstracts presented at a poster session on Tuesday, July 16, 2019, discussing various aspects of Pluto and its atmosphere. Here are the abstracts in a structured format:

### Poster Session: Discovery of Pluto and the Kuiper Belt: The Imperative for Exploration

**Authors:** Spilker B. C., Christiansen E. H., Radebaugh J.

**Abstract Title and Summary:** Revisions to the Online Textbook Exploring the Planets (explane.info): Pluto [ID:7062]

Since New Horizons' flyby, we have learned a lot about the planetary body Pluto. Our project is updating the Pluto chapter of the online textbook Exploring the Planets so college students can be up to date on discoveries associated with Pluto.

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### Poster Session: Pluto’s Got Atmosphere

**Authors:** Jacobs A., Summers M., Gladstone G., Rtl D., Lisse C., Young L., Pesnell D., Gao P., Kammer J., Weaver H., Bertrand T.

**Abstract Title and Summary:** Observations and Theory for Waves in Pluto’s Atmosphere [ID:7065]

Pluto’s atmosphere has an extensive background haze with as many as 20 relatively bright embedded layers within this background haze. We use microphysical models and atmospheric scattering simulations, to analyze the existing observations.

**Authors:** Sickafoose A. A., Bosh A. S., Levine S. E., Person M. J., Schindler K., Zuluaga C. A.

**Abstract Title and Summary:** Stellar Occultations by Pluto: 2017–2018 [ID:7026]

Pluto’s evolving atmosphere has been studied by stellar occultations since the 1980s. New Horizons provided in situ measurements in 2015. We present results from five occultations by Pluto in 2017/2018, which continue the atmospheric monitoring.


**Abstract Title and Summary:** Radio Science Experiment (REX) on New Horizons: Results from the Pluto Flyby [ID:7018]

Summaries of the REX investigations during the Pluto flyby, including an atmospheric radio occultation, radio thermal emission measurements, a bistatic radar experiment, and a system mass determination, are presented.

**Authors:** Mardon A. A., Zhou G.

**Abstract Title and Summary:** Understanding of Pluto Atmospheric Dynamics and Behaviour from New Horizons Mission [ID:7074]

The New Horizons flyby of Pluto and its satellite system in 2015 changed our original understanding of this distant planet and its moons. Amongst this is the renewed information about the structure and composition of Pluto’s atmosphere.

**Authors:** Tucker O. J., Johnson R. E., Bell J., Collier M. R., Farrell W. M., Glocer A., Killen R. M., Saxena P.

**Abstract Title and Summary:** Limits on X-Ray Luminosity from Pluto’s H₂ Corona [ID:7080]

We examine the effect of diffusion and escape of H₂ on the thermal structure of Pluto’s upper atmosphere, and potential limits on its contribution as a source X-ray emission from Pluto’s corona.
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<th>Authors</th>
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</table>
| Ahrens C. J.  Byrne P. | **Characterizing Faults Across the Surface of Pluto [#7036]**  
Distributions and variations of fault systems observed across Pluto’s icy surface suggest that localized conditions may be important to the structural evolution. This preliminary work begins with the mapping and calculating shear stress. |
The highest resolution images, as well as haze-light images of Pluto and Charon, can be processed with stereogrammetry and photoclinometry to extract the highest possible degree of topographic information. |
| Lenhart E. M.  Berrondo M.  Radebaugh J.  Telfer M. W.  Parteli E. | **Application of a Physical Model to Dune Pattern Emergence on Pluto [#7064]**  
Recent images of dunes on Pluto open questions about the movement of loose, sand-sized particles, and the conditions under which this movement can form familiar patterns. We seek to better understand these patterns using physical models. |
| Mills A. C.  Montesi L. G. J. | **Elastic Flexure Around Sputnik Planitia, Pluto, and Evidence for a Very High Heat Flux [#7030]**  
We test if the current topography of Sputnik Planitia and its surroundings contain evidence for a flexural bulge that formed by a large load of nitrogen ice. We find evidence for a very high heat flux when the flexure took place. |
| Robbins S. J.  Schenk P. M.  Singer K. N. | **The Depth-Diameter Relationship of Well-Preserved Impact Craters on Pluto and Charon [#7055]**  
Impact crater depths / Can be measured in many / Ways: We report here. |
We provide a morphological comparison of the blocks that make up chaos terrain on Pluto, Jupiter’s moon Europa, and Mars by measuring block diameters, heights, and axial ratios. We discuss the implications of our results for crustal lithology. |
### Tuesday, July 16, 2019
**POSTER SESSION: PLUTO’S CLIMATE AND REDISTRIBUTION OF VOLATILES**
4:00 p.m.  North Dining Room

<table>
<thead>
<tr>
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Analysis of “matched pairs” of near-infrared spectra of Pluto between 2014 and 2017 indicate a possible increase in CH₄ concentration on the sub-Charon hemisphere, in agreement with global modeling performed following the New Horizons flyby. |
| Shi H. S. Lai I. L. Ip W. H. | **The Long-Term Evolution of Pluto’s Atmosphere and Its Effect on Charon’s Surface Tholin Formation [#7014]**  
We use a coupled treatment based on the energy balance equation to compute the long-term evolution of Pluto’s surface temperature and pressure and applied the DSMC method to explore the corresponding escape dynamics of Charon’s tholin-like materials. |

### Tuesday, July 16, 2019
**POSTER SESSION: BEYOND PLUTO: 2014 MU69 AND THE KUIPER BELT ENVIRONMENT**
4:00 p.m.  North Dining Room

<table>
<thead>
<tr>
<th>Authors</th>
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</table>
The New Horizons flyby of 2014 MU69 “Ultima Thule” provided a close-up view of a pristine cold-classical binary Kuiper belt object [1]. The goal of this poster is to put it in context relative to similarly-sized objects throughout the solar system. |

### Tuesday, July 16, 2019
**POSTER SESSION: PLUTO GEOLOGY, COLORS, AND COMPOSITION**
4:00 p.m.  North Dining Room

<table>
<thead>
<tr>
<th>Authors</th>
<th>Abstract Title and Summary</th>
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</table>
| Ahrens C. J. Chevrier V. F. | **Spectral Behavior of Methane in Binary and Ternary Icy Mixtures in Experimental Pluto Conditions [#7034]**  
Methane when mixed in binary ice mixtures with nitrogen or carbon monoxide show variability in spectral band strengths and shifting. When in ternary mixtures, certain methane bands depend on the ratio of the constituents. |
We use intensity-based registration methods to co-register high-resolution LEISA data with lower-resolution imagery taken during the approach to Pluto, and produce the first global compositional maps of Pluto’s surface. |
| Verbiscer A. J. Showalter M. R. Buie M. W. Helfenstein P. | **The Pluto System at True Opposition [#7050]**  
Photometric properties of Pluto and its five moons from HST observations at the smallest possible solar phase angles. |
### POSTER SESSION: CHARON
4:00 p.m.  North Dining Room

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<tr>
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<th>Abstract Title and Summary</th>
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<tr>
<td>Chen H. Z. Yin A</td>
<td><em>Tectonic History of the Oz Terra of Charon as Revealed by Systematic Structural Mapping</em> [#7007]</td>
</tr>
<tr>
<td></td>
<td>We established a new tectonic evolution history of Oz Terra by conducting a systematic photo-geological mapping across the region, during which fault association and kinematic compatibility was considered. An early compressional event was discerned.</td>
</tr>
</tbody>
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### POSTER SESSION: ORIGIN AND DYNAMICS OF THE PLUTO SYSTEM
4:00 p.m.  North Dining Room

<table>
<thead>
<tr>
<th>Authors</th>
<th>Abstract Title and Summary</th>
</tr>
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<tbody>
<tr>
<td>Jacobson R. A.</td>
<td><em>The Orbits and Masses of Pluto’s Satellites</em> [#7031]</td>
</tr>
<tr>
<td>Brozovic M.</td>
<td>This paper reports on our latest integrated orbits of the satellites and the masses of all bodies in the Pluto system.</td>
</tr>
<tr>
<td>Showalter M.</td>
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<tr>
<td>Verbiscer A.</td>
<td></td>
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<tr>
<td>Helfenstein P.</td>
<td></td>
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<tr>
<td>Perov N. I.</td>
<td><em>Resonances in Pluto’s System</em> [#7001]</td>
</tr>
<tr>
<td></td>
<td>In the frame of the restricted circle plane seven body problem “Pluto-Charon-Styx-Nix-Kerberos-Hydra” (any) “resonances” particles with the satellites motion is considered. Common conditions for the existence of the horseshoes trajectories are found.</td>
</tr>
<tr>
<td>Coppieters B.</td>
<td><em>Can Abkhazia be a State if Pluto is not a Planet? Recognition and Non-Recognition of Status in Astronomy, International Law and Political Science</em> [#7078]</td>
</tr>
<tr>
<td></td>
<td>The research compares definitions of entities emphasizing inherent properties and definitions highlighting interactions between entities and the external world, covering planets in astronomy and states in international law and politics.</td>
</tr>
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6:00 p.m.  END OF DAY 2
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<th>Times</th>
<th>Authors (*Denotes Presenter)</th>
<th>Abstract Title and Summary</th>
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<tr>
<td>8:30 a.m.</td>
<td>[INVITED] Jessup K. L. * Cheng A. Gao P. Luspay-Kuti A. Mandt K.</td>
<td>Photochemistry and Haze Formation [#7032]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Photochemical and haze production models will be reviewed, highlighting the key processes supporting Pluto’s atmospheric structure and thermal balance, and outstanding questions about these topics. Similarities between Titan and Pluto will also be discussed.</td>
</tr>
<tr>
<td>9:00 a.m.</td>
<td>[INVITED] Bertrand T. * Forget F. Toigo A. Hinson D.</td>
<td>Pluto’s Atmosphere Dynamics: How the Nitrogen Heart Regulates the Circulation [#7017]</td>
</tr>
<tr>
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<td></td>
<td>Pluto’s climate is remarkably active. The N₂ icecap within Sputnik Planitia seems to be the heart of the climate system, since it controls the evolution of surface pressure, regulates the general circulation, and triggers atmospheric waves and tides.</td>
</tr>
<tr>
<td>9:30 a.m.</td>
<td>Gladstone G. R. * Kammer J. A. Yung Y. L. Pryor W. R. Stern S. A.</td>
<td>Constraining Pluto’s H and CH₄ Profiles with Alice Lyman-Alpha Observations [#7071]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alice Lyman alpha airglow observations are compared with detailed simulations to extract constraints on H and CH₄ densities in Pluto’s atmosphere.</td>
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<tr>
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<td></td>
<td>The thin, nitrogen-dominated atmospheres of Pluto and Triton have been explored through a series of observations using ALMA. We will highlight our results and look toward future investigations in this presentation.</td>
</tr>
<tr>
<td>10:00 a.m.</td>
<td></td>
<td>Break</td>
</tr>
<tr>
<td>10:30 a.m.</td>
<td>Jovanovic L. * Gautier T. Carrasco N. Vuitton V. Quirico E. Wolters C. Orthous-Daunay F.-R. Vettier L. Flandinet L.</td>
<td>Laboratory Simulation of Pluto’s Atmosphere and Aerosols [#7021]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>We will present laboratory investigation of Pluto’s atmosphere and its aerosols formation to help understand the data provided by the New Horizons spacecraft.</td>
</tr>
<tr>
<td>10:45 a.m.</td>
<td>Krasnopoulosky V. A. *</td>
<td>Photochemical Model of Pluto’s Atmosphere and Ionosphere [#7002]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The detailed model of Titan’s photochemistry is adjusted to Pluto’s conditions during the NH flyby. The model fits all observational constraints, includes ion chemistry, and does not require revision of saturated vapor densities of C₂H₄ and C₃H₆.</td>
</tr>
<tr>
<td>11:00 a.m.</td>
<td>Johnson P. E. * Young L. A. Protopapa S. Schmitt B. Lewis B. L. Stansberry J. A. Mandt K. E. White O. L.</td>
<td>Pluto’s Minimum Surface Pressure and Implications for Haze Production [#7025]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pluto’s surface is heterogeneous despite uniform deposition of haze particles onto it. We use the VT3D energy balance model to investigate if the atmosphere ever becomes sufficiently thin to interrupt haze production, explaining this heterogeneity.</td>
</tr>
</tbody>
</table>
11:15 a.m.  [INVITED] Erwin J. T.  *  

*Atmospheric Escape* [#7048]  
All planetary bodies with an atmosphere experience some process of atmospheric escape. In the context of Pluto, this topic remains active and continues to evolve as the New Horizons’ measurements are considered.

11:45 a.m.  
Lunch Break

Wednesday, July 17, 2019  
**PLUTO’S GOT ATMOSPHERE II**  
1:30 p.m.  Auditorium  
Chairs: Amanda Sickafus and Alissa Earle

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<tr>
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</table>
New Horizons’ SWAP and PEPSSI instruments measured plasma and charged particles. We review the history of studies of the solar wind interaction with Pluto, describe results from these instruments, and compare with models and with remote observations. |
| 2:00 p.m.   | Barnes N. P.  *  Delamere P. A.                                                                 | *Hybrid Simulations of Pluto’s Solar Wind Interaction* [#7076]  
Pluto’s interaction with the solar wind is investigated by comparing simulations to data. |
| 2:15 p.m.   | Mandt K. E.  *  Luspay-Kuti A.                                                                | *Comparative Planetology of the Ion Chemistry at Pluto, Titan, and Triton* [#7047]  
We describe comparative planetology studies between Pluto and Titan and Triton to understand the origin and evolution of nitrogen at Pluto. |
| 2:30 p.m.   | ----                                                                                           | Break                                                                                     |

Wednesday, July 17, 2019  
**PLUTO’S CLIMATE AND REDISTRIBUTION OF VOLATILES**  
3:00 p.m.  Auditorium  
Chairs: Brian Holler and Perianne Johnson

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<tr>
<th>Times</th>
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This talk will explore Pluto’s insolation history and its implications for Pluto’s atmospheric pressure, surface temperatures, and volatile distributions over various timescales. |
| 3:30 p.m.   | [INVITED] Howard A. D.  *  Moore J. M.                                                        | *Climate History of Pluto as Revealed by Its Landscapes* [#7010]  
Pluto’s landforms are dominated by processes involving volatile sublimation, condensation, and flow. These processes are controlled by the several timescales of climate variation: seasonal, obliquity, and long-term evolution. |
<table>
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<th>Time</th>
<th>Speaker(s)</th>
<th>Title</th>
</tr>
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<tbody>
<tr>
<td>4:00 p.m.</td>
<td>Forget F. * Tanguy T.</td>
<td><em>Modeling Nitrogen and Methane Ices and Glaciers on Pluto over Diurnal, Seasonal, and Astronomical Timescales [#7003]</em> To understand the origin and the evolution of Pluto N\textsubscript{2} and CH\textsubscript{4} ice reservoirs, we developed a hierarchy of models simulating the volatile cycles over multiple timescales: years with a 3D atm. model to millions of years with a volatile transport model.</td>
</tr>
<tr>
<td>4:15 p.m.</td>
<td>White O. L. * Moore J. M. Howard A. D. Keane J. T. Schenk P. M. Singer K. N. Stern S. A. Weaver H. A. Olkin C. B. Enrico K. Young L. A. New Horizons Geology and Geophysics Imaging Team</td>
<td><em>Washboard and Fluted Terrains on Pluto as Evidence for Ancient Glaciation [#7008]</em> Our mapping and spatial analysis of Pluto’s washboard and fluted terrains leads us to hypothesize that they represent crustal debris that were deposited after recession of pitted glacial nitrogen ice from a portion of Pluto’s uplands via sublimation.</td>
</tr>
<tr>
<td>4:30 p.m.</td>
<td>Trafton L. M. * Tan S. Stansberry J. A.</td>
<td><em>On the Equilibrium State of Pluto’s Surface Ice [#7070]</em> We investigate the contradiction between the excess atmospheric CH\textsubscript{4} concentration and the apparent lack of saturation in Pluto’s N\textsubscript{2}-rich ice in terms of the composition of a thin, CH\textsubscript{4}-rich boundary layer on the N\textsubscript{2}-rich ice surface near equilibrium.</td>
</tr>
<tr>
<td>4:45 p.m.</td>
<td>Young L. A. * Tan S. P. Trafton L. M. Stansberry J. A. Grundy W. B. Protopapa S. Schmitt B. Umurhan O. M. Bertrand T.</td>
<td><em>On the Disequilibrium of Pluto’s Volatiles [#7039]</em> The volatiles present as ices on Pluto’s surface and in its atmosphere are in state of disequilibrium. There is new work on predicted equilibrium, drivers to disequilibrium, and relaxation timescales.</td>
</tr>
<tr>
<td>5:15 p.m.</td>
<td>Strobel D. Young L.</td>
<td>GUIDED DISCUSSION: New Insights to Pluto’s Atmosphere Composition, Structure, Processes, and Climate Variation</td>
</tr>
<tr>
<td>5:45 p.m.</td>
<td></td>
<td>END OF DAY 3</td>
</tr>
</tbody>
</table>
### Thursday, July 18, 2019
#### BEYOND PLUTO: 2014 MU69 AND THE KUIPER BELT ENVIRONMENT

8:30 a.m. Auditorium  
**Chairs:** Susan Benecchi and John Cooper

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| 8:30 a.m.     | [INVITED] Fornasier S. * Barucci M. A. Dalle Ore C.  | *The Kuiper Belt as the Context for Pluto* [#7012]  
In this work we will give a state of the art overview of the physical properties of the Transneptunians and Centaurs, including composition, size, albedo, bulk density, and rotational and thermal properties. |
The New Horizons flyby of the KBO 2014 MU69 gave the first close-up view of a member of the Cold Classical Kuiper Belt, the most primitive population of small bodies in the solar system. MU69 is a contact binary unlike anything previously seen. |
| 9:30 a.m.     | Benecchi S. D. * Zangari A. M. Verbiscer A. J. Porter S. B. | *Kuiper Belt Lightcurves in Light of the Fly-By Results of 2014MU69* [#7061]  
We briefly review the current state of knowledge about Kuiper Belt lightcurves, we present the impact of geometry on various object configurations, and then attempt to de-bias the reported KBO lightcurve measurements for geometric considerations. |
| 9:45 a.m.     | Cooper J. F. *                                        | *Plasma and Radiation Environment in the Kuiper Belt: Pioneer to New Horizons* [#7056]  
Orbits of Pluto and the Kuiper Belt Objects collectively span plasma and energetic particle radiation environments of the supersonic heliosphere, the heliosheath, and local interstellar space. Time-averaged flux spectra are derived for such regions. |
| 10:00 a.m.    |                                                     | *Break*                                                                                   |

### Thursday, July 18, 2019
#### FUTURE INVESTIGATIONS OF THE PLUTO SYSTEM AND KUIPER BELT

10:30 a.m. Auditorium  
**Chairs:** S. Alan Stern and Kelsi Singer

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| 10:30 a.m.    | Dalle Ore C. M. * Barucci M. A. Fornasier S. Cruikshank D. P. Grundy W. M. Protopapa S. | *Pluto Data Before and After New Horizons: The Takeaway for Future Observations* [#7040]  
We present what we have learned in the comparison of observations of Pluto taken before and after New Horizons, and we draw conclusions on how we should proceed with future observation planning of TNOs. |
| 10:45 a.m.    | [INVITED] Hofgartner J. D. * Buratti B. J. Buie M. W. Bray V. J. Lellouch E. | *Future Spacecraft Missions to the Pluto System* [#7022]  
An orbiter mission to the Pluto-Charon system would make fundamental contributions to all three crosscutting themes (formation, habitability, and workings) of planetary science. |
| 11:15 a.m.    |                                                     | *Lunch Break*                                                                             |
## ORIGIN AND DYNAMICS OF THE PLUTO SYSTEM

### Thursday, July 18, 2019

**Auditorium**

**Chairs:** Douglas Hamilton and Kirby Runyon

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<td>1:00 p.m.</td>
<td>[INVITED] Neveu M. * Canup R. M. Kratter K. M.</td>
<td>On the Origin of the Pluto System [#7027] We describe constraints and review models for the origin of the Pluto-Charon binary and the small moons Styx, Nix, Kerberos, and Hydra. We also highlight open issues and discuss implications.</td>
</tr>
<tr>
<td>1:30 p.m.</td>
<td>Nimmo F. * McKinnon W. B.</td>
<td>Geodynamics of Pluto [#7013] Limited geophysical data suggest a partially- or fully-differentiated Pluto with a rigid, porous ice shell and a subsurface ocean that has been slowly refreezing, leading to surface expansion and, potentially, cryovolcanism.</td>
</tr>
<tr>
<td>2:00 p.m.</td>
<td>Keane J. T. * Matsuyama I.</td>
<td>True Polar Wander of Pluto [#7046] Pluto is a unique world where rotational dynamics, volatile transport, and geophysics collide. We will discuss past, current, and future work that use this confluence to explore Pluto’s interior and geologic history.</td>
</tr>
<tr>
<td>2:15 p.m.</td>
<td>Kamata S. * Nimmo F. Sekine Y. Kuramoto K. Noguchi N. Kimura J. Tani A.</td>
<td>An Interior Structure Model of Pluto that Solves its Geophysical and Geochemical Mysteries [#7009] Pluto is mysterious; extremely cold and depleted in heat but possesses a subsurface ocean; an ocean is present, but the overlying ice shell is cold; surface is rich in nitrogen unlike comets. These mysteries are solved by a single, simple idea.</td>
</tr>
<tr>
<td>2:30 p.m.</td>
<td>Runyon K. D. * Metzger P. T. Stern S. A. Bell J.</td>
<td>Dwarf Planets are Planets, Too: Planetary Pedagogy after New Horizons [#7016] Teaching students the natural organization of the solar system — especially dwarf planets like Pluto — benefits from ignoring the IAU planet definition and using the precedent set by planetary scientists counting dwarf planets as a class of full planet.</td>
</tr>
<tr>
<td>2:45 p.m.</td>
<td>[INVITED] McKinnon W. B. Glein C. R. Rhoden A. R. *</td>
<td>Formation, Composition, and History of the Pluto System: A Post-New-Horizons Synthesis [#7067] This talk draws on the phenomenal results of the 2015 New Horizons encounter with the Pluto system, and aims to synthesize and summarize what we have learned, highlighting some of the less understood or appreciated aspects of the system’s evolution.</td>
</tr>
<tr>
<td>3:15 p.m.</td>
<td>McKinnon W. Parker A.</td>
<td>GUIDED DISCUSSION: Origins of the Pluto System and the Future of Pluto — Kuiper Belt Exploration</td>
</tr>
<tr>
<td>3:45 p.m.</td>
<td></td>
<td>CLOSING ANNOUNCEMENTS</td>
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   S. Fornasier, M. A. Barucci, and C. Dalle Ore ........................................... 7012

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SPECTRAL BEHAVIOR OF METHANE IN BINARY AND TERNARY ICY MIXTURES IN EXPERIMENTAL PLUTO CONDITIONS. C.J. Ahrens and V.F. Chevrier, 1Arkansas Center for Space and Planetary Science, Fayetteville, AR 72701 (ca006@email.uark.edu).

Introduction: Pluto’s volatile surface ices are predominantly methane (CH₄), nitrogen (N₂), and carbon monoxide (CO) as observed by the NASA New Horizons fly-by [1-3]. However, the development of physical and mineralogical models requires new laboratory data for interpreting these mission observations. The New Horizons Linear Etalon Imaging Spectral Array (LEISA) data consists of the observational wavelength range 1.25 μm – 2.5 μm [4]. Therefore, spectral data acquired under experimental Plutonian conditions would be ideal to compare with LEISA data and for extending theoretical modeling of mineralogical effects on ices.

Pluto’s surface temperatures range from 33 K – 55 K (though can be > 33 K in certain seasons or cold-trap settings) with a surface pressure of approximately 14 – 25 μbar [5-6]. This temperature range gives rise to potential phase changes and binary/ternary mixture behavior. Differing ice abundances and interactions therefore play many roles in the development of mineralogical structures, different localized sublimation behavior, and geological or rheological processes [3, 7-8]. However, spectral characteristics of ice (binary and ternary) mixtures in the system N₂-CH₄-CO remain poorly studied. CH₄ in N₂ is particularly of interest due to the observed presence of two phases: one highly diluted in solid beta-nitrogen and another that is still unknown, but hypothesized to be a segregated layer in patches or intimate with the diluted phase [9]. CH₄-CO mixture, however, has a lack of literature and experimental data at Pluto’s low temperature and pressure conditions. Finally, CH₄-N₂-CO ternary mixtures also pose an interesting question to phase changes and behavior at low temperatures and pressures.

Experimental Setup: The Pluto simulation chamber at the W.M. Keck Laboratory for Space and Planetary Simulations at the University of Arkansas is 1.31 m. in length and 0.56 m. in diameter [10-11]. This stainless steel vacuum chamber includes FTIR capabilities and a camera system for visual observation of the ice samples and phase behavior. The experimental protocol for this task is as follows: a main gas constituent (CH₄) is mixed in a set molar ratio with a second constituent (CO or N₂) within a pre-mixing chamber connected to the simulation chamber. Then the mixture is injected into the cryo-vacuum pre-chilled simulation chamber at a temperature of 10 K and 14 μbar, and condenses onto the vertical coldhead where recording from the FTIR and camera begins. The mixture is then heated by 1 K, 5 K, or 10 K increments, which helps determine the temperature of phase transition detected by spectroscopy or optical instruments. FTIR spectra is acquired using a Thermo Nicolet 6700 Spectrometer with a TEC InGaAs detector at a resolution of 2 and 450 second intervals. Long acquisition times allows a higher resolution to identify and separate more complex intimate mixtures. The spectra are collected using the OMNIC software. Peak changes, shifts, and band areas can be analyzed using this software for ice structure behavior.

Spectral Results: CH₄-N₂ mixtures, according to Prokhvatilov and Yantsevich [12], show specific phase transitions within Pluto’s temperature range. N₂ alpha-beta transition occurs at ~35 K at 1.5 μm (Figure 1), whereas CH₄ II to CH₄ I transition occurs at ~21 K, mainly noticeable in the pure CH₄ ice samples.

Figure 1: IR spectra of binary mixture CH₄:N₂ = 0.5:0.5 mol ratio at various temperatures (20 K top spectrum, increase in 10 K increments). Starred bands (*) denote nitrogen. The box outlines the observation of the 1.46 μm band starting at > 40 K. Spectra has been offset for clarity.

With the CO-CH₄ mixtures, our experiments (Figure 2) show that by increasing the ratio percentage of CO in the mixture, the more prominent and wider the 2.38 μm CO band becomes and, in turn, the methane bands appear to weaken. A weaker 1.58 μm band does appear with these mixtures. However, the 2.35 μm methane band does not appear in these mixtures. This may provide a further study on how methane bands between 2.2 - 2.5 μm may not interact with CO to form the 2.35 μm CO band or that this band simply only appears when mixed with N₂.
With the preliminary ternary mixtures, our experiments (Figure 3; 10% CH₄: 50% N₂: 40% CO) show that by increasing the temperature of the chamber, the nitrogen micron band at 1.5 μm becomes more prominent. The 2.38 μm CO band remains fairly stable as temperature increases. It is interesting to note the 2.194 μm CH₄ band weakening from 20 K – 50 K and will be studied more in future experiments.

**Figure 3:** 10% CH₄, 50% N₂, 40% CO ternary mixture at varying temperatures. Shaded sections signify constituent: CH₄ (blue), N₂ (yellow), CO (red). Spectra offset for clarity.

The preliminary ternary experiments is also being compared to binary mixtures. In the initial study, we have found that the methane bands are more prominent with higher ratios of methane and nitrogen. The 2.38 μm CO band has shifted slightly (< 0.2 μm) from the binary CO-CH₄ to the ternary mixtures (Figure 4).

**Figure 4:** Binary and ternary ice mixture comparisons at 40 K temperatures. Binary mixtures at 0.5:0.5 molar ratios. Ternary 1: 10% CH₄, 50% N₂, 40% CO mixture. Ternary 2: 50% CH₄, 40% N₂, 10% CO mixture. Shaded sections signify constituent: CH₄ (blue), N₂ (yellow), CO (red). Spectra offset for clarity.

**Conclusions:** CH₄-N₂ mixtures show the phase transitions using the FTIR instrumentation, allowing for further investigation to other potential phase transitions. CO-CH₄ mixtures show a possible interaction of certain methane spectral bands having possible dependence on the molar ratio amount of CO present. In ternary mixtures, the amount of N₂ or CO could influence the strength of the CH₄ bands. This implies the polarity interactions of the volatiles (i.e. CH₄-N₂ being nonpolar-nonpolar; CH₄-CO being nonpolar-polar) having an observed effect on band strength and shifting.

This observed behavior could influence the evolution of certain mineralogical aspects of Pluto, such as boundary layers and glaciation. Laboratory measurements of planetary surface compositions provide crucial support to science instrument measurements from ground-based, orbital, and lander observations.

**Acknowledgments:** This work was funded by NASA Solar System Workings Grant 80NSSC19K0163.

**References:**

[1] Stern, S. et al. (2015), AAS DPS 47, Abstract 100.01
CHARACTERIZING FAULTS ACROSS THE SURFACE OF PLUTO. C. J. Ahrens1, P. K. Byrne2, V.F. Chevrier1, 1Arkansas Center for Space and Planetary Science, Fayetteville, AR 72701 (ca006@email.uark.edu), 2Planetary Research Group, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695.

Introduction: The New Horizons mission imaged numerous tectonic structures on the surface of Pluto [1-3]. The distributions and variations of these fault systems suggest that localized conditions (i.e. stresses, crack propagation, displacement) may be important to the structural evolution. Several fundamental questions motivate this study, including: What are the various morphological structures of these fault systems? Do these morphologies differ across the Pluto surface and, if so, how? And what roles does local differences in composition, stress, etc., play in how faulting on Pluto manifest?

To better understand Pluto’s multiple faults, we identify and map key examples of characteristic fault morphologies (laterally offset pre-existing features, strained nearby geologic structures) from New Horizons images.

We have mapped 17 distinct fault areas on the surface (Figure 1). Here, we present results from that mapping, with particular focus on faults in differing compositional settings [4]. Specifically, we investigated the Virgil Fossae in the water-ice-dominant Cthulhu Macula region and, as a comparison to the Sleipnir Fossa in the nitrogen-methane-dominant eastern close-encounter hemisphere.

Morphological classification: We map 17 faulted regions on Pluto as separate sets, though some morphological characteristics appear similar in a common region (i.e. Virgil and Beatrice Fossae). The morphologies include fracture trends and branching, overlying or offset surrounding environments, and orientations. A preliminary focus was done on four different fault regions based on morphology: Sleipnir Fossa, South Voyager Terra, Djanggawul Fossae, and Virgil Fossae (Figure 2). Structures within Sleipnir Fossa have a radial morphology with numerous intersecting troughs with a NE-SW trend (Figure 3A); this region has a dominantly methane-nitrogen composition [4]. Southern Voyager Terra, a region with a dominantly methane-carbon monoxide composition [4], hosts thin fractures overlain by craters and fluted terrain that have a dominant strike of NW-SE (Figure 3B). Djanggawul Fossae have multiple troughs, with smaller fractures (< 3 km width, ~60 km length) cross-cut by larger, wider faults (5.5 km width, ~340 km length) with strikes of NW-SE (Figure 3C). These structures are in a nitrogen-carbon monoxide dominated area [4]. The Virgil Fossae fractures are relatively angular in the fault branching morphology. However, the strikes remain consistent in a NE-SW direction (Figure 3D). These tectonic features occur in the water-ice dominated area of Cthulhu Macula [4].

Preliminary Stress Results: Foster and Nimmo [5] approximated fault topography with a cosine curve, and predicted the maximum resolved shear stress on that fault, \( \sigma_{s-max} \). The value of \( \sigma_{s-max} \) is given by [6-7]:

\[
\sigma_{s-max} = \frac{\rho_c g h}{2 e} \frac{\lambda}{\tau_c} \left( \frac{\lambda}{\tau_c} \right)^{\frac{\pi}{2}}
\]

where \( \rho_c \) is the density of the faulted basement material (in the case of Pluto, water ice), \( g \) is the acceleration due to gravity, \( h \) is the maximum vertical displacement of the fault (at a vertical precision of ~100 m [3], \( e \) is the base natural logarithm, and \( \lambda \) is the horizontal displacement of the fault trough. The minimum elastic thickness (\( T_e \)) used in these calculations was 10 km [8].

In our preliminary calculations, taking an average of six topographic profiles at each fault site, the maximum shear stress are shown in Table 1.

<table>
<thead>
<tr>
<th>Fault region</th>
<th>( \sigma_{s-max} ) (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleipnir Fossa</td>
<td>135.3</td>
</tr>
<tr>
<td>South Voyager Terra</td>
<td>63.2</td>
</tr>
<tr>
<td>Djanggawul Fossae</td>
<td>73.4</td>
</tr>
<tr>
<td>Virgil Fossae</td>
<td>252.3</td>
</tr>
</tbody>
</table>

It is interesting to note that the higher shear stress values correspond to areas that are rich in the water ice and methane-nitrogen ice. The differing compositions of each region may therefore give us insight to the roles of these ices in fault morphology and localized stress.

Conclusions: The morphologies and orientations of several sets of faults on Pluto give us insight into the varying lithospheric properties present on the body. For example, differences in mechanical strength may be responsible for variations in maximum resolved shear stresses on several of the fault populations we map.

We are currently acquiring more topographic profiles for the remainder of the faults we identify across Pluto, with which we will acquire a better understanding of regional variations in fault morphology, driving stresses, mechanical properties of Pluto’s icy crust.

Figure 1: Map of Pluto with 17 designated fault regions from this study. Preliminary regions: Sleipnir Fossa (red), South Voyager Terra (yellow), Djanggawul Fossae (blue), and Virgil Fossa (green).

Figure 2: Examples of fault morphologies from this preliminary study. A) Sleipnir Fossa (radial, curved); B) South Voyager Terra (shallow); C) Djanggawul Fossae (curved); D) Virgil Fossa (angular, branched).

Figure 3: Rose diagrams from each of the preliminary regions. A) Sleipnir Fossa; B) South Voyager Terra; C) Djanggawul Fossae; D) Virgil Fossa.
OVERVIEW OF THERMAL AND RHEOLOGICAL PROPERTIES OF ICES ON PLUTO AND OTHER BODIES OF THE OUTER SOLAR SYSTEM. C. Ahrens¹, O. M. Umurhan²,³, and V. Chevrier¹, ¹University of Arkansas (ca006@email.uark.edu, vchevier@email.uark.edu), ²SETI Institute, Mountain View, CA or-kan.m.umurhan@nasa.gov, ³NASA Ames Research Center, Moffett Field, CA,

Introduction: Pluto’s surface is an active low temperature physics laboratory [1]. From the solid-state convection-induced pit featuring ovoid patterns of Sputnik Planitia (SP), the glacial flow onto SP from the surrounding highlands of Eastern Tombaugh Regio, the ubiquitous glacially eroded terrain, the high-standing bladed terrain constructs of Tartarus Dorsa, the washboard terrain in surrounding Voyager and Pioneer Terra, the scarps of Piri Planitia, the putative cryovolcanic constructs of Wright and Picard Mons, and the apparent flow-emplaced tholin-covered surfaces around Virgil and Inanna Fossae, Pluto’s surface exhibits geology shaped by volatile materials in all phases [2]. Understanding the geophysics of these features and crafting an evolutionary history of these places hinges on knowing the thermophysical and rheological properties of the materials in question. This presentation is an outline of the review manuscript in preparation intended as a compilation of what is known about these volatile ice material properties in the temperature range 20-91K. We will also discuss the methods by which these quantities are measured in laboratory experiments.

The cast and roles: The main volatile ices found on Pluto as observed by New Horizons were N₂, CH₄, CO, and these were found alongside relatively stable and dark H₂O ice. The low albedos are likely due to the spectroscopically identified presence of organic “tholin” compounds painted upon surface H₂O. The current surface temperature conditions are around 40K, but owing to their highly insulating nature, the volatile ices can reach temperatures can reach temperatures as high as 60K underneath as little as 500-750m of cover. Interestingly, these surface volatiles are not very far from their triple points which is probably why Pluto’s surface geomorphology shows rich variety. Given the ubiquity of these materials on the icy bodies of the outer solar system --e.g., like Titan, Triton as well as the Kuiper Belt objects like Eris and Makemake -- it will be of utility to compile the known thermophysical and rheological properties of these volatiles in the temperature range 20-91K. By way of example below, we present a limited selection of various landforms found on Pluto in relation to their attendant processes and we highlight the required physical inputs necessary to explain and predict what is happening in them.

Solid state convection and Sputnik Planitia. Spectroscopy of SP’s shows significant abundance of all three volatiles N₂, CH₄, CO and the leading interpretation of the observed ovoid patterning is that SP is filled with predominantly N₂ ice undergoing solid state convection (Figure 1A) [3]. Modeling infinite Prandtl number convection requires understanding (i) the rheology of the convecting material (i.e., how the ice deforms when stressed), (ii) the temperature dependence of solid density (its equation of state) and (iii) coefficient of thermal expansion, (iv) the thermal conductivity. Moreover, knowledge of these quantities is needed for these materials as binary and ternary alloys. SP probably sits upon a H₂O ice bedrock that likely passively conducts geothermal energy into the volatile ice layer above.

Glacial flow and glaciated terrain. In addition to rheology, understanding the observed glacial flow of volatile ices (Figure 1B) requires reliable knowledge of the flowing material’s phase transitions and their associated energies [4,5]. For example, owing to their strong insulation, thick layers of N₂ ice might flow as a wet-glacier requiring reliable data about liquid N₂ like its density and, furthermore, how effective tracers diffuse through the liquid. Also, N₂ ice glaciers likely flow over and erode a H₂O ice bedrock. As such, it is essential to have information on the compressive and brittle fracture strength, Young’s modulus in order to assess rates of erosion and other related surface modification processes.

Bladed terrain and pitting on SP. Tartarus Dorsa’s high standing bladed terrain structures are believed to be CH₄ instances of penitentes found in dry terrestrial climes like the Atacama Desert (Figure 1C) [6]. The development of penitentes involves a subtle atmosphere-surface exchange processes requiring detailed knowledge of vapor pressure curves and latent energies [7,8]. Supporting such structures requires reliable information on grain-size dependent rheology of CH₄, and (perhaps) H₂O-CH₄ clathrates. Suncups, which are muted versions of penitentes, are thought to describe the widespread pitting seen on convection cells in SP. These pits involve the complex interplay of insolation, temperature, reradiation rheology and sublimation [9].

Wright/Picard Mons, Virgil Fossae and cryovolcanism. Wright Mons (Figure 1D) and Picard Mons are considered putative cryovolcanic structures [10] while the darkened ammonia laden lanes found inside various fossae like Virgil Fossae are suggested to be emplaced by some kind of cryovolcanic flow [11]. H₂O cryovolcanism has been proposed as the responsible mechanism in these places. To test these hypothe-
sis through modeling, information about the viscosity of H$_2$O ice slurries, with and without thickening agents like NH$_3$ and CH$_3$OH (methanol).

**Quantities of interest:** The review manuscript will contain a comprehensive compilation of the aforementioned quantities references in the 20-90K range in the form of tables and graphs. This discussion will include literature references to all pertinent published laboratory and theoretical results. Our attention will be restricted to pressures not to exceed 1 MPa. Each section will contain a terse primer discussing how various quantities are used in modeling associated physical processes, e.g., a discussion on solid-state convection will review the definition of the Rayleigh number, how it is understood and what basic inferences can be drawn from it. For H$_2$O and each of the main the volatiles of interest -- and (wherever this information is available) their alloy mixtures -- we will compile all published information about:

**Thermophysical data:** including the temperature dependence of (i) coefficients of thermal expansion, (ii) specific heats, (iii) latent energies, (iv) liquid and solid densities and (v) coefficient of thermal conduction. These will include the phase transitions

**Vapor Pressure data:** Tables and formulae describing vapor pressures.

**Rheological data:** The ice viscosity dependencies including activation energies, grain size dependence, a discussion on the preferred mode of deformation (e.g., whether by creep, grain-boundary sliding, etc.) We will include known laboratory measurements on water ice slurries.

**Material properties:** The temperature dependencies of (i) Young’s modulus, (ii) compressive strength, (iii) brittle fracture strength.

**Transport properties:** The ability of trace species to diffuse through solid and liquid phases of each material. Diffusion coefficients will be tabulated for several species.

**Mitigating matters and open questions:** The many outstanding challenges in obtaining these quantities will be discussed. For example, there are challenges to experimental work, mainly the control of the ice sample production, accidental sticking of the ice sample with instruments, contamination of sample, and technical support for measurements and instrumentation [12]. A tentative list of challenges and questions, which will be elaborated at length in the final manuscript, include:

- Understanding rheological properties of Pluto’s surface can help us answer how the observed geomorphology took root,
- What is the composition and structure of subsurface material? How does this effect what is seen on the surface?
- What is the structure of surface material (especially in pure vs complex mixtures)? Can we understand the observed appearances based on published data or are further experiments warranted?
- What are the power sources and processes driving geologic evolution?
- What is the extent and quality of cryovolcanism on places like Pluto?
- What is the diffusion coefficients of materials in liquid/slushy states in relation to volatile transport? Can this be used to explain the observed surface coloration?
- What are the effects of organic/tholin particles (as a bulk or intimate ice mixture)?

**References:**
PLUTO’S INTERACTION WITH THE HELIOSPHERE. F. Bagenal¹, R.L. McNutt, Jr.² D.J. McComas³, H.A. Elliott⁴, M.E. Hill², P.Kollmann², C.M. Lisse², P.A. Delamere⁵, N.P. Barnes⁵, and the New Horizons Science Team.¹Laboratory for Atmospheric & Space Physics, University of Colorado (Boulder, CO bagenal@colorado.edu), ²Johns Hopkins University Applied Physics Laboratory (Laurel, MD), ³Department of Astrophysical Sciences, Princeton University (Princeton, NJ), ⁴Southwest Research Institute (San Antonio, TX), ⁵Department of Astrophysical Sciences, Princeton University (Princeton, NJ), ⁶Geophysical Institute, University of Alaska Fairbanks (Fairbanks AK)

The scientific objectives of NASA’s New Horizons mission include quantifying the rate at which atmospheric gases are escaping Pluto and describing its interaction with the surrounding space environment. The two New Horizons instruments that measure charged particles are the SolarWind Around Pluto (SWAP) instrument and the Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) instrument. This paper first reviews the history of studies of Pluto’s interaction with the distant solar wind. We then describe results from these instruments when New Horizons flew past Pluto in July 2015 at a distance of 32.9 astronomical units (AU) from the Sun. We also compare these results with model explorations of the interaction and with remote observations of Pluto obtained during 2015.
Hybrid Simulations of Pluto's Solar Wind Interaction. N. P. Barnes¹ and P. A. Delamere¹, ¹University of Alaska Fairbanks (npbarnes@alaska.edu), ²University of Alaska Fairbanks (padelamere@alaska.edu).

The Interplanetary Magnetic Field (IMF) strength during the Pluto flyby has been inferred based on plasma data from the SWAP instrument [1]. This was done by making comparisons between a hybrid simulation (kinetic ions, fluid electrons) and SWAP data via a detailed model of the SWAP instrument. The ability of kinetic simulations to include arbitrary ion velocity distributions allowed us to reproduce most of the details of the energy spectrograms produced by SWAP. Structural elements of the wake like the width of the heavy ion tail, heavy ion energies, and the thermal pressure profile were found to be sensitive to both IMF and the presence of interstellar pick up hydrogen in a shell distribution [2]. These results, together with new simulations that include an updated solar wind model that incorporates interstellar pick up helium are presented.


**Introduction:** Lightcurve observations, the change of an object’s reflectance over time, of Kuiper Belt Objects (KBOs) require large amounts of telescope time, on moderate to large telescopes (2.5-8m) spaced in time, to properly sample the full set of possible rotation periods. To date these periods range from 3.9 hours (Haumea [1]) to 154 hours (Pluto-Charon [2]) with an average of 7 to 9 hours [3,4,5] apparently dependent upon where the objects are located in the Kuiper Belt. The amplitudes of the lightcurves provide information about the ellipticity of the objects themselves, however, this information is coupled with observing geometry (primarily effect) and physical surface properties (secondary effect). For example, a highly elongated object rotating in a face-on orientation will present a very low amplitude lightcurve then a fully elliptical object in the same configuration. In this presentation we briefly review the current state of knowledge about Kuiper Belt lightcurves, we present the impact of geometry on various object configurations, and then attempt to debias the reported KBO lightcurve measurements for geometric considerations providing a revised estimate for contact-binary fractions for the different dynamical populations.

**Geometric Considerations/Biases of Observations:** The most fundamental observation one can make of a distant object is the change of its reflectance over time. An elongated object will present a double-peaked lightcurve whereby it reflects more light when viewed equatorially than at the pole, assuming that the object is in simple rotation around the shortest axis. Other factors that will affect the observed lightcurve include: the sphericity of the object (a perfectly spherical objects with minimal surface inhomogeneities will present a ~flat lightcurve), albedo patches due to different surface composition, the object being a binary, contact binary or having some other irregular shape and the phase angle of observation – higher phase angles appear to result in larger amplitudes [7]. The average effect of each these considerations can be modelled in a statistical sense, however the specific effect of these on any single object requires a significant amount of dedicated telescope time for distant KBOs, and in some cases, either facilities that allow for high resolution imaging or spacecraft in positions outside of Earth’s orbit, like New Horizons, to provide for observations from different geometric configurations.

Since discovery of the first KBO [8] astrometry and photometry have been the primary means for understanding the locations, shapes and surface colors of these objects. While it is relatively easy to construct highly temporally resolved lightcurves for near Earth and main belt asteroids, KBOs have proven much more difficult since the majority of them have V>20. Integration times are typically 5-15 minutes per photometric point depending on telescope size and desired signal-to-noise resulting in 40-100 datapoints on an average 9 hour rotation period assuming constant integration. Most observing programs sample multiple targets over a few consecutive nights so coverage on single objects is rarely dense limiting full shape interpretation.

**A Review of Kuiper Belt Object Lightcurves:** Summary studies of the KBO lightcurve database at progressive intervals have attempted to characterize the different dynamical populations. However, most lightcurves are not uniquely identified as single or double-peaked, and many flat lightcurves are not reported. Duffard et al. [9] used Maxwellian fits to the published rotation frequencies distribution and found 7.35 hours for the combined KBO and Centaur dataset and 7.71 hours for KBOs alone and 8.95 hours for Centaurs. A study by Benecchi & Sheppard [10] showed statistical differences between the Classical-Scattered and Classical-Resonant populations with Classical objects having larger amplitude lightcurves then all other populations. Evidence for larger amplitudes among smaller objects is further supported by the work of a Hyper-Suprime Camera variability survey of respectively fainter (and smaller) KBOs by Alexandersen et al. [11]. Recent work by Thirouin & Shppard [12] estimated a high contact-binary fraction, up to 40%, among resonant objects. They also found Cold Classicals to have lightcurves averaging 9.48±1.53 hours when separated out from the KBO population in general, for which the average rotation period was revised to 8.45±0.58 hours [13]. They estimated that the contact binary fraction for Cold Classicals, 10-25%, is significantly less than that of the Resonant population.

**Debiasing the Lightcurve Database:** A statistical study was carried out by Lacerda [14] to estimate the detectability of KBO lightcurves assuming on an am-
plitude threshold since, in general, amplitudes are easier to measure robustly for KBOs than shapes. They considered the implications of sphericity and observing geometry at a basic level, however, they provide no specific numeric results since the lightcurve database at the time of write was quite small. They indicate that over time comparison of KBO lightcurves to those of asteroids will be able to tell us whether the KBO shapes are primarily collisional or accretionally derived. In our analysis of the 2014 MU69 lightcurve we modelled the impact of a primarily face-on geometry coupled with a contact binary or elliptical object (Figure 1) on the observed photometry. The primary implication of the fly-by observations [15] coupled with the earth-based lightcurve campaign is that the contact binary fraction of the different dynamical populations is likely being underestimated which we will attempt to quantify.

**References:**

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**Figure 1.** (Top): Model ellipsoidal lightcurve results for the full range of pole inclinations based on the work of Connolley & Ostro 1984. (Bottom) Model contact binary light curves for the full range of pole inclinations assuming both objects are completely spherical, there is no “neck” and that the light reflected from each object is exactly proportional to the visible object area. The 14° inclination of 2014 MU69’s pole relative to the Earth is highlighted in red on each of these plots and changes by a factor of 6 between the two configurations. While these models are both simplistic, for a lightcurve amplitude as large as the scatter in our data, 0.15 magnitudes, to be produced would require a contact binary pole inclination of ≥52° or an ellipsoidal pole inclination of ≥40° (gray area in each plot). From Benecchi et al. [16].
PLUTO’S ATMOSPHERE DYNAMICS: HOW THE NITROGEN HEART REGULATES THE CIRCULATION. T. Bertrand¹, F. Forget², A. Toigo³, D. Hinson⁴, ¹Space Science Division, NASA Ames Research Center Moffett Field, CA 94035, USA (tanguy.bertrand@nasa.gov), ²Laboratoire de Météorologie Dynamique, IPSL, CNRS, Sorbonne Université, Paris, France (forget@lmd.jussieu.fr), ³Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, United States (anthony.toigo@jhuapl.edu), ⁴Carl Sagan Center, SETI Institute, Mountain View, CA 94043, USA, ⁵Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA (dhinson@stanford.edu)

Introduction: Pluto’s tenuous atmosphere is mainly nitrogen and is in solid-gas equilibrium with the surface nitrogen ice [1]. Over the past three decades, Earth-based stellar occultations have been an effective method to study the evolution of its temperature, composition, pressure, and density [e.g. 2-7]. In particular, these datasets revealed (1) a much warmer atmosphere (70-100 K) than the surface (40 K), with a strong inversion in the first 20 km above the surface, (2) a threefold increase of surface pressure since 1988, and (3) global-scale oscillations in the vertical density and temperature profiles [8-10], which could be due to inertia-gravity waves and atmospheric tides forced by diurnal variations of N2 sublimation [11,12]. This unique atmospheric structure and activity hinted at an exotic atmospheric circulation regime.

In 2015, the observations made by the New Horizons spacecraft revealed an astonishing world and provided unprecedented constraints on the nature of Pluto's surface and on the state of its atmosphere [13-16]. Although no atmospheric diurnal variations were observed nor were clouds unambiguously detected [17,18], hints of dynamical activity were highlighted by magnificent haze layers, possibly due to gravity waves arising from sublimation and orographic forcings [19]. Evidence of eolian activity was provided by some observed surface features, interpreted to be wind streaks and linear dunes [20].

Finally, Global Climate Models of Pluto’s atmosphere (GCMs) have recently emerged to explore in deeper details the dynamics of Pluto's atmosphere [21,22]. At the Pluto conference, we will review our knowledge of Pluto’s dynamics and present the latest results obtained with a post-New Horizons version of the Pluto GCM developed at the Laboratoire de Météorologie Dynamique (LMD).

Challenges of modeling Pluto’s atmosphere: Because Pluto orbits far from the Sun, its seasonal cycle is much longer than on the Earth (one Pluto year is 248 Earth years). Above all, Pluto receives very little energy, which results in low sublimation-condensation rates and slow surface processes. This is an issue for Pluto GCMs because simulations need to be performed over many Pluto years in order to be insensitive to the initial state, which requires significant computing time. To solve this issue, a volatile transport model of Pluto is used to create initial states for the GCM which are the results of 30 million years of volatile ice evolution and contain equilibrated combinations of surface conditions, such as soil temperatures and ice distributions [23]. This approach enables 3D GCM simulations of Pluto to be performed typically from 1984 to 2015, the first 20 years corresponding to a spin-up time for the atmosphere.

Near surface circulation: GCM studies showed that near-surface winds on Pluto are controlled by the topography and the N2 condensation-sublimation flow [21,22]. They showed that down-slope katabatic winds unavoidably dominate everywhere on Pluto's globe, as a result of the surface being much colder than the atmosphere. At the locations close to N2 ice deposits, katabatic winds may be balanced during daytime by N2 sublimation flows, and strengthened during nighttime by condensation flows.

Within Sputnik Planitia, the prominent equatorial N2 ice sheet, the LMD GCM predicts an intense nearsurface western boundary current in 2015, which is consistent with the dark wind streaks observed on the icy plains of this region. This atmospheric current could also explain the differences in ice composition and color observed in Sputnik Planitia, and could play a role in the formation of the cold near-surface atmospheric layer south of the basin as seen by New Horizons [23].

General circulation in the upper atmosphere: In addition, we find that this peculiar near-surface flow inside Sputnik Planitia leads to a significant transport of N2 from the northern to the southern hemisphere, which is enough to trigger westward winds at all latitudes, by conservation of angular momentum. Thus, we find that the general circulation of Pluto’s atmosphere is dominated by a retro-rotation, with zonal westward winds reaching 8-13 m s⁻¹ at altitudes 20-250 km. Similar results are obtained regardless of the N2 ice distribution outside Sputnik Planitia.
Multi-year simulations of Pluto’s climate: We extended the LMD GCM simulation at relatively low resolution to about three Pluto years. We find that the retro-rotation regime is maintained during most of Pluto’s year, with maximum westward winds centered above Sputnik Planitia. This is because there is always enough cross-equatorial transport of gaseous N$_2$ in Sputnik Planitia (and outside), from north to south in northern spring and summer or south to north at the opposite season.

This exotic circulation regime could explain many of the geological features and longitudinal asymmetries in ice distribution observed all over Pluto’s surface, such as (1) The presence of the CH$_4$-rich Bladed Terrain Deposits east of Sputnik Planitia, and that of the volatile-free dark region of Chulhu at the opposite longitudes, (2) The formation of the bright eastern part of Tombaugh Regio (the right lobe of the heart), covered by covered by N$_2$-rich and CH$_4$-rich frosts, (3) The formation of the so-called blades on top of the Bladed Terrain deposits, which display a dominant N-S orientation.

Conclusions: Despite a frozen surface and a tenuous atmosphere, Pluto’s climate is remarkably active. The nitrogen icecap within Sputnik Planitia seems to be the heart of this climate system, since it controls the evolution of surface pressure, regulates the general circulation, and triggers atmospheric waves and tides.

References:

Figure 1: Map of the horizontal winds at 1 km above the local surface, obtained from an LMD GCM simulation at the date of July 14, 2015 (the local time at longitude 180° is 2:00pm). At the center of the figure, within the bright half-heart shaped Sputnik Planitia ice sheet, we obtain a western boundary current (~5 m s$^{-1}$) crossing the basin from the north to the south. These winds, induced by the sublimation of nitrogen in the northern latitudes of the basin and the Coriolis force, transport cold nitrogen air toward the southern latitudes of the basin.
HIGH-RESOLUTION PIXEL-SCALE TOPOGRAPHY OF PLUTO AND CHARON. R.A. Beyer\textsuperscript{1,2}, P. Schenk\textsuperscript{3}, J.M. Moore\textsuperscript{2}, C. Beddingfield\textsuperscript{1,2}, O. White\textsuperscript{1,2}, W.B. McKinnon\textsuperscript{4}, J.R. Spencer\textsuperscript{5}, S.A. Stern\textsuperscript{5}, L.A. Young\textsuperscript{6}, C.B. Olkin\textsuperscript{6}, K. Ennico\textsuperscript{2}, H.A. Weaver\textsuperscript{6}, and the New Horizons Science Team. \textsuperscript{1}SETI Institute (rbeyer@seti.org), \textsuperscript{2}NASA Ames Research Center, CA \textsuperscript{3}Lunar \& Planetary Institute/USRA, TX (schenk@lpi.usra.edu); \textsuperscript{4}Washington U. in St. Louis, MO; \textsuperscript{5}Southwest Research Institute, CO; \textsuperscript{6}Johns Hopkins University, Applied Physics Lab., MD.

\textbf{Introduction:} The geology of the Pluto system as revealed by \textit{New Horizons} in July 2015 proved to be surprisingly diverse [1]. A prime objective of the mission was to acquire topographic maps of Pluto and Charon to provide physical constraints on the formation of these geologic features. Multiple observations permit topographic mapping at a variety of scales, and initial analyses focused on global and regional scale mapping to survey as much territory and terrain types as possible. Preliminary results were described [1,2], and full reports on these data sets have now been published [3,4]. These global data products (Fig. 1) have also been archived to the PDS. Here we report on high-resolution topographic data products for the Pluto system that address the origins of specific features on both the planetary and local scales.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image1.png}
\caption{Topographic maps [3, 4] of Pluto (top) and Charon (bottom). Color-coding indicates vertical elevation.}
\end{figure}

\textbf{Sputnik Planitia Topography:} Most of the high-resolution topography of Pluto is centered on Sputnik Planitia (SP). Key questions remain unresolved in the global product regarding the topography of the SP \textsuperscript{2} ice sheet: How deep is it? How flat is it? These questions arise because the global-scale digital terrain model (DTM, Fig. 1) relies on MVIC line-scan data and ambiguities remain regarding pointing knowledge and hence reliability of long-wavelength components. To address this, we use geometrically controlled LORRI-only framing camera stereo data, which give us an undistorted topographic swath of \(~1/4^{th}\) of the basin (Fig. 2) from NW to SE.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image2.png}
\caption{High-resolution mosaics across Sputnik Planitia basin on Pluto, color-coded for topography. Relief shown is 6 km (red is high, blue is low).}
\end{figure}

LORRI stereo data for SP reveal that the basin is ~2.5 to 3 km deep relative to the rim region sampled by the DTMs (a backup stereo sequence that includes surrounding terrains is in production). Further, the data reveal that the surface of the SP ice sheet is flat (Fig. 2) with respect to the global spheroid and to the limit of the data set’s ~100-150 m stereo height accuracy. The only significant large-scale relief within the ice sheet is the along the outer 30-40 km perimeter which forms a moat several hundred meters deep to the north and a rampart rising several hundred meters to the southeast (where it meets glaciated deposits [2, 3]. These data place important constraints on the formation and dynamics of the ice sheet.

\textbf{Sputnik Planitia Features:} The ice sheet also features smaller scale features [1], notably the 20-50 km scale ovoid cells, and the multitude of km-scale pits scattered across the surface, each of which represent different physical processes.

Shading patterns in \textit{New Horizons} images suggest that the cells within the SP ice sheet are domical. A few of these cells are marginally resolved in the global stereo DTM but with relief on the order of the vertical precision of the data. To supplement these
products we use shape-from-shading (photoclinometry, PC) toolkits developed at LPI to improve DTM resolution. PC can be used on all data products with low-Sun shading and at resolutions of 315 to 70 m/pixel scales. These data (Fig. 3) confirm that cells are elevated in the central portions by 100-150 m, consistent with convective overturn [5].

Figure 3. Preliminary PC-DTM and profile across ovoid cells within Sputnik Planitia, Pluto. Spatial resolution ~80 m, stereo height accuracy <100 m. Data not yet integrated with stereo data in Figure 2.

Figure 4. Preliminary PC-DTM and profile across km-scale pits within Sputnik Planum. Spatial resolution ~70 m, stereo height accuracy <100 m.

Kilometer-scale pitting across SP (Fig. 4) is not resolved in stereo DTMs, and can only be resolved in PC-DTMs. Preliminary PC tests (which depend on knowledge of photometric parameters as a function of phase angle) indicate depths of 100 m or so. The data are robust enough to indicate that reliable statistics on the depths of the pits, and hence any layers they may be exposing, can be derived.

Charon: The highest-resolution LORRI mosaic across the Charon disk at ~150 m/pixel reveals small-scale linear troughs and pitting across the surface of the volcanic plain informally named Vulcan Planitia [1]. A merged PC- and stereo-DTM product reveals the troughs to have relief of ~200-650 m and the pitting ~100-150 m (Fig. 5).

Figure 5. Stereo/PC-DTM of portion of Vulcan Planitia, Charon, showing pitting on surface of plain.

Conclusions: Pluto’s topography is complex and reflects a diversity of geologic processes throughout its history [e.g., 1,2]. Supplemental topographic data now in production increase our knowledge and understanding of processes occurring on Pluto and Kuiper Belt objects generally. The SP ice sheet appears to be remarkably level within the limits of measurement (~125 m). The outer 20-40-km of the ice sheet can be either depressed or raised several hundred meters, with the depressed moat forming north of ~30° latitude or so, the raised portions forming south and corresponding to areas where glacier-like flow of material from the elevated rim regions meets the ice sheet [2]. A relative SP depth of 2.5 to 3 km implies a possible maximum thickness of the observed ice sheet of ~6 km, depending on assumptions about the preexisting surface. The ice sheet is also characterized by polygonal and ovoid ‘cells’ diagnostic of convection, which can be elevated at their centers 100-150 m. The ice surface is also extensively pitted at smaller scales, and pit depths of 100-200 m suggest there may be an eroding surface layer of equivalent depth on a more resilient subsurface ice sheet.

GEOLOGY OF CHARON Ross A. Beyer1,2, J. Spencer3, S. Robbins3, K. Singer3, C. Beddingfield1,2, W. M. Grundy4, K. Ennico2, J. T. Keane5, W. B. McKinnon6, J. M. Moore2, F. Nimmo7, C. Olkin3, K. Runyon8 P. Schenk9, A. Stern3, H. Weaver8, L. A. Young3, and the New Horizons Science Team. 1Carl Sagan Center at the SETI Institute, 2NASA Ames Research Center, Moffett Field, CA, USA (Ross.A.Beyer@nasa.gov), 3SwRI, 4Lowell Observatory, 5Caltech, 6WUSTL, 7UCSC, 8JHU APL, 9LPI

Figure 1: The C_LORRI_FULLFRAME_1 observation (LOR_029914776, ~2.4 km/pixel) showing the New Horizons encounter hemisphere of Charon.

The New Horizons flyby of the Pluto system [1] transformed our understanding of Charon from an astronomical object [2] to a geological one [3]. And while Pluto was certainly the prime focus of the encounter, Charon proved to be a geologically complex world in its own right, different in character from Pluto. Charon shows signs of tectonic disruption in the northern Oz Terra region, and evidence for large-scale resurfacing in the equatorial Vulcan Planitia. 1

Geological Speculations Before the New Horizons flyby, we could only speculate on what the surface of Charon might look like [5] based on our understanding of icy satellites and their evolution.

It was expected that Charon would have undergone a differentiation process with radiogenic heating that might have led to a subsurface ocean, but due to its size, that heat (and any ocean) would be gone today. The tectonically fractured surface of Ariel was a possible analog. Given the telescopic spectroscopic identification of ammonia-hydrates [6], it was also hypothesized that cryovolcanic features [7] might be observed.

New Horizons Imaging of Charon There is whole disk coverage of Charon starting one rotation from closest approach at 17 km/pixel, and then approximately every 15 degrees of rotation, all the way to the best full-disk mosaic at 0.89 km/pixel. The highest resolution observation consisting of a strip of images was at 0.16 km/pixel.

The best mapping and stereo imaging [8] were from the illuminated Pluto-facing hemisphere of Charon captured near closest approach.

Cratering and Ages Cratering on Charon is detailed in Robbins et al. [9] and Singer et al. [10]. The cratering statistics tell the story of a globally old surface, even across the varying terrains described below. This is consistent with most of the interesting geological activity happening very early in Charon’s history.

Geological Mapping of Charon Robbins et al. [11] identified ten primary geomorphologic unit categories covering 35% of Charon’s surface and used lower resolution data to speculate about less-resolved areas of Charon. Over a thousand linear features were mapped, 90% of them being tectonic in nature. A chronostratigraphy was constructed from examination of cross-cutting and embayment relations that supports the evolutionary story of Charon’s disrupted crustal blocks and vast smooth plains.

Disrupted Crustal Blocks Across Charon’s northern region are a variety of terrains that display extensional tectonic features with kilometers of relief. Oz Terra comprises the area on the encounter hemisphere north of Vul-
can Planitia, and has three latitudinal zones: (1) low-latitude chasmata, (2) mid-latitude crustal blocks, and (3) high-latitude depressions and ridges [4].

The low-latitude scarps and chasmata are roughly aligned with the border of Vulcan Planitia, indicating a stress-relationship with Vulcan or more precisely the events that led to the resurfacing in that area. The chasmas appear to be graben, and the numerous scarps appear to be the traces of normal faulting.

The mid-northern latitudes are characterized by large areas bounded by scarps. These appear to be large crustal blocks several hundred kilometers across separated by troughs. There is no major alignment in this zone, indicating that there was no preferred direction of stress.

The highest latitudes display an irregular landscape. Views of the limb show large relief here, and stereo topography reveals a depression 8 km deep. There is no evidence for compressional or strike-slip faulting. Based on the crater counts, all of this extension was ancient. This implies global expansion of the surface on the order of 1%, and the likely mechanism for driving such an expansion is the freezing of a subsurface ocean early in Charon’s history [4].

**Smooth Plains** The smooth plains of Vulcan Planitia that occupy the equatorial area of Charon are likely the result of global expansion driven by the freezing subsurface ocean which yielded a large cryoflow that completely resurfaced at least 400,000 km² [12]. The textures on Vulcan are very different from those in Oz Terra and the topographic relief much less. The boundary consists of southward facing scarps from Oz Terra overlooking Vulcan Planitia.

Vulcan Planitia consists of smooth material and mottled material and is criss-crossed with a pattern of rilles (small graben) that are primarily aligned with the border scarps of Oz Terra. In addition to the ‘normal’ terrain of Vulcan, there are also some curious, isolated mountains that stand a few kilometers above the plains, surrounded by depressions that are either the downward flexure of plains material or incomplete embayment of pre-existing mountains [3]. The embayment hypothesis is also supported by depressions along the border scarps.

The most reasonable explanation for Vulcan Planitia is that it is the result of a large cryoflow of ammonia-rich material that erupted during the period of global expansion and sub-surface ocean freezing. This was not a flow from a single effusive center, but likely erupted from many locations across the region flooding the area in a manner similar to lunar maria emplacement [12].

**Summary** Many icy worlds in the solar system show signs of having subsurface oceans today or in the past, indicating that they are a normal part of icy world evolution, and Charon seems to be no different. The advantage of Charon is that its small size allowed the dynamic of an early ocean, freezing, global expansion, and resurfacing to play out, and then stop without overprinting by other processes; leaving us a clear record of those geologic events.

**References:**

RADIO SCIENCE EXPERIMENT (REX) ON NEW HORIZONS: RESULTS FROM THE PLUTO FLYBY
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Introduction: The New Horizons Radio Science Experiment REX addressed several poorly understood issues related to the Pluto–Charon system [1]. Primary among these was a determination of the structure of the neutral atmosphere near the surface and up to about 100 km in terms of density, pressure and temperature. Secondary objectives included a search for and possible measurement of the Pluto ionosphere and a radiometric measurement of the thermal emission temperatures of Pluto and Charon at the wavelength 4.2 cm. Augmented by an additional uplink from Earth, a successful bistatic radar experiment was performed in combination with the highest resolution radiometry observations. Tertiary objectives addressed by REX were a determination of the Earth occultation chord of Pluto to high accuracy, and a determination of the Pluto–Charon system mass with a possible separation of the individual masses of Pluto and Charon. Brief summaries of the results of the REX investigations are presented below.

Atmospheric Height Profile: Approximately two hours after closest approach, on 14 July 2015, New Horizons performed a radio occultation (RO) that sounded Pluto’s atmosphere down to the surface. The RO geometry, as viewed from New Horizons, is shown in Fig. 1 [2].

Pluto Atmosphere. Four DSN antennas, each radiating 20 kW at a wavelength of 4.2 cm, transmitted uplink signals to New Horizons during RO ingress and egress. The polarization was right circular (RCP) for one pair of signals and left circular (LCP) for the other pair. The four signals were separated for processing by two independent receivers, each referenced to a different ultra-stable oscillator. Profiles of number density, pressure, and temperature were retrieved from the combined phase measurements. The temperature profiles are shown in Figs. 2A (radial distance scale) and 2B (altitude scale) [3]. The uplinks during RO ingress sounded the atmosphere at sunset at 193.5°E, 17.0°S — on the southeast corner of Sputnik Planitia (SP); RO egress occurred at sunrise at 15.7°E, 15.1°N — near the center of the Charon-facing hemisphere. The ingress and egress profiles above 25 km are nearly identical and consistent with ground-based stellar occultation measurements. The ingress profile shows a cold boundary layer where the temperature is nearly constant, 38.9 ± 2.1 K (close to the saturation temperature of N2). This boundary is missing in the egress profile, where the surface air temperature is 51.6 ± 3.8 K. The mean values of the pressure and radius were determined to be 11.5 ± 0.7 μbar at 1189.9 ± 0.2 km. Pluto Ionosphere. The RO phase measurements were also carefully examined for a possible signature of the Pluto ionosphere [4]. The solar zenith angle was 90.2° (sunset) at ingress and 89.8° (sunrise) at egress. No ionosphere was detected, but a significant upper bound, corresponding to a peak electron density at the terminator of about 1000 cm -3, was derived. An ionospheric model used to guide the interpretation of the data predicts an electron content at the terminator only slightly lower than the RO detection threshold.

Radio Thermal Emission: The New Horizons radio system was calibrated for REX radiometry obser-
Measurements at wavelength $\lambda = 4.2$ cm were taken during approach, departure, and in the interval between occultation ingress and egress [2]. Two scans with the highest resolution measurements at Pluto were recorded a few minutes after closest approach: the first being diametric near the equator; the second in the reverse direction across the winter pole. The brightness temperatures for these latter scans are shown in Figs. 3A and 3B, respectively [6].

The radio flux density received from Pluto and Charon is gray-body thermal emission from a subsurface layer at depths down to the electrical skin depth, which ranges from less than 1 m for ice-free regions and perhaps up to 500 m for methane ice. The brightness temperature of Pluto across the nightside scan reached a maximum of $29.0 \pm 1.5$ K in the center of the disk. The drop off toward the limbs is attributed to the lower emissivity at lower emission angles. The radio emissivity is of the order of 0.7 or even lower if the atmospheric temperatures near the surface determined from the REX RO measurements are also valid for the subsurface.

**Bistatic Radar**: A bistatic radar experiment was conducted during the REX observation slot shortly after closest approach to Pluto. A special 80 kW transmitter at the DSN Goldstone complex was enlisted for this most distant bistatic experiment attempted to date. Echo power at an SNR near 30 dB was recorded when the signal reflected from regions near the spectral point on Pluto’s surface. Interpretation of these data is ongoing.

**Pluto and Charon mass determination**: The system mass and the separate masses of Pluto and Charon were determined by combining regular two-way radio tracking and REX one-way uplink data recorded during selected intervals during the 24 hours about closest approach. The solution for the individual masses was not as precise as anticipated due to the copious thrust activity during the flyby, which, unfortunately, could not be fully corrected.

PHOTOMETRY AND ALBEDO MAPS OF PLUTO AND CHARON. B. J. Buratti1, J. Hofgartner1; J. H. Hillier2, M. D. Hicks1, A. J. Verbiscer3, S. A. Stern4, H. A. Weaver5, C. J. A. Howett4, C. B. Olkin4, and the New Horizons Science Team. 1Jet Propulsion Laboratory California Institute of Technology (4800 Oak Grove Dr. Pasadena, Ca 91109; bonnie.buratti@jpl.nasa.gov); 2Grays Harbor College; 3University of Virginia; 4Southwest Research Institute Boulder; 5Johns Hopkins Applied Physics Laboratory; 6NASA Ames

Introduction: The acquisition of multispectral imaging observations with New Horizons during the flyby of the Pluto-Charon system in July 15, 2015 represents the first opportunity to study in detail the photometric properties of a body that is not rocky or water-icy. Pluto is covered mainly with methane and nitrogen – while Charon’s composition is mainly water ice [1, 2]. Combined with ground-based observations of the system at “true opposition” in 2018, the measurements of New Horizons during cruise and encounter provide a fairly complete solar phase curve that can be used for robust photometric modeling.

Here we report on the results of that modeling as well as the creation of albedo maps for both Pluto and Charon.

Solar Phase Curves: From Earth, the maximum observable solar phase curve of the Pluto-Charon system is less than 2°. The minimum solar phase angle observed during the New Horizons flyby was 11°. Thus, both ground-based and spacecraft data are required for a full photometric analysis of the system. Large solar phase angles are ideal for understanding macroscopic roughness and the directional scattering properties of the surface, while small solar phase angles are required to understand the textural nature of the surface. In 2018 observations from the adaptive optics system at Palomar that show a huge surge in brightness in the last tenth of a degree were successfully acquired [3]. These observations are especially key to determining the geometric albedo of an object, while the full excursion in solar phase angles is required to determine the phase integral. Combined, these two parameters yield a Bond albedo, which in turn is required to model volatile transport and thermal variations on the object.

Charon’s phase curve is straightforward to model because the moon is an atmosphereless body [4]. Photometric modeling shows that Charon is similar in its photometric properties to other icy moons, except that its single particle phase function is more isotropic, suggesting the Kuiper Belt may represent a new regime for surface alteration processes. Charon’s phase integral is 0.70±0.04 and its Bond albedo is 0.29±0.05.

Modeling of Pluto’s solar phase curve is more challenging as its surface is overlain by a thin atmosphere and a complete radiative transfer model such as that described by Chandrasekhar’s “planetary problem” is required. This work is ongoing.

Albedo Maps: Images were obtained by the Long Range Reconnaissance Imager (LORRI) of both Pluto and Charon [6]. These images have been used to construct maps of the normal reflectance of the surface, corrected for all effects of viewing geometry [7].

![Figure 1. The solar phase curve of Charon (large red and black dots) shown with data from Cassini of Dione (blue dots). The data at the very smallest solar phase angles (<10°) is from [5]; while any data beyond 10° is from the LORRI instrument on New Horizons [4]. The red data is constructed from disk resolved images, while the black data is from full-disk images. The solar phase curve of Charon is from [4] and Cassini data is unpublished. No rotational corrections have been done for the Dione data. The similarity of Charon to an icy moon is apparent.](7023.pdf)

Most of the changes in intensity on planetary surface are not intrinsic but rather due to changes in the radiance geometry. The medium and high resolution images of Pluto and Charon during the New Horizons encounter enabled the creation of maps of normal reflectance for both objects [6]. Charon shows albedo variations that are typical of other icy moons, but the albedo map of Pluto shows that it has the most extreme variations in albedo of any object in the Solar System except for Iapetus [8]. Pluto’s normal reflectance in the Cthulhu region is less than 0.10, suggesting a substratum of polymerized molecules, while on Sputnik Plani-
tia it is nearly unity. This value is close to that of bright icy moons such as active Enceladus, suggesting ongoing geologic processes in that region of Pluto. Furthermore, this huge variation in albedo—an order of magnitude—translates to a temperature difference of ~20K, spawning such exotic phenomena as snow and high winds, with concomitant eolian processes.

Figure 2. A map of the normal reflectance of Pluto, showing more variations—a factor of an order of magnitude—than any airless body in the Solar System except for Iapetus. From [7].

Figure 3. A map of the normal reflectance of Charon, showing variegations that are more typical of icy moons. From [7].

Ground-based observations: The smallest solar phase angle obtained by New Horizons was 11°. Ground-based observations must be obtained by adaptive optics (AO) systems to resolve Charon from Pluto. Four nights were obtained on the AO system on the Hale Telescope on Palomar Mountain in 2018, when the smallest solar phase angle for 161 years was reached, showing a huge opposition surge for both objects [3].

Summary: When combined with ground-based observations, the New Horizons data at Pluto provides a full excursion in solar phase angles to perform photometric modeling. Work on Pluto is still ongoing as the removal of the atmospheric component requires that its properties be modeled separately. The albedo map of Charon is unremarkable, although the pole is darker, unlike most icy bodies where the pole is brighter as it is a cold-trap for volatiles. Pluto, however, exhibits an extreme range in albedos, consistent with its place as an active body with a fresh surface.


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OBSERVATIONS OF PLUTO’S SURFACE WITH ALMA.  B. J. Butler¹, W. M. Grundy², M. A. Gurwell³, E. Lellouch⁴, R. Moreno⁵, A. Mouillet⁶, and L. A. Young⁷. ¹National Radio Astronomy Observatory, ²Lowell Observatory, ³Harvard-Smithsonian Center for Astrophysics, ⁴Observatoire de Paris, ⁵SOFIA, ⁶SWRI.

Introduction:  The New Horizons spacecraft flyby of the Pluto/Charon system has revolutionized our knowledge of the dwarf planet and its largest satellite. Pluto’s surface varies regionally; some areas appear to be composed primarily of a substrate of non-volatile H₂O, others may have a deep overlying deposit of higher hydrocarbons or reddish materials, still others have a veneer of volatile N₂, CH₄ and CO ices or frosts that may be kilometers deep in specific areas [1-5]. It is clear that the distribution of volatile ices on the surface is influenced by a combination of season (including heliocentric distance), latitude, height and slope, albedo, and thermal properties of the materials, and is intimately involved in the complex geology of the surface.

Recently developed volatile transport models include the thermal inertia, albedos and emissivities of the volatile component and substrate [6-8]. With one set of parameters, they predict the evolution of Pluto’s surface appearance and pressure over a full orbit. Comparison with the limited available pre-flyby data, which notably indicate a factor-of-3 pressure increase over the last 25 years, generally favored models with high substrate thermal inertia and a permanent N₂ ice cap at Pluto’s north pole [9]. However, other models, including one with lower thermal inertia and a smaller volatile inventory, and one with even smaller volatile inventory involving atmospheric collapse, could not be ruled out. Alternate models may explain the lack of N₂ at the pole, using Sputnik Planum as a source region [8,10]. Revision of these volatile transport models is underway, but even with all of the information from New Horizons, some parameters in the model are poorly constrained; namely the global subsurface thermal properties. These properties can be determined from Earth-based observations at long (sub-millimeter and longer) wavelengths, if such observations have sufficient resolution. The Atacama Large Millimeter Array (ALMA) telescope provides the requisite resolution (< 0.1 arcsec).

New Horizons Thermal Observations: While the New Horizons flyby has provided amazing data on both Pluto and Charon, surface and subsurface temperature measurements were much more limited. The whole-disk 4.2 cm brightness temperature was measured for both the dayside and nightside of Pluto and Charon on approach and departure, and a few scans across Pluto (both dayside and nightside) were obtained by the Radio Science Experiment (REX) [11]. At these centimeter wavelengths, because of the low loss tangent of the ices comprising the surface of both Pluto and Charon, measurements from REX likely sample down to a depth > 1 m, making determination of surface temperatures from the data difficult [12]. The N₂ ice temperature – expected to be uniform over Pluto due to latent heat exchanges – can be determined from the shape of the 2.15 µm feature [13] but temperatures of the other ices are poorly constrained. In addition, these measurements are a sample at a single time, in an evolving system; continued Earth-based thermal observations of Pluto and Charon are needed, and shorter wavelengths are preferred as they provide surface temperatures more directly. The ability to resolve not only the two bodies from each other, but each of them individually, is critical in understanding the volatile inventory, and its migration (at least for Pluto), on their surfaces.

Pre-ALMA Earth-based and Spacecraft Observations: Thermal measurements with ISO, Spitzer and Herschel indicate that the mean brightness temperature of the Pluto/Charon system decreases considerably with increasing wavelength, from ~52 K near 20 µm to ~38 K near 500 µm ([14]). This behavior likely results from a combination of subsurface sounding and emissivity effects at the longest wavelengths (associated with dielectric constant and/or reflectivity effects), and the fact that there are warmer and colder regions and the warmer regions dominate the emission at shorter wavelengths (because the emission goes like T⁴ at short wavelengths but goes like T at long wavelengths). Such emissivity effects are seen in millimeter-wavelength measurements of various kinds of ice and snow on Earth [15]. In the submm/mm range, ground-based results are more dispersed, but suggest that the trend might continue. All previous Earth-based thermal measurements – except for SMA observations at 1.35 mm [16] and one VLA observation at 9.1 mm [17] separating Pluto and Charon – have mixed the contribution of the two bodies.

ALMA Observations: In 2015 we observed Pluto and Charon with ALMA on June 12 and 13. At that time we did not resolve them individually, but easily separated them on the sky [18]. We observed the system again in 2017 on three dates (September 27 and 29, and October 14), with the intention of getting three separated longitudes to cover as much of the surface as we could with decent resolution. In those observations, the resolution was sufficient to easily resolve Pluto, and marginally resolve Charon (resolutions ranged from 27 to 54 masec). Figure 1 shows the images from those observations [19]. At least one clear brightness temperature enhancement is seen, along with another tentative one, as highlighted in Figure 2. We believe the clear enhancement is associated with Piri Planitia, which is thought to be a region where methane is sublimating, revealing the water “bedrock” below. Analysis of this data is ongoing (with our thermal model [18]), but is hampered by the somewhat limited resolution. We have proposed to use ALMA to observe the system again, but with even higher...
resolution (as good as 17 masec) during Cycle 7. Images from these observations, should they be approved, should allow for regional temperature contrasts to be determined.


**Figure 1.** Images of Pluto at three longitudes from our 2017 ALMA observations. These are as seen on the plane of the sky. The insets are New Horizons MVIC images, with a cartographic grid of Pluto superimposed.

**Figure 2.** The image from Figure 1 for September 27, with the ALMA data rotated so that north is up in the image. The resolution size is shown in the lower left. The lower inset is the color map from [20], with formal and informal place names. The upper inset is a compositional map, with blue representing N₂, red representing H₂O, and green representing CH₄. The ALMA data has a cartographic grid superimposed, and rough outlines of features.
Tectonic History of the Oz Terra of Charon as Revealed by Systematic Structural Mapping. H. Z. Chen* and A. Yin1, 1Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA 90095-1567, USA (*now at Structural Geology Group, China University of Geosciences (Beijing), Beijing 100083, China; 1002141229@cugb.edu.cn)

Introduction: The fly-by of NASA’s New Horizons spacecraft revealed the presence of complex surface features on Pluto’s satellite Charon [1], which have been used to infer its tectonic history [2]. For example, the rugged Oz Terra is interpreted to have formed during an extensional event [3]. Although this interpretation provides a testable hypothesis, its predictions have not yet been fully validated by detailed structural analysis in terms of well understood fault association and kinematic compatibility. In this study we address this issue by conducting a systematic photo-geological mapping across the Oz Terra. The main goal of this work is to establish the tectonic history of the region and its role in constructing the observed landforms.

Data and Methods: All data used in this study are publically available from the USGS astrogeology website (https://astrogeology.usgs.gov/search/map/Charon/NewHorizons/Charon_NewHorizons_Global_Mosaic_300m_Jul2017;https://astrogeology.usgs.gov/search/map/Charon/NewHorizons/Charon_NewHorizons_Global_DEM_300m_Jul2017). In this data set, the raw images were obtained by the Long Range Reconnaissance Imager (LORRI) and Multicolor Visible Imaging Camera (MVIC) [6] from the New Horizons spacecraft. The well preserved morphology of the oldest impact structures on the satellite surface suggest that the landform modification by deposition and erosion are negligible. This starting point allows us to decipher whether an observed morphological feature was generated by tectonic deformation or planetary surface processes [4]. For example, faulting may disrupt earlier formed surface features in the following manners: (1) a strike-slip fault zone would display en echelon secondary synthetic and antithetic strike-slip fracture zones, oblique folds, oblique thrusts, and oblique normal faults to the main fault strand; (2) a normal fault zone would induce footwall uplift, hanging-wall tilting, and a relatively straight linear escarpment; and (3) a thrust system may consist of fault-related folds with asymmetric topographic profiles perpendicular to the fold traces, imbricate thrusts expressed as multiple fault traces merging and diverging along strike, flexurally induced basins in thrust footwalls, and lateral ramps linking thrusts. Surface processes may be expressed by mass wasting, impact-generated deposition, and viscous flows. The latter may be characterized by tongue-shaped flow fronts and parallel rim ridges along the margins of flow channels. Finally, extensional fractures should be associated with linear depressions bounded by steeply dipping to nearly vertical chasma walls.

Results: Our mapping indicates that the Oz Terra has experienced three main phases of deformation (Fig. 1): (1) local closely spaced extensional faults morphologically associated with subdued troughs trending both northeast and northwest, (2) discrete north-striking thrust zones spaced ~200 km from one another, and (3) east-striking extensional faults parallel to the southern margin of the Oz Terra. Viscous flow materials were emplaced after the last tectonic event marked by north-south extension.

The oldest NE- and NW-striking extensional structures are exposed in the west-central part of the Oz terra (dark red fault traces in Fig. 1). The extension-induced troughs are ~100 km long and ~10 km wide. They are crosscut by younger east-striking extensional faults. NE-trending troughs controlled by the earliest extensional structures are truncated by east-striking grabens whereas the NW-trending troughs associated with the earliest extensional structures are segmented by the younger east-striking normal faults.

The evidence for the second-phase thrusting comes from (1) truncated craters, (2) curvilinear fault traces, (3) fault-bounded highlands that display asymmetric topographic profiles similar to those generated by thrust-induced hanging-wall anticlines, and (4) thrust-bounded depressions that resemble flexural basins. Three thrust zones are mapped, each of which is ~300 km long and ~50 km wide (Figs. 1A, 1B and 1C) and consists of multiple strands with slightly variable trends along strike. Thrust zone 1 dies out via a horsetail structure system in the north and transfers strike-slip motion to a local northeast-striking normal fault zone in the south. This observation indicates that the thrust zone has accommodated a right-slip transpressional component (Fig. 1A). Thrust zone 2 is located in the central part of Oz Terra, characterized by an NW-trending elevated belt, which dies out at its northwest end and gets truncated by a graben in the south. A plain region lies east of it, interpreted as a foreland basin. The plain region was thought to have undergone a resurface event during emplacement of cryo-lava [3]. Thrust zone 3 shows complex cross-cutting relationships between interpreted north-striking thrusts and east-striking extensional faults (Fig. 1C).

The last major tectonic event is north-south extension expressed by the development of an NEE-striking normal fault system. This fault system defining
the southern margin of the Oz Terra is dominated by south dipping normal faults and related tilted hanging-wall blocks. An en echelon normal fault zone marks the eastern end of the extensional fault system; the fault pattern indicates a right-slip motion. North-south extension is also expressed by east-striking normal faults within the Oz Terra at a mid-latitude of ~45° N (Fig. 1).

Our mapping revealed two types of flow materials: (1) those appear to be sourced from the base of fault scarps [7], and flow into nearby depressions over a distance of a few km; (2) those might developed by flow of ejecta towards low lands. The latter type of flow shows a radial pattern. The flow length varies between ~10 km and ~50 km (Fig. 1).

Impact craters in the Oz Terra are far from saturated. Most of them are post-tectonic as they overprint fault-generated morphology. However, a few of them appear to be modified by tectonic events [8] and were interpreted to be pre-tectonic. In thrust zone 2, three impact craters that have diameters of ~50 km show different relative ages to the thrusting event (Fig. 1B). Crater a is post-thrusting as it overprinted the thrust trace and erased thrust-induced topography. Crater b lacks its northeast half in a thrust footwall while preserving the other half in the thrust hanging wall. Crater burial by cryo-lava does not explain the above observation. Instead, a thrust-induced dislocation of about 3 km is needed to eliminate the footwall trace of the crater. Crater c was interpreted to be syn-tectonic. This is based on the observation that though the thrust trace cut through the crater, the thrust related dislocation is negligible in the DEM map (i.e., less than 0.2 km), suggesting that the impact occurred while the fault was still active.

CHARON’S SURFACE COMPOSITION  J. C. Cook¹, S. Protopapa², D. P. Cruikshank³, C. M. Dalle Ore³,4, W. M. Grundy⁵. ¹Pinhead Institute, Telluride, CO., ²Southwest Research Institute, Boulder, CO, ³NASA Ames Research Center, Moffett Field, CA, ⁴SETI Institute, Mountain View, CA, ⁵Lowell Observatory, Flagstaff, AZ. (jasoncampbellcook@gmail.com)

Introduction: From its 1978 discovery [1] to the weeks prior to New Horizons’ July 2015 encounter [2], our understanding of Charon’s composition was limited. From 1985-1990, Pluto and Charon underwent a season of mutual events, one eclipsing the other, every few days as viewed from the Earth. Ground-based observations were able to obtain color and low-resolution near-infrared spectra that were composed of a few spectral points for each object. These data were sufficient to show that Charon’s eclipsed hemisphere was distinctly bluer than Pluto and nearly neutral in color with respect to the Sun [3] and covered in H₂O-ice [4, 5]. [6] used Keck to obtain a more detailed spectrum of Charon that was separate from Pluto, when Pluto and Charon were at maximum angular separation (∼0.9″) and seeing was extremely favorable. These observations determined the H₂O-ice present on Charon was in the crystalline phase. They also found evidence for an absorption band at 2.21 μm which they suggested was NH₃ · H₂O. Shortly after, [7] and [8] reported similar findings with Hubble Space Telescope/NICMOS spectra taken over multiple longitudes.

The detection of the absorption band at 2.21 μm and its identification as NH₃ · H₂O relied on two to four spectral points at low signal-to-noise. In order to examine the issue more thoroughly, [9] used the adaptive optics system on Gemini North to obtain spatially resolved spectra of Pluto and Charon. The higher spectral resolution and higher signal-to-noise data showed that the absorption at 2.21 μm was indeed real and it appeared on the anti- and sub-Pluto hemispheres of Charon. Observations by [10] showed the absorption band was present at other longitudes as well. [11] provided a comprehensive examination of the band position and depth with longitude using all known data up to that point.

Observations of Charon separated from Pluto from 2.5 to 4 μm were obtained using the NACO instrument at the 8.2-, Very Large Telescope. These data confirmed the presence of H₂O-ice on the surface of Charon and enabled the characterization of a continuum featureless absorber on its surface [12].

Observations: In this invited talk, we review the composition of Charon as determined by data from New Horizons obtained during its approach and encounter with the Pluto system on July 14, 2015. Using the Ralph [13] instrument, New Horizons successfully obtained images and spectra necessary to map the distribution of ices on the surface of Charon. Ralph is a dual channel instrument with MVIC (Multi-spectral Visible Imaging Camera), the visible color imager, and LEISA (Linear Etalon Imaging Spectral Array), the near-infrared spectograph. LEISA covers the spectral range 1.25 to 2.50 μm at a resolving power (λ/Δλ) of 240, and 2.10 to 2.25 μm at a resolving power of 560. While New Horizons did obtain several scans across the disk of Charon while it was spatially resolved, only the highest spatial resolution observation of Charon has been published [14]. These data were obtained at a distance of ∼81,000 km and a spatial resolution of ∼5 km/pix. In order to provide a thorough review of Charon’s surface composition, we will include analysis of data from the two prior scans taken on approach to the Pluto system. These observations were taken at distances of 136,000 and 483,000 km, and have spatial resolutions of 9 and 30 km/pix, respectively.

Results: In their examination of the highest spatial resolution data, [14] applied statistical clustering to identify spectrally distinct regions and radiative transfer models to interpret the variation in the 2.0 μm H₂O-ice band across Charon’s surface. Using this, they map the distribution of H₂O-ice and NH₃ products. They concluded that H₂O-ice is largely found in the crystalline phase, with enhanced fractions of amorphous H₂O-ice in low-albedo regions. High albedo regions, particularly bright rays from craters, are characterized by larger H₂O-ice grains and are presumably younger than the surrounding terrain.

NH₃ · H₂O has at least two distinct bands within our spectral range. The strongest is centered near 2.21 μm, and a second, weaker band is centered near 1.99 μm. [15] examined lab spectra to show how these bands change for different concentrations of NH₃ in H₂O and temperatures. [14] found two behaviors of the 2.21 μm band on Charon. First, they found the 2.21 μm band is present in more terrain in the northern hemisphere than the other NH₃ · H₂O band. Second, they found both bands are present in bright crater rays, but not present in all craters. Since the 2.21 μm band is present on Nix and Hydra [16] with little evidence for the weaker band, [14] concluded that there are multiple forms of NH₃ products on Charon. One known NH₃ product that produces a band at 2.21 μm, but not one at 1.99 μm is NH₃Cl [17]. In their analysis of Pluto’s small satellites, [16] suggested NH₄NO₃ and (NH₄)₂CO₃ may also explain the spectrum. While these two ammoniated salts have absorption near 2.21 μm, no information is available at wavelengths shorter than 2.05 μm to know whether or not the weak band is present in these
species, nor are these spectra obtained at Charon-like temperatures. More lab work is needed covering the 1.25-2.5 μm range and appropriate temperatures (~40-50 K) of these and other ammoniated species in order to best understand what is present on Charon, Nix and Hydra.

At the meeting, we will present the latest compositional maps of Charon. We will compare the findings of [14] to pixel-by-pixel Hapke modeling of Charon and discuss their differences and similarities. We will examine the distribution of crystalline and amorphous H₂O-ice and the 2.21 μm band in further detail.

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References

Plasma and Radiation Environment in the Kuiper Belt: Pioneer to New Horizons

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The orbits of Pluto and thousands of other Kuiper Belt Objects (KBO) collectively cover a huge range of plasma and energetic particle radiation environments including the supersonic solar wind within the heliosphere inwards of the solar wind termination shock, the heliosheath layer beyond the shock to the heliopause, and finally the local interstellar environment now being surveyed by the Voyager 1 and 2 spacecraft. Pioneer 10 and 11 first explored the supersonic region beyond the orbits of Jupiter and Saturn, later followed by the two Voyagers. More recently the New Horizons spacecraft again made measurements of plasma and energetic particles outwards toward its primary flyby target, Pluto, later to Ultima Thule, and now continuing beyond into the Kuiper Belt. The main challenge in modeling all these measurements is that the data are taken from multiple instruments and spacecraft at very different dates and locations. All these measurements being spread over several solar cycles, the fluxes at Pluto and elsewhere vary during the minimum and maximum phases of each 11-year cycle. The twenty-two year solar magnetic cycle also variously drives inward fluxes of so-called “anomalous component” ions accelerated in the heliosheath. Solar cycle activity also drives the fluxes of particles from large solar energetic events occasionally reaching out to the Kuiper Belt. Galactic cosmic ray fluxes from interstellar space are modulated in the solar wind, so that peak fluxes occur at solar minimum and lowest fluxes at solar maximum. Important for space weathering of KBO surfaces and atmospheres, solar ultraviolet radiation also varies with solar activity. Chemical effects of UV and particle irradiation accumulate at KBOs over times much longer than solar cycles, so it is necessary to look at time-averaged fluxes from the multiple instrument and spacecraft sources to assess potential surface and atmospheric impacts. The final question is how representative the measurements of the modern space age are of paleoheliosphere fluxes extending thousands to billions of years back in solar system history.
CAN ABKHAZIA BE A STATE IF PLUTO IS NOT A PLANET? RECOGNITION AND NON-RECOGNITION OF STATUS IN ASTRONOMY, INTERNATIONAL LAW AND POLITICAL SCIENCE.
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Abstract: Status is central to debates on statehood in legal analysis and political science, and the same is true of debates in astronomy on the classification of celestial bodies. The status of both planets and states derives from their respective definitions. The paper compares the distinctions drawn in astronomy, international law and political science between a definition that emphasizes the inherent properties of a planet/of a state and one that, instead, stresses its interactions in a dynamic context with the external world. Astronomers, international lawyers and political scientists are divided on this particular question. Pluto’s demotion results from a shift of the majority opinion in astronomy from the former towards the latter approach. The declaratory view on statehood in international law [1] and the concept of ‘de facto statehood’ in political science [2] are based on the assumption that the essential characteristics that define a state are inherent in the political entity under scrutiny, including its ability to interact with the international community. By contrast, the constitutive view in international law [3] and the political science concept of a ‘contested state’ [4] stress the dynamic interaction with the international environment, highlighting the significance of state recognition.

In all three disciplines, discussions on definition also include the questions of size and numbers. The term ‘dwarf planet’ has come up in astronomy, but there is no consensus on whether this constitutes a subcategory of planets or a distinct one. International law has discussed in depth the option of having limited legal rights and duties ascribed to microstates. This option has been abandoned thanks to the principle of the sovereign equality of states [5]. In political science, there are various ways of analyzing the particular behavior of small states and microstates in international relations.

A final point in the comparison is how divergences on definition coexist within these three disciplines. The dynamic contextual definition of planethood is the majority view in astronomy, whereas the majority in international law and political science prefers a definition of statehood that stresses its inherent characteristics. But majority views within subdisciplines – planetary geophysics, international relations, etc. – often diverge from the majority position within the discipline overall.

The 2006 IAU decision has led to acrimonious debates between astronomers about how to define planets, which have no equivalent in the international law literature on the role of recognition in the creation of statehood or the status of microstates. Where the creation of statehood is concerned, jurists confine themselves to comparing the strong and weak points in the declaratory and constitutive positions. And the concept of a ‘de facto state’ coexists in political science with that of a ‘contested state’, even without in-depth methodological discussions.

When it comes to defining contested concepts, international associations of political scientists do not take decisions by majority vote. International lawyers refer to the Montevideo Convention – the last international convention to include a definition of statehood. It was signed in 1933 and it is hard to imagine a new international convention to be signed on this issue in the foreseeable future [6].

According to international law, the act of recognition is a political decision – taken by states – either to acknowledge or to create statehood, and it has legal consequences. These consequences are studied by international lawyers. Political scientists examine the reasons why the international community of states recognizes or does not recognize particular entities as states, and the political consequences thereof. In both cases, they leave the decision (on whether or not to recognize the statehood of a political entity) to states. There is here a division of tasks between states and scholars regarding recognition and non-recognition. A similar division of tasks cannot be found in astronomy: astronomers are very much on their own when they recognize or contest planethood.


**Introduction:** Several structures on Pluto's surface seen in the images and supported by spectroscopic data from the New Horizons spacecraft appear to have originated by cryovolcanic processes. The pronounced constructional edifices known as Piccard Mons and Wright Mons south of Sputnik Planitia exhibit high relief and deep central pits, and may be cryovolcanic in origin [1]. In the broad arc west of Sputnik Planitia, some tectonic fractures and graben structures appear to be conduits through which cryolavas have emerged onto the surface from one or more subsurface reservoirs. Crustal fractures comprising the Virgil Fossae complex, which cuts through the north rim of Elliot crater, are seen in New Horizons data as sources of a cryolava consisting of H2O containing NH3 or an ammoniated compound, and that is strongly colored by a red-orange pigment (Fig. 1). The pigment is regarded as a tholin, a complex organic component that can be synthesized in the laboratory by energetic processing (UV, charged-particle, and thermal) of hydrocarbons and other C- and N-bearing molecules, and probably occurs in fluids in Pluto's subsurface reservoirs (see also [2]).

In Fig. 2, the distribution of the NH3 spectral signature is shown, with high concentration within the main trough of Virgil Fossae and decreasing concentration with distance from the trough. From the spectral band at ~2.2 μm attributed to NH3 in some form, we are unable to distinguish among an ammonia hydrate (NH3•nH2O), an ammoniated salt (e.g., NH4Cl), and, although unlikely, pure NH3 in H2O. Ammonia can be destroyed by UV radiation and charged-particle radiolysis. Accordingly, Cruikshank et al. [2] evaluated the effects of the potential destructive forces at Pluto and estimated that the ammoniated H2O was emplaced sometime in the broad timeframe 10^9 to 10^10 y ago, but in any case not on the primordial surface of the planet.

**Additional Evidence of Cryovolcanism:** North of Virgil Fossae is another fault complex in Viking Terra that exhibits evidence of cryovolcanic flooding. In the section of a major graben trough running from northwest to southeast there is a ~100-km reach that is mostly filled with colored material presumed to be tholin carried in the fluid that erupted onto the surface. An adjacent 28-km crater has been embayed with the same material. At the southeast extremity of the trough, there are three, possibly four, narrow troughs or faults about 40-50 km long, and the same colored material appears to have ponded at the distal ends of at least two of them (Fig. 2). The smooth upper surface of both the crater and the filled fossa trough suggest that the filling material was originally a fluid. In support of this view, elevation transects across the region and the topographic features (Figs. 3,4) show that the upper surface of the fossa fill and that of the crater lie at the same depth (~1 km) below the local mean datum.

We have processed New Horizons LEISA spectral images of this crater-fossa complex and find the spectral signature of NH3 that is similar or greater in strength than found previously in the Virgil Fossae region [3]. As in the case of Virgil Fossae, the colored H2O ice appears to have emerged onto the surface from multiple sources in the same general vicinity, some in craters and some associated with surface fissures. The Virgil Fossae exposures and the exposures in Viking Terra presented here, as well as other patches of red-colored H2O seen in other locations along the broad arc of structurally modified terrain west of Sputnik Planum point to an origin in Pluto's subsurface. The view reached in the present investigation is that surface fractures in the bedrock, which is presumed to be H2O ice, create pathways for internal water-rich fluids at some relatively shallow depth to reach the surface. That fluid also carries one or more ammonium components, the red material of presumed organic composition, and most likely other chemical components not identified in our data. In the case of Virgil Fossae, Cruikshank et al. [2] have presented evidence for an explosive cryovolcanic component to the effusion of the cryolava, although in the Viking Terra fossa-craterr complex, it is unclear whether the fluid was debouching only along the faults defining the main fossa trench or if there is an explosive component of the emplacement.

As in the case of Virgil Fossae, the presence of the ammonium signature in the filling material in the fossa and crater in Viking Terra is an indicator of the relative youth of its emplacement, and suggests that water-rich fluid existed late in Pluto's history, and may still be present in shallow reservoirs accessible to fractures and areas of structural weakness in the planet's crust.


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Fig. 1. Virgil Fossae and Elliot crater. Distinct red color in fossa trough and surroundings represent the ammoniated H₂O that carries the red chromophore. The white frame denotes the region in Viking Terra with the flooded trench and embayed crater.

Fig. 2. Distribution of NH₃ in the Virgil Fossae region, showing concentration (arbitrary units) derived from the strength of the spectral absorption band attributed to an ammonia hydrate or an ammoniated salt [3,4]. Gray regions of the image show no absorption of H₂O or NH₃, and appear to be largely covered with CH₄ frost or ice.

Fig. 3. Filled fossa trough and embayed crater in Viking Terra. Filling material is H₂O ice with the spectral signature of ammonia, and also carries the orange-brown chromophore. Black arrows (lower right) indicate ponded material at the distal ends of fractures or graben troughs.

Fig. 4. Positions of elevation transects across the fossa trough, embayed crater, and surroundings.

Fig. 5. Elevation profiles along transects shown in Fig. 4.
PLUTO DATA BEFORE AND AFTER NEW HORIZONS: THE TAKEAWAY FOR FUTURE OBSERVATIONS. C. M. Dalle Ore$^{1,2}$, M.A. Barucci$^3$, and S. Fornasier$^3$, D. P. Cruikshank$^2$, W. M. Grundy$^4$, and S. Protopapa$^5$, $^1$SETI Institute, Mountain View, CA (cmdalleore@gmail.com); $^2$NASA Ames, Moffett Field, CA; $^3$LESIA, Observatoire de Paris, 92195 Meudon Principal Cedex, France; $^4$Lowell Observatory, Flagstaff, AZ; $^5$Southwest Research Inst., Boulder, CO.

Introduction: Pluto is the largest of the transneptunian objects (TNOs), a group consisting of thousands of objects that populate the ‘third zone’ of the Solar System, after the terrestrial and giant planet zones. Because of its location and size Pluto offers the unique advantage of having been investigated both as an unresolved point of light, i.e., as a TNO, and recently, as the target of the New Horizons flyby, close up with high spatial resolution and spectral mapping.

Pluto has been observed over time with ground-based instruments that have yielded an overall preview of a varied world with intriguing variations in albedo and subtle but important spectral changes. The ground-based observations have given us tools to gauge the importance of the observed changes by providing temporal and therefore contextual information to the in situ data that New Horizons provided during the 2015 flyby.

The Pluto flyby has confirmed the previously predicted variations in albedo, so far paralleled in the Solar System only by Iapetus, and has also linked them to impressive geological and compositional features that herald processes that could not have been foreseen with only remotely sensed data.

Spectral Data Before and After New Horizons: When comparing spectral data obtained before and after the New Horizons flyby it is evident that only high spatial resolution can yield the information needed to constrain the physical and geological properties of the surface. This is demonstrated clearly in Figure 1 where ground-based spectra taken over the time span 2001-2012 with IRTF/Spex [1] are compared to those obtained in situ during the flyby [2]. For instance, the spectrum taken by [1] (Fig. 1, green spectrum on the left bottom panel) provided a good view of Cthulhu, corresponding to the New Horizons spectrum marked by the letter ‘c’ (Fig 1, right side). However, because ground-based spectra represent an entire hemisphere of Pluto, this spectrum includes a wide variety of terrains. Further, much of Pluto’s surface is rich in CH$_4$, whose spectral signature is dominant over that of the almost featureless dark material, and even that of the icy regions where the much weaker N$_2$ and CO absorption bands occur. It is partly for this reason that data taken with only hemispheric resolution before the flyby show relatively little spectral variation, hinting at a degree of homogeneity that is not representative of the great variety seen with the spatial resolution achieved in the New Horizons data.

Conclusions: From the comparison of data taken before and after New Horizons one of the takeaways is that subtle longitudinal variations in ground-based data can correspond to dramatic variations at regional scales. While the amount of information provided by New Horizons on Pluto is immense its impact on the rest of the TNOs future data gathering is also very important. We present what we have learned in the comparison of before and after New Horizons observations and we draw conclusions on how we should proceed with future observation planning of TNOs.

References:

Figure 1. Left top panel: Geographical location of the spectra considered in this work. Left bottom panel: Ground based observations of Pluto taken in the time period of 2001-2012 [1]. Right panel: spectral averages of pixels sampled in the regions marked on the map with corresponding letters [2].

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PLUTO DARK REFRACTORY MATERIAL: A CLOSE LOOK AT COMPOSITION AND ORIGIN.

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Introduction: The variety of terrains on Pluto surface has provided us with an opportunity to investigate a bounty of data on processes and conditions that before the New Horizons flyby were unsuspected [1]. One particular region has attracted a lot of attention, Cthulhu, with its dark coloration and location on the equatorial belt, which on the encounter hemisphere, is interrupted only by the bright and icy Sputnik Planitia. Cthulhu is otherwise a region deprived of volatile ices, with the possible exception of protected valleys and mountain peaks showing presence of CH4 ice [2], [3]. However, careful analysis of the spectral signature of selected regions shows presence of H2O ice, the main component of the bedrock layer that lies under the volatile ices [2]. It is in some of these regions that ammonia and its products have been detected [4]. The presence of ammoniated product in H2O prompted an investigation that led to the uncovering of evidence of cryovolcanism [5]. We present results of further analysis of these areas, stripped of volatile ices and composed mainly of dark material and H2O laced with ammoniated products.

Data Analysis: The goal of our study has been to extract the purest possible signature of the dark constituent(s) covering Cthulhu making use of data from LEISA (Linear Etalon Imaging Spectral Array) and corresponding MVIC (Multi-spectral Visible Imaging Camera) [6]. We have analyzed several Regions of Interest (ROIs) spread over the strip (P_LEISA_HIRES) covered at the highest spatial resolution of 2.7 km/px by New Horizons during the July 2015 flyby, from a mean range of 45,000 km and with a mean phase angle of 33°.

Making use of a ‘recursive’ clustering technique we have isolated those pixels that are not contaminated by CH4 but still show the presence of H2O in varied amounts.

We compare the spectral signature of those CH4 free pixels across areas of the strip that have different amounts of H2O contamination in an effort to study the behavior of the dark material and its constituents as well as the presence of ammoniated products present in the H2O.

Preliminary results: The very first region to be investigated was the trough running west from Elliott Crater known as Virgil Fossae. It was studying this region that we uncovered evidence of ammoniated products laced into the H2O spectral signature [4].

Using the same approach we then investigated a few other ROIs, deemed geographically interesting because of their location with respect to areas where H2O had been previously detected. Figure 1 shows the geographical distribution of pixels with different degrees of H2O and ammoniated products contamination in the region north of Virgil Fossae, near Inanna Fossae. The blue pixels are those with the largest amount of H2O as shown in Figure 2 where the average spectra corresponding to each cluster are shown. The blue trace shows the deepest bands at 1.5 and 2.0µm an indication of H2O being present in this area. The spectra in color are germane to the different pixels in the map shown in Figure 2, the grey trace instead belongs to the cluster average of the pixels falling on Virgil Fossae.

We will compare and contrast the signature of a few ROIs across Cthulhu, and we will present the results and preliminary interpretation with the ultimate goal of tracing the origin and evolution of the material(s).

References:


**Figure 1.** Map of part of Inanna Fossae, north east of Virgil Fossae showing regions with different amounts of H$_2$O laced with ammoniated products.

**Figure 2.** Spectral averages corresponding to the different clusters shown in Figure 1. Cluster 5 appears the most H$_2$O rich based on the depth of the 1.5 and 2.0 µm bands. The grey trace belongs to the spectral average of pixels located on and near Virgil Fossae.

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**Volatile and Climate Cycles on Short and Long Timescales.** A.M. Earle\(^1\), R.P. Binzel\(^1\), L. A. Young\(^2\), T. Bertrand\(^3\), M. W. Buie\(^4\), D. P. Cruikshank\(^5\), K.S. Ennico\(^6\), F. Forget\(^7\), W. M. Grundy\(^8\), J. M. Moore\(^9\), C. B. Olkin\(^9\), B. Schmidt\(^9\), J. R. Spencer\(^2\), J. A. Stansberry\(^7\), S. A. Stern\(^2\), L.M. Trafton\(^8\), O.M. Umurhan\(^9,9\), H. A. Weaver\(^10\), and The New Horizons Science Teams.

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**Introduction:** Pluto’s high obliquity (currently around 119°) varies by 23° over a period of less than 3 million years while Pluto’s longitude of perihelion regresses 360° over 3.7 million years [1,2]. As a result of this pair of orbital variations Pluto’s sub-solar latitude at perihelion has ranged between 53° South and 76° North over the past 3 million years (Figure 1). Pluto has a high orbital eccentricity (\(e \approx 0.25\)) which causes its heliocentric distance to vary from less than 30.4\(\text{AU}\) out to almost 50\(\text{AU}\), which leads to the solar constant changing by a factor \(~3\) over the course of its orbit [2].

Insolation intensity and distribution is dependent on instantaneous heliocentric distance and obliquity [3]. Pluto’s high eccentricity coupled with its changing obliquity and sub-solar latitude at perihelion create substantial difference in insolation patterns on Pluto when averaged over different time intervals [4-6]. During Pluto’s current epoch, equinox and perihelion occur relatively close together, causing both hemispheres to have fairly similar seasonal cycles. However, the phasing of Pluto’s obliquity and longitude of perihelion variations create epochs of “Super Seasons” where one pole is pointed towards the Sun at perihelion, causing that hemisphere to experience a short intense summer and long period of winter darkness while the other hemisphere experiences a very short winter and much longer, but less intense summer (Figure 2) [7]. Pluto’s high and varying obliquity also leads to unusual “Climate Zones” that vary over time [8]. Understanding these patterns can provide important insight in interpreting surface features revealed by New Horizons and understanding volatile transport on Pluto. Pluto’s atmosphere is probably in vapor pressure equilibrium with isothermal surface ice, so the surface atmospheric pressure is controlled by the surface volatile temperature [2, 9]. Given the magnitude of Pluto’s orbital variations (and consequently its insolation distribution) over millions year timescales, it could be expected that Pluto’s volatile distribution, atmospheric pressure, and surface geology are impacted by these variations.

**Overview:** This talk will explore Pluto’s insolation history and its implications for Pluto’s atmospheric pressure, surface temperatures, and volatile distributions over various timescales. We will provide an overview of some of the early modeling results since the New Horizons’ flyby of the Pluto system and give background and context for some of the more advanced modeling efforts currently underway. In particular we will consider how differences in insolation between the current epoch and “Super Season” epochs may impact Pluto’s atmosphere and volatile distribution.

Preliminary atmospheric pressure models suggested Pluto’s “Super Season” epochs may be responsible for past epochs of higher atmospheric pressure (with values exceeding 100 \(\text{Pa}\)) on Pluto that would explain some of the geomorphological features on Pluto that would be difficult to form at current atmospheric pressures [10]. More detailed atmospheric pressure modeling has since suggested pressures above 100 \(\text{Pa}\) are unlikely to occur but still supports the significance of Pluto’s orbit variations as a driver of Pluto’s surface evolution and volatile transport [11]. Pluto’s seasonal and orbital variations likely impact Pluto’s atmosphere in other ways beyond surface pressure, for example vertical structure, dynamics, and haze production [e.g. 12-14].

Pre-encounter volatile transport models [e.g. 2, 15, 16] generally focused on shorter timescales (covering just the current Pluto epoch and not including timescale long enough for Pluto’s orbit variations to be considered). They also used a simple treatment of albedo and no consideration of geology (since it was not yet mapped), so their results cannot explain the stark longitudinal contrasts in composition, geology, and albedo which were revealed in detail by New Horizons [17]. The first post-encounter paper to address volatile transport adapted existing thermal models [18, 19] and compared the results to explore the significance of albedo for Pluto’s volatile distribution, this work provided an early indication the Pluto’s equatorial and mid-latitudes were particularly sensitive to albedo variations [7].

Since then additional time and more detailed analysis and processing of the New Horizons data has allowed for more detailed modeling of Pluto’s volatile transport and atmospheric cycles. [20] has performed a
more detailed study of how Pluto’s surface volatiles respond to albedo differences, exploring these processes over the current epoch as well as past “Super Season” epochs. They found that Pluto’s high obliquity creates unique conditions that make its equator and mid-latitudes highly sensitive to albedo feedback effects, resulting in them being able to maintain stark, longitudinal albedo and volatile abundance variations over long timescales. A global circulation model has been developed for Pluto and used to explore N$_2$, CH$_4$, and CO cycles [21], the interactions between Pluto’s atmosphere and topography [22], nitrogen cycles over astronomical timescales [11] and methane cycles over astronomical timescales [23]. Additionally, work is underway to update the model presented in [24] run over longer timescales and better account for the volatile distribution observed by New Horizons [25, 26].


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ATMOSPHERIC ESCAPE. J. T. Erwin, The Royal Belgian Institute for Space Aeronomy (BIRA-IASB), Ringlaan-3-Avenue Circulaire, B-1180 Brussels, Belgium (justin.erwin@aeronomie.be).

Introduction: All planetary bodies with an atmosphere experience some process of atmospheric escape, whether it is primarily due to thermal, diffusive, or non-thermal escape. These escape processes affect the density, temperature, and compositional structure of the upper atmosphere. In addition, in some circumstances, they can have importance in the lower atmosphere and the evolution of the entire atmosphere. This field of research remains active and continues to evolve as we explore our solar system and beyond.

Atmospheric Escape: Historically, atmospheric escape was thought to occur within two extremes: fast, supersonic expansion (via Parker’s solar wind model) [1], and slow kinetic escape (via Jeans escape model). The former, with some modifications named Slow-Hydrodynamic Escape (SHE), was applied to many small bodies in the solar system as it was thought the low gravity would facilitate fast escape [2,3]. More recently, kinetic models of atmospheric escape have been used to properly model the transition between the collisional and collisionless regimes [4]. A systematic study showed that there exists a dynamic transition between the previous two extremes, with an enhanced Jeans-like region in between [5,6].

Therefore, recent models combine a fluid model with a kinetic upper boundary condition [7,8], or to combine a fluid and kinetic model to simulate the upper atmosphere and exosphere together [9,10].

In the above figure from [20], the 3 different escape models of Pluto’s upper atmosphere result in different atmospheric structures. In particular, the SHE model is cooler and an atmosphere significant contracted compared to the kinetic models. However, the escape rates determined by these 3 models are very similar (due to conservation of energy). This case demonstrates that the atmospheric structure can be very sensitive to the escape mechanism (or alternatively the upper boundary condition).

A summary of these different escape models will be presented, along with a discussion of their respective implications. In addition, further concepts such as diffusion limited escape to the trace species, and energy limited escape will be put into context.

Pluto and New Horizons: Since the discovery of Pluto’s atmosphere, significant effort has been made to understand it atmosphere. As a light body, the escape process was thought to be large and therefore dominant the upper atmospheric structure significant. Several models were applied and the prevalent theory evolved from SHE [2,11,12] to an enhanced Jeans Escape verified by kinetic models [19, 20]. Escape from the upper atmosphere, driven by UV absorption, drives adiabatic cooling to the mid and lower atmospheres. Hence it became necessarily to model the entire atmosphere together as many processes overlapped [13]. The result was a highly extended atmosphere, with a large but subsonic escape rate.

New Horizons found a very different atmosphere [14,15]. The upper atmosphere is much cooler and isothermal resulting with a slow escape rate. Some work has been made to explain this new picture of Pluto’s atmospheric structure by including additional cooling agents (e.g. hydrocarbons and water) [16].

References:
TESTING THolinS AS ANALOGS OF THE DARK REDDISH MATERIAL COVERING THE CThULHU REGION. M. Fayolle1,2, E. Quirico1, B. Schmitt1, L. Jovanovic3, T. Gautier1, N. Carrasco3, W. Grundy4, V. Vuitton1, O. Poch1, L. Gabasova1, S. protopapa5, L. Young5 and the New Horizons Surface Composition Science Theme Team.

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Introduction: Pluto’s flyby by the New Horizons spacecraft in July, 2015 has brought many insights into the chemical composition of Pluto’s surface. Of particular interest is the equatorial Cthulhu region, whose terrains seem to contain a dark, reddish and non-icy surface material. This material has not yet been firmly identified, and might result from the sedimentation of aerosols formed in Pluto’s tenuous atmosphere, from a chemistry triggered by the dissociation of $N_2$, $CH_4$ and CO gases [2]. Complex macromolecular organic materials sharing similarities with those forming Titan’s haze may then coat Cthulhu’s terrains as a ~5 m layer (assuming the present deposition rate has been the same since the formation of Pluto). Here, we question this scenario through the interpretation of MVIC/LEISA data based on laboratory experiments. The optical properties of analogs of Pluto’s aerosols (tholins) were determined by spectro-gonio- radiometry, and were used to fit the reflectance spectra collected by the MVIC and LEISA instruments.

Experimental: Tholin samples were synthesized in a cold plasma reactor at LATMOS and recovered as a dusty material composed of spherical grains, with a size distribution peaking at ~210 nm in radius (estimated from Scanning Electron Microscopy). Two gas compositions were used, $N_2$:CH$_4$=99:1 and 95:5 (with 500 ppm of CO for each), relevant to atmospheric compositions at ~ 400 km and 600 km, respectively. The tholin reflectance spectra were collected with a spectro-gonio-radiometer at IPAG operating in the range 0.4-4 $\mu$m, covering the full spectral range of MVIC/LEISA observations (0.4-2.5 $\mu$m). The absolute photometric accuracy was of 1 %, and measurements could be done under various illumination and observation geometries [3]. Measurements were carried out under vacuum and with gentle heating in order to remove adsorbed water.

Reflectance measurements: The reflectance spectra collected in the laboratory are displayed in Figure 1, along with spectra calculated from optical constants published in the literature. They reveal absorption bands at 1.5, 1.75, 1.9 and 2.3 $\mu$m, due to overtones and combinations of N-H, C-H and CN [4]. Tholin reflectance spectra were collected for incidence angles of 0, 30 and 60°, and emission angles between -70 and 70° (every 10°). Their single scattering albedo (SSA) and phase function were determined through a least-squares inversion of a simplified Hapke reflectance model fitting the experimental data.

Comparison with MVIC/LEISA: A direct comparison of tholin spectra and MVIC/LEISA spectra (for similar illumination and observation geometries) reveals a clear mismatch: (1) tholins have a higher reflectance factor in the near-infrared; (2) the tholin absorption bands are not observed in Pluto spectra. To get a quantitative assessment, MVIC/LEISA spectra of the Cthulhu region were fitted with a Hapke reflectance model, using the inverted tholin SSA. The surface was modelled as a spatial mixing of two units: one covered with $CH_4$ ice and the second as a mixture of $N_2$, $C_2H_6$, $CH_3OH$ ices and tholins, following [5]. An optimization algorithm has been applied to solve for the mass ratios of these compounds. This process has been conducted for two different Cthulhu spectral data, the first one corresponding to the $H_2O$-rich region and the other one to the $H_2O$-poor region. The best match (Fig. 2) between the numerical model and MVIC/LEISA data has been obtained with the $N_2$:CH$_4$=99:1 tholins. Once mixed with hydrocarbon ices, they account fairly well for the Cthulhu photometric level, but not for the visible spectral slope in the $H_2O$-poor terrains, and they still display weak overtone/combination bands that are not present in LEISA observations.
Three explanations, at least, are possible to account for this misfit. (1) The terrains may be contaminated by interplanetary dust impacting, bringing dark materials into the aerosols layer. However, additional experiments on tholins mixed with pyrrhotite (an opaque mineral as analog of dark interplanetary dust) and subsequent modelling led to a drop of the reflectance in the near-infrared. (2) Galactic Cosmic Rays (GCR) irradiation is known to promote dehydrogenation reactions, carbonization and perhaps amorphization. This scenario needs to be tested through experimental simulations. Nevertheless, if the dark materials of the Cthulhu terrains result from aerosol sedimentation, the effective exposure duration would not last over ~50000 years, which corresponds to a low irradiation dose. (3) A high porosity of the dark terrains is the third explanation. Laboratory experiments have shown that a highly porous tholin crust, formed from sublimation experiments, does not display combination/overtone bands in the near-infrared [6]. On Pluto, ice/tholin sublimation, or simply low gravity deposition, may promote the formation of highly porous materials, which do not show bands in the near-infrared.

MODELING NITROGEN AND METHANE ICES AND GLACIERS ON PLUTO OVER DIURNAL, SEASONAL AND ASTRONOMICAL TIMESCALES. F. Forget1 and T. Bertrand2,3, 1 Laboratoire de Météorologie Dynamique, IPSL, CNRS, Sorbonne Université, Paris, France (forget@lmd.jussieu.fr), 2Space Science Division, NASA Ames Research Center Moffett Field, CA 94035, USA (tanguy.bertrand@nasa.gov).

Introduction:
The high obliquity and eccentricity of the orbit of Pluto induce seasonal cycles of condensation and sublimation of the main volatile ices: N₂, CH₄, and CO. In 2015, New Horizons revealed a complex distribution of these ices [1-7], including the thousand-kilometers nitrogen ice-sheet in Sputnik Planitia, a combination of N₂, CO and CH₄ deposits at mid-latitudes, massive methane-rich deposits forming the Bladed Terrain at low latitudes, a methane mantle at high latitudes, CH₄ snow-capped mountains near the equator, etc.

To understand the distribution and evolution of the nitrogen and methane ice reservoirs at the surface of Pluto and their origins, we have developed a hierarchy of models able to simulate the volatile cycles over multiple timescales: (1) A Global Climate Model [8,9] to represent the evolution of the 3D atmospheric circulation, the transport of gases and surface ices (N₂, CH₄ and CO) over up to several tens of Earth years (2) a 2D volatile transport model [10] able to simulate the N₂, CH₄ and CO cycles over several tens of thousands of years (tuned using the GCM) and 3) A long-term Pluto evolution model combining the volatile transport model simulations with the variations of Pluto’s orbit and obliquity to simulate the evolution of the volatile reservoirs over up to 50 million Earth years [11,12].

Such tools are based on universal equations, with the minimum of ad-hoc hypothesis. Yet we found that the modeled Pluto climate system and the evolution of its volatile reservoirs are surprisingly sensitive to a few model parameters such as the ice albedos and deep subsurface thermal inertia. Nevertheless, by choosing a set of selected values we could reproduce many characteristics of the planet observed by New Horizons in 2015.

The nitrogen cycle
On our modeled Pluto, most N₂ ice tends to accumulate in Sputnik Planitia due to its low elevation corresponding to an higher pressure and condensation temperature [10]. Outside the Sputnik Planitia basin, thick N₂ deposits are able to persist over tens of millions of years [11], in particular in the equatorial regions and in depressions, before being trapped in Sputnik Planitia. Long-term N₂ ice is not stable at the poles.

Within Sputnik Planitia, the N₂ ice budget is controlled by the diurnal, seasonal and astronomical cycles of Pluto. We found that the obliquity changes drive the long-term N₂ cycle. Over one obliquity cycle, the latitudes of Sputnik Planitia between 25°S-30°N are dominated by N₂ condensation, while the northern regions between 30°N-50°N are dominated by N₂ sublimation. According to the model, a net amount of 1 km of ice has sublimed at the northern edge of Sputnik Planitia during the last 2 million of years and must have been compensated by a viscous flow of the thick ice sheet [10]. By comparing these results with the observed geology of Sputnik Planitia, we can relate the eastern glacial flows and the erosion of the water ice mountains all around the ice sheet to the N₂ sublimation and condensation occurring at the astronomical timescale. The formation of the small pits and the brightness of the ice at the center of Sputnik Planitia are instead related to the annual timescale.

Another result is that the minimum and maximum surface pressures obtained over the simulated millions of years remain in the range of milli-Pascals and Pascals, respectively.

The methane cycle
By assuming fixed solid ice mixing ratios, we explored how changes in surface albedos, emissivities and thermal inertias impact volatile transport [12]. We found that bright CH₄ deposits can create cold traps for N₂ ice outside Sputnik Planitia, leading to a strong coupling between both N₂ and CH₄ cycles. Depending on the assumed albedo for CH₄ ice, the model predicts CH₄ ice accumulation (1) at the same equatorial latitudes where the Bladed Terrains are observed, supporting the idea that these CH₄-rich deposits are massive and perennial, or (2) at mid-latitudes, forming a thick mantle which is consistent with New Horizons observations. In our simulations, both CH₄ ice reservoirs are not in an equilibrium state and either one can dominate the other over long timescales, depending on the assumptions made for the CH₄ albedo. This suggests that long-term volatile transport exists between the observed reservoirs.

In Pluto’s current orbital configuration, if we assume a relatively bright CH₄ ice (albedo larger than 0.6), the model is able to reproduce the formation of N₂ deposits at mid-latitudes and in the equatorial depressions surrounding the Bladed Terrain, as observed
by New Horizons. At the poles, only seasonal CH₄ and N₂ deposits are obtained, regardless of the chosen ice albedo.

The longitudinal distribution of the methane deposits (east of Sputnik Planitia rather than west where the ground is almost volatile ice-free) is not easy to simulate using a volatile transport model. This asymmetry must involve atmospheric dynamics and transport of methane as influenced by Sputnik Planitia [13].

Finally, we show that Pluto’s atmosphere always contained, over the last astronomical cycles, enough gaseous CH₄ to absorb most of the incoming Lyman-alpha flux, which raises questions about the mechanisms leading to the formation of the dark organic materials observed on Pluto’s surface.

Explaining methane snow-capped mountains.

Within the dark covered equatorial regions, CH₄ ice is not detected on most surfaces except on crater rims and mountain tops, sometimes providing strong resemblance to terrestrial snow-capped mountain chains. However, the process controlling the preferential accumulation of methane on mountains is completely different from what occurs on the Earth. To understand this, we performed high-resolution numerical simulations of Pluto’s climate performed with the 3D Global Climate Model that includes the present-day CH₄ cycle.

The model predicts CH₄ condensation at high-altitude in the equatorial regions, where the CH₄-capped mountains are observed, on the ridges and crests of the Enrique Montes in eastern Cthulhu. This high-altitude condensation results from the fact that the atmosphere is much more CH₄-rich a few kilometers above the zero-datum (where the atmosphere is warm) than in the lowest atmospheric levels. The mountain top extending into the CH₄-rich levels are cold-traps for the gaseous methane. Why are the lowest levels methane depleted? Our model shows that this is controlled by the diurnal cycle of nitrogen (N₂) which induces a N₂-rich, CH₄-poor sublimation flow depleting the lower atmosphere in gaseous CH₄.

We derive more realistic simulations taking into account surface albedo feedbacks which highlight the stability of these CH₄ frosts. These results show that the presence of high-altitude CH₄ frosts on Pluto is controlled by an atmospheric process unique in the Solar System. The same mechanism could be at the origin of the sharp crests on top of the Bladed Terrain CH₄ deposits.

Conclusion.

At the Pluto System After New Horizons conference we will review what we have learned from these numerical simulations, but also put forward the observations that remains enigmatic and difficult to understand and predict with our numerical models.

References
The Kuiper Belt as the Context for Pluto. S. Fornasier1, M.A. Barucci1 and M. C. Dalle Ore2,
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Introduction: The Kuiper belt is populated by the Transneptunians Objects (TNOs), frozen leftovers from the formation period of the outer Solar System. More than 3000 TNOs have been discovered, including the dwarf planets Pluto, Eris, Makemake and Haumea. The investigation of the TNOs’s physical properties is essential for understanding the formation and the evolution of the Solar System, and sheds light on the composition of the primordial protoplanetary disk, and, by extension, of other exoplanetary systems. The Kuiper Belt is sculpted in a complex manner as indicated by the presence of bodies with highly inclined and/or very eccentric orbits and the existence of distinct dynamical classes including classical, resonant, scattering, and detached objects [1]. The Kuiper Belt region seems to be the source both of short period comets and of Centaurs, thought to have been injected into their present unstable orbits by gravitational instabilities and collisions.

In this work we will give a state of the art overview of the physical properties of the Transneptunians and Centaurs, including composition, size, albedo, bulk density, and rotational and thermal properties.

Size, albedo and Thermal Properties: Knowledge of TNOs albedos and sizes is important to constrain the surface composition and understand the dynamical evolution of the outer Solar System. Size and albedo values, mostly derived from radiometric modeling of the thermal observations performed with Herschel, Spitzer and Wise, and a few from occultations, are available for a total of ~170 TNOs and Centaurs [2].

TNOs show a huge variation in geometric albedo (p_v), including both extremely dark surfaces (p_v = 2-3%) and high reflective bodies (p_v > 50%). Globally, excluding the volatile rich bodies, transneptunians have dark surfaces with a mean albedo value of ~10%.

The size of TNOs ranges from a few tenths of a km to ~2380 km for the dwarf planet Pluto. The size distribution is affected by discovery and selection biases in thermal observations affecting the smallest TNOs, hard to detect and to characterize. Centaurs sizes range from ~1 km to ~240 km for Chariklo, but most of them are smaller than 120 km.

Average values for size and albedo have been analyzed for the different populations [3, 4, 5, 6]. Centaurs and Scattered Disk objects have both dark surfaces with similar albedo values (7%). In the Classical population the cold objects, i.e., those having inclination lower than 5°, have an higher albedo and a steeper size distribution than the hot classicals (i.e., those having higher inclination orbits). All cold classicals are smaller than 400 km, while the hot ones show a wider size distribution.

Models of the TNOs thermal emission permit to constrain surface properties such as thermal inertia, spin state, surface roughness, and emissivity. The so-called “beaming factor” (η), a proxy for the combined effect of thermal inertia, spin state and surface roughness, show a relative variability ranging from 0.34 to ~2.5, with an average value of 1.07 [7]. The thermal inertia derived from the η value using a statistical approach on the bodies spin rate and surface roughness is 2.5 ± 0.5 J m^-2 s^-0.5 K^-1 [7], that is 2-3 orders of magnitude lower than expected for compact ices. The TNOs emissivity has been found to decrease with wavelength in the submm and mm range from Herschel and Alma observations [8, 9]. This, together with the low thermal inertia value, indicates that TNOs have highly porous surfaces with absorption coefficients much stronger than those of pure water ice.

Density: Density measurements are available for 27 binary/multiple systems, showing a clear dichotomy between relatively small and big objects (Fig. 1): transneptunians smaller than 400 km have densities lower than that of water ice (with median value of 0.79 g cm^-3), while those bigger than ~750 km have all density higher than 1 g/cm^3, indicating a larger rock to ice ratio and less porosity. The huge variation in density, by a factor of ~5, between small and large bodies may be related to different formation location/times/processes of large TNOs and dwarf planets compared to smaller bodies.
Composition: Good spectra in the visible and near-infrared are available for a limited number of objects and only about 50 of them (TNOs and Centaurs) show clear or possible absorption features. Others show almost featureless spectra, which make any attempt at deriving surface compositions particularly challenging.

The visible part of the spectrum is generally featureless, with the exception of methane enriched bodies and of a few TNOs showing absorption bands attributed to aqueously altered minerals [12, 13]. The presence of hydrated minerals is intriguing. They may have been produced by post-accretional heating processes such as cryovolcanism or impacts on ices, or they may have condensed directly in the solar nebula, considering that they are also observed on debris disks and in the interplanetary dust.

The near-infrared observations in the range 1-2.4 micron are the most diagnostic to detect the presence of volatiles. Three main kind of surfaces have been detected [16]:

(i) water-ice rich (about 30 objects) showing absorption bands at ~1.5 and 2 micron. Most of those having high S/N ratio also show the 1.65 micron band indicating that the water ice is in the crystalline state. This requires temperatures T > 100 K, well beyond the environmental temperature of the Kuiper belt. The heating could have occurred by impacts or generated in the deep interiors. Water ice rich objects are found in all the dynamical classes, and the abundance of water ice is correlated with the objects size.

(ii) volatile-rich bodies including methane and/or nitrogen or methanol. Pluto, Eris, Makemake and Sedna all show spectra dominated by methane ice, pure or diluted in nitrogen. Methanol has been detected in ultrared bodies like (5145) Pholus, (55638) 2002 VE₉₅, and Sedna. The methanol signature is considered an indication of a chemically primitive surface and methanol is an abundant component of active comets and of the interstellar medium. Orcus and Charon show the ammonia band at 2.25 µm. The presence of ammonia has been suggested to be the result of a flow of ammonia-rich interior liquid water onto the surface.

(iii) featureless bodies, with different spectral gradient, indicating surfaces enriched in carbon or in organics. Irradiation processes are thought to be responsible for these properties as all these objects are supposed to have been originally composed of ices.

Correlations between physical and orbital parameters and compositions have been investigated and will be presented. The lesson learned by Pluto for the other TNOs will be also discussed.

References:
[16] Barucci et al., 2011, Icarus, 214, 297
GLOBAL COMPOSITIONAL CARTOGRAPHY OF PLUTO FROM LEISA DATA. L. R. Gabasova, B. Schmitt, W. Grundy, C. B. Olkin, J. R. Spencer, L. A. Young, K. Ennico, H. A. Weaver, S. A. Stern, and the New Horizons Composition Team; 1Université Grenoble Alpes, CNRS, IPAG (Grenoble, France, leila.gabasova@univ-grenoble-alpes.fr), 2Lowell Observatory (Flagstaff, AZ, USA), 3SwRI (Boulder, CO, USA), 4NASA Ames Research Center (Mountain View, CA, USA), 5JHU-APL (Laurel, MD, USA).

Introduction: The July 2015 flyby of the Pluto system by the NASA New Horizons mission returned a wealth of data, greatly advancing our knowledge of its surface topography, geology, and composition, as this is the first time we have been able to observe and map it directly. The highest-resolution data is limited to the encounter hemisphere of Pluto, but lower-resolution images obtained during the approach allow for the production of global mosaics.

Schmitt et al. [1] gives a comprehensive qualitative analysis of the spatial distribution of the various materials present on the surface of the encounter hemisphere. N₂ and CH₄ ices are present both separately and in a ternary molecular mixture with CO ice, as is H₂O ice and a dark red organic material. While extending this study globally is possible via the lower-resolution approach images, pointing imprecisions result in several degrees of misregistration between the encounter and approach datasets, necessitating additional co-registration before global mosaics can be created.

Schenk et al. [2] produced a panchromatic global reflectance map using both the LORRI framing camera and the MVIC panchromatic channels, and Earle et al. [3] co-registered the MVIC colour channel images to the LORRI map. The high-resolution LEISA data has also been registered to the panchromatic map using feature-based methods. These methods, however, have proven inadequate for registering the LEISA approach imagery, as the imaging distance combined with the lower resolution of the instrument result in there not being any readily identifiable feature edges in the far hemisphere.

A class of methods that is promising for this kind of data is intensity-based registration, which involves comparing intensity patterns in the images to be registered. Different metrics can be used to evaluate their similarity, such as cross-correlation, mutual information, or sum of squared intensity differences. Intensity-based registration is a very common tool in medical imagery processing, and is very easily adapted to planetary data.

Methods: We process 12 approach cubes in order to have complete global coverage, with native pixel resolutions ranging from 30 to 354 km/px. The highest-resolution of these is registered using the closest-approach high-resolution data as a target image and each subsequent cube is registered to the one above it in resolution order (e.g. second-highest resolution to highest, third-highest to second-highest, etc.). This is done to maximise overlap between the source and target images and provides overall more accurate registration, despite the risk of error propagation.

The LEISA hyperspectral datacubes are captured over a short time, which means the same transformation matrix will be applicable to all wavelengths. This means we can calculate the transformation matrix using a subset of the datacube — one which features large contrasts and clear patterns — and apply it to all the other wavelengths. The CH₄ ice map produced by [1] using the integrated band depth of the 1.7 μm band group has precisely these properties, and serves as the basis for the registration.

We apply intensity-based registration algorithms from ITK (Insight Segmentation and Registration Toolkit, an open-source library). As we expect the misalignment between the datasets to be due entirely to imprecisions in the spacecraft pointing information, we restrict ourselves to global similarity transformations (i.e. translation, rotation, and scale). We use an evolutionary algorithm-based optimiser and a Mattes mutual information metric [4].

Results: We verify the registration accuracy using a small number of control points based on identifiable features (shown in Figure 1) as well as visual comparison with the global panchromatic reflectance map. The six highest-resolution approach maps registered accurately to better than 1 pixel of each map’s native resolution. Due to the lack of a spectrally-analogous anchor on the opposite hemisphere, some latitudinal drift occurred for the next six maps. This was corrected manually and will be automated in a future iteration of the algorithm.

Figures 2–4 show the global maps for the CH₄ integrated 1.7 μm band depth, the H₂O spectral index, and the red material spectral index. The N₂ and CO spectral index maps will also be shown at the meeting.

Discussion: The global CH₄ map allows us to confirm the presence of a methane belt in the 0–30°N latitude range, extending globally beyond the bladed terrains seen in the high-resolution images [5]. The macula region covering most of Pluto’s surface between 0–30°S is also quite clearly visible in the global red material map.

These are the first global registered composition maps of the surface of Pluto, allowing us to study the correlation of composition with geological features on
the non-encounter hemisphere. They also provide a cartography of volatiles for radiative transfer models, and will allow the calculation of latitudinal and longitudinal means of $N_2$, $CH_4$, and CO, from which we can obtain the global radiation budget of Pluto in 2015. These maps also provide useful inputs and constraints for global circulation models to study the origin of the current ice distribution of Pluto.


Figure 1: Example of intensity-based registration results for the Pluto $CH_4$ 1.7 $\mu$m band depth map, showing the Pulfrich crater area. Left: high-resolution image, centre: unregistered lower-resolution image (native resolution 30 km/px), right: registered lower-resolution image.

Figure 2: Global registered $CH_4$ map (1.7 $\mu$m integrated band depth).

Figure 3: Global registered $H_2O$ spectral index map.
CONSTRAINING PLUTO’S H AND CH₄ PROFILES WITH ALICE LYMAN-ALPHA OBSERVATIONS.
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Introduction: The Alice instrument on New Horizons performed several observations of Pluto’s far-ultraviolet (FUV) airglow emissions during the 2015 flyby. While Pluto’s atmosphere is dominated by N₂, the brightest airglow feature at Pluto is due to Lyman-alpha (Lyα) emission of atomic hydrogen. This is because H atoms, produced at lower altitudes during photolysis of CH₄, are able to resonantly scatter the very bright Lyα lines from both the Sun and the interplanetary medium (IPM). While the IPM Lyα flux at Earth is much less than direct solar Lyα, the IPM Lyα brightness falls off much more slowly with distance from the Sun than 1/r², so that at Pluto the two sources are of comparable strength [1,2].

Although the Alice instrument has poor spatial resolution, at about 40 minutes prior to closest approach a short “ride-along” scan of Pluto during an MVIC color observation, obtained the highest resolution airglow data of the flyby. For this observation, 11:08:27-11:12:11 UTC on 14 July 2015, the range to Pluto when the Alice slit was centered on Pluto (at 11:11:09 UTC) was 33,750 km, and the Alice 0.3° pixel size was ~175 km (~0.15 RP), as seen in Fig. 1a.

Resonant Scattering of Lyα at Pluto: At 32.9 AU from the Sun, Pluto was distant enough that the solar Lyα line was considerably extincted due to scattering by H atoms in the interplanetary medium. Since Pluto was close to upstream in the interstellar wind, however, this extinction was shifted from line center by about 20 km/s (~18 Doppler widths from line center for 70-K H atoms in Pluto’s upper atmosphere) and thus has very little affect. Using predicted H and CH₄ densities from a recent model of Pluto’s photochemistry appropriate for the New Horizons flyby [3], we find that the brightness of Lyα due to resonantly scattered sunlight is ~30 Rayleighs (R), and that, behind this, Pluto’s methane absorbs the brighter (~70 R) IPM Lyα background to an altitude of ~450 km (Fig. 1b). The actual P_Color2 observation matches the prediction quite well (Fig. 1c).

In this talk we will further discuss how Lyα emissions are formed at Pluto, and will show curve-of-growth predictions for Pluto’s Lyα corona as seen from New Horizons to constrain both the H and CH₄ densities for use in photochemical models.

References:
**PLUTO’S SURFACE COMPOSITION.** W.M. Grundy¹, D.P. Cruikshank², S. Protopapa³, and B. Schmitt⁴. ¹Lowell Observatory (Flagstaff AZ; w.grundy@lowell.edu); ²NASA Ames Research Center (Mountain View CA); ³Southwest Research Institute (Boulder CO); ⁴Université Grenoble Alpes, CNRS, IPAG (Grenoble France).

New Horizons’ instruments revealed spectacular compositional contrasts across Pluto’s surface [1]. Some of the most striking landscapes involve the volatile molecules methane (CH₄), nitrogen (N₂), and carbon monoxide (CO), frozen solid at Pluto’s low temperatures in the 35 to 60 K range [2]. These volatile ices have appreciable vapor pressure even at such low temperatures. Their volatility supports Pluto’s complex atmosphere [e.g., 3] and it enables them to sublime and condense in response to daily and seasonally varying patterns of insolation [4,5]. The mobility of Pluto’s volatile ices enables significant transport over seasonal and longer timescales, creating a diverse array of landforms ranging from the penitente-like bladed terrain of Tartarus Dorsae [6,7], to the valley glaciers of eastern Tombaugh Regio [8,9,10], to the mantled, fretted, and pitted terrains at high northern latitudes [11]. Differences in the volatilities of N₂, CO, and CH₄ ices result in very distinct regional distributions, with the less-volatile CH₄ tending to occur at high altitudes and high northern latitudes at the time of the encounter, while the more volatile CO and N₂ were seen at mid-northern latitudes and in topographic lows [2]. A distillation sequence has been mapped in some regions where, initially, all three volatiles condense together, but the more volatile N₂ gradually sublimates away, followed by the CO, leaving a CH₄-rich residue [12]. One of Pluto’s primary reservoirs of N₂ ice is Sputnik Planitia [13,14], a partially-filled basin in which the N₂ ice deposit is so thick that it undergoes solid-state convective overturn, refreshing its surface in a way not seen in terrestrial glaciers [15,16]. At smaller scales, the surface of Sputnik is modified in some regions by the formation of sublimation pits [14,17], while other regions appear to be resurfaced by wind-blown dunes of CH₄ ice [18].

Underlying Pluto’s volatile ices is a comparatively non-volatile substrate dominated by H₂O ice. H₂O ice is detected spectroscopically in a variety of settings, often accompanied by dark reddish material. These include the rugged mountains in western Sputnik Planitia, that may consist of fragments of crustal material buoyantly supported in Sputnik’s N₂ ice. H₂O ice is also seen in Cthulhu and Krun, two examples from an equatorial belt of dark red maculae that appear to be too warm to condense much volatile ice [19,20]. H₂O ice also appears in association with dark, red deposits north of Cthulhu, such in the floors of craters and in Piri Planitia, a region where CH₄-rich scarps appear to have retreated, exposing substrate material [21]. Finally, H₂O appears associated with a variety of pits in eastern Tombaugh and further north, notably in Supay Facula. This class of H₂O deposits may be indicative of eruptive processes dredging it up from the interior and exposing it at the surface. Additional potential eruptive provinces have been identified in Wright and Piccard Mons [8,22], and in Virgil Fossae [23]. These regions will be discussed more in other talks. It is as-yet unclear what drives the eruptive activity, and whether it involves molten H₂O or Pluto’s more volatile materials that require much less energy to mobilize. Potential anti-freezes such as NH₃ and CH₃OH have been identified spectroscopically [24,25], and may assist in the mobilization of H₂O, now or earlier in Pluto’s history.

A third important class of materials on Pluto is complex organics, generally referred to as tholins. At the time of the New Horizons flyby, their production appeared to be dominated by UV photolytic chemistry in Pluto’s upper atmosphere [e.g., 26,27,28,29]. Photochemical products agglomerate into haze particles that settle out of Pluto’s atmosphere, accumulating at the surface. They are presumed to account for the dark red coloration of Pluto’s equatorial maculae, but where they settle on regions dominated by volatile ices they are evidently rapidly buried by seasonal volatile transport cycles. They may also interact chemically with molecules on Pluto’s surface, leading to further compositional evolution [30]. Some forms of energetic radiation are able to penetrate through Pluto’s atmosphere, driving chemical evolution of the surface ices themselves, and it is possible that during certain epochs, this mechanism could become a dominant driver of chemical evolution. A third potential source of organics is the subsurface, where molten H₂O and NH₃ can interact chemically with tholins incorporated into Pluto from the protoplanetary nebula [31]. Warmer subsurface temperatures enable chemistry to proceed much faster and are likely to lead to production of biologically interesting molecules, which could then be delivered to the surface environment via the various eruptive mechanisms mentioned earlier.

**Acknowledgments**

This work was supported by NASA’s New Horizons project. We are grateful to the thousands of people whose work over the course of nearly two decades...
made the mission a success. Names of Pluto surface features mentioned in this abstract include a mix of official and informal names.

References
**The Atmospheres of Pluto and Triton: Investigations with ALMA.** M.A. Gurwell1, E. Lellouch2, B.J. Butler3, R. Moreno4, A. Moullet5, D.F. Strobel6, and P. Lavvas7. 1Center for Astrophysics | Harvard & Smithsonian (Cambridge, MA 02138 USA; mgurwell@cfa.harvard.edu), 2LESIA, Observatoire de Paris (92195 Meudon, France; emmanuel.lellouch@obspm.fr), 3National Radio Astronomy Observatory (Socorro, NM 87801 USA; bbutler@nrao.edu), 4LESIA, Observatoire de Paris (92195 Meudon, France; raphael.moreno@obspm.fr), 5SOFIA Science Center, NASA Ames Research Center (Moffett Field, CA 94035 USA; amoullet@usra.edu), 6Departments of Earth & Planetary Sciences and Physics & Astronomy, Johns Hopkins University (Baltimore, MD 21218 USA; strobel@jhu.edu), 7GMSA, Université Reims Champagne-Ardenne (51687 Reims Cedex 2, France; panayotis.lavvas@univ-reims.fr)

**Introduction:** Pluto and Triton hold unique clues for understanding the composition and evolution of the outer solar system, and are recognized as benchmarks for studies of the Kuiper Belt. They are two of the largest known and most easily observed KBO members (from Earth, but with caveats), and they are similar in many ways; for one example, they both possess thin (10 microbar class), N2-dominated atmospheres.

The surface, atmospheric structure, and escape rate are tightly connected on these bodies. The N2 atmosphere, in at least bulk vapor-pressure equilibrium with N2 ice, depends critically on surface temperature. Minor species (CH4, CO) and photochemical products (such as HCN) control the temperature structure, and thus the escape rate. Escape rates of volatiles are powerful tools for understanding surface evolution on Triton, Pluto, Charon, Eris, Orcus and other KBOs [1].

While only Pluto and Triton have known atmospheres, other dwarf planets and large KBOs may retain enough volatiles to develop sublimation atmospheres near perihelion. Such atmospheres may be common in other stellar systems as well.

**Planetary Astronomy using ALMA:** The Atacama Large Millimeter/Submillimeter Array (ALMA) consists of a main array of fifty 12-m antennas with baselines up to 16 km, located on the Chajnantor plateau at 5000m altitude in northern Chile. The unprecedented sensitivity and resolution of ALMA now allows for detailed investigations of even small distant worlds like the Pluto system, Triton, and other larger (>250 km) KBOs in thermal emission, as well as molecular line emission from atmospheric species such as CO and HCN on Pluto and Triton. While not approaching the extreme detail and complex science suite provided by New Horizons in the Pluto system flyby ([2] etc), ALMA does provide the capability to resolve Pluto-sized bodies up to 10 linear resolution elements in thermal emission [3], and 2-3 elements for spectral line observations from minor atmospheric species [4].

**Pluto:** Initial spectral line observations of the Pluto-Charon system were acquired with the ALMA interferometer on June 12-13, 2015 (just one month prior to the New Horizons flyby). They led to spatially unresolved detections of the CO(3-2) and HCN(4-3) rotational transitions from Pluto (including the hyperfine structure of HCN; see Fig. 1), providing a strong confirmation of the presence of CO, and the first observation of HCN in Pluto's atmosphere. The results are detailed in [5] and summarized here. The CO and HCN lines probed Pluto's atmosphere up to ~450 km and ~900 km altitude, respectively. The CO mole fraction was 515 ± 40 ppm for a 12 μbar surface pressure. Strong constraints on Pluto's mean atmospheric dayside temperature profile over ~50-400 km were also determined, with clear evidence for a well-marked temperature above the 30-50 km stratopause and a best-determined temperature of 70 ± 2 K at 300 km, lower than estimated from earlier stellar occultations, and in agreement with inferences from New Horizons/Alice solar occultation data. The HCN line shape requires a high upper atmospheric abundance, with a mole fraction >1.5 × 10⁻⁵ above 450 km and 4 × 10⁻⁵ near 800 km. For HCN at saturation this requires a warm (>92 K) upper atmosphere layer; while not ruled out by the ALMA-measured CO emission, it is inconsistent with Alice-measured CH4 and N2 line-of-sight column densities. The large HCN abundance and the cold upper atmosphere suggest supersaturation of HCN to a degree (7-8 orders of magnitude) hitherto unseen in planetary atmospheres, probably due to a lack of condensation nuclei above the haze region and the slow kinetics of condensation at the low pressure and temperature conditions of Pluto's upper atmosphere. HCN is also present in the bottom ~100 km of the atmosphere, with a 10⁻⁸-10⁻⁷ mole fraction; this implies either HCN saturation or undersaturation there, depending on the precise stratopause temperature. Although HCN rotational line cooling affects Pluto's atmosphere heat budget, the amounts we found are insufficient to explain the mesosphere and upper atmosphere's ~70 K temperature. Upper limits for HCN mole fraction and the ¹⁵N/¹⁴N ratio in HCN were also determined.

We have continued our exploration of Pluto's atmosphere using ALMA [4]. On April 27, 2017, we explored portions of the 1.1mm band searching for HNC, CH3CN, and H¹⁳CN in disk-averaged observations. This led to the detection of the HNC(3-2) line at 271.98 GHz, a narrow emission line with a 15 mJy contrast. This first identification of HNC in Pluto's...
atmosphere reinforces the similarity to Titan's upper atmosphere, where HNC has been also observed [6,7]. We also imaged with ALMA the same CO and HCN emission lines from our 2015 study, on July 30, 2017. The synthesized beam of 96 x 54 mas beam provided some spatial resolution of the Pluto disk in the North-South direction. Analysis is ongoing.

**Triton:** Our success with Pluto atmospheric observations motivated a new study of the atmosphere and surface of Triton using the same techniques [8]. While larger and possessing a similar atmosphere to Pluto, high dynamic range observations of Triton are difficult due to the proximity of Neptune, whose flux density is order 10³ that of Triton. Observations of were obtained October 25 and 26, 2016 using ALMA, providing baselines ranging from 19 m to 1.4 km. During the observations Triton ranged between 13.6" and 16.6" from Neptune, and was just over 127 mas in diameter. The spectral coverage was nearly identical to the 2015 observations of Pluto, covering CO(3-2) and HCN(4-3). The FWHM of the ALMA primary beam is ~18" at these frequencies; Neptune was not fully excluded, and significant sidelobes affected the imaging. Using a spatial high-pass filter (using spatial frequencies >400 kHz), we effectively eliminated confusion from Neptune, providing high dynamic range imaging of Triton at 155 mas x 122 mas resolution. The thermal continuum of Triton was 27.1±0.3 mJy at 355.6 GHz, equivalent to a mean $T_B$ of 31.9+/−0.4 K (formal error, systematic error ~2.5 K); within the error of Pluto’s brightness temperature measured in 2015 (e.g. [3]) further emphasizing their similarity.

These observations also yielded high SNR detections of both CO and HCN line emission (Fig 2). Neither line is as strong as seen on Pluto, which is a function of atmospheric temperature structure and species abundance differences. While dependent on the atmospheric surface pressure (not determined from these observations since Ni is not detectable by ALMA), the CO mole fraction is found to be between 30 ppm (30 μbar surface pressure) and 230 ppm (11 μbar surface pressure), a range suggested by stellar occultations. The weak HCN emission, unlike on Pluto, does not suggest any supersaturation in the upper atmosphere of Triton. Analysis of both lines is ongoing, and an update will be provided.

**References:**


Fig 1. CO(3-2) and HCN(4-3) rotational line emission (above the ~18 mJy continuum) from Pluto’s atmosphere observed with ALMA in June 2015.

Fig 2. The same rotational lines as in Fig. 1, but from Triton’s atmosphere observed with ALMA in October 2016. Note the change in the vertical scale between Fig. 1 and Fig 2, emphasizing that these spectral features on Triton are relatively weaker than on Pluto, particularly for HCN.

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THREE-BODY AND SPIN-ORBIT RESONANCES IN THE PLUTO SYSTEM. D. P. Hamilton\textsuperscript{1} and T. de Santana\textsuperscript{2}, Astronomy Department, University of Maryland, (College Park, MD) dpham\textsubscript{il}@umd.edu, \textsuperscript{2}UNESP, (Guaratingueta, SP, Brazil) t.santana@unesp.br.

Introduction: The four small satellites of Pluto, Styx, Nix, Kerberos, and Hydra, orbit near simple two-body mean motion resonances with Pluto’s large moon Charon: the 3:1, 4:1, 5:1, and 6:1, respectively. Somewhat paradoxically, however, while near the resonances, the satellites are decidedly not in the resonances. How can these resonances be simultaneously important (suggested by the satellites’ proximity to them) and unimportant (all resonances are inactive)? Further mysteries involve the rotation states of the satellites which all feature non-synchronous rotation and large obliquities.

Three-Body Resonance: Showalter and Hamilton [1] showed Hydra, Nix and Styx do participate in a 2:5:3 three-body resonance that is analogous to the 2:3:1 three-body resonance that affects Jupiter’s Ganymede, Europa, and Io. At Jupiter, additional 2:1 resonances between Io and Europa and between Europa and Ganymede are also active; at Pluto, conversely, no two-body resonances are active. We suggest a history for Pluto’s satellites, driven by the tidal migration of Charon, that first temporarily put satellites in two-body resonances, then activated the 3:5:2 three-body resonance, and finally moved the satellites out of the original resonances [2]. The two body resonances that would most naturally activate the observed three-body resonance are the 5:4 Styx-Nix and 2:1 Styx-Hydra two-body resonances. When the two body resonances both involve the pericenter of Styx, the three-body resonance activates. We also show that the three-body resonance, once activated, can drive the system away from the two-body resonances, thus leaving a system near, but not in, these resonances. A similar situation may have also occurred for Kerberos, which today is found close to, but not precisely in, the 43:85:42 Styx-Nix-Kerberos three-body resonance.

Spin-Orbit Resonance: Hamilton and Ward [3][4] invoked a spin-orbit resonance to explain the 27 degree tilt of Saturn and there is some hope that a similar mechanism can be found to explain the more extreme tilt of Uranus [5]. These spin-orbit resonances may also be important in the Pluto system. There, tidal migration of Charon early in Pluto’s history causes the relevant frequencies to slowly change, bringing satellites into spin-orbit resonances that can potentially drive obliquities up. The main secular spin-orbit resonance studied by [3][4] is an attractive possibility for producing the obliquities of the small satellites, as it is insensitive to satellite spin rates and can drive initially small obliquities toward 90 degrees. More exotic families of spin-orbit resonances also exist, including those that involve multiple satellite orbital frequencies, satellite spin rates, or both. These resonances, however, require more specialized circumstances to activate [6]. Nevertheless, given the unknown, but likely complicated, past history of the satellites we remain open to all of these possibilities.

Numerical Approach: We use the N-body code \texttt{hnbody} for both the three-body resonances and secular spin-orbit resonances. We are currently evaluating several promising scenarios and will report on our most recent results. On a longer timescale, we are extending \texttt{hnbody} to handle the spin-orbit resonances that depend explicitly on the spin rates of the satellites [5].

**Future Spacecraft Missions to the Pluto System.** J. D. Hofgartner*, B. J. Buratti¹, M. W. Buie², V. J. Bray³, E. Lellouch⁴, *Jason.D.Hofgartner@jpl.nasa.gov, ¹NASA Jet Propulsion Laboratory, California Institute of Technology, ²Southwest Research Institute, ³University of Arizona, ⁴Observatoire de Paris, Meudon.

**Introduction:** The NASA New Horizons mission revealed Pluto, Charon and their satellite system to be far more active and complex than was expected for small icy worlds in the distant outer solar system [1-6]. These discoveries indicate that further observation and exploration of the Pluto system offers unique opportunities for fundamental advances in planetary science. The Planetary Science Decadal Survey identified three crosscutting themes of particular importance in planetary science: building new worlds (formation), planetary habitats (habitability) and workings of solar systems (workings) [7]; the Pluto system offers important insights into all three of these themes.

**Formation.** The Pluto-Charon binary is the only known fully tidally evolved binary pair in the solar system and was likely formed by a giant impact [5]. Thus, it is an important record of giant impacts and the formation of binary systems. By virtue of its formation in the Kuiper belt, the Pluto system also records the physical and chemical properties of the Kuiper belt. It may also record important clues about the dynamical rearrangement of the solar system [8].

**Habitability.** Organic matter is a crucial ingredient of a habitable environment [7] and Pluto’s Cthulhu Regio as well as other low albedo, equatorial maculae are a large reservoir of processed organic matter (tholins) [3]. Pluto’s tholins are the most spectroscopically accessible complex organics in the solar system in the sense that they are the largest known deposits aside from those on Titan (and Earth) but are not obscured by an opaque atmosphere. Pluto is also a possible ocean world [9,10] with evidence for geologically recent cryovolcanism [2] and Charon likely harbored an ocean in its past [11].

**Workings.** Pluto is astoundingly active given the limited endogenic and solar power available for geologic processes. Convective resurfacing, glacial flow, and sublimation/condensation are all presently ongoing [2,12]. Convection of Pluto’s 1000 km wide, nitrogen-rich Sputnik Planitia is a geologic process unique to Pluto’s surface; it is the only known example where this very dynamic resurfacing process can be studied [12]. In contrast, glacial flow is a familiar process on Earth and Mars, but the glaciers on Pluto are composed of entirely different volatiles, offering an excellent opportunity for comparing how composition and planetary conditions affect glacial processes [2]. The Pluto system also exhibits volatile exchange between Pluto and Charon, resulting in a tholin deposit on Charon that is unique from all other icy satellites [13]. The system has diverse, unique, and ongoing processes, all of which are valuable characteristics for understanding the workings of solar systems.

Thus, further observation and exploration of the Pluto-Charon system is valuable for all three of planetary science’s crosscutting themes.

**Science Goals:** The Pluto-Charon system offers a wide breadth of science questions covering many disciplinary and multidisciplinary topics. We divide the major science goals for future observations and spacecraft missions into six groups.

**Geology.** Pluto displays diverse, unique, and active surface processes and understanding these processes, their interplay, and history should be a focus of future investigations. Other important geology questions include whether liquids at the surface or near-surface have influenced Pluto’s geology and whether Pluto has stratigraphy in its crust, glaciers, and volatile deposits that are records of its geologic and climatic history.

**Geophysics.** Whether or not Pluto is a current ocean world, and Charon a former ocean world, are key questions for understanding their evolution and habitability. Several important questions focus on Sputnik Planitia including how and when the basin formed, its total depth, and whether other similar basins exist in the unseen southern hemisphere. The Pluto-Charon binary is in a tidal end-state and understanding their mutual tidal evolution is an important goal for understanding tides in general.

**Atmosphere and Climate.** Hazes with spectacular layering and continuity over hundreds of kilometers were discovered in Pluto’s atmosphere by New Horizons [4], generating many new questions. The composition and structure of the haze molecules, their influence on the thermal structure of the atmosphere and relationship with tholins on the surface, as well as what controls their layering, are all interesting new questions. Pluto’s climate likely varies over seasonal and mega-seasonal timescales, possibly including extreme excursions in pressure and temperature [14]. These variations and how they affect the surface and atmosphere are not well understood. It is clear that Pluto’s atmosphere and surface are intimately linked and cannot be studied in isolation, future observations and missions must take this coupling into account.

**Charon.** Charon has extreme topographic variations with mountain tops and valley bottoms differing by > 20 km [15]. It has a roughly north-south hemispherical dichotomy between rugged highlands and smooth plains [2]. The formation of Charon’s topography and hemispherical dichotomy and their relation to a
subsurface ocean and cyrovolcanism are all important questions for future investigations. Other interesting questions focus on Charon’s Mordor Macula, which is unique among icy satellites, including its composition, depth, and whether an analogous feature exists over Charon’s south pole [13].

**Small Satellites.** The small satellites: Styx, Nix, Kerberos, and Hydra, likely resulted from the binary forming impact and may record key clues about giant impacts [5]; deciphering these clues is an important topic for future observations and missions. Their chaotic rotation and relationship to dynamical resonances are also interesting questions [5].

**Exploration.** New Horizons imaged ~80% of the surfaces of Pluto and Charon, but only ~40% at high-resolution, leaving full hemispheres yet to be explored in detail. Other icy worlds in the solar system are known to have dramatic hemispherical differences [16]. Basic reconnaissance of the unexplored regions of the Pluto system is an important goal for the future.

**Orbiter Mission:** The nominal planetary exploration track begins with Earth-based characterization, followed by flyby reconnaissance, then orbital observations, lander in situ investigations, mobile in situ elements such as rovers, and concluding with sample return. The Pluto system was characterized by many decades of observations prior to the New Horizons flyby exploration. Continued observations with Earth-based telescopes could address some of the outstanding questions for the Pluto system but the majority will require a spacecraft mission. Following the nominal exploration track, an orbiter mission is likely the best next step and indeed, with the appropriate instruments and capabilities, could address most of the science goals described above.

The science goals for the Pluto system indicate that an orbiter mission is likely the best next mission, however, many aspects of such a mission require further study. We recommend that concepts for future orbiter missions include at a minimum the following key capabilities: (1) global observation of all surfaces in the Pluto system, including surfaces in polar night, (2) sampling of Pluto’s atmosphere and hazes, (3) close flybys of the four small satellites, primarily to measure their masses, and (4) observation of changes of Pluto’s atmosphere and surface over multiple timescales via comparison between the New Horizons flyby and orbiter data sets, and within the orbiter dataset [17]. Trade studies of the scientifically most compelling instruments are an important avenue for future work.

In summary, the Pluto system is scientifically compelling with a diverse array of new questions following the New Horizons exploration. Future observations of the system with Earth-based telescopes and near-Earth space telescopes (such as JWST) will continue to refine our understanding of the system, however, a spacecraft mission is necessary to address the majority of the science. An orbiter mission is the likely best next step and would be competitive with other priority missions in planetary science.


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Introduction: The New Horizons flyby in July 2015 delivered unprecedented detail of the surface and atmosphere of Pluto [e.g., 1-3]. The flyby observations established “ground truth” for Pluto, providing useful constraints for modeling and ground-based data sets. However, flybys are naturally short-duration events, so New Horizons was not able to leverage its high spatial resolution and unique vantage point for temporal studies over longer timescales. An analysis was performed over one Pluto rotation, at varying spatial scales, to search for very short duration, localized events such as plumes, but nothing significant was identified [4]. Spectroscopy over longer time baselines is required to probe for regional and global changes across Pluto’s surface [e.g., 5].

Detection of short-term (~1-3 year) variability on Pluto remains elusive. Work by [6] presented a strategy of matching near-infrared spectra obtained with the IRTF. These spectra are referred to as “matched pairs.” Spectra at roughly the same sub-observer latitude and longitude can be obtained ~14 months apart due to the inclination of the Earth’s orbit with respect to the ecliptic (Fig. 1). The primary benefit of this strategy is to eliminate the effects of rotational variability when attempting to identify temporal changes over these timescales.

Data and Analysis: We performed our own matched pair investigation for Pluto using the TripleSpec spectrometer at the Apache Point Observatory in Sunspot, NM. Spectral observations from 0.7-2.4 μm were made between June 17, 2014, and August 27, 2017. A matched pair consisted of one nightly-averaged spectrum from June and one from August in the following year. Pluto came to opposition in July during this period, so observations in June and August were made at roughly the same phase angle. Observed hemispheres of Pluto on dates of APO observations are shown in Fig. 2.

Spectra from each night were extracted using tspec-tool, a version of spextool [7] specifically for TripleSpec data. All spectra were combined into a nightly average and corrected for solar features and telluric lines by dividing by the G2V standard star obtained throughout the night. A more sophisticated method of removing telluric lines was not attempted because the lines saturated in both the Pluto and solar analog spectra. Each nightly-averaged spectrum was then normalized to the flat continuum region between 1.03-1.08 μm.

Band areas were calculated for methane (CH₄) features at 0.97, 0.99, 1.16, 1.19, 1.33, 1.66, and 1.72 μm. Relative band depths were calculated for the CH₄ features at 2.20 and 2.32 μm because of the breadth of these

Figure 1: Sub-observer (blue) and sub-solar (red) latitudes on Pluto between June 1, 2014, and October 31, 2017. Black circles mark the dates of APO spectral observations. (Values from JPL/Horizons.)

Figure 2: Visible hemispheres of Pluto on the dates of APO observations. Matched pairs are color-coded. One “matched pair” includes 4 dates at roughly the same sub-observer latitude and longitude covering the full period from 2014-2017. One night in 2015 does not have a match. (Pluto image from JPL Photojournal.)

Spectra from each night were extracted using tspec-tool, a version of spextool [7] specifically for TripleSpec data. All spectra were combined into a nightly average and corrected for solar features and telluric lines by dividing by the G2V standard star obtained throughout the night. A more sophisticated method of removing telluric lines was not attempted because the lines saturated in both the Pluto and solar analog spectra. Each nightly-averaged spectrum was then normalized to the flat continuum region between 1.03-1.08 μm.
absorption features. Band areas and depths were compared for each matched pair, with a 3σ significance threshold for believable short-term changes. A direct comparison of two components of a matched pair is presented in Fig. 3.

Figure 3: Comparison of the nightly-averaged spectra from August 19, 2015 (green), and June 17, 2014 (purple). Note the differences in band shape and band depth of the CH₄ features centered at 1.66 and 1.72 μm.

Results and Discussion: Preliminary results are broadly consistent with no change in CH₄ band areas and depths on the anti-Charon hemisphere of Pluto, which is dominated by Sputnik Planitia, whereas the sub-Charon hemisphere generally shows an increase in CH₄ band areas and depths. Fig. 4 summarizes these results.

Figure 4: Significance of CH₄ band area changes for each matched pair. Green indicates an increase in band area while red indicates a decrease over the period of the matched pair. Dashed lines mark the +3σ and -3σ thresholds. The visible hemisphere of Pluto is provided for each matched pair.

The preliminary detection of increased CH₄ band areas in spectra of the sub-Charon (anti-Sputnik) hemisphere suggests one of two physical processes: (1) deposition of CH₄, the least volatile of Pluto’s confirmed ices species, from the atmosphere preferentially onto this hemisphere, (2) an increase in CH₄ grain size, or (3) increased sublimation of N₂, leaving behind CH₄ “slag”.

Occultations during this period [e.g., 8] suggest that Pluto’s atmosphere has not started condensing onto the surface, providing evidence against option (1). Furthermore, the high albedo on the Sputnik hemisphere should result in this region being a cold trap and therefore a preferential site for deposition of volatiles. There is no immediately obvious reason for why the CH₄ grain size would be increasing.

Thus, we are left with option (3), an increase in CH₄ concentration as N₂ preferentially sublimates in the northern hemisphere. This is consistent with the fact that the sub-solar latitude is increasing on Pluto and with modeling work performed following the New Horizons flyby [9]. This work suggests that Pluto’s northern hemisphere will be completely devoid of volatile ices (N₂ and CH₄) by 2030, but in the present day should be dominated by pure CH₄ ice.

Future Work: Observations are ongoing with the IRTF to continue the APO program and obtain additional matched pairs to test this hypothesis. If the hypothesis is correct, we should continue to see an increase in CH₄ concentration for possibly a few more years, followed by a decrease sometime in the 2020s.

CLIMATE HISTORY OF PLUTO AS REVEALED BY ITS LANDSCAPES. A.D. Howard¹ and J. M. Moore²,
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Introduction: Worlds with atmospheres and surfaces invariably have landscapes that manifest the effects of climate evolution. Pluto is certainly no exception. In this abstract and its associated chapter we will characterize its diverse landforms and terrains, and what they tell us about past and present climate over the last 4 Ga. The two most important abundant volatiles on Pluto’s surface and atmosphere (methane and nitrogen) are close to their phase change temperatures and so drive its geological processes.

Observations and Interpretations: For space reasons in the abstract, we are combining observations and interpretations.

Young Landforms: 1) Active flow features. On the eastern boundary of Sputnik Planitia (SP) a series of converging depressions lead from upland, N₂-mantled surfaces westward to the SP surface. Convergent lines analogous to those on terrestrial glaciers indicate flow converging into the depressions and spreading onto SP. The vigorous glacial flow is consistent with the low viscosity of N₂ ice [1, 2]. 2) Pits and convective cells on SP. The nearly level surface of SP displays two textural elements, polygonal cells tens of kilometers across with well-defined edges and covered with abundant pits 200-400 m in size, generally superimposed on the cells. The geometry and size of the cells are consistent with convective overturn of SP nitrogen ice to a depth of hundreds of meters driven by the geothermal heat flux [3, 4]. Pit morphology ranges from space-filling pitting (i.e. elongated, mutually aligned depressions sometimes with dark floors) to isolated, shallow depressions. A few portions of SP are free of pits. The volatility of N₂ ice is consistent with pits forming through an enhanced sublimation in depressions due to reflected solar illumination, analogous to penententes on terrestrial glaciers [5]. The scale and morphology of the pits may either increase through time with an equilibrium shape [6] or the scale of the pits is determined by a balance between sublimation deepening and N₂ ice flow infilling [7]. 3) Flow features on SP. At the northern margin of SP, light and dark patterning on the SP surface are suggestive of northward bulk flow as affected by surface and subsurface topography [1, 8]. The southern end of SP has a southward-sloping surface indicating southward N₂ ice flow [1]. 4) Reticulate and bladed terrains on E. Tombaugh Regio (TR). The plateau-like eastward extent of TR features reticulate km-wide ridges of CH₃-dominated ice interspersed with flat depressions several km in diameter flooded by N₂ ice [5, 9, 10]. This landscape has been created by spatially-patterned sublimation and condensation of N₂ and CH₃ ices, but the process interactions controlling landscape form and scale are presently uncertain. Bladed terrain features prominent, largely north-south oriented ridges spaced a few km apart with relative relief of several hundred meters and a dominant CH₃ spectral signature [10, 11]. Its occurrence is limited to high elevations and low latitudes [10]. The north-south orientation is likely related to the dominant illumination angle during Pluto’s obliquity cycle, but the relative roles of sublimation, condensation, elevation, and subsurface structure in determining blade size and the history of blade formation is potentially complex [10]. 5) Streaks and dune-like forms. Aligned, sub-km spaced ridges at the northwestern margin of SP are suggestive in morphology to terrestrial transverse dune fields, and have been postulated to form from sublimation-lofting, transport and deposition of N₂ grains [12] 6) Possible shorelines. An irregular, 50 km wide depression on the lower southwestern rim of SP displays light-toned concentric banding surrounding an N₂-floored depression. Stern et al. [13] suggest the banding may have originated as recessional shorelines associated with past epochs of higher atmospheric pressure.

Older Upland Landforms: 1) Mantles and pits. Several types of mantles cover portions of the landscape north and east of SP [9]. These mantles are younger than most of the craters forming subsequent to the SP impact. Most of these mantles display a prominent CH₃ spectral signature. A rough-textured region north of SP has relative relief of ~1.5 km, suggesting appreciable erosion subsequent to mantle deposition. Northeast of SP a mantled landscape alternates with craters and pits, some up to ~30 km across. Some of the pits are flat-floored with an N₂ signature, and other pits and pit fields are sharp-edged with conical shapes. Portions of the mantle have been modified by the valleys (discussed below) and fine-textured erosional pitting. Where N₂ floored depressions occur within the mantles the thickness of the mantle decreases away from the depression edges, suggesting the depressions may have sourced the mantle [9] 2) Washboard and Fluted terrain; Portions of the northeast rim of SP display aligned ridges (Fig. 1) which are superimposed on underlying topography [14]. The ridges are dominantly aligned about 75°E of north and spaced 1-2 km crest to crest. Origin of these features is uncertain, but may be related to imprinting of aligned surface deposits on former N₂ glaciers now sublimated away [14]. 3)
Channels, valley, and dissected terrain. The uplands surrounding SP display a variety of linear depressions (valleys) in a variety of topographic settings including mountainous, dissected plateau, and dendritic textures (Fig. 1). Some valleys may be traced for 150-200 km, often in dendritic patterns [1, 15]. An origin of these valleys through runoff from liquid N₂ precipitation is disfavored by the low temperature and low atmospheric pressure under modern seasonal and obliquity climate cycling, although arguments have been advanced that significantly higher pressures may have episodically allowed liquid N₂ precipitation [13]. These valley features have alternatively been attributed to sculpture beneath past N₂ glaciers earlier in Pluto’s history with a larger N₂ inventory [7]. Liquid N₂ flows resulting from basal glacier melting may have sculpted the valleys, and direct scours of the surface by flowing ice may have been possible, analogously to terrestrial valley glaciation.

Four timescales of Pluto’s climate: Annual: Pluto’s annual climate cycle is extreme due to its 249 earth-year duration and 0.25 orbital eccentricity which makes solar illumination vary by a factor of 2.75. Obliquity: Pluto’s eccentric orbit coupled with its high obliquity produce a complex variation in the seasonality and latitudinal distribution of illumination with a ~3 Ma periodicity [16-18]. This periodicity greatly influences the latitudinal redistribution of N₂ and CH₄ [19, 20]. The combination of the beat frequency between the 3 Ma obliquity period and the 3.7 Ma longitude of perihelion precession period results in cycles of extreme seasonal solar insolation that likely cause substantial changes in regional surface temperature and atmospheric pressure at the surface, which may even permit liquid N₂ [17], among other effects [12]. Long-term evolution: Few constraints exist concerning the past climate and volatile inventory of Pluto, although volatile redistribution is likely to have occurred over timescales longer than that of obliquity [19, 20]. Observations during the New Horizons encounter suggest low rates of N₂ loss to space [21], although evidence for extensive upland glaciation suggests appreciable long-term depletion of N₂ inventory [1, 14]. Climate shortly after Pluto formation: Some of the inferred paleoglacial features, including washboard terrain [1, 14] and the extensive mantles [9] may have formed in the first billion years after formation of Pluto, the SP impact, and may have been affected by orbital migration and the long-term increase in solar luminosity.

Conclusions: The New Horizons mission revealed a dynamic planet whose complex landscape is dominated by volatile redistribution controlled by climatic cycles on seasonal and Milankovitch-like scales, superimposed upon probably non-cyclic long-term (multi-Ga-scale) trends in the volatile inventory. Many of these volatile-related landforms have familiar analogs on Earth and Mars despite different materials and a much colder environment, including glaciers, valleys possibly formed by fluid flow, and formation of condensation deposits that then develop pinnacles and pits through sublimation controlled by variations in solar illumination. The details of the formative processes controlling the scale and morphology of the landforms are poorly constrained, but mechanistic modeling may help to clarify them. Further understanding will await future missions giving a global picture of landforms and processes.

Acknowledgements: This work was supported by NASA’s New Horizons project.


Fig. 1. Large glacial valleys (blue arrows) formed during an epoch of abundant N₂. Also note Washboard texture (red).
CHARON’S COLORS AND PHOTOMETRIC PROPERTIES. C.J.A. Howett¹, C.B. Olkin¹, S. Protopapa¹, W.M. Grundy², A. Verbiscer³ and B.J. Buratti⁴. ¹Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, Colorado, 80301 (howett@boulder.swri.edu). ²Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001. ³University of Virginia, Charlottesville, VA 22904, 4 Jet Propulsion Laboratory, 4800 Oak Grove Dr, Pasadena, CA 91109.

Introduction: In 2015 the New Horizons spacecraft revolutionized our understanding of the Pluto-system [1]. The Ralph instrument’s Multispectral Visible Imaging Camera (MVIC) [2] took a large number of color images of Pluto’s large moon Charon on approach, during the encounter and upon departure. Since we focus upon Charon’s surface color we primarily use the sunlit approach/encounter observations which show surface color more clearly than the departure ones (that covered Charon’s nightside).

MVIC: MVIC is made of a single substrate, which holds seven independent CCD arrays. Four of these CCDs have a color filter (Red, Blue, NIR, CH4, see Table 1). Details of the post-launch calibration of MVIC are given in [3].

<table>
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Table 1 - The details of MVIC color arrays.

Close Approach Observations: Figure 1 shows the highest spatial resolution (1.4 km/pixel) MVIC enhanced color observation of Charon. As the figure shows Charon is predominantly grey, with the exception of its red north polar region. Small scale color variations are seen across the surface, which are correlated with geology (e.g. the bluer Nasreddin and Ripley craters, and more neutral Skywalker crater).

All of the resolved MVIC observations made of Charon are outlined in Table 2. As the table shows all observations have a sub-spacecraft latitude in the northern hemisphere (between 25° and 43° N); the subsolar latitude for all observations was 52° N.

Charon’s Red North Polar Region: There were two initial hypotheses to explain why Charon’s north polar region is red. One idea is that the redness is connected to the large crater feature at the pole, implying a red impactor (or less plausibly the impactor uncovered redness under Charon’s surface). The other hypothesis is that Charon’s north polar region is cold trapping molecules from Pluto’s escaping atmosphere, which then are turned red by radiolysis. The key evidence to distinguish between these two hypotheses comes from panchromatic observations of Charon’s south winter pole, in which Charon’s surface is illuminated by Pluto-shine. The ratio of the reflectance seen in these observations and that of a Hapke model (which accounts for the changing bidirectional reflectance of the observations) are shown in Figure 2 [4]. They show that both the north and south poles have a comparable darkening towards their poles. The probability of an impactor hitting, and reddening both poles in such a similar way is very small. Therefore this result supports the cold trapping hypothesis (which would naturally occur at both poles). Thermal models of Charon show that temporary cold-trapping of material escaping from Pluto is feasible at the poles. The cold-trapped material would be photolytic processed into more complex, red, less volatile molecules while trapped.
**Approach Observations:** Figure 3 shows lightcurves derived from fifty seven MVIC color observations taken between 9th April and 3rd July 2015, at phase angles between 14.5° and 15.1°, sub-observer latitude from 51.2 °N to 51.5 °N, and a sub-solar latitude of 41.2 °N [5]. The Blue and Red channels provide the most reliable results, as the NIR band has gain drift (when taken on the primary electronics side) and the CH4 band is noisy (primarily due to its smaller bandwidth than the other channels resulting in a lower signal to noise ratios).

These early observations are consistent with previous studies made with the Johnson B and V bands, which are at shorter wavelengths than that of the MVIC Blue and Red channel respectively (e.g. [6]). They showed that Charon is neutral in color, but slightly brighter on its Pluto-facing hemisphere.

**Charon Photometry:** Disk-integrated observation of Charon by MVIC, and by New Horizons’ panchromatic imager LORRI [6] were used to perform photometry on Charon [7] at solar phase angles between 1.8° and 170°. The results (Figure 4) show Charon has similar photometric properties to other icy moons, albeit with a more isotropic phase function (which may imply we are seeing a new regime in surface alteration on Charon).

Charon’s isotropic phase function may be due to the same processes that causes Charon’s red north polar region [4]: the accretion of molecules that have escaped from Pluto’s atmosphere onto the surface [7]. However, since methane is not stable on Charon (except at the poles) another explanation is possible.

Charon’s phase integral ($q$) is $0.70 \pm 0.04$, which is in keeping with other icy satellites (e.g. Rhea, Dione, and Europa) [8]. Charon’s Bond albedo ($A_B$) is $0.29 \pm 0.05$, which is darker than Europa ($0.62 \pm 0.14$ [9]) and in keeping with that of Ganymede ($0.35 \pm 0.03$ [10]).

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**Table 2 – Resolved MVIC observations of Charon.**

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OBSERVATIONS AND THEORY FOR WAVES IN PLUTO’S ATMOSPHERE. A Jacobs¹, M. Summers¹, G.R. Gladstone², A.F. Cheng³, D. F. Strobel⁴, C. Lisse⁵, L. Young⁶, D. Pesnell⁷, P. Gao⁷, J. Kammer², H. Weaver³, T. Bertrand⁸, ¹George Mason University, MSN 3F3, George Mason University, Fairfax, VA 22030, ajacob12@masonlive.gmu.edu, ²Southwest Research Institute, San Antonio, TX, ³The Johns Hopkins University Applied Physics Laboratory, ⁴The Johns Hopkins University, Baltimore, MD, ⁵Southwest Research Institute, Boulder, CO, ⁶NASA Goddard Space Flight Center, Greenbelt, MD, ⁷University of California, Berkeley, Berkeley, CA, ⁸NASA Ames Research Center, Mountain View, CA.

Introduction: Observations during the New Horizons spacecraft flyby of Pluto in July 2015 revealed that Pluto’s atmosphere has an extensive background haze with as many as 20 relatively bright embedded layers. Several mechanisms that include possible microphysical and/or dynamical processes operating in the atmosphere have been proposed to produce these layers. The purpose of this poster is to use the New Horizons observations, along with microphysical models and atmospheric scattering simulations, to analyze the existing observations in a manner that allows testing of the proposed mechanisms.

The existence of gravity (buoyancy) waves and Rossby (planetary) waves in Pluto’s atmosphere have been proposed to explain the wave-like structure. Two forcing mechanisms to produce gravity waves and explain observed structure are currently proposed— (1) tidal oscillations driven by geographic differences in surface ice sublimation over Pluto’s diurnal cycle, and (2) orographically generated oscillations by flow over mountain ridges or large topographic features (applicable to both gravity and Rossby waves here). Only the latter mechanism has been used to model direct correspondence between wave dynamics and the observed haze layering through generation of haze particle density perturbations [1,2]

In addition, the haze layer associations with geographic variation are characterized in the context of evaluating the generation of a range of possible wave types in Pluto’s atmosphere. Atmospheric gravity (buoyancy) waves - both tidally and orographically driven, as well as Rossby waves, have been previously proposed as the source of density perturbations observed in stellar occultations before the New Horizons flyby of Pluto [3].

Stellar occultation measurements of waves in Pluto’s atmosphere before the flyby of New Horizons predicted density amplitudes of ~0.006 for 8km vertical wavelength gravity waves and ~0.015 for 20km vertical wavelength gravity waves [4], and ~0.01 for ~35km vertical wavelength Rossby waves [4]. These measurements and predictions were for higher altitude waves (>150km) than the altitude range for which LORRI images contained best S/N (~0-200km), however some consistency should still exist.

Figure 1. Simulation mosaic of all 6 unique FOV images within the P_MULTI sequence showing clock angle locations (red text) and frame boundary positions with labels A-F for reference in examining the unwrapped mosaic features. Image frames B and C (blue and orange diamonds in Figure 1) contain the layering that is most distinct. Pluto North and South directions are also indicated in red.

The LORRI observed background relative density amplitudes for the P_MULTI image sequence ~20km vertical wavelength signal are around 5x larger than that predicted by the stellar occultations measurements (~0.05 for altitudes of 0-150km), but the FULLFRAME sequence amplitudes are more consistent with the previously measured signal (~0.01-0.04, for altitudes 0-250km). The PSD 18-20km signal in Hubbard et al. 2008 is also consistent with that found as the large-scale oscillation in both the P_MULTI and FULLFRAME sequences.
Figure 2. Unwrapped LORRI image mosaic from the P_MULTI sequence with the locations of regions P_MULTI R1-3 outlined. Pre-whitening was done by subtracting regional row averages from the columns to generate waveforms and PSDs were extracted. Frame borders are indicated at top with bold white lines corresponding to the frame letters A-F defined in Figure 1.

A signal below 200km in the stellar occultations (~10km) is also consistent in vertical wavelength with the P_MULTI sequence signals. In the HIRES sequence, much larger amplitudes were observed, in the range of 0.2 - 0.3. Oscillation amplitudes in this image were observed to grow with altitude from ~5km to the profile extent, 60km. A vertical wavelength signal ~8km was also identified.

Thermal tides and Rossby wave models need to be reconsidered with the more recent New Horizons constrained temperature and pressure profiles by the REX instrument measurements. The upper atmosphere was found to be much cooler than anticipated, and the surface pressure considerably larger than implemented in the thermal tides model. Resulting Global Climate Model (GCM) zonal mean winds reach speeds as great as 10 m/s by 40km altitude [4], directly challenging Rossby wave vertical propagation with horizontal scales that compare well with observed layer slopes. The thermal tides model also assumed negligible wind speeds—another feature that limits the application of the current model results. Once the models are updated and run for the atmospheric state measured by New Horizons, perturbations should then be calculated and extended to resulting perturbations in haze particle number densities (or some other variable that can manifest itself as haze brightness variations) to validate structure and amplitudes calculated by the models. A scattering model adapted in a companion study acts as a bridging tool between the orographic gravity wave model calculations to facilitate direct comparisons of the characteristic/criteria outlined here.

**Conclusions:** We investigated the vertical and horizontal structure of the complex haze layers using three Long Range Reconnaissance Imager (LORRI) image sequences at high phase angles (148° - 169°) and three different resolutions (0.093 km/pix, 0.96 km/pix, and 3.86 km/pix). This analysis allowed a picture of the horizontal structure of the individual layers along the limb to be characterized. Several haze characteristics were extracted, i.e., their slope, amplitude, as well as their waveforms and power spectral densities (PSDs). Observational criteria to which model calculations predicting certain wave dynamics can be compared and validated. Initial comparisons between orographic gravity wave model slopes and observed slopes indicate that the horizontal wavelength may need to be increased, and that a sufficient increase may lead to waves that are evanescent (trapped) below Pluto’s temperature inversion close to the surface. More modeling of the layers needs to be done to confirm projection effects are not significant. However, the observations contained in this study, combined with GCM output and established theory on gravity and/or Rossby waves [5] may also indicate the presence of new wave dynamics than previously considered in Pluto’s atmosphere.

THE ORBITS AND MASSES OF PLUTO’S SATELLITES. R. A. Jacobson¹, M. Brozovic¹, M. Showalter², A. Verbiscer³, M. Buie⁴, and P. Helfenstein⁵; ¹Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, ²SETI Institute, 189 Bernardo Ave., Mountain View, CA 94043, ³U. Virginia, PO Box 400325, Charlottesville, VA 22905, ⁴SwRI, 1050 Walnut St., Boulder, CO 80302, ⁵Cornell U., 320 Space Sci. Bldg, Ithaca, NY 14853

Introduction: Prior to the New Horizons flyby through the Pluto system in 2015 July, Brozovic et. al. [1] reported on the orbits and masses of Pluto’s satellites. These were found by fitting numerically integrated orbits to an extensive set of Earth-based and HST astrometry, mutual event light curves, and stellar occultation observations. The observations spanned the time from Charon’s discovery (1965 April) to 2012 July. Ephemerides based on these orbits were the initial ephemerides for New Horizons Pluto encounter operations. During the flyby they were periodically updated by the New Horizons navigation team using imaging of the satellites against the stellar background. Subsequent to the flyby, Jacobson et al. [2] produced new orbits and mass estimates by fitting the integrated orbits to a combination of the pre-encounter observations, all of the imaging acquired by New Horizons, and HST astrometry of Charon, Nix, and Hydra from 2013.

Current Analysis: We have now acquired additional HST data through 2018. Moreover, the entire HST observation set beginning in 2005 was reprocessed with an improved technique resulting in more precise position measurements. In this paper we report on our new integrated orbits and the masses of Pluto and its satellites obtained by fitting the entire collection of observations.

PHOTOCHEMISTRY AND HAZE FORMATION. K. L. Jessup¹, A. Cheng², P. Gao³, A. Luspay-Kuti², K. Mandt² 1: Southwest Research Institute, Boulder CO, 80302 jessup@boulder.swri.edu; 2: John Hopkins University, APL, Laurel, MD; 3: California Institute of Technology, Pasadena, CA;

Introduction: Observations and Analogs

On July 14, 2015 the New Horizons spacecraft successfully flew through the Pluto system, confirming that the chemistry in Pluto’s atmosphere is strikingly similar to Titan’s, with bulk atmosphere composition consisting of N₂, CH₄ along with trace hydrocarbon gases such as C₂H₂, C₂H₄ and C₂H₆. Details of the vertical structure of Pluto’s atmosphere were derived from the combined New Horizons Alice, REX, MVIC and LORRI instruments, including the discovery of extensive globally distributed haze layers [1-2,4] and a vertical temperature profile that experiences strong gradients between 0 and 400 km, including, as Fig. 2 shows, a maximum inflection point of ~106 K at ~22 km, a minimum inflection point of ~63 K near 400 km and a near constant profile of ~70 K at 1000 km and higher altitudes [3]. These results show Pluto’s upper atmosphere to be a cryosphere that does not experience hydrodynamic escape but may, in fact, be cooled by its own hydrocarbon haze [5-6].

Though an ionosphere was not directly detected [1], by comparison to Titan, Pluto’s atmospheric structure should be supported by ultraviolet photons dissociating and ionizing N₂ and CH₄, providing the photolysis products that result in the formation of complex hydrocarbons and nitriles [1] that are in turn ionized resulting in aerosol formation. I.e., the haze formation is supported by ionospheric processes that produce negatively charge macromolecules that form aerosols that grow, sediment, coagulate and aggregate forming spherical fractals [7]. These upper atmosphere ionospheric processes distinguish the chemical evolution of Titan and Pluto’s upper atmosphere from that of Triton, on which CH₄ is destroyed in the lower atmosphere before reaching higher altitudes [1].

Overview: We will present a review of recent photochemical and haze production models developed for investigation of the physical processes controlling Pluto’s gas species and haze profiles, discussing how these models answer and raise questions about the mechanisms supporting Pluto’s atmospheric structure and thermal balance. We will also highlight questions raised by these models about the origin and isotope fractionation of N₂ gas at Pluto, discussing the differences and similarities to Titan.

Lessons from Photochemical Modeling: Using Titan’s aerosol processes as an analog, [8] successfully developed and implemented a coupled ion-neutral-photochemistry (INP) which specifically solves the continuity equation at each altitude including EUV driven photochemistry occurring in the upper atmosphere along with the hydrocarbon condensation occurring below 400 km and aerosol trapping processes—without assuming hydrodynamic escape.

Using this model [8] simulated the NH observed atmospheric density profiles published by [2]. Simulations including only chemistry and condensation are incapable of replicating the near constant C₂ hydrocarbon profiles observed at altitudes of 300 km and lower.
of C₂ hydrocarbons to aerosol particles as a function of aging process proposed for Titan’s aerosols [9]. Additionally, [8] empirically derived the sticking efficiency of C₂ hydrocarbons to aerosol particles as a function of altitude, finding that the sticking efficiency is inversely related to the aerosol surface area. With the inclusion of the aerosol aging mechanisms in the INP model [8] inferred a high eddy diffusion of 10⁶ cm² s⁻¹ that replicated the observed profiles in the altitude range between 100 and 150 km, and 3×10⁴ cm² s⁻¹ above 150 km for Pluto’s atmosphere. However, at 10⁶ to 10³. These lower values are in conflict with the eddy diffusion rate inferred by [8], but agree with the results from [10] who both use a simpler photochemical modeling scheme than [8], and also traces loss via aerosol growth/gas condensation differently from [8]. Intriguingly, when using the lower eddy mixing rate in the INP model [8] the CH₄ profile in the lower 100 km region is well fit, but not at higher altitudes. Noting the sensitivity of the vertical species profiles to condensation loss, inclusion of the new temperature profiles [3] in the photochemical models should increase the rate of CH₄ condensation at multiple altitudes including in the region below 100 km; thus, it will be important to determine the impact the new temperature profile behavior might have on the eddy diffusion rate and homopause level inferred from the INP model. Together, the current modeling efforts and observation analysis results imply that further resolution is needed in understanding how chemistry, condensation and diffusion work to maintain the CH₄ profiles at all altitudes.

**Lessons on HC¹⁵N and Nitrogen Fractionation:**
Recent ground based Atacama Large Millimeter Array (ALMA) sub-millimeter observations [11] provided only Pluto’s HC¹⁵N abundance upper limit. Photochemical modeling of the HCN production and loss processes have been investigated by [10 and 12]. [12] conclude that condensation and aerosol trapping should have a major impact on the altitude profile of the nitrogen isotope ratio in HCN—thus, non-detection of HC¹⁵N implies that condensation and aerosol trapping must be much more efficient for HC¹⁵N compared to HC¹⁴N. Investigations into the isotopic fractionation behaviors at Pluto imply that Pluto’s nitrogen isotope chemistry differs significantly from that at Titan, where for the latter extreme fractionation occurs because of self-shielding—while at Pluto it appears the opposite effect occurs. But modeling of fractionation behaviors is still in a very preliminary state and more concrete results will arise as the evolution of Pluto’s atmosphere over a full solar year is more fully investigated, incorporating any potential changes in the rate of surface frost sublimation.

**References:**
PLUTO’S MINIMUM SURFACE PRESSURE AND IMPLICATIONS FOR HAZE PRODUCTION. P. E. Johnson¹, L. A. Young², S. Protopapa², B. Schmitt³, B. L. Lewis⁴ J. A. Stansberry⁵, K. E. Mandt⁶, O. L. White⁷, and the New Horizons Composition and Atmospheres Teams, ¹Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder (perianne.johnson@colorado.edu), ²Southwest Research Institute, ³Institut de Planétologie et Astrophysique de Grenoble, ⁴University of California, Los Angeles, ⁵Space Telescope Science Institute, ⁶Johns Hopkins University Applied Physics Laboratory, ⁷NASA Ames Research Center.

Introduction: Pluto’s surface exhibits extreme contrasts in color, albedo, and composition [1]. Pluto’s atmosphere is globally hazy, and haze particles should be deposited onto the surface at a rate of ~1 micron/Pluto year [2, 3]. This deposition should form a uniform, optically thick layer quickly, which is in contradiction with the observed surface heterogeneity.

If the atmospheric pressure at the surface gets low enough, haze production may be altered, suppressed or stopped completely. In Pluto’s current atmosphere, haze aggregation occurs at pressures higher than 0.5 µbar, therefore if the surface pressure drops below this level, monomer haze particles may be deposited instead of aggregates, potentially changing the appearance on the surface [3]. Additionally, if the surface pressure drops to less than 10⁻¹ µbar to 10⁻⁴ µbar, the atmosphere would be transparent to ultraviolet radiation [5], which would shut off the photolysis of N₂ and CH₄, suppressing haze production at its source and allowing direct photolysis of surface ices [6]. For surface pressures less than ~0.06 µbar Pluto cannot support a global atmosphere [7], and instead the atmosphere becomes local, or “patchy”, which would restrict the region in which haze particles are deposited.

Climate Model: As described in [7, 8], the 3-Dimensional Volatile Transport (VT3D) model imposes local energy balance (insolation, thermal emission, conduction, and latent heat of sublimation) and global mass balance for volatile-covered bodies with efficient transport of volatiles. Here, we (i) assume one of the two static N₂ distributions described below, (ii) calculate the solar insolation onto the N₂-covered surfaces (iii) run VT3D for twenty orbits, producing a temperature versus time curve, and finally (iv) use the compilation of [9] to convert these surface volatile temperatures into surface pressures.

As used here, VT3D has three free parameters: Bond albedo A, thermal inertia Γ, and emissivity ε of the volatiles. For each pair of A and Γ, there exists a unique ε such that the model-predicted pressure in 2015 matches the 11 µbar surface pressure observed at the New Horizons flyby. We constrain our grid search of the (A, Γ, ε) parameter space by two criteria: (i) that the emissivity is less than one and greater than some minimum physical value, and (ii) that the modeled increase in pressure change between 1988 and 2015 matches the pressure increase measured from occultations. Comparing the pressures at 1205 km radius (~15 km altitude), the 2015 New Horizons radio occultation pressures [10] are 1.82 to 3.14 times higher (3-σ range) than the pressures from the 1988 ground-based occultation [11]. If the modeled pressure ratio is not within this range, then the (A, Γ, ε) triplet will be eliminated. This gives a restricted range of allowable parameter space.

Nitrogen Distributions: Fig. 1 shows the N₂ spatial distributions used here. The red outline encloses Sputnik Planitia (SP), as defined in [12]. For our first distribution, we assume everything enclosed by this outline is filled with N₂ ice of uniform albedo, thermal inertia, and emissivity, and that no N₂ ice is present elsewhere on the surface. This is not a realistic situation, but serves as a lower limit. For our second (more realistic) distribution, we use the N₂ map created by [13]. This map combines spectral data from observations and Hapke modeling on the encounter hemisphere of Pluto [14, 15]. [13] extends the observed/modelled fractional coverage of N₂ ice to the non-encounter hemisphere, by assuming the fractional coverage is constant within a zonal band (across all longitudes at a given latitude).

Climate Modeling Results:

SP-only distribution. The restricted parameter space, and five example pressure versus time curves using the SP-only distribution are shown in the top panels of Fig. 2. Pressures in three of the five cases (black, red, and orange) stay above all of the critical haze production pressures, so atmospheric collapse is not a viable means of disrupting haze for these sets of (A, Γ, ε) values. In
Full northern \( N_2 \) distribution. The bottom panels of Fig. 2 show the analogous restricted parameter space and pressure vs. time curves for the full northern \( N_2 \) distribution from [13]. The allowable \((A, \Gamma, \epsilon)\) triplets are shifted towards higher thermal inertia, and the minimum pressures are higher than the SP-only case; the surface pressure never drops below any of the haze-production pressures for this \( N_2 \) distribution.

Conclusions: Based on these \( N_2 \) distributions, haze production is not likely to be significantly disrupted by reductions in atmospheric pressure. With a SP-only distribution, there is a short amount of time when monomers might be deposited instead of aggregates, but this is not the case for the more realistic full \( N_2 \) distribution. The addition of unseen \( N_2 \) in the southern hemisphere might be sufficient to cool the atmosphere and affect haze production, which we will explore in the future.

Additionally, the haze particle sedimentation may occur at a faster rate during the low-pressure period near northern winter solstice, although more work is needed before conclusions can be drawn about how this would affect the surface heterogeneity.


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Laboratory Simulation of Pluto’s Atmosphere and Aerosols.

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Introduction: During Pluto’s elliptical orbit, the surface ices made of molecular nitrogen N₂, methane CH₄ and carbon monoxide CO go through a sublimation/condensation cycle supplying its tenuous atmosphere [1,2]. This atmosphere composed of N₂, CH₄ and around 500 ppm of CO [3,4] was suspected since the 1990’s to instigate the production of photochemical aerosols [5,6]. These aerosols were finally unambiguously detected on July 14th, 2015, when Pluto was flown by New Horizons, by means of forward scattering observations and solar occultations. Pluto’s aerosols aggregate into several thin haze layers, extending at an altitude of more than 350 km [1,3,7,8].

In order to understand not only Pluto’s atmospheric chemistry, but also its climate and its heterogeneous surface, simulating in laboratory Pluto’s atmosphere is of prime importance. So is producing Pluto’s aerosols analogues for further physical and chemical analyses.

For the very first time, we used the PAMPRE experiment [9] (LATMOS, France) to reproduce Pluto’s atmosphere and to synthetize Pluto’s aerosols analogues.

Experimental setup: PAMPRE [9] is a Radio-Frequency Capacitively Coupled Plasma (RF CCP) generated in a gas mixture representative of Pluto’s atmosphere. For this work, the gas was composed of variable proportions of molecular nitrogen and methane, with 500 ppm of carbon monoxide [3,4]. The plasma was maintained at a pressure of 0.9 ± 0.1 mbar, at ambient temperature.

Analogues synthesis. Two types of analogues were synthetized. One with an atmosphere containing 99 % of N₂, 1 % of CH₄ and 500 ppm of CO, setting representative of Pluto’s atmosphere at 400 km of altitude [3]. The other sample was produced from a gas mixture composed of 95 % of N₂, 5 % of CH₄ and 500 ppm of CO, condition representative of Pluto’s atmosphere at 600 km of altitude [3].

Analogues ex situ analyses. These samples were observed by Scanning Electron Microscopy (SEM). Their chemical composition was determined by high-resolution mass spectrometry (Orbitrap technique) and infrared spectroscopy.

Results: Morphology. Pluto’s aerosols analogues are spherical fluffy particles of 400 to 500 nm of diameter in average (Fig. 1).

Chemical composition. Our high-resolution mass spectrometry (HRMS) study has shown: (1) a co-polymeric structure of the molecules constituting Pluto’s aerosols analogues; (2) an important incorporation of nitrogen atoms in these molecules; (3) a significant proportion of oxygenated molecules in them; (4) an impact of CH₄ mixing ratio, and so of the altitude of aerosols formation [3], as a different reactivity between N₂, CH₄ and CO and especially a boosted incorporation of oxygen atoms in the molecules with increasing CH₄ mixing ratio.
**Discussion and Conclusion:** The aerosols may impact Pluto’s atmospheric photochemistry and climate by depleting the atmosphere of the C$_2$ hydrocarbons and by playing the role of condensation nuclei for clouds [10]. This idea can be supported by the fact that in our analogues, we have detected heavy unsaturated molecules that are likely very reactive and may therefore interact with the gaseous molecules and serve as condensation nuclei.

They can also have an influence on Pluto’s atmospheric thermal profile by absorbing incident solar radiations, making that Pluto’s atmosphere is around 30 K colder than theoretically predicted, at about 400 km of altitude [7,11]. Due to the presence of oxygenated molecules in our samples, we can hypothesize that Pluto’s oxidized aerosols may impact Pluto’s radiative cooling by absorbing longer ultraviolet wavelengths [12].

Future experimental study on the aerosols/gas interactions and on the aerosols optical indices is needed, in order to further finely constrain Pluto’s atmospheric models.


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AN INTERIOR STRUCTURE MODEL OF PLUTO THAT SOLVES ITS GEOPHYSICAL AND GEOCHEMICAL MYSTERIES. S. Kamata†, F. Nimmo‡, Y. Sekine†, K. Kuramoto†, N. Noguchi‡, J. Kimura‡, and A. Tani§, †Department of Earth and Planetary Sciences, Hokkaido University (†kamata@sci.hokudai.ac.jp), ‡Department of Earth and Planetary Sciences, University of California, Santa Cruz, §Earth-Life Science Institute, Tokyo Institute of Technology, †Graduate School of Technology, Industrial and Social Sciences, Tokushima University, ‡Department of Earth and Space Science, Osaka University, §Department of Human Environmental Science, Kobe University.

Introduction: New Horizons found a “white heart” near the tidal axis of Pluto to Charon [1]. The left half of this bright region is a large ellipsoidal basin named Sputnik Planitia (SP) [1]. This observation suggests that the SP basin is a positive gravity anomaly, similar to “mascon” (i.e., mass concentration) basins on the Moon [2]. While nitrogen plains on the SP basin are a mass excess, their contribution to the gravity field is likely insufficient to make the basin a positive gravity anomaly; an uplifted subsurface denser layer is required, and implies the surficial layer is locally thinned beneath the basin. On Pluto, these layers are interpreted as a subsurface ocean and an ice shell [2]. Such an interior structure, however, is difficult to explain if the long history of Pluto is considered.

Mysteries of Pluto: The first mystery is the long-term maintenance of the subsurface ocean. For icy satellites possessing subsurface oceans, tidal heating plays the major role in maintaining subsurface oceans [2]. However, tidal heating is negligible on Pluto [2]. Consequently, to avoid complete freezing of a subsurface ocean, a low heat transport efficiency through the ice shell is needed. This indicates that solid-state thermal convection should not occur in the ice shell, though Pluto’s thick ice shell is likely to be conductive if pure water ice is the major constituent [4].

The second mystery is the long-term maintenance of large contrasts in the ice shell thickness. Because ice behaves as a viscous fluid over geologically long timescales, surface and basal topographies viscously relax with time. A simple model assuming an ice shell composed of pure water ice overlaying a subsurface ocean composed of pure liquid water leads to a timescale of viscous relaxation of basal topography of only ~1% of ammonia with respect to water [7]. In addition, such an ocean should have a low density [8], preventing the SP basin from being a positive gravity anomaly.

The third mystery is the chemical composition of Pluto; the surface and atmosphere of Pluto is rich in nitrogen compared to carbon monoxide. This is in contrast to the chemical composition of comets from the KB [9].

Thin Cap of Clathrate Hydrates above the Ocean: We propose a new interior structure model of Pluto that resolves these mysteries: a thin clathrate hydrate (gas hydrate) layer exists between the ice shell and the subsurface ocean (Fig. 1). Clathrate hydrates are solid materials that look like water ice, and water molecules creates cages trapping gas molecules. Clathrate hydrates have four key properties related to the above mysteries. (1) Low thermal conductivity [10]. Clathrate hydrates would behave as a natural “thermal insulator”, keeping the ocean warm and the ice shell cold. (2) Hard rheology [11]. This is important to avoid viscous relaxation. (3) Selective trapping of gas molecules [12]. This would change the surface chemistry from the bulk chemistry. (4) The major component of clathrate hydrates is water. Unlike the ammonia-rich ocean hypothesis, a clathrate hydrate layer hypothesis does not require a bulk composition of Pluto significantly different from those of comets.

Numerical Calculations: We perform numerical calculations of long-term thermal evolution assuming interior structure models with and without a clathrate hydrate layer at the base of the ice shell. A modified version of the calculation code developed by [13] is used. We find that a warm ocean and a cold ice shell can be maintained for a long time and that the freezing of the ocean is ineffective (Fig. 2). Note that, because of ineffective freezing, the thickening of the clathrate hydrate layer is also ineffective. Consequently, only a few percent of gas with respect to water is sufficient, and this is consistent with cometary composition.

We also perform numerical calculations of long-term viscoelastic deformation using the model with and without a clathrate hydrate layer. The same calculation code used by [14] is used. We find that significant viscous relaxation of basal topography requires billions of years if a basal clathrate hydrate layer exists (Fig. 3). In addition to the high viscosity of clathrate
hydrate itself, a low temperature of the overlying ice shell also contributes to a long relaxation timescale.

**Chemical differentiation on Pluto:** Many gas species can be trapped in clathrate hydrates, but the guest gas composition can differ from gas composition supplied to the ocean. For example, methane and carbon monoxide are more easily trapped than nitrogen molecules [15,16]. Thus, CH₄ and/or CO contained in precursor bodies and/or produced later in a hot rocky core are the most likely guest gases. On the other hand, nitrogen molecules initially contained and/or produced later in the core would not be trapped in clathrate hydrates; they would degassed to the surface, resulting in a nitrogen-rich surface.

**Implications:** What we propose in this study is a new, generic mechanism to maintain subsurface oceans in icy worlds. This mechanism does not require a large amount of tidal heat nor a large amount of antifreeze molecules such as ammonia to maintain a subsurface ocean for billions of years. The formation condition of clathrate hydrates would be satisfied in oceans in large icy bodies. Clathrate hydrates may also play an important role in maintaining minimally-heated icy oceans.

Our proposal may also explain the diversity of surface chemistry of Kuiper Belt Objects; nitrogen molecules are found on large bodies but not on small bodies [17]. An enrichment of volatile species not likely to be trapped in clathrate hydrates may be a signature of the presence of a subsurface ocean.


![Fig. 1: Schematic diagram of the interior structure of Pluto proposed in this study.](image1)

![Fig. 2: Typical results of thermal and interior structure evolution calculations.](image2)

![Fig. 3: Summary of viscous relaxation calculations.](image3)
TRUE POLAR WANDER OF PLUTO. J. T. Keane1 and I. Matsuyama2. 1California Institute of Technology (Pasadena, CA 91125 USA; jkeane@caltech.edu); 2Lunar and Planetary Laboratory (University of Arizona, Tucson, AZ 85721, USA).

Summary: One of the most important results of the New Horizons mission to Pluto was the inference that Pluto reoriented due to the formation and evolution of Sputnik Planitia (Pluto’s “Heart”). This process, known as true polar wander, yields critical insight about Pluto’s interior structure, and provides a framework for understanding Pluto’s long-term geologic and climatic history. In this abstract, we summarize the evidence for true polar wander, and the broader implications for the Pluto system and other Kuiper Belt objects.

Sputnik Planitia (SP): In July 2015, the New Horizons flyby revealed Pluto to be an astonishingly active world (Fig. 1) [1–3]. Of all of the geologic features on Pluto, the largest and most dramatic is Sputnik Planitia (SP). SP is a 1,000 km diameter, tear-drop shaped topographic depression—likely formed early in Pluto’s history by a giant impact [1–2, 4]. The interior of SP is characterized by a smooth, craterless plain, 3–4 km beneath the surrounding rugged uplands. The plains are the surface of a massive, actively convecting glacier of volatile ices (N₂, CH₄, CO) several kilometers thick [1–3, 5–6].

The Curious Location of Sputnik Planitia: SP is located very near the Pluto–Charon tidal axis (Fig. 1). The tidal axis is the line connecting the centers of Pluto and Charon (Pluto’s large, tidally-locked moon), and it intersects the surface of Pluto at 0°E, 0°N (the sub-Charon point), and 180°E, 0°N (the anti-Charon point). For a tidally-locked world, like Pluto, the tidal axis corresponds to the largest minimum axis of inertia. SP overlaps the anti-Charon point, and extends to the NW. There is only a 5-10% probability of any feature on the surface being this close to the tidal axis.

True Polar Wander (TPW) of Pluto: The alignment of large geologic features with the principal axes of inertia of a body is often the hallmark of true polar wander (TPW) [7]. TPW occurs when geologic phenomena redistribute mass on/in a planetary body. This action changes the orientation of the body’s principal axes of inertia. As energy is damped out of the system, the entire body will reorient to realign these principal axes with the tidal/spin axes—resulting in motion of the tidal/spin poles across the geographic surface.

To determine if SP could drive TPW, we calculated the inertia tensor for a variety of different models (Fig. 2), and self-consistently accounted for the flexural response. TPW solutions were determined by combining the inertia tensor from our nominal Pluto model with the inertia tensors from our SP models, and determining the new lowest-energy configuration.

This TPW analysis reveals several important details about SP and Pluto’s interior structure [9–10]. The most significant is that SP must be a positive mass anomaly (i.e., a mass excess). This is seemingly in contrast with the large negative topography associated with SP [11], which should yield a large negative mass anomaly. While the SP glacier is expected to be denser than the average crust of Pluto, it is insufficient to create the requisite mass anomaly. Nonetheless, there are other ways to make SP a larger positive mass anomaly, including: making the underlying basin isostatically compensated,
incorporating an ejecta blanket around SP, or adding an uplift of the subsurface ocean. The latter was favored by [10], and is the primary piece of evidence for an extant subsurface ocean on Pluto.

**Tectonics from TPW:** As an object reorients by TPW, each surface location experiences a change in the tidal-rotational potential, which generates stress in the lithosphere with a characteristic pattern determined by the TPW geometry. We calculated the expected tectonic stresses arising from SP-driven TPW and global expansion from the freezing of a subsurface ocean [9]. Amazingly, the predicted tectonic stresses closely match the observed tectonic patterns on Pluto (Fig. 3). Proximal to SP, loading stresses dominate—resulting in predominantly radial extensional faults. Far from SP, the TPW stresses dominate—resulting in extensional faults that are roughly circumferential to SP in the regions imaged by New Horizons. This hypothesis provides the single most comprehensive explanation for the global pattern of faults on Pluto. Alongside SP’s location, Pluto’s tectonics is the second critical piece of evidence for TPW.

**Implications for Cryovolcanism:** TPW-generated tectonic stresses can enable the ascent of subsurface cryomagmas. There are several plausible cryovolcanic constructs on Pluto, including constructional mounds south of SP, Piccard and Wright Mons [12], and flow-like deposits west of SP associated with Virgil Fossae and other tectonic fractures [13–14]. These putative cryovolcanic features are all located in an annulus around SP associated with the maximum extensional stresses arising from TPW and volatile loading [9, 15]. The formation and evolution of SP may have indirectly enabled cryovolcanism across Pluto.

**Implications for Pluto’s Volatile Cycle and Climate:** Since the orientation of Pluto depends on the mass anomaly of SP (which is partly controlled by the volatile content of the basin) it is plausible that Pluto experiences a feedback between volatile transport, climate, and rotational stability. While SP is located near the Pluto–Charon tidal axis, it is also located near the latitude of the minimum mean solar insolation [16]. TPW analyses suggest that SP initially formed at higher latitude, and was progressively loaded with volatile ices (Fig. 4) [9]. Depending on the rate at which volatiles migrate in and out of the basin, it is conceivable that Pluto undergoes small-amplitude wobbles (analogous to Earth’s annual, atmospheric-pressure-driven wobbles) on a variety of timescales. This may provide an additional source of energy into the Pluto system.

**Implications for Worlds:** Beyond Pluto, volatile-driven reorientation may be active on a variety of planetary bodies. Neptune’s large moon, Triton, possesses a comparable volume of volatiles and has an orbital/rotational configuration more susceptible to these processes [17]. Analogous processes may also occur on hot, tidally-locked exoplanets with large quantities of mobile volatiles (where volatiles in this case are silicates).

**References:**

![Fig. 3 | Observed and predicted tectonic patterns on Pluto. Base-map of Pluto: NASA/JHUAPL/SwRI.](https://example.com/fig3)

![Fig. 4 | The complicated interplay between volatiles and rotation on Pluto. Sketch by J. T. Keane.](https://example.com/fig4)
PHOTOCHEMICAL MODEL OF PLUTO’S ATMOSPHERE AND IONOSPHERE. Vladimir A. Krasnopolsky, Moscow Institute of Physics and Technology (PhysTech), Moscow, Russia (vlad.krasn@verizon.net).

Introduction: The New Horizons flyby of Pluto along with ground-based high-resolution spectroscopy in the infrared and submillimeter ranges and the recent stellar occultations resulted in significant progress in Pluto’s atmosphere. Vertical profiles of N₂, CH₄, C₂H₂, C₂H₄, C₂H₆, haze, and temperature and abundances of CO and HCN have been retrieved from the observations.

These new data require updated photochemical modeling [1, 2]. The model by Wong et al. [1] includes detailed neutral chemistry at 40 levels up to 1300 km. To fit the observations, the authors adopted saturated vapor densities of C₂H₂ and C₂H₆ equal to those of C₂H₄, though they differ by orders of magnitude.

Here we present a model that does not require the revision of the laboratory data on the saturated vapor densities and involves ion chemistry that affects the neutral composition and is missing in [1].

Model: We apply the model [3, 4] that reproduces fairly well the observed properties of Titan’s atmosphere and ionosphere. The model is adjusted to the conditions of Pluto during the New Horizons flyby. It involves 419 reactions of 83 neutrals and 33 positive ions plus 10 reactions of CO⁺ and HCO⁺ that are negligible on Titan. The model has 289 altitude steps that extend up to the exobase at 1600 km. Thermal escape for neutral species and diffusion velocities for ions are the upper boundary conditions.

Model Results: Hydrocarbons: The adopted eddy diffusion \( K = 3 \times 10^4 \text{ cm}^2 \text{ s}^{-1} \) facilitates transport of C₂H₂ and C₂H₆, their condensation on the surface (Fig. 2), and does not require the revision of the laboratory data on saturated vapor densities of C₂H₂ and C₂H₆ by orders of magnitude to fit the New Horizons observations [6]. The CH₄ homopause is at 90 km for this \( K \), and the CH₄ vertical profile (Fig. 2) is mostly controlled by molecular diffusion and agrees with the New Horizons observations. The CH₄ mole fraction near the surface is chosen at 0.45%.

Major chemical production and loss processes of the observed hydrocarbons and their escape and condensation rates are briefly discussed. Ion chemistry significantly contributes to those. The most abundant C₃, C₄ hydrocarbons and benzene are shown in Fig. 3a, b. Diacetylene C₄H₂ is effective in polymerization with C₆H and C₃N.

Nitriles and H₂: Photoionization returns N₂ in charge exchange, while predissociation at 80-100 nm, dissociative ionization \( \lambda<51 \text{ nm} \), and photodissociation dissociation are effective in the N₂ loss and formation of nitriles and amines. The C≡N triple bond is strong and does not dissociate in nitriles. The N-H bond in amines is comparable to the C-H bond in hydrocarbons, and amines lose N in their reactions and less abundant than nitriles. Total loss of N₂ is 38 g cm⁻².
Byr⁻¹ with lifetime of 1.9 Myr in the atmosphere and exceeding the age of the Universe in the ice.

Fig. 3. Vertical profiles of C₃ hydrocarbons (a), C₄ hydrocarbons and benzene (b), nitriles and H₂ (c), and oxygen species (d).

The calculated HCN column abundance 1.7×10^{14} cm⁻² (Fig. 3c) agrees with that observed using ALMA [7]. Ion reactions are very significant in the production and loss of HCN. The comparatively warm layer below 150 km contributes ≈90% of the HC₃N column abundance (Fig. 3c) that is weakly sensitive to the adopted sticking coefficient and exceeds the observed upper limit of 2×10^{13} cm⁻² [7] by a factor of 2. The reaction CN+C₂H₂ and condensation dominate in the production and loss of HC₃N, respectively.

H and H₂ are formed by photolysis of hydrocarbons. 60% of the production of H escapes, and the remaining 40% reacts with radicals and form H₂. Almost all H₂ escape. The H₂ homopause is at 15 km, and the H₂ mole fraction increases up to 400 km due to diffusive separation. Further increase is determined by a balance between the production and escape.

**Oxygen Species:** CO and the meteorite H₂O are sources of oxygen chemistry on Pluto (Fig. 3d). The interplanetary dust dynamic model [8] predicts very low delivery of water with a rate of 8500 cm⁻² s⁻¹ scaled to the surface. The ion chemistry initiated by charge exchange between N⁺ and N₂⁺ and CO is more effective.

**Ionosphere:** Photoionization and the galactic cosmic rays dominate in the ionosphere above and below 300 km, respectively (Fig. 4). The ionospheric peak on the day side is at 750 km with e_{max} = 800 cm⁻³. Radio occultations in the outer Solar System refer to terminators, and the expected values are h_{max} ≈ 850 km and e_{max} ≈ 300 cm⁻³, smaller than the upper limit of 1000 cm⁻³ in the New Horizons radio occultations [9].

The heavy ion C₄H₁₁⁺ is the most abundant below 650 km (Fig. 4a). The main ions above 650 km are HCNH⁺, C₂H₃⁺, and C₄H₅⁺. The predicted ion densities are well within the range of the Cassini INMS.

Evolution: The calculated annual mean rates are 150 g cm⁻² Byr⁻¹ for escape of CH₄ + CH₃ and H₂ + H, 150 and 50 g cm⁻² Byr⁻¹ for precipitation of hydrocarbons and nitriles, respectively. The surface is young, and the surface mixing is significant.

**Pluto and Triton:** The great differences (by orders of magnitude) between the atmospheres and ionospheres of Pluto and Triton are caused by the methane abundances. Transition from Triton’s conditions observed in the Voyager flyby to Pluto’s conditions in the New Horizons flyby is expected near CH₄ ≈ 0.05%. Both Triton and Pluto undergo these transitions during their annual cycles.

INTRODUCTION: We conducted an extensive search for rings, dust clouds, and debris features at all phases of the New Horizons 2015 exploration of the Pluto/Charon system. This program was supplemented with HST imaging searches conducted in advance of the encounter. No features were discovered at I/F limits roughly comparable to those at which faint rings had been detected around other solar system objects. The search is described in detail in [1].

BACK SCATTERING SEARCHES: A dedicated search for rings by back-scattered sunlight was initiated nine weeks prior to the encounter. This approach used repeated sequences of deep imaging with the New Horizons LORRI camera with the primary goal of detecting any aggregates of fine particles within the Pluto/Charon system that might have been hazardous to the spacecraft. The final I/F limits on rings or any other faint dust cloud within 10^5 km of Pluto was resolution dependent, ranging from I/F ~ 2 x 10^{-8} for 1500 km wide rings, 1 x 10^{-8} for 6000 km rings, and 7 x 10^{-9} for 12,000 km rings, all at ~15° phase angle. HST imaging conducted in advance of the encounter established limits of I/F ~ 8 x 10^{-8} for radii > 10^5 km from Pluto.

FORWARD SCATTERING SEARCHES: Several deep imaging surveys were conducted after the time of closest approach, with New Horizons looking back at Pluto and Charon at ~165° phase angle for forward-scattered light from any rings or dust clouds as it departed from the system. Because of the small sun-angle, correcting for light scattered into the camera optics was crucial. The most sensitive searches were thus made with the MVIC instrument, given its markedly superior scattered light performance over LORRI. I/F limits from forward scattering were 8 x 10^{-7} on 10^4 km scales interior to the 6 x 10^6 km Hill radius of Pluto.

OCCULTATIONS AND DUST IMPACTS: Apart from the LORRI and MVIC imaging searches for light scattered by rings, four stars were monitored at closest approach by the Alice instrument to look for occultations by any rings or dust clouds. Again, no events were detected. Exact limits depend on the extent of the occulting object being tested for, but rough limits of optical depths of ~10^{-2} are reached on scales of a few km. Lastly, the Student Dust Counter instrument detected no dust impacts over the duration of the encounter that can be attributed to the Pluto/Charon system.

DISCUSSION: The New Horizon ring limits in back-scattered light are at least an order of magnitude stronger than the best limits provided prior to the encounter by HST observations [2], and provide the first constraints on detection by forward scattered light. The red points in the figure below [1] locate the New Horizon ring detection limits in the context of various components of the Jovian ring system and the more diffuse Saturnian rings. The limits on rings in the Pluto/Charon system fall below all known systems except the Jupiter Thebe gossamer ring.

Estimates of the impact gardening of the small satellites of Pluto made prior to the New Horizon mission argued for a substantial possibility that rings would be seen above the limits of the present searches [3]. The paucity of small impact craters on Pluto and Charon seen in New Horizons images [4], however, implies a strong downward revision in the gardening rates assumed by [3]. The complete absence of and dust concentrations in the Pluto/Charon system is also expected as consequence of efficient clearing of the system by solar radiation pressure [5].

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APPLICATION OF A PHYSICAL MODEL TO DUNE PATTERN EMERGENCE ON PLUTO. E. M. Lenhart1, M. Berrondo1, J. Radebaugh1, M. Telfer2, and E. Parteli3. 1Department of Physics and Department of Geological Sciences, Brigham Young University, Provo, UT 84602 (elenhart417@gmail.com), 2School of Geography, Earth and Environmental Sciences, Plymouth University, Plymouth, UK, 3Department of Geosciences, University of Cologne, Pohligstraße 3, 50969 Cologne, Germany.

Introduction: Recent images of Pluto strongly suggest that dunes are present on the dwarf planet's surface [1]. This finding opens questions about the movement of loose, sand-sized particles, and the conditions under which this movement can form familiar patterns such as ripples and dunes. We seek to better understand these patterns using physical models.

Fundamentals of Sand Transport. Sand movement occurs via several mechanisms: saltation, suspension, reptation, creep, and granular convection. Saltation refers to a small leap that a particle makes—usually a few centimeters. This can occur either due to the wind velocity exceeding a threshold of motion or due to particles colliding against each other in a chain reaction started by wind. Suspension occurs as the smallest particles are carried large distances through air. Reptation occurs when (generally large) particles move across the surface due to wind forces.

The final two processes, creep and granular convection, are driven primarily by the force of gravity. Creep is often defined to include reptation, but for our purposes, it will be defined exclusively as sand movement at or near the surface. Effectively, it means that larger particles end up near the surface over time.

It is important to note that these processes are mainly a function of three physical forces: gravity, the force of wind, and the static frictional force between the particles (Fig. 1).

Composition of Plutonian Sand. When considering dunes on Pluto in particular, an important question arises: since silica is not abundant on Pluto, what material could Pluto’s dunes be composed of? When assessing the likelihood of a given potential dune material, important considerations include (1) the abundance of the material on the surface of Pluto, (2) the physical properties of the material in Plutonian conditions, such as its phase at given temperature and pressure ranges, and (3) the chemical properties of the material in Plutonian conditions, such as inter-particle attractive forces.

While Pluto’s surface includes ices of H2O, CH4, CO, N2, and NH3 [2] that could all potentially contribute to dunes, the primary composition of Pluto’s dunes is most likely methane (CH4) [1]. This is because of both its abundance near dune regions and its behavior at these temperatures as a rigid ice [1].

Models for this Project: Theoretically, the formation of all aeolian morphologies can be reduced to physical laws. However, no simple computational model can perfectly capture the reality of wind dynamics and particulate movement. It is important, therefore, to understand the strengths and limitations of what each model measures and returns.

A Model of Threshold Velocity. A crucial factor in determining sand transport—and the distinguishing factor between the transport of loose particulate matter and the dynamics of fluids—is the threshold velocity: the minimal velocity at which wind forces exceed frictional forces, and the particle begins to move. Consider the following physical equation:

$$u_T \approx A_N \frac{\rho_p - \rho_a}{\rho_a} g d \quad (i)$$

In this model the threshold velocity, $u_T$, is dependent on the densities of the air and of the particle, $\rho_a$ and $\rho_p$, respectively; the acceleration due to gravity, $g$; the diameter of the particle, $d$; and a constant $A_N$. [e.g., 3]

Nishimori’s Model. A model of sand transport developed by Nishimori [4] takes into account saltation and creep to describe the progress of emergent patterns, such as ripples, over time. The key inputs are the saltation length, saltation height, and saltation proportionality constant. Its primary use is in understanding the overarching patterns in dunes and ripples rather than the individual ripples or dunes themselves.

Specifically, the simulations of Nishimori’s model we ran began with a spatial matrix of a sand surface, where the value at each point, $h$, represented sand height. In each time step, an amount, $q$, saltated a
length \( L \) (a linear function of \( h \)), as shown in these equations:

\[
h_{n+1} = h_n(x, y) - q \quad (ii)
\]

\[
h_{n}(x + L(h_n(x, y)), y) = h_n(x + L(h_n(x, y)), y) + q \quad (iii)
\]

Additionally, creep was modeled by changing the value \( h \) at each point as a function of the value \( h \) of the points nearest neighbors (NN) and next-nearest neighbors (NNN), as well as of a diffusion constant, \( D \) (which depends on the angle of repose):

\[
h_{n+1}(x, y) = h_n(x, y) + D \left[ \frac{1}{12} \sum_{NN} h_n(x, y) + \frac{1}{12} \sum_{NNN} h_n(x, y) \right] \quad (iv)
\]

Using these simulations, the degree of frustration in the pattern was evaluated by counting the frequency of bifurcations after a given amount of time.

**Analysis:** By counting bifurcations in various runs of Nishimori’s model, we have concluded that frustration in the emergence of aeolian patterns correlates much more strongly with the saltation proportionality constant than with the saltation height. This means that for an otherwise perfect transverse wave pattern in sand, interruptions—bifurcations, in particular—occur in part due to a difference in wind velocities as a function of height (the saltation proportionality constant); these interruptions do not, however, appear to depend on the amount of sand transported in a given time frame (saltation height).

This conclusion is significant, because if emergent patterns like ripples or dunes experience high enough levels of frustration, no recognizable pattern will be visible in the disorganization. Therefore, in determining whether dunes will form (and what they will look like if they do) the dynamics of the wind as a function of height (the saltation proportionality constant); these interruptions do not, however, appear to depend on the amount of sand transported in a given time frame (saltation height).

The difference in wind velocities as a function of height has previously been confirmed to contribute to the unstable nature of dunes with respect to along-axis perturbations [5]. Our findings also suggest that for familiar aeolian patterns to form, it is not as important that the atmosphere transports as high a volume of sand in a given period of time as Earth’s atmosphere does.

On Pluto specifically, the atmosphere is much thinner than on Earth, which may mean particulate matter is transported less often than it would be in terrestrial wind conditions. Still, as long as *some* transport is occurring, and no external forces disturb the area, very similar patterns should form if given enough time. Another implication of these findings is a possible explanation of disparities in the apparent organization of Pluto’s dunes. If we assume that the composition of the dunes is homogeneous on a large scale, and that the underlying geology of Sputnik Planitia is essentially flat (which may or may not be true), then a difference in wind velocities as a function of height may be one important reason that some dune patterns are regular, while others have more defects and discontinuous crests.

**Data of Pluto:** Images of linear features on the surface of Pluto were captured by New Horizons. Evidence strongly suggests that these patterns are transverse dunes that may be composed of sand-sized solid methane particles [1].

Measurements of the average spacing of the dunes and the frequency at which defects occur can be compared with these model outputs to help reveal the conditions under which these features form on Pluto.

![Figure 2](Pluto System After New Horizons 2019 (LPI Contrib. No. 2133) 7064.pdf)

Figure 2: A portion of the northwest boundary of the Sputnik Planitia region of Pluto. The linear forms are transverse dunes. Image by New Horizons.

Introduction: The New Horizons (NH) mission flyby of 14 July 2015 verified the presence of an extensive surface ice sheet consisting of CO + N2 ice in Sputnik Planitia, and a near global covering of layered and structured CH4 ice around the planet [1]. At first glance, assuming Pluto was aggregated out of billions of cometary planetesimals, the prominence of large amounts of N2 ice seems in tension with the ~0.2% vs water abundance found in comets. A similar tension results when the ~1.0 % CH4 vs water in comets is analyzed. Using the new results of the 01 Jan 2019 New Horizons flyby of KBO MU69 [2], we have new constraints on the icy makeup of the smaller KBOs, which differ substantially from the icy makeup of comets in having abundant composite amorphous water ice and pure hydrogen-bonded ice phases [3]. In this paper we use this new information and new modeling of the thermodynamic properties of MU69’s and Pluto’s ices to argue that slow accretion of hypervolatile rich amorphous ice phases present in small KBOs is the most likely source of the hypervolatiles observed in the large KBOs today.

Evidence for Abundant Hypervolatile Ices on Large KBOs, But No Evidence for Them on MU69 or the Most Distant Centaurs: Water and methanol, but also the hypervolatile ices (N2, CO, and CH4), are known to be present on the largest KBOs, like Pluto [5-6]. By contrast, MU69 & the Centaurs show absorptions only due to H2O and CH3OH ices [5-7; Fig. 1]. Correlations of the activity of 23 Centaurs with their perihelion distance from the Sun led Jewitt [8] to conclude that the activity of the inner (r < 10 AU) Centaurs is driven not by CO or CO2 ice sublimation, but instead by crystalization of amorphous water ice and the “squeezing out” of other icy molecules unable to fit into the lattice pores of the newly crystallized ice. SP comet surface spectra do not show any obvious absorption features due to ices [9-11]; however, their coma, produced most actively by water ice sublimation, show an abundant range of icy species [12-13], with most species on the order of 0.1 – 1.0 % of the H2O gas abundance, with the exception of CO (0.5 – 25%), CO2 (2-12%), and CH3OH (0.5 – 5.0%). The comet minor species abundances are consistent with their being sourced from crystalline water ice clathrate phases [14]. One final piece of important evidence is that on Pluto and Charon, we see extensional surface features & extremely spherical morphologies from internal processing & differentiation [15-16].
volatile rich Pluto (after rejecting an exogenous impactor hypervolatile source due to the work of Singer [17]).

(1) Since pure hypervolatile ices should be exhausted on small proto-KBOs within the first $10^5$-$10^6$ yrs of their formation and warming by internal radioactivity and external sunlight (Fig. 2), one simple solution to the presence of N$_2$ and CH$_4$ is to form Pluto and the other large KBOs very quickly, within 1 Myr of the PPD midplane clearing, while the hypervolatiles are still contained in the small source KBOs. The ices seen on Pluto’s surface in this scenario would be extracted from source KBOs by differentiation and concentrated on the surface. This scenario, while possible, is in some tension with the long dynamical timescales found in the large heliocentric distance, low total PPD mass Kuiper Belt. It would also require that the heating effects of short lived radionuclides be minimal.

(2) Another physical possibility that explains the hypervolatile ice presence is the formation of Pluto early on, but while there is still appreciable nebular gas in the KB region containing the hypervolatiles. This can include the time in the first $10^6$ yrs when the small KBOs are outgassing their hypervolatiles, thus acting as local secondary gas sources. The large KBOs thus act as large gravitational ‘cold’ traps for the ices being shed from the small KBOs as well as for any leftover primordial disk gas. The hypervolatile ices seen on Pluto’s surface in this scenario are a “late Patina” accreted on top of a nearly fully developed Pluto, differentiated or not. The timescale for this scenario is also relatively quick, the ~10 Myr PPD disk gas lifetime measured for nearby Milky Way stars in the latest surveys [18].

(3) Extraction of hypervolatile ices from amorphous & crystalline water ice phases in differentiated Pluto. In this scenario, the ices we see on the surface of Pluto are endogenous, and the least dense and most volatile species making up Pluto. They are analogous to the ~10$^{-4}$ fraction (by mass) of the Earth of water that covers ~70% of its surface. Whether one has to use a “strict comet crystalline water ice abundance recipe” + total complete Plutonian differentiation (in order to get enough hypervolatiles on the surface), or the higher abundances of hypervolatiles available in amorphous water ice phases of the small KBOs [3] + partial internal differentiation is a matter of debate. McKinnon+ 2017 [19] argued from impact modeling of the Pluto-Charon system that full differentiation is unlikely for these bodies.

Current evidence from the NH MU69 flyby for the “hyperabundance” of surface methanol ice, the strong similarity in the NIR surface spectrum of MU69 and the distant Centaur Pholus, and the outgassing activity patterns of the Centaurs as a whole all argue for the presence of abundant amorphous water ice phases and refractory hydrogen bonded pure non-water ice phases (CH$_3$OH, HCN, etc.) in the small KBOs [3]. The carrying capacity for the large pore spaces in the hypervolatile species in amorphous ice is, in general, much higher than that of clathrated material in the interstitial regions of the crystalline water ice phases [20] existing in the inner system comets.

Thus amorphous-water-ice-rich small KBOs could easily carry a few % of N$_2$ vs H$_2$O (by number), an order of magnitude higher than the ~0.2 % found vs water in comets [9, 21]. Since Glein & Waite [22] have already calculated that Pluto can be made from fully differentiated comet stuff with the lightest phases on the surface, an object made from small KBO stuff that contains more hypervolatiles in cold amorphous water ice, rather than annealed inner system crystalline water ice, could produce Pluto’s surface N$_2$ and CH$_4$ even more easily and without requiring complete internal differentiation of the body. It could also produce the surface hypervolatiles seen today in spite of earlier higher atmospheric loss rates due to an early warm Pluto, the Charon-forming impact, passing OB stars and nearby supernovae, or periodic “super seasons” [23, 24].


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COMPARATIVE PLANETOLOGY OF THE ION CHEMISTRY AT PLUTO, TITAN, AND TRITON. K. E. Mandt and A. Luspay-Kuti, 1 Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd, Laurel, MD 20723 (Kathleen.Mandt@jhuapl.edu).

Introduction: Understanding the origin and evolution of volatiles in the atmospheres of small bodies in the outer solar system is critical for constraining conditions in the Protosolar Nebula (PSN) during the formation of the solar system. In previous work we have found that Titan’s nitrogen originated as NH3 in the PSN based on our understanding of how chemistry and escape fractionate the isotopes [1,2]. Our work with studying photochemistry and escape of Pluto’s atmosphere found that the processes in Pluto’s atmosphere are more complex, and current understanding about condensation and aerosol interaction prevent us from concluding what the source of Pluto’s nitrogen was in the PSN [3]. Comparing processes that take place in Triton’s atmosphere with what we know of Pluto’s could provide valuable insight into this problem.

![Figure 1 - 14N/15N throughout the solar system [3 and refs.]. Primordial values are shown as triangles and evolved ratios are circles. The large uncertainty for the possible evolved 14N/15N in N2 at Pluto is due to uncertainties in the influence of condensation, aerosol trapping and sublimation on the isotopes. We have extended our work to evaluate the evolution of 14N/15N in N2 in Triton’s atmosphere.](image)

Origin of Nitrogen: Nitrogen is a useful tool for understanding the conditions in the outer regions of the PSN because N2 and NH3 are incorporated into icy building blocks at different temperatures [2,4]. The nitrogen isotopes provide a clear separation between N2 and NH3 in the PSN as shown in Fig. 2, where we illustrate measurements of 14N/15N throughout the solar system. We divide them into two groups: primordial (triangles), or the value presumed to represent the value in the PSN; and evolved (circles), or a value that has changed over time due to atmospheric processes like escape and chemistry. Evolved observations of 14N/15N are not direct measurements of building block composition. This means that Pluto’s current atmospheric composition cannot be used to make conclusions about Pluto’s primordial composition. The evolution of the atmosphere must be evaluated to understand the origin of Pluto’s volatiles.

Evolution of Atmospheres: The 14N/15N in planetary atmospheres evolve as a result of processes that affect each isotope differently. These processes include: atmospheric escape, photochemistry, electron-impact chemistry, condensation, sublimation, and aerosol trapping.

The atmospheres of Pluto, Titan and Triton are similar to each other in their general composition and in the types of processes at work in the atmosphere. However, the details of their composition, such as the methane abundance, and the rate at which each process works differs for each atmosphere. This means that different processes dominate in influencing nitrogen at Pluto compared to Titan and Triton. Photochemistry driven by solar photons combined with atmospheric escape are most important at Titan [1,2]. For Pluto, HCN is the reference gas for tracing evolution of nitrogen at Pluto. This molecule is strongly influenced by condensation and sticking to aerosols in Pluto’s atmosphere and work is ongoing to understand the implications of this for the evolution of nitrogen at Pluto. As one step in trying to improve understanding of Pluto, we are using comparative planetology with Titan, which is well understood, and with Triton, which is currently poorly understood. We outline below a comparison with Triton.

Comparative planetology to understand the evolution of Pluto’s atmosphere: The most notable difference between Pluto and Triton is the intensity of Triton’s ionosphere compared to Pluto. The Voyager observations of Triton found that the peak electron density [5] is significantly greater than peak densities observed in Titan’s solar-driven ionosphere [6], suggesting that energetic particles from Neptune’s magnetosphere play an important role in chemistry in Triton’s atmosphere. We illustrate in Fig. 2 the electron density observed at Triton compared to average dayside ion densities at Titan [6] and the upper limit for Pluto [7].
Figure 2 - Triton’s total ionospheric electron density [5] at ingress (black solid line) and egress (black dashed line) is ~10x greater than Titan’s peak daytime ion density (orange circles; [6]) and the upper limit for Pluto (cyan-shaded; [7]).

Ion chemistry and molecular growth: Ion chemistry at Titan is thought to play an important role in driving molecular growth that leads to the formation of organic hazes in Titan’s atmosphere [8]. However, Pluto’s haze layers [9] are more extensive than Triton’s [10] even though Pluto’s ionospheric density has an upper limit that is more than an order of magnitude lower than Triton’s. This suggests that the processes driving molecular growth are more complex and by extension means that evolution of the atmosphere due to chemistry is also more complex.

Drivers of ion chemistry at Pluto, Triton, and Titan: The ionospheres of Pluto and Titan are both driven by solar photons ionizing atmospheric neutrals leading to complex chemistry. The total ion density in a solar-driven ionosphere is a result of the balance of production and loss processes. Titan is closer to the Sun and has higher ion production rates due to solar input than Pluto and Triton. These higher rates should lead to higher densities at Titan than at Pluto or Triton. This is the case for Pluto, but not for Triton. Modeling studies from the Voyager era found that the high electron densities in Triton’s atmosphere required high ion production rates resulting from the input of energetic electrons from Neptune’s magnetosphere [e.g. 11]. These models predicted that either N+ or C+ would be the dominant ion in Triton’s ionosphere. However, the C+ production in these models required assuming a high rate for a reaction that had not been measured in the laboratory [12]. Since these models were published, significant progress has been made in understanding the chemistry in atmosphere like Triton’s thanks to comparisons made with observations by Cassini of Titan [e.g. 6,13] and New Horizons at Pluto [3,14]. To test if advances in photochemical modeling can explain the high electron density at Triton, we have adapted our Pluto Ion Neutral Photochemical (Pluto-INP) model to conditions at Triton (Triton-INP) and compare simulated atmosphere conditions with results from the Voyager 2 flyby of Triton. Fig. 3 shows that the simulated total ion density (black line) using only solar input is ~6x lower than the electron density observed by Voyager confirming that Neptune’s magnetosphere plays an important role in ion chemistry in Triton’s atmosphere. However, the main ion produced in a solar driven ionosphere is HCO+, and not N+ or C+, showing that what we have learned from Titan and Pluto is important for understanding Triton.

Figure 3 – Results of our ion chemistry pilot study [15] showing Triton-INP ion composition using only solar EUV as an energy source. Total ion densities (black solid line) are 3-6 times lower than observed electron densities (gray solid and dashed lines). The most abundant ion is HCO+.

UNDERSTANDING OF PLUTO ATMOSPHERIC DYNAMICS AND BEHAVIOUR FROM NEW HORIZONS MISSION. A. A. Mardon1, and G. Zhou2, 1University of Alberta (116 St. and 85 Ave. Edmonton, Alberta T6G 2R3, CANADA, aamardon@yahoo.ca), 2George Washington University (2121 I St NW, Washington, DC 20052, USA, gzhou@gwu.edu)

Introduction: The New Horizons flyby of Pluto and its four surrounding satellites system in 2015 changed our original assumptions and understanding of this distant planet and its moons. The information provided from the mission gave new geological, compositional and atmospheric datasets along with a complex range of images never seen before. Amongst the shear volume of new datasets arriving from New Horizons is renewed information about the structure and composition of Pluto’s atmosphere.

Research: The Alice Instrument on the New Horizons spacecraft was used to assess Pluto’s atmosphere during the flyby event in 2015. An ultraviolet solar occultation is sensitive to measuring the structure and composition of N2 rich atmospheres. The findings from the observation confirmed our past understanding of Pluto atmospheric composition of the presence of N2, CH4, C2H2, C2H4, and C2H6 [1]. Gladstone et al. also investigated the atmosphere of Pluto and found that the upper atmosphere is colder and more compact than expected [2]. Because Pluto's extremely cold upper atmosphere, it also infers that the escape rate of nitrogen is ~10,000 times slower than predicted [2].

The research team shows that the planet's atmosphere is much more complex and diverse than originally expected - it hosts numerous extensive layers of haze. The extensive expanse of haze throughout the planet at all altitudes can be seen in images provided by New Horizons. The blueish colour and the scattering properties of the haze are consistent with the aforementioned atmospheric composition. It is currently still unclear of the cause, dynamic and formation of this haze or what its implications are on the overall behavior of the planet’s atmospheric system.

Pluto’s atmospheric system has direct links to climatic and seasonal changes. This interconnected system shows that atmospheric composition and pressure changes have a significant impact on surface characteristics including planetary frost bands [3]. The mapped infrared spectra across the encountered hemispheres of Pluto show us that the volatile methane, carbon monoxide and nitrogen ices dominate the planet’s surface as originally expected [3]. The complex spatial distribution is resulting from sublimation, condensation and glacial flow from seasonal, geological and atmospheric changes.

Conclusion: The colder than expected outer atmosphere of Pluto along with slower rate of escape rate of nitrogen have an important implication for the continued evolution of Pluto’s atmosphere. No sufficient details for the study of dynamics and formation of the haze has been completed and should be further explored. The mission lacked capability to make in-situ atmospheric measures to study the haze-like phenomenon and overall atmospheric dynamics. Future missions should account for these capabilities for further study of Pluto's atmospheric composition.

References:
TECTONISM ACROSS PLUTO: MAPPING AND INTERPRETATIONS. P. J. McGovern, O. L. White, P. M. Schenk. 1Lunar and Planetary Institute, 3600 Bay Area Boulevard, TX, 77058 (mcgovern@lpi.usra.edu), 2SETI Institute, 189 Bernardo Avenue, Suite 200, Mountain View, CA, 94043, 3NASA Ames Research Center, Moffett Field, CA, 94035-1000.

Introduction: The flyby of Pluto by NASA’s New Horizons spacecraft in 2015 returned high quality image data that reveal an unexpectedly complex geology [1,2], including extensive tectonic deformation across the well-resolved encounter hemisphere. We aim to exploit this image dataset, and products derived from it such as topography, to constrain the tectonic and cryovolcanic history of Pluto at regional to global scales, through an integrated program of detailed structural mapping and quantitative analysis of icy shell lithosphere stress and deformation states via finite element method models. We present our structural mapping of Pluto’s encounter hemisphere and assign mapped tectonic features into orientational classes. We will consider the implications of our results in terms of what factors control tectonism across Pluto.

Mapping and Morphological Classification: Pluto’s tectonics have been surveyed previously, less than a year after the flyby [3], which was prior to the availability of the latest high quality global mosaic and digital terrain model (DTM) [4]. The datasets used for our mapping include a global mosaic that covers the encounter hemisphere at a pixel scale ranging from 234 to 880 m/pixel, and a DTM of the encounter hemisphere, which can resolve topographic features as small as ~1.5 km across and has vertical precision ranging between 100 m and 800 m [4]. The flyby nature of the New Horizons mission meant that, for the encounter hemisphere, each point on the surface was only imaged at a single solar incidence and emission angle. Assessing topographic relief based on shading in imaging is therefore more difficult in areas around the subsolar point of 130.5°E, 51.5°N, and so the DTM plays a particularly important role in identification of fractures here, as well as in areas imaged at oblique angles near the edge of the encounter hemisphere.

Fig. 1 shows our mapping of tectonic features across the encounter hemisphere. We have identified four morphological categories, including normal fault scarps, which often form graben that can reach >10 km wide; sharp-crested ridges, which in some cases may represent two normal fault scarps back-to-back; troughs that are typically narrow (reaching tens of km long whereas graben can reach hundreds); and pit chains, which are mostly confined to mantled terrain to the east of the nitrogen ice plains of Sputnik Planitia (SP), and which may indicate where collapse has occurred as underlying tectonism disturbs the overlying mantle [5]. We concur with earlier findings [3] that Pluto possesses a non-random system of extensional faults, although we discuss a possible region of compressional tectonism below.

Orientational Trends: We have categorized our mapped tectonic features into nine orientational classes, which are described below, along with their colors as mapped in Fig. 2.

Ridge-Trough System (blue): A complex, eroded, fragmentary band of troughs, ridges, elevated plateaus and elongate depressions that extends at least 3200 km along the 155° meridian, from the north pole to the limit of coverage at ~45°S. It is likely the earliest tectonic system yet seen on Pluto, and may predate the
Sputnik basin-forming impact [4].

**Sputnik-Azimuthal (cyan):** These fractures are orientated azimuthally about a pole located at 170°E, 25°N, very close to the geographic center of SP (Fig. 2). The fractures are removed from the pole by 1100 to 1500 km and fall into two main groups: Djanggawul Fossae and Mwindo Fossae. Their configuration implies an origin tied to SP, perhaps reorientation of Pluto in response to infilling of the Sputnik basin with nitrogen ice [3]. Mwindo Fossae are unusual in that while they are mostly oriented NNE-SSW, they also converge to a point, suggesting that a localized stress field within the crust caused them to diverge from the Sputnik-azimuthal orientation.

**West Sputnik (red):** This class features generally sharply-defined graben and troughs, which at their northern extent are quasi-radial to SP, but which bend southwards to reach a N-S orientation in the southern hemisphere. May have formed concurrently with the Sputnik-Radial class.

**Sputnik-Radial (dark red):** The graben and troughs of this class are also sharply-defined. Most form a belt with a consistent NE-SW orientation that is essentially radial to SP, although a possible outlier of this class at 28°S is not radial to SP.

**Southwest (purple):** A sparsely-populated belt of WNW-ESE-trending fractures in the far southwest of the encounter hemisphere.

**North Sputnik (green):** NW-SE-trending fractures (including many pit chains) that exist both to the east and west of SP, with a gap at its northern rim. They are neither radial nor azimuthal to SP and their relation to it is uncertain.

**Far West (orange):** These fractures trend E-W and WNW-ESE and appear to crosscut Djanggawul Fossae. They typically form shallow, narrow troughs, in contrast to the deep graben of Djanggawul Fossae themselves.

**South Sputnik (violet):** A tenuously defined class featuring localized clusters of generally NE-SW-trending ridges, scarps, and troughs on the southwestern rim of SP. Their sparseness and variable morphology lends uncertainty to the interpretation that they share an origin in a single episode of tectonism.

**Miscellaneous (yellow):** Fractures not categorized in any other class, which tend to occur in small clusters within other tectonic systems that do not share their orientation or which may originate from very localized crustal stress conditions.

**Interpretations:** Tectonic trends that follow "great circle" or large-radius "small circle" paths (e.g., the Ridge-Trough and Sputnik-Azimuthal systems, respectively) are suggestive of response to planetary-scale phenomena like despinning and tidal stress [6] and polar reorientation [7,3]. Tectonic trends radial to regional features like SP (e.g. Sputnik-Radial and elements of West Sputnik) are consistent with extensional "hoop" stresses from membrane-mode loading [8] such as nitrogen ice infill of the SP basin [3].

While Pluto’s surface tectonics appear dominantly extensional in nature, some planetary-scale loadings predict regions of enhanced compression [6,7]. Tartarus Dorsa are broad topographic swells with a consistent NE-SW orientation, superposed by bladed terrain [9]; an origin as compressional lobate scarps could explain the base topography. Further, when taken collectively with elements of the extensional West Sputnik and Sputnik-Radial classes a quarter of the way around the planet, the overall pattern resembles a despining and tidal stress scenario for a paleo-south pole several hundred km southwest of Wright Mons.

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**Figure 2.** The nine different mapped orientational classes of tectonic features, overlain on a DTM that is polar projected and centered on SP. Geographic coordinates on Pluto are shown as thin black lines, and coordinates relative to the SP pole as thick white lines. White concentric circles are spaced 200 km apart.


Introduction: The New Horizons encounter with Pluto revealed not just a remarkable dwarf planet, but a complex, scientifically rich planetary system far out in the Kuiper belt [1]. This talk will draw on encounter results, and together with other talks at this PANH conference, synthesize and summarize what we have learned from New Horizons, highlighting some of the less understood or appreciated aspects.

Formation: As now understood, the Pluto system was emplaced into its 3:2 mean motion resonance with Neptune as part of the overall dynamical rearrangement of the outer solar system attendant upon a compact, but ultimately unstable, arrangement of 4 or more giant planets emerging from the protosolar nebula [2]. The Kuiper belt as a whole is almost entirely derived from a ~15–20 $M_{\text{Earth}}$ remnant planetesimal disk originally orbiting exterior to Neptune, a disk whose main mass extended not much further than 30 AU (Neptune’s present semimajor axis) [3]. The most natural time scale for this instability is early, within a few 10s of Myr of dissipation of the gaseous protosolar nebula, and not 100s of Myr later [3]. Implantation into the Kuiper belt is not particularly efficient, of order $10^{-3}$. This implies many Pluto-scale dwarf planets were lost, ejected to the scattered/scattering disk, Oort cloud, or accreted by the giant planets, or in the case of Triton, captured.

The origin of the Pluto-Charon binary is widely regarded as due to a relatively giant (for the Kuiper belt) impact [4]. Other mechanisms for binary formation have been proposed for Kuiper belt objects, but the large masses of Pluto and Charon, the great specific angular momentum of the pair, and coplanar system of smaller satellites, all argue for an impact origin similar to that of the Earth-Moon [1].

Numerical simulations of the Charon-forming impact to date favor a relatively slow collision (i.e., an impact speed $\approx v_{\text{esc}}$), and partially differentiated precursors [4]. Completely differentiated precursors (i.e., bodies with ice mantles and rock cores) yield, post-impact, a very icy Charon in orbit about Pluto, contrary to Charon’s mean density, whereas totally undifferentiated precursors yield very rock- and organic-rich small satellites, in apparent contradiction to their extremely icy nature [2]. More specific constraints await higher resolution impact simulations.

The inference of a relatively slow moon-forming collision is consistent with late oligarchic growth in the ancestral planetesimal disk; that the precursors were only partially differentiated could be a signature of earlier growth by pebble accretion in the presence of nebular gas, i.e., by collisions so small that accretional heat was not deeply buried. Once the dynamical instability initiates, however, impact speeds would have necessarily climbed to several km/s, arguably inconsistent with forming Charon, though not with violent collisions generally (e.g., Sputnik basin, which we note is far too small to be the impact scar of the Charon-forming impact, though it must also have formed prior to Pluto’s emplacement into the 3:2 resonance).

Composition: Pluto’s composition provides a key constraint on formation conditions, as well as interior and atmospheric evolution. With regards to the diagnostic volatiles, the surface is dominated by molecular nitrogen and methane [5,6]. The nitrogen is concentrated in Sputnik Planitia, while the methane is more widely distributed. It has been estimated that there are $10^{20}$ moles of $N_2$ in Sputnik Planitia [7]. Carbon monoxide is also concentrated in Sputnik Planitia, but it appears to be substantially less abundant, at least in the surface. The global abundance of methane has not yet been estimated, but the integrated loss with time, using the present observed escape rate, could have exceeded $10^{19}$ moles [1]. Spectral signatures of NH$_3$ have been found, whereas there is no evidence of CO$_2$. The atmospheric composition reflects the surface, with fractionation driven by different vapor pressures and temperatures of the dominant volatile sources. The most abundant atmospheric volatile is nitrogen, followed by methane, and then CO [8,9].

The available data allow us to develop and constrain different hypotheses of volatile origin and evolution, but the data are insufficient to deduce a uniquely favored scenario. One possibility is that the volatiles were accreted in the same chemical forms in which they now exist. In a primordial scenario, cold building blocks of Pluto would have contained CO, CH$_4$, and N$_2$, as in the most thoroughly characterized comet, 67P/Churyumov-Gerasimenko. The abundance of N$_2$ in comet 67P can yield the inventory in Sputnik Planitia, if the cometary abundance is scaled up to the mass of Pluto [7]. Comets, however, appear to contain too much CO to be consistent with that observed at Pluto, unless most of Pluto’s accreted inventory of
CO is buried in deeper layers of glacial ices, or the CO could have been destroyed by aqueous chemistry in a subsurface ocean [7].

An alternative scenario that requires further consideration involves the formation of N₂ and CH₄ by the thermal decomposition of organic materials in a rocky core. This type of model was recently proposed for Titan [10]. Abundant CHON organic solids should have been present in rocks accreted by Pluto, as in cometary and interplanetary dust particles. These organic-rich rocks could have undergone substantial heating if incorporated into a core on Pluto. Heating favors the formation of the small, stable molecules CH₄, CO₂, NH₃, and N₂ in addition to graphite. Qualitatively, the surface assemblage of volatiles suggests relatively high temperatures (to form N₂) and somewhat reduced conditions (to inhibit CO₂ formation). It is, however, unclear if a metamorphic process can account for the presence of CO, or if an exogenic source of CO might need to be considered. The more refractory, insoluble organic fraction could also form an important, internal structural layer within Pluto, especially if the bulk organic fraction is anywhere close to that observed at 67P [11].

**History:** The post-formation tidal evolution of Pluto-Charon should have followed a path familiar from studies of the Earth-Moon system. Following relatively rapid circularization of their mutual orbits and spin down of Charon to spin-orbit synchronism, Charon should have slowly been driven outward until Pluto itself reached the 1:1 spin-orbit resonance [12]. Only by fine-tuning tidal parameters is it possible for Charon to maintain a finite orbital eccentricity as it retreats from Pluto [13]. If Pluto remains relatively non-dissipative then the orbital expansion time scale could in principle be quite long [14], but evidence for active geology, including circumstantial evidence for an internal ocean, argues against this being the case. Nevertheless, the orbital expansion could easily have lasted long enough to complete post-emplacement of the binary in the 3:2 resonance with Neptune. The four exterior small satellites, or their precursors, were nominally also being tidally driven out, but a self-consistent story for how this was accomplished has proved elusive [1].

Some clues to Charon’s evolution may be contained in the tectonic features visible on its surface. Charon exhibits a large canyon system as well as many, more dispersed fractures in Oz Terra [15], which have been interpreted as evidence of global expansion. If Charon once had a subsurface ocean, freezing of the ocean would have resulted in a net volume increase, perhaps causing the expansion. If, however, Charon possessed an ocean during its orbital circularization and recession, it may have been responsive enough to tides to induce stresses that fractured the surface [16]. Even if the stress magnitudes are low, the presence of a freezing ocean can add a large, uniform background stress that can combine with tidal stresses to achieve failure [e.g., 17]. More detailed comparison between observed fractures and tidal stress patterns is warranted and may provide the best test of a past ocean as well as constraints on Charon’s orbital evolution. In deep time, other processes could have contributed to global volume change on Pluto and Charon as well, such as differentiation and de/serpentinization [15].

During the tidal expansion of Charon’s orbit, Pluto’s tidal bulge (bulges in the case of Charon) should have collapsed, but there is no evidence in the spherical shapes of Pluto and Charon (to the limits of measurement [18]) for fossil bulges, nor obvious tectonic evidence of the predicted degree-2 shape changes [14]. The former sets important limits on the early thickness, rigidity, and brittle strength of the lithospheres of both bodies, whereas the latter has not been tested for in detail.

On Pluto, younger tectonic features are (almost) exclusively extensional (normal faults and graben). Although plausibly also driven by ocean freezing and global expansion [15], their predominant orientation perpendicular to Sputnik Planitia matches the extensional stress pattern predicted for an angularly broad positive load (mascon) on a spherical shell (in the manner of Tharsis) [19], and is part of the circumstantial evidence for a dense oceanic upwelling beneath Sputnik [20]. Ammonia has also been detected on both Pluto and Charon [e.g., 21], supporting the possibility and/or preservation of putative oceans through freezing point depression.

**References:**
ELASTIC FLEXURE AROUND SPUTNIK PLANITIA, PLUTO, AND EVIDENCE FOR A VERY HIGH HEAT FLUX. A. C. Mills1,2 and L. G. J. Montési1, 1Department of Geology, University of Maryland, College Park, MD 20742, amills12@umd.edu. 2Smithsonian Institution National Air and Space Center for Earth and Planetary Studies, Washington, DC 20560.

Overview: One of the most remarkable geological features of Pluto is the 1,300 × 500 km² elliptical basin called Sputnik Planitia. Currently, the basin is filled by about 10 km of convecting nitrogen ice [1, 2, 3]. Sputnik Planitia has been interpreted as an impact basin hosting a nitrogen ice deposit [4, 5] or a flexural basin resulting from the deposition of a large ice cap [6]. Here, we test if the current topography of Sputnik Planitia and its surroundings contain evidence for the flexural bulge that would have formed in a thin elastic plate loaded by a large deposit of nitrogen ice inside Sputnik Planitia.

Methods: Forty 600 km-long tracks perpendicular to the edge of Sputnik Planitia (Figure 1) were extracted from a stereo-derived digital elevation models (DEM) of Pluto [1] and imported into Matlab as vectors of distance x vs. elevation t. Data points in regions clearly modified by craters were removed from the profile to focus on possible flexural signals.

The topography was compared to the deflection of a thin elastic plate subjected to a series of vertical loads \{\text{L}_i\} at position \{x_i\}. According to [7] the deflection, w, produced by a single load obeys Eq. 1:

\[
P \frac{d^2 w}{dx^2} + \rho_m g w = \text{L}_i \delta(x - x_i)
\]

where \(\rho_m\) is the density of water underneath the ice (1030 kg/m³), g is the acceleration of gravity (0.62 m/s²), \(\delta\) the Dirac distribution, and \(D \equiv \frac{EH^3}{12(1-\nu^2)}\) is the flexural rigidity, with \(E\) the Young’s modulus (9 GPa), \(\nu\) Poisson’s ratio (0.3), and \(h\) the elastic thickness of the plate, which is not specified \textit{a priori}. Each load induces a deflection of the plate given by

\[
w_i(x) = w^0_i M_i(x), \quad \text{with}
\]

\[
M_i(x) \equiv \left[ \frac{4D}{\rho_m g} \right]^{1/4} \sin \frac{x - x_i}{\alpha} + \cos \frac{x - x_i}{\alpha} \exp \left[ -\frac{x - x_i}{\alpha} \right]
\]

where \(\alpha = \left[ \frac{4D}{\rho_m g} \right]^{1/4}\) is the flexural parameter and \(w^0_i \equiv \frac{V_i t a^3}{6D}\) is the deflection amplitude. In addition, the reference elevation of the region surrounding Sputnik Planitia is \(w^0_0\). Therefore the expected topography is given by

\[
w = \sum_{i=0}^{n} w^0_i M_i(x)
\]

with \(M_0(x) = 1\).

For each profile, we invert for \(\alpha\) and \(\{w^0_i\}\). To do this, we specify possible load location \(\{x_i\}\) every 50 km from -2000 km to 0 km, where 0 km is the start of the profile outside Sputnik Planitia. Then, for each candidate value of \(\alpha\), we assemble the functional forms in Eq. 4 into an operator matrix \(M\) with elements \(M_{ij} = M_i(x_j)\). The load vector that produces the best fitting profile for this value of \(\alpha\) is given by

\[
w^0 = (M'M + C)^{-1}(M't)
\]

Where \(C\) is a mass matrix helping to regularize the solution. Misfit is quantified using

\[
\chi^2 = \sum_{j} \left( \frac{t_j - w_j}{\sigma_j^2} \right)^2
\]

where \(\sigma_j^2\) is an estimate of the noise level in the profile, taken as the variance of \(t\) over the last 200 km of the profile.

The procedure is repeated for all candidate values of \(\alpha\) and the value providing the minimum \(\chi^2\) is recorded as the optimum \(\alpha\). Uncertainty on \(\alpha\) is given by the range of values for which \(\chi^2\) exceeds the minimum \(\chi^2\) by less than a threshold value \(\Delta \chi^2\) such that

\[
1 - p = P \left( \frac{\alpha}{\sigma^2} \right)
\]

Where \(P \equiv \frac{\int_0^\infty e^{-t^2} t^{n-1} dt}{\int_0^\infty e^{-t^2} dt}\) is the incomplete gamma function, \(n\) is the number of degrees of freedom, and \(p = 68\%\), is the confidence limit (1σ) [8].

Results: Fourteen profiles (1-3, 6-7, 20, and 29-36) provide well-constrained elastic flexure estimates. Figure 2 shows the example of profile #31, one of the best constrained profiles, with \(\alpha = 128.5_{-32}^{+59}\) km, and profile #1, with \(\alpha = 90.3_{-68}^{+36}\) km. Sixteen profiles (4-5, 10-11,
13-16, 18, 21, 24-26, 37-38, and 40) are consistent with flexure. Only ten profiles (8-9, 12, 17, 19, 22-23, 27-28, and 39) showed no evidence of flexure. A rigid plate cannot be ruled out for these profiles, due to high topographic variance (degraded terrains). Profiles that do not show evidence for elastic flexure are typically in the northwest tip of Sputnik Planitia or at its southwest end, where the Planitia opens to pitted plains [1].

The flexural parameter obtained for each profile, weighted by the range of acceptable value as described above, provides an ensemble view of the structure of the terrains surrounding Sputnik Planitia (Figure 3). The overall flexural parameter is 92 ± 23 km, which corresponds to an elastic thickness of \( h_e = 23 ± 8 \) km. The minimum nitrogen ice load thickness required for this elastic thickness is 4.6 ± 0.4 km (Figure 4). Thus, the flexure does not require a nitrogen ice load thickness that exceeds the current amount inside Sputnik Planitia.

To better understand the implications of this elastic thickness value for Pluto, we estimate the heat flux associated with these estimates according to

\[
Q = \frac{567}{T_e} \left( \frac{T_e}{T_s} \right)^{5/3 \ln\left(\frac{T_e}{T_s}\right)} \]  

(8)

where \( T_s \) is the surface temperature, \( T_e \) the maximum temperature for which elastic behavior dominates (estimated as 100 to 150 K), and we assume a thermal conductivity \( k = \frac{567}{T_e} \) Wm\(^{-1}\)K\(^{-1}\) [9]. A heat flux of at least 15 mW/m\(^2\) is necessary to explain the elastic thickness. This value is twice as high as the maximum heat flux estimated from thermal evolution models [10, 11]. The origin of the heat flux anomaly is unclear, as neither tidal heating nor radiogenic heat production are likely to exceed the estimates used in previous studies. The high interior temperature might be related to heat deposited by the proposed Sputnik Planitia impact [4,5].

ON THE ORIGIN OF THE PLUTO SYSTEM. M. Neveu1,2, R. M. Canup3, and K. M. Kratter4, 1U. of Maryland, College Park, MD, USA. 2NASA Goddard Space Flight Center, Greenbelt, MD, USA (marc.f.neveu@nasa.gov). 3Southwest Research Institute, Boulder, CO, USA (robin@boulder.swri.edu). 4Astronomy Department / Steward Observatory, U. of Arizona, Tucson, AZ, USA (kkratter@email.arizona.edu).

Introduction: We describe constraints and review models for the origin of the Pluto-Charon binary and the small moons Styx, Nix, Kerberos and Hydra. We also highlight open issues and discuss implications.

Observational Constraints: The heliocentric orbit of the Pluto system at ≈40 AU is triply resonant with Neptune’s orbit, involving mean motions (3:2), arguments of perihelion, and longitudes of ascending node. Therefore, Neptune likely shaped the Pluto system’s eccentric and inclined heliocentric orbit [1,2].

System dynamics. The plane of the Pluto system is highly oblique to its heliocentric orbit. The Pluto-Charon mass ratio, 8.2 [3], is low. Their close (distance 16.5 Pluto radii), tidally locked, circular mutual orbit coplanar with both equators implies that the binary is in tidal equilibrium. Circularization timescales, which increase dramatically in wider orbits, imply that the binary has always been close together [4]. The small moons, of combined mass ≈6x10^−6 times that of the binary [3], orbit it with high obliquity on circular, coplanar orbits close to (but not exactly in) 3:4:5:6 mean motion resonance with Charon. This could result from a stable resonant configuration perturbed by the binary [5,6]. The small moons are not tidally locked, likely because Pluto’s small mass cannot synchronize their spins in <1 Gyr, longer than the timescale of perturbation by impacts [7]. More distant Kerberos/Styx-sized regular moons (~10^16 kg) are unlikely on dynamical grounds and based on searches with New Horizons [8-10].

Compositions. Charon’s bulk density (1700 kg m^−3 [11]), lower than Pluto (1854 kg m^−3), implies that Charon is icier [12,13]. The densities of the small moons are not tightly constrained [3]. Pluto displays surface CH4, N2, and CO frosts in addition to H2O and sparse NH3. In contrast, H2O and NH3 make up much of Charon and the puzzlingly brighter surfaces [14] of Nix, Hydra, and (for H2O) Kerberos [15,16]. Styx’s composition is unknown.

Formation Models: The influence of Neptune over the system’s orbit makes it very likely that Pluto and Charon accreted closer to the Sun (<30 AU) than today, with orbital expansion and excitation caused by a rearrangement of the giant planets including the outward migration of Neptune [2,17]. Pluto’s moon system could have survived this migration [18], so whether the heliocentric migration predated the system-forming event is an open question.

Giant impact. The Pluto-Charon binary’s low mass ratio, high angular momentum, and close separation makes an impact on Pluto from a like-sized impactor its prime origin scenario [19-21 and references therein]. This impact must predate Charon’s ≈4 Gyr old surface [22]. At ≈40 AU, binary-forming impacts could have occurred every 100-300 Myr [23], and likely more often closer in. The mass ratio is reproduced with an impact velocity only slightly higher than proto-Pluto’s escape velocity [20]. Two scenarios yield the observed mass and angular momentum distribution [20]: collision between differentiated (or partially so [24,25]) progenitors forming a disk from which Charon accretes, or quasi-intact formation of Charon from un- or partially-differentiated progenitors [20,24]. If the small moons originate as collisional debris [26,27], they would likely be icier in the disk scenario [25], or icier or with the same ice/rock ratio as the progenitors in intact Charon models [24]. The disk scenario would yield an icier Charon [12], but it is difficult to explain Charon’s large mass in this case [20]. The disk density and debris size distribution, an open issue, might be inferred from crater populations on Charon [28].

Orbital expansion of the small moons out to today’s tens of Pluto radii must have been much faster than expansion driven by the feeble solid tides raised by these moons on Pluto. Resonant interactions with Charon could have sped up their migration on Charon’s orbital expansion timescale [27]. This scenario reproduces the moons’ high obliquity [7], but also yields eccentric orbits incompatible with observations [29]. Alternatively, the small moons might have formed in an extended debris ring, requiring less migration [23]. This issue remains open.

Identifying a Pluto collisional family, as found for Haumea [30], would validate the impact scenario. Members of such a family should have survived, but are dynamically difficult to spot [28].

Alternatives. Fission of a fast-spinning Pluto could also explain a high-angular-momentum binary [31,32], but the amount of spin up needed to launch material into a ring from which Charon accretes [33] is only achievable with a giant impact [21]. Co-accretion as a binary cannot supply Pluto’s high obliquity or the system’s high angular momentum [21]. With accretion by streaming instability, the high angular momentum may have prevented accretion into
a single body [34], but this demands an instability of unduly high (~Pluto) mass [35]. Capture could be enabled by dynamical friction from surrounding small bodies [36] or pebbles, but this requires an excessively dense disk [14]. These alternatives must also explain the system’s high obliquity and form small moons near orbital resonances with Charon from smaller impacts onto Pluto or Charon, the breakup of prior satellite(s), collisional capture [37], or co-accretion, all of which are unlikely [14, 24, 28, 38, 39].

**Implications:** Physical state of proto-Pluto and giant impactor. Pluto and Charon’s relative masses and densities can be reproduced with several partially differentiated structures for the progenitors: an icy mantle overlying a rock-ice core [24], undifferentiated crust surrounding an ice mantle and rock core [25], and a ‘mud’ mantle of fine-grained rock and ice above a rock core [40]. This degeneracy prevents pinpointing their time of formation. In all cases, the progenitors (radius ≈1000 km) could maintain a thin global H₂O-NH₃ ocean just above the core.

**Thermal processing and loss of volatiles.** Pluto’s N₂ abundance is consistent with a primordial supply [41], but could also result from the oxidation of NH₃ and/or organic nitrogen. The lack of N₂ on lower-gravity Charon suggests loss during the giant impact, later degassing and escape [42] during resurfacing [22], or (if N was supplied in reduced form) a lack of oxidation. The latter case would imply that oxidation kinetics were only fast enough on post-impact Pluto, presumably warmed by a greater supply of radionuclides and/or the impact itself. Likewise, the presence of CH₄ on Pluto but not Charon suggests either a primordial supply that escaped from Charon [43], or a product of the reduction of CO₂, CO, or organic C that did not occur on Charon. In the latter case, carbon reactions were partial even on Pluto, whose surface CO would otherwise have been converted to more stable species [41, 44]. Pluto and Charon may be two archetypes of the bimodal volatile inventories detected on other large Kuiper belt objects [45].

**Other binary dwarf planets.** Differences in impact angle and velocity between two like-sized dwarf planets can lead to larger ice/rock fractionations [46], e.g. possibly for Eris-Dysnomia [47, 48] and Orcus-Vanth [49]; or outcomes other than a binary [24, 47], such as Haumea which only has small moons [50]. Although the orbit and compositions of Pluto-Charon suggest an impact origin, those of other binary systems may be compatible with alternative origins such as capture [36], e.g. for Eris and much darker Dysnomia [48, 51], Orcus-Vanth [49], or the eccentric moon of 2007 OR₁₀ [52]; or co-accretion [34, 53], e.g. for Glkünl’hömdimá-Glö’élhú [53]. Possible origins may depend on formation location (dynamical class).

GEODYNAMICS OF PLUTO. F. Nimmo¹, W. B. McKinnon² ¹University of California Santa Cruz, Santa Cruz, CA 95064, USA ²Washington University in St. Louis, St. Louis, MO 63130, USA

Introduction: Thanks to the New Horizons flyby it has become possible to think about the interior and evolution of Pluto (and Charon). Despite the rather limited data sets available, some preliminary conclusions can be made, as discussed below, notably the likely presence of a subsurface ocean.

Observations: The radius, and thus the density, of Pluto are now precisely known, at 1188.3±1.6 km and 1854±11 kg m⁻³, respectively [1], while Charon is 9% less dense than Pluto. No sign of a fossil bulge was seen on either body, and no other gravity data are available.

Pluto’s surface exhibits abundant extensional tectonic features, some of which appear to be stratigraphically young [2], and which may be associated with cryovolcanic deposits [3]. Two enigmatic mountains (Wright and Picard Montes) may also be of cryovolcanic origin [2]. The bedrock of Pluto is mostly water ice, although surficial deposits of CH₄ and NH₃ are also present. The smooth, low Sputnik Planitia basin contains a layer of solid N₂ (+CH₄ +CO) of uncertain thickness (at least several km), but which is apparently convecting at the present day [4]. Some ~100 km scale impact craters are suggestive of viscous relaxation, though this has not yet been fully explored [5].

Inferences: Below we will focus on four questions to which we can provide at least preliminary answers: What is the bulk structure? Is there an ocean? What is the ice shell structure? And how has Pluto evolved over time?

Bulk Structure: Pluto’s density indicates that it is roughly two-thirds rock and one-third ice, with uncertainty arising from the unknown fraction of carbon-rich material [6,7] and from porosity. A completely undifferentiated Pluto can be ruled out, as deeply-buried ice would have transformed to higher-pressure phases as Pluto cooled, leading to surface contraction which is not observed [6]. Notably, however, Pluto cannot have been fully differentiated when Charon formed (assuming a giant impact was responsible) because this would be inconsistent with Charon’s bulk composition [8].

The heat released by radioactive decay in the silicates is sufficient to drive solid nitrogen convection [4] and also to melt and sustain a subsurface water ocean ~100 km thick [9-11] as long as the ice shell is not convecting. The absence of any rift flank uplift observed is consistent with the expected peak radiogenic flux of ~6mW m⁻² [12], but if crater relaxation is really present [5], higher heat fluxes are required at some time in the geologic past, at least regionally.

Is there an ocean? If Pluto developed at ocean, it will have slowly refrozen over time. The effect of this refreezing is to cause extensional surface stresses [13] and to pressurize the ocean beneath, potentially leading to cryovolcanism [14]. Thus, the surface observations are consistent with a refreezing subsurface ocean, though they do not require it. Similarly, the absence of a fossil bulge is consistent with the presence of an ocean: the decoupling of the ice shell from the interior allows the bulge to collapse [9].

The location of Sputnik Planitia, close to the tidal axis, may also be an indication that a subsurface ocean is present [15]. A positive mass anomaly will cause Pluto to reorient such that the anomaly moves towards the tidal axis, and the tectonic pattern observed is consistent with such true polar wander having occurred [16]. Loading by nitrogen is insufficient to cause a positive mass anomaly unless the nitrogen layer is ~30 km thick [15]. On the other hand, a positive gravity anomaly arises naturally if dense water is present beneath a thinned ice shell at Sputnik Planitia. This situation arises naturally if Sputnik Planitia was formed by an impact [17], as seems likely, and resembles the situation seen at the lunar mascon basins. Thus, Sputnik Planitia’s location is likely indirect evidence for the presence of a subsurface ocean.

What is the ice shell structure? If an ocean is present, thermal modeling indicates that the ice shell cannot be convecting [9] and should have a present-day thickness of about 150 km. Moreover, for a thinned shell region to persist over billions of years, the base of the ice must be very cold [15]. A cold ice shell is also indicated by the large elastic thicknesses required to avoid excessive subsidence at Sputnik Planitia [15]. One way of achieving this is to posit a very NH₃-rich, and thus cold, ocean. But the layer must not be so cold as to lead to formation of dense ice II at depth, which would drive surface compression [11] (as noted above, unseen). An interesting alternative is to appeal to a clathrate layer plated onto the base of the ice shell [18]; because clathrates have a very low thermal conductivity, even a thin clathrate layer results in a thinner, colder ice shell above than if clathrates are absent.

The density difference between Pluto and Charon can be explained almost entirely by the latter having a much thicker layer of porous ice [7,10]. A higher thickness is expected on Charon because overburden pressures are smaller and so are temperature gradients. Model predictions [10] suggest that the porous layer thickness on Pluto is a few tens of km thick, though there is no direct observational evidence for this.

How has Pluto evolved over time? The energy budget of Pluto is dominated by that of radioactive
decay [9]; other sources of heat, such as impact energy or tidal heating, are likely minor. Simple conductive models of Pluto suggest that peak heating of the ice occurred at 2.5-3.5 Ga, and that the ocean has been slowly refreezing ever since. Charon may have developed a thin ocean, but it will not have survived to the present day [10].

Thus, over the second half of its history Pluto will have experienced continued surface expansion (strain rate \(\sim 10^{-19} \text{ s}^{-1}\)) and ocean pressurization, which is broadly consistent with the observations. If Sputnik Planitia is an impact basin, this probably happened prior to the onset of ocean refreezing, by analogy with similarly-sized basins in the inner solar system. Extrapolating present-day impact crater production on Pluto back in time does not make formation of a basin the scale of Sputnik Planitia likely [19]. The implication is that such an impact occurred quite early in Pluto’s history, when Pluto was embedded in the massive planetesimal disk that was ultimately scattered outward to form the Kuiper belt, or during that scattering event [20].

Surficial nitrogen will probably have been redistributed over the surface via orbital forcing, and will also have slowly escaped to space (see talk by Howard & Moore). This redistribution may have caused Sputnik Planitia’s location to vary in a complicated fashion [16]. Whether any significant replenishment of surface volatiles from the interior occurred is unclear.

**Summary:** Despite the relative dearth of geophysical data, we can make some preliminary conclusions. Pluto is at least partially, and probably fully, differentiated. There are several indirect lines of evidence for a present-day subsurface ocean on Pluto, though none of them is incontrovertible. Pluto’s ice shell is likely cold and rigid, which may limit communication between the subsurface and surface. Its long-term thermal evolution involved monotonic slow cooling and refreezing, in contrast to tidally-heated bodies where non-monotonic behavior can occur [e.g. 21].

**Going Forwards:** There are probably nuggets of information yet to be gleaned from New Horizons. In particular, if relaxed craters really are present, then our picture of a cold, rigid ice shell will need modification.

However, further progress will ultimately require another mission. And in some ways Pluto is a more challenging target than other, similar-sized icy bodies. In particular, the standard techniques of looking for an ocean are unlikely to work. The induction technique used at Jupiter will not work, because there is no background, time-varying magnetic field. And looking for a characteristic tidal response will fail, because Pluto and Charon are mutually tidally-locked and are thought to have zero obliquity, so there is no time-dependent tidal forcing.

By far the most informative approach will be to measure the static gravity and topography. A combination of gravity and topography measurements will yield the moment of inertia (and thus the differentiation state), even if Pluto is somewhat non-hydrostatic [cf. 22]. The same measurements at shorter wavelengths can be used to infer the total and elastic thickness of the ice shell, in a similar manner to missions to Venus and Mars. And of course the prediction that Sputnik Planitia is a mascon would be readily testable with such techniques.

Given the presumed thickness of the ice shell, a radar instrument would not be able to image the ocean, but should give a constraint on thermal gradients. It would also probably be able to constrain the thickness of the N\(_2\) layer at Sputnik Planitia, which is currently unknown.

**Conclusions.** Geodynamics on Pluto is still in its infancy. Nonetheless, with the limited data available in particular stereo-derived topography [23] and limb profiles – it is possible to make quantitative conclusions and testable predictions. Pluto has certainly shown itself to be more interesting than expected, with its likely subsurface ocean expanding the habitable zone of the solar system out to 40 AU. The Kuiper Belt is likely a menagerie of similarly fascinating worlds, and we eagerly await the next opportunity to take a close-up look.

**References:**

THE COLORS AND PHOTOMETRIC PROPERTIES OF PLUTO. C.B. Olkin\(^1\), C.J.A. Howett\(^1\), S. Protopapa\(^1\), W.M. Grundy\(^2\), M.W. Buie\(^3\), A. Verbiscer\(^3\), S. A. Stern\(^1\), H. A. Weaver\(^4\), L. A. Young\(^1\), K. Ennico\(^5\)

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**Introduction:** On the 14\(^{th}\) of July 2015 the New Horizons spacecraft had its closest approach of Pluto, imaging it in unprecedented detail. On approach, during closest approach and on departure the Ralph Multispectral Visible Imaging Camera (MVIC) \([1]\) took a large number of color images of the entire Pluto system. We will explore the approach and closest approach images MVIC took of Pluto, in which Pluto’s surface is sunlit and clearly resolved (i.e. much bigger than an MVIC pixel).

**MVIC:** MVIC has seven independent CCD arrays, held on a single substrate. Four of these CCDs have a color filter (Red, Blue, NIR, CH4, see Table 1). Details of the post-launch calibration of MVIC are given in \([2]\), which uses both stellar observations and observations of Pluto’s moon Charon.

<table>
<thead>
<tr>
<th>Array name</th>
<th>Wavelength range (nm)</th>
<th>Pivot wavelength (nm)</th>
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</thead>
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<tr>
<td>Blue</td>
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<td>492</td>
</tr>
<tr>
<td>Red</td>
<td>540-700</td>
<td>624</td>
</tr>
<tr>
<td>NIR</td>
<td>780-975</td>
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<tr>
<td>CH4</td>
<td>860-910</td>
<td>883</td>
</tr>
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</table>

**Table 1** - The details of MVIC color arrays.

**Pluto naming conventions:** Figure 1 shows a map of Pluto with the formal and informal names of different regions indicated. This is the naming convention we use throughout this work.

**Observations:** Resolved color observations MVIC made of Pluto are given in Table 2, which details the observation’s time, image scale and sub-spacecraft longitude and latitude. As the table shows the spatial resolution varies from 127 km/pixel on approach to 0.66 km/pixel during closest approach.

<table>
<thead>
<tr>
<th>Mid-Time of Observations (UTC)</th>
<th>Image Scale (km/pix)</th>
<th>Sub-Spcft Lon (° E)</th>
<th>Sub-Spcft Lat (° N)</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
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<td>114.03</td>
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<td>18.8</td>
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<tr>
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<td>0.2</td>
<td>43</td>
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<td>335.1</td>
<td>43</td>
</tr>
<tr>
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<td>66.54</td>
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</tr>
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</tr>
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**Table 2** – Details of resolved color MVIC observations.
was at 51.6° N during encounter, so the northern hemisphere is the sunlit one).

Results: Figure 2 shows an overview of the highest closest approach enhanced color observations of Pluto [3]. The images are made using MVIC’s NIR, Red and Blue filters for the image’s Red, Green, Blue channels respectively using the same reduction technique outlined in [3]. Thus, they are not true color (i.e. how a human would see Pluto if viewed from New Horizons).

Global Color: As Figure 2 shows, a large range of colors are seen across Pluto’s surface. The global colors can be splits into four distinct regions: 1) The northern polar regions, which are notably more yellow than the bluer lower latitude regions that surround it; 2) The heart-shaped Tombaugh Regio, which appears much bluer towards the East (right hand side) and more neutrally colored on the West (Sputnik Planitia); 3) A dark red band that wraps around Pluto’s equatorial region, informally known as Cthulhu Regio indicated by the two regions at the upper right.

Regional Color: The consistency of color within a given region, and the differences between regions is highlighted by the color-color plot shown in Figure 3. In this figure, color ratios are plotted and the values of five discrete regions are highlighted. The most red regions (unsurprisingly) occur across Cthulhu. Sputnik Planitia and terrains surrounding the yellow northern terrain make up the neutral terrain. The transitional terrain describes regions south of Cthulhu, and north of Cthulhu but south of the neutral terrain. The figure shows this transitional terrain has the largest variation in Red/Blue/NIR color. We will discuss these regional color variations further in our presentation.

Figure 2 – Highest spatial resolution enhanced color observations of Pluto (i.e. bottom four observations of Table 2). The highest resolution image (bottom left hand side) is referred to as P_COLOR2. The geometry of the image is depicted by a wiregrid globe with the equator highlighted in pink and the prime meridian indicated in yellow.

Figure 3: Color–color plot from the highest resolution Pluto image (bottom right hand image in Figure 2, P_COLOR2). For each pixel in the image the NIR/Red is plotted against Red/Blue. A neutral color is indicated by the black circle at the intersection of the lines. The color of each point represents the ratio of I/F in the methane channel to the I/F in the NIR channel, with Blue indicating more methane. Adapted from [3].

Photometric Properties: An overview of photometric modeling will be presented.


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RESONANCES IN PLUTO’S SYSTEM. N. I. Perov, State Autonomous Organization of Cultural and Education named after V.V. Tereshkova. Ul. Chaikovskogo, 3, Yaroslavl, 150000. Russian Federation. E-mail: perov@yarplaneta.ru.

Introduction: “New Horizons” obtained new data about the system of Pluto, which are allowed to forecast new phenomena in this group of the bodies and to construct in particularly new celestial mechanical theories for localization of undiscovered regions of gas and dust matter near Pluto. Taking into account the work [1] here the small body (dust matter) motion is considered in the frame of the restricted plane circle seven body problem (Pluto–Charon–Styx–Nyx–Kerber–Hydra–a particle). For motion of particles which are in resonance with Hydra are especially paid attention. The aim of this work is to state, using numerical simulations, the extended stable regions of particles motion near the Hydra’s resonances: 1:1; 1:2; 1:3; 1:4.

The Basic Equation: Let’s denote G is gravitational constant; m_P, m_C, m_S, m_N, m_K, m_H, are mass of Pluto, Charon, Styx, Kerber, and Hydra respectively; r, r_C, r_S, r_N, r_K, r_H are the Pluto’s centrically radii-vectors of the particle and Pluto’s satellites correspondingly; P_C, P_S, P_N, P_K, P_H are the periods of Pluto’s satellites motion along the circle orbits accordingly. The differential equation of the particle put in the form [2]

\[
d^2r/dt^2 = -Gm_P/r^3 - Gm_C(r-r_C)/|r-r_C|^3 - Gm_S(r-r_S)/|r-r_S|^3 - Gm_N(r-r_N)/|r-r_N|^3 - Gm_K(r-r_K)/|r-r_K|^3 - Gm_H(r-r_H)/|r-r_H|^3.
\]

(1)

In the equation (1) instead of the Newtonian’s time \( t \) the angle \( \varphi \) of Charon uniformly rotating is used. The following units are used: m_P is the units of mass, r_C is the units of length and G=1.

Examples: Using the data from [3] it is possible to draw the figures (Fig.1 - Fig. 6), illustrated motion of the Hydra’s “resonance” particles in the Pluto’s system. Below \( P \) is a period, \( e_0 \) is an initial eccentricity, \( v_0 \) is a velocity of the particle in the initial moment of time (\( t_0=0 \)).
Conclusion: 1. For \( k=1 \) and \( e=0 \) the region of the particles motion is greater than in the case \( k=4, \ e=0 \) (Fig. 1 and Fig. 5).

2. For \( k=1 \) the particles leave out the system at \( e=0.05 \) (Fig. 4), while for \( k=4 \) the particles leave out the system at \( e=0.6 \) (Fig. 6 and Fig. 7).

3. For the definite initial conditions \( r_0 \) and \( v_0 \) there are horseshoes trajectories (Fig. 2 and Fig. 3).

4. In the work [1] for the first time in the frame of the restricted circle three body problem (\( m_1>m_2>>m \)) in the system of reference origin of which is placed in the center of mass it is shown: the stable horseshoes trajectories always exist if we have \( m_1/m_2>700, \ x_0=-x_2, \ y_0=0, \ v_{x0}=0, \ v_{y0}=0 \). So, in the Pluto’s system the stable horseshoes trajectories must exist for the subsystems of “Pluto, a satellite of Pluto and a body with negligible mass” (Fig. 3), but there are no the such stable trajectories for the subsystem “Pluto–Charon–a particle”, because \( m_P/m_{Ch}=8.2156 << 700 \). (Mass \( m_i \) of a satellite-i we determined using the formula \( m_i=4/3\pi a_ib_ic\rho_{Ch} \), where \( a_i, b_i, c_i \) are the semi axis of a satellite-i, \( \rho_{Ch} \) is density of Charon [3]).

In the book [3] a partial case of the horseshoe trajectory for a satellite of Saturn is only considered.


Background: The four small satellites of Pluto form a fascinating circumbinary system that is unique in the solar system in both its architecture and the fact that has been visited by a spacecraft [1]. The four small satellites Styx, Nix, Kerberos, and Hydra are all on circular, roughly coplanar orbits around the central Pluto-Charon binary. The rotation rates of the small satellites are all significantly super-synchronous, but similar to small KBOs [1]. All of them are smaller than 52 km. Because of their circular, coplanar orbits, the small satellites are likely fragments from the original giant impact that formed Charon [2]. This is supported by the spectral similarities between Charon and the small satellites [3]. Nix and Hydra were discovered right after New Horizons launched, and were imaged at a few epochs during the New Horizons flyby, at sufficient resolution to resolve their rough shape and spectra. Styx and Kerberos were both discovered after the New Horizons flyby sequence had already been planned, and so had to be imaged with the backup “retargetable” observations. This meant that only two low-resolution observations of Kerberos were obtained by New Horizons LORRI, and only one low-resolution observation of Styx. It is thus very hard to restrict the shape and pole of Styx and Kerberos. In this talk, we will provide the best estimates for the shape and pole of Nix and Hydra.

Shape and Pole Fitting: Because Nix and Hydra cannot be resolved except in New Horizons images, the major constraints on the pole are the same images that are used to fit the shape. Solving for shape is thus a degenerate with solving for the poles. We will show results of our combined shape and pole fitting method. This method forward-models all the available images with a given rotational pole, rotational phase, parametric model shape, and rough photometric model. The shape is parameterized with the octantoid formalism [4], with a regularization to minimize shape detail in the unimaged areas. This forward modeling is performed in GPU using OpenGL, much faster than would be possible in CPU. We then convolve the rendered image with the point-spread function (PSF) of the image, allowing us to compare directly to the images of Nix and Hydra obtained by New Horizons LORRI. We calculate the sum of square of the difference of the real images with the forward-modeled images to provide a $\chi^2$ for a given parameter set. We then optimize the pole, shape, and photometric parameters to minimize $\chi^2$ and produce the best-fit model for the shape and pole. This model was originally developed for Nix and Hydra [5], refined for 2014 MU69, and now re-applied to Pluto’s satellites.

Nix: Nix was resolved in eight LORRI approach images, one MVIC PAN frame at closest approach, and one very faint crescent LORRI image. It has a rotational period of 43.9 hours, and its pole was pointing 73° from the New Horizons approach vector. This gave good coverage of most of the surface. Nix appears to be a single elongated body with best-fit dimensions 48x32x30 km, and equal volume to a sphere with a diameter equal to 36.5 km. With the best-fit Nix mass in [6], this results in a density of 1.8 g/cm³. The equatorial profile of Nix is roughly trapezoidal. The limb profile of Nix is curiously angular, but the resolution is not sufficient to tell the exact geologic reason for this. Nix’s pole is inclined 125° to Pluto’s pole, making a super-synchronous retrograde rotator.

Hydra: Hydra was resolved in seven LORRI visits. It has a rotational period of 10.3 hours, and its pole was pointing roughly 24° from the direction of the spacecraft on approach. This meant that only the northern half of Hydra was imaged, and the rotation of Hydra could be seen between images of the last two LORRI epochs. The best-fit dimensions for Hydra roughly 51x37x21 km, and equal volume to a sphere with a diameter equal to 35.0 km. With the best-fit Hydra mass in [6], this results in a density of 2.1 g/cm³. However the smallest axis is poorly constrained due to the encounter geometry. Hydra has an irregular shape, consisting of a large main body (~40 km diameter), and a smaller extension (~10 km long). Hydra’s pole is inclined 64° from Pluto’s pole, and the combination of this with Hydra’s rapid rotation rate should cause its pole to precess over time.
Implications for Pluto and KBO formation:
Both Nix and Hydra have elongated shapes, rapid rotation rates, and poles that are highly inclined to the plane of their orbits around the central Pluto-Charon binary. This may imply that they have been bombarded by sufficient impacts since formation to increase their rotation rate and incline their poles. Alternatively, they could have excited into high rotation rates and inclinations by spin-orbit interactions, though it may be hard to produce the retrograde rotation of Nix by that process. Neither Nix nor Hydra is a contact binary in the style of 2014 MU69, implying that the formation of Nix and Hydra around Pluto could have been a very different process to KBO formation from the circumsolar disk.

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PHOTOMETRIC PROPERTIES OF PLUTO’S MAIN SURFACE UNITS. S. Protopapa¹, C. Olkin¹, W. Grundy¹, J.Y. Li³, A. Verbizker³, D.P. Cruikshank³, C. J.A. Howett¹, A. Stern¹, H.A. Weaver⁵, L.A. Young¹, the New Horizons Science Team ¹Southwest Research Institute, Boulder, CO 80302, USA; ²Lowell Observatory, Flagstaff, AZ 86001, USA; ³Planetary Science Institute, Tucson, AZ 85719, USA; ⁴University of Virginia, Charlottesville, VA 22904, USA; ⁵NASA Ames Research Center, Moffett Field, CA 94035, USA; ⁶Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA, (sprotopapa@boulder.swri.edu)

Introduction: The chemistry of Pluto’s atmosphere and surface has become a key factor in understanding the origin and evolution of this icy dwarf planet, and by extension that of a vast number of similar sized and smaller bodies in the Kuiper Belt, beyond the terrestrial and giant planets.

A pixel-by-pixel Hapke radiative transfer model has been developed by Protopapa et al. [1] and applied to two resolved scans of Pluto’s encounter hemisphere acquired by the New Horizons (NH) infrared imaging spectrometer, LEISA [2]. This model yields compositional maps defining the spatial distribution of the abundance and textural properties of the materials present on the surface of Pluto. This has been by far the most successful approach to date in terms of providing quantitative information about the composition of Pluto. However, this analysis has some limitations, namely:

1) Important compositional information is hidden in the visible wavelength range where low albedo organic compounds known as *tholins* present the most diagnostic spectral signatures [3]. High quality filter band imagery in this range exist from the NH Ralph/MVIC instrument [2], but have yet not been studied with this technique. One of the main findings of the Protopapa et al. study [1] is the correlation between Pluto’s coloration and the abundance of *tholins* used in the best-fitting models. As an example, the highest concentration of these dark compounds is found in Cthulhu Macula, the lowest albedo and reddest unit of Pluto’s observed surface [4,5]. On the other hand, Lowell Regio, which displays a golden coloration, was found to be highly depleted in *tholins*. This result is a clear example of how the true contribution of the coloring agents cannot be assessed if the visible spectral domain is disregarded.

2) The estimates of the concentration and particle size of each surface compound strongly rely on the choice of Pluto’s photometric properties (Hapke parameters as the cosine asymmetry factor $\xi$, compaction parameter $h$, amplitude of the opposition effect $B_o$, and mean roughness slope $\theta$). These properties have previously been treated as global quantities, constant across all of Pluto’s terrains [6]. However, given the high degree of surface variations on Pluto [4,5], this approximation is likely incorrect.

We report here a detailed study of disk-resolved photometric properties of Pluto using NH Ralph/MVIC images in the visible wavelength range 400-910 nm acquired during the Pluto’s flyby [7].

The derivation of a regionally-based photometric model permits us to (1) decouple the intrinsic surface albedo variability from effects related to the observing geometry, and therefore investigate quantitatively the true heterogeneity of Pluto’s surface; (2) combine visible (MVIC) and near-IR observations (LEISA) accounting for the different viewing geometries at which these data were acquired; (3) model visible and near-infrared measurements of Pluto to derive quantitative information of its surface composition.

Methodology: Photometric models describe the dependence of the radiance factor (RAFT, also commonly referred to as I/F) on scattering geometry, which is defined by the incident angle ($i$), emergent angle ($e$) and phase angle ($g$). We employ the Hapke radiative transfer model [8] to assess the photometric properties of Pluto using a single-lobe Henyey-Greenstein phase function [9].

Fig. 1: Left panel: “Enhanced” color image of Pluto obtained with MVIC’s BLUE, RED, and NIR filter images displayed in blue, green, and red color channels, respectively. Right panel: The same as on the left but over-plotted in magenta are the points selected as representative of the Cthulhu Macula region.

As a preliminary step in the analysis, we re-project each MVIC color frame to a common perspective view. This enables us to select the same region of
interest across Pluto’s scans acquired at different viewing geometries. Figure 1 shows, as an example, the region selected as representative of the Cthulhu Macula, while Fig. 2 shows the photometric data from this region in the BLUE filter (which has a central wavelength of 492 nm). This set of measurements represents an example of data set to be fit with photometric models.

![BLUE filter](image)

**Fig. 2:** Photometric data in the BLUE filter (central wavelength of 492 nm). The three panels show the radiance factor I/F of the Cthulhu Macula region (see Fig. 1 right panel) plotted with respect to phase angle (upper), incidence angle (middle), and emission angle (lower). Different colors correspond to different MVIC scans.

Given the limited phase angle coverage, we consider the amplitude of the opposition effect as well as the compaction parameters constant and equal to the values obtained from disk-integrated analysis (Verbiscer, private comm.). We solve instead for single scattering albedo (w), cosine asymmetry factor (ξ), assuming backscattering, and mean roughness slope (θ). We used a nonlinear least squares minimization program to find the best fit solutions. These parameters, along with the final reduced chi-squared are shown in Fig. 3. We conclude that the phase angle range is too limited to solve for the mean roughness slope (θ). With respect to the average single scattering albedo of Pluto, which is on the order of 0.6 (Verbiscer, private comm.), Cthulhu Macula displays a systematically lower value of 0.15 at 492 nm. This is consistent with a high abundance of tholins in this region.

![BLUE filter](image)

**Fig. 3:** The joint error distribution in the BLUE filter of (w,ξ) and (w,θ) on the left and right panel, respectively for Cthulhu Macula. The 1-, 2-, and 3-σ contours are shown. The solutions for the Hapke parameters and the correspondent 3-σ errors are displayed in the panels.

**Summary:** We present a multi-wavelength, regionally dependent photometric analysis of Pluto’s surface similar to the one shown here for Cthulhu Macula. We will perform a comparative analysis and use these properties to quantitatively infer the composition of Pluto’s different terrains and investigate the different coloring agents across Pluto’s surface and discuss this at the meeting.


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A NEW ANALYSIS OF THE RHEOLOGY OF CRYOLAVA FLOWS IN VULCAN PLANITIA. Lynnae C. Quick1,2, 3Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560, NASA Goddard Space Flight Center, Greenbelt, MD 20771, Lynnae.C.Quick@nasa.gov.

Introduction: Placing firmer constraints on the emplacement timescales of cryolava flows in Vulcan Planitia is essential to obtaining a better understanding of the resurfacing history of Charon, the proximity of fluids to the surface during its evolution, and the frequency of surface-subsurface exchange in the Pluto system. Cryolava flows in Vulcan Planitia are likely water-ammonia mixtures [1-3] that were emplaced similar to the lunar maria [3]. Although the composition and emplacement style of cryolavas in Vulcan Planum have been reliably constrained, questions still remain as to their likely viscosity values. Rheologically speaking, the maintenance of extremely thick, 1-2 km flows necessitates the emplacement of high-viscosity cryolavas [3], while their ammonia-rich composition suggests that viscosities of the erupted fluids should be quite low. Further, numerous quantitative issues, such as the nature and duration of fluid supply, how long subsurface conduits remained open and capable of supplying cryolava to the surface, volumetric flow rate, and the role of the rigid insulating crust in influencing flow and final morphology all have implications for cryomagma ascent and the local surface stress conditions at the time of flow emplacement.

Assuming a constant cryolava viscosity, [3] utilized the methods of [4] to analyze the motion of lava flows in Vulcan Planitia [3]. These methods have also been used to investigate lava emplacement on Venus, Europa, Ariel, and Miranda [5-8]. However, the methods of [4], on which these models are based, contain fundamental shortcomings, and recent studies suggest that improved constraints may be placed on the motion of lava on these bodies by considering flow emplacement while a constant flux of lava is erupting at the vent, and temporal changes in lava viscosity as the flow advances [9-11]. Here, a new modeling approach that alleviates the shortcomings in the models of [4, 12] and considers temporal changes in the viscosity of the flowing lava has been applied. The application of this new approach warrants a re-assessment of the rheology of cryolava flows in Vulcan Planitia.

New Modeling Approach: Here, I have investigated the emplacement of cryolava flows on Charon, exploring the effect of boundary conditions on the solution of the Boussinesq equation for pressure driven fluid flow in a cartesian geometry. The continuity equation describing the horizontal expansion of a Newtonian fluid with an unbounded (free) upper surface and a time-dependent viscosity is:

\[
\frac{\partial h}{\partial \theta} - \frac{g}{3v_0} \frac{\partial}{\partial x} \left( h^3 \frac{\partial h}{\partial x} \right) = 0
\]

[4] found a similarity solution to the general form of (1) for a constant fluid volume with constant viscosity. This solution has been previously applied to the emplacement of lava flows on both rocky and icy bodies in our solar system [5-8]. Here we offer an alternative similarity solution to (1) that eliminates the singularity at \( t = 0 \) inherent to the solution in [4] and allows for the investigation of associated plausible boundary conditions. This model also addresses the issue of time dependent changes in lava viscosity due to cooling. Akin to previous investigators [4, 7-10, 12], and in keeping with the recent work of [3] it has been assumed that a constant volume of material is rapidly emplaced onto the surface, supply terminates, and the flow is shaped by subsequent relaxation of the fluid as it travels away from the vent. The similarity solution for flow thickness, \( h \), is:

\[
h(x, t) = \frac{\nu'^2}{8x_0(1+\theta/t)^{3/5}} \left[ 1 - \frac{1}{(1+\theta/t)^{2/5}} \frac{x^2}{x_0^2} \right]^{1/3}
\]

where \( V' \) is the volume per unit length of the flow and \( \theta \) is the time transformation constant of the form:

\[
\theta(t) = \nu_c \int \frac{dt}{\nu'(t)}
\]

The time constant that eliminates the singularity at \( t = 0 \) is \( \tau = (4/3)^4 (5V')^3 v_0 x_0^3/\rho g \). A variety of forms can be chosen for the time-dependent kinematic viscosity. However, since viscosity increases exponentially as cryolava cools [13], we assume a time dependent viscosity of the form \( \nu(t) = \nu_0 e^{\gamma t} \), as in [10]. For this expression of \( \nu(t) \), \( \theta(t) = \Gamma(1-e^{\gamma t}) \).

Fig. 1 shows the solution of a radially spreading, Newtonian fluid with \( \nu_0 = 10^7 \text{ m}^2/\text{s} \) (equivalent to a dynamic

![Figure 1. Axially symmetric Newtonian fluid flow profiles for an aqueous cryolava that contains 32 wt% NHs. Profiles are obtained from (2).](image-url)
viscosity $\sim 9 \times 10^9$ Pa-s for an NH$_3$-H$_2$O cryolava density of 884 kg/m$^3$ at the 273 K NH$_3$-H$_2$O liquidus temperature [14]) at four times. Here, the overall “shape” of the flow surface, as well as the aspect ratio at the final time, is very similar to the dimensions of the Vulcan Planitia flows described in [3] when $t = 1 \times 10^3$ sec (1.3 days), and $T = 1.2$ months. The flow’s total relaxation time is $\sim 1$ year, which is well within the range of plausible emplacement times for lavas on icy and rocky bodies in our solar system. [7-10].

Cryolava Crust: The vapor pressure of an aqueous solution containing 32.1 wt% NH$_3$ is $\sim 537$ Pa [15]. Owing to this very low vapor pressure, cryolavas erupted onto Charon’s surface will boil violently until an approximately 2 m thick coherent crust forms. As is the case for silicate lavas on Earth and Venus, and cryolavas on the icy moons in our solar system, flows can then be maintained beneath this insulating carapace [10, 16]. In the case of cryolava flows on Charon, this insulating crust will form in $\sim 4$ days. The entries in Table 1 illustrate the sensitivity of flow emplacement time to flow viscosity for NH$_3$-H$_2$O flows. While it is clear that flows on Charon may have apparent bulk viscosities between $10^5$ and $10^8$ m$^2$/s ($10^5$-10$^{11}$ Pa s), much runnier flows, with bulk viscosities $<10^5$ m$^2$/s ($10^5$ Pa s) are unlikely to exist, as their emplacement times are less than the formation time of the insulating crust that would prevent flows from boiling away in Charon’s low-pressure environment.

![Table 1. Sensitivity of emplacement time to bulk viscosity for cryolava flows in Vulcan Planitia.](image)

Conclusions: Previous workers have shown that the insulating crust will not inhibit lava flow [10-11, 17]. However, the crust will act to increase the apparent bulk viscosity of the cryolava by up to 4 orders of magnitude [8, 13]. Hence, the initial kinematic viscosity of the erupted lava illustrated in Fig. 1 would be $10^3$ m$^2$/s (10$^5$ Pa), which is consistent with the viscosity of supercooled NH$_3$-H$_2$O fluids [18] and has previously been considered as an appropriate viscosity value for flows in Vulcan Planitia [1]. Subtracting the effects of the cryolava crust suggests that according to Table 1, realistic kinematic viscosities, at the time of eruption, for cryolava flows on Charon range from $10^2$-$10^7$ m$^2$/s (realistic dynamic viscosities range from $10^4$-$10^7$ Pa s). The results of this work suggest that flows on Charon may have had rheologies similar to terrestrial basalt or basaltic andesite. The results presented here, and those of [9-11], illustrate that improved constraints may be placed on lava viscosities when models that consider the time change in viscosity due to cooling, and lava flow in the midst of constant eruption at the vent, are applied. Determining how the rheologies of cryolavas on Charon compare to the rheologies of lavas on other planetary bodies is an important step in understanding the various ways that volcanism manifests itself throughout the solar system. The next step of this work will therefore be to apply this new modeling approach to the emplacement of cryolava flows on other small, volatile-rich bodies in the outer solar system.

**THE SHAPES AND DISTRIBUTIONS OF DUNES ON PLUTO.** J. Radebaugh\(^1\), M.W. Telfer\(^2\), E.J.R. Parteli\(^3\), R.A. Beyer\(^4\) and R.L. Kirk\(^5\), \(^1\)Department of Geological Sciences, Brigham Young University, Provo, UT (jani-rad@byu.edu), \(^2\)School of Geography, Earth and Environmental Sciences, Plymouth University, Plymouth, UK, \(^3\)Department of Geosciences, University of Cologne, Pohligstraße 3, 50969 Cologne, Germany, \(^4\)NASA Ames Research Center and SETI, Mountain View, CA, \(^5\)USGS Astrogeology Division, Flagstaff, AZ.

**Introduction:** The surface of Pluto as revealed by New Horizons has many geological features similar to other bodies in the solar system, including mountains, craters, tectonic fractures, cryovolcanic constructs and even a convecting glacier [1,2,3]. Included among the geological landforms are hundreds of sand dunes, stretched across the Sputnik Planitia glacier (Fig. 1) [4]. These features have many morphological similarities to dunes on Earth, Mars, Venus and Titan, such as bifurcations or “y-junctions”, an increase in size towards the center of a given dune patch (or “pattern coarsening”), alignment with wind streaks, and deviation around topography [4]. New Horizons MVIC (Multispectral Visible Imaging Camera) images revealed a concentration of methane ice associated with the dunes, meaning they are made of methane sand (where “sand” means a loose, subground, small particle of any composition) [4,5]. Here we describe their shapes and relative heights, the variations in their patterns, and their distribution across the underlying glacier.

![Fig. 1. Dunes on Sputnik Planitia at the base of the Al Idrisi Montes. NASA/New Horizons](image)

**Shapes and Heights of Pluto’s Dunes:** The features initially described as dunes on Pluto are concentrated in the NW corner of the Sputnik Planitia glacier, near the 5-km-high Al-Idrisi Montes. They have regularly spaced [4], elevated and ridge-like morphologies that vary in height and spacing across the terrain. Features in the middle of the heart-shaped feature in Fig. 1 (a convection cell, typical of other cells across Sputnik Planitia, [6]) are straight over distances of several tens of kilometers, are relatively closely spaced (~400 m) and are highly parallel (upper left, Fig. 2) [4]. They have some y-junctions, indicating excursions from the regular pattern, but defects like these are comparatively rare. In many ways, their morphologies are like ripples; in fact, they were modeled as “elementary” transverse dunes, which are the smallest dunes that can be formed by wind on a flat surface [supplemental material in 4]. Features at the bottom of Fig. 1 (upper right, Fig. 2) are generally larger, more widely spaced (~700 m) [4], and based on their shading appear to be taller than those in the north.

Features far to the left in Fig. 1 (bottom of Fig. 2) are more laterally discontinuous and have almost a boxed pattern in planview. These features also appear to have slightly flatter tops than the other dunes (Fig. 3). This may result from a gradual flattening of the crestlines, either through wind- or sublimation-related erosion [7]. That the dunes of Pluto are relatively small is consistent with them being elementary forms, and also makes them analogous to snow dunes on Earth, which tend to have smaller heights.

![Fig. 2. Dune shapes discussed from Fig. 1.](image)

**Distributions of Pluto’s Dunes:** Away from the base of the Al-Idrisi Montes, there are many regularly spaced linear ridges across Sputnik Planitia that have patterns consistent with being dunes [4]. The ridges are perpendicular to wind streaks, appropriate for dunes that form transverse to the winds [4]. Most ridged forms on Sputnik Planitia are oriented roughly NNE-SSW, consistent with a regional wind blowing from Al-Idrisi across Sputnik [4]. Ridged forms at first glance are randomly distributed across Sputnik, covering perhaps 40% of the surface (Fig. 3). They do not favor an upwind or downwind portion of a convection cell; however, they are preferentially found away from the convection cell centers (Fig. 4). No one reason stands out for why this concentration occurs, but potential reasons...
include: 1 – the convection cell centers are the most active regions on the glacier, acting to erase all landforms on the surface, 2 – the dunes have not yet formed on the active centers or 3 – the convection cell centers are warm and act to sublimate the methane snow or ice sand that makes up the dunes.

Fig. 3. Rough distribution of dune-like linear ridges (blue) across Sputnik Planitia. Map is made from 32ppd mosaic; small features are not visible or mapped.

Linear ridges away from Al-Idrisi have much less lateral continuity. The box-like morphology of the features in the SW of Fig. 1 (bottom of Fig. 2) is seen in many locations, and progresses to the point of demonstrating an enclosed, sometimes circular, depression morphology (Fig. 4). In these locations, the patterned forms are sublimation-dominated, probably even caused by sublimation [7]. These features are distributed more commonly on the southern and eastern margins of Sputnik Planitia.

So what is it that defines features as being depositional (dunes) vs. erosional (sublimation pits)? Features that appear to stand proud of an originally flat surface are most likely depositional, originating as dunes. Features that are the reverse, clearly being pits in an originally flat surface, are instead erosional, or from sublimation [4,7]. But there are features that almost appear to be transitional between the two endmembers (Fig. 4). It is possible there is a close relationship between the two forms that depends on materials. Perhaps the dune sands sinter together from solar heating and the salination impact process. This then means that the dunes become immobile, solid forms that can only undergo transport in the form of erosion through sublimation or wind-stripping [4]. Depending on the times required for alteration of the dunes, this may indicate some dunes are young and fresh, perhaps currently forming, while others have formed and undergone sintering and are now eroding by sublimation [4]. In general, Pluto’s dunes must be fairly young, given the rate of the convection thought to be occurring on Sputnik Planitia [6]; however, it is uncertain if they are forming today or when winds were stronger in the past [4,8].

Fig. 4. Centers of convection cells (dark) are free of linear or cell-like forms. The shapes of the ridges are discontinuous and may be transitional between depositional and erosional. Image located 200 km E of the S margin of Al-Idrisi.

Conclusions: The dunes of Pluto have forms that vary in size and shape across Sputnik Planitia. They display shapes, spacings and heights consistent with shapes of dunes seen on other planets, especially elementary forms and snow dunes on Earth. While stereogrammetry of New Horizons data is insufficient to resolve the morphology of these features, photochinometry algorithms [9,10] may be able to derive their shape. Paired with regional mapping of their locations and models for wind effects on Pluto’s sands [11], will provide a more conclusive picture of the differences and relative ages of the features and the state of activity on Pluto today.

THE DEPTH-DIAMETER RELATIONSHIP OF WELL-PRESERVED IMPACT CRATERS ON PLUTO AND CHARON.  S.J. Robbins\textsuperscript{a,}\textsuperscript{1}, P.M. Schenk\textsuperscript{b}, K.N. Singer\textsuperscript{c}. \textsuperscript{a}stuart@boulder.swri.edu, \textsuperscript{b}Southwest Research Institute, 1050 Walnut Street, Ste 300, Boulder, CO 80302, \textsuperscript{c)Lunar and Planetary Institute, 3600 Bay Area Blvd, Houston, TX 77058.

Introduction and Background: Impact craters form via an excavation event caused by a hypervelocity impact. Because of the nature of the event, in most cases, almost all of the information about the original impactor is lost, except for the energy (where the energy is a vector function of various components, such as the impactor velocity and mass). The target body on which the crater forms will also have some control over the final crater shape, and that control is based primarily on the strength of the target material in which the crater forms. This is despite most craters that are studied (~100s meters and larger) forming in a gravity regime, for subsequent modification of the crater shape is still driven by target material properties (e.g., a crater formed in sand will collapse soon after formation much more than a crater formed in metal).

As impact crater studies have been conducted across the solar system for the last ~50 years using spacecraft-based data, trends have emerged that show crater depth – the excavation depth below the surface and relative to the height of the rim uplift – relative to crater diameter – the rim-to-rim distance – can yield important information about target properties [1]. Therefore, the measurement of these two properties is a relatively straightforward datum that can yield useful scientific information, and it is often one of the primary kinds of crater measurements made about a surface. In particular, the crater depth for a given diameter has been linked to the type of material that the crust is made of – crystalline rock, sedimentary rock, or an icy-rock mixture – and the transition between a steep depth-vs-diameter ratio for simple craters versus a more shallow ratio for complex craters has been similarly linked to the strength of the crust material.

However, exactly how that measurement is made varies considerably depending upon the data available and the researcher(s) making the measurement. Measurement of impact crater diameter can vary anywhere from using two points to using all available pixels along the rim and yield different results that tend to be repeatable and replicable at the \(\pm 10\%\) level [2].

Crater depth, however, is subject to significantly more measurement variation. This variation can result from three primary sources: Data used, method used, and researcher biases (where “biases” is not a judgement call, it is related to small, unconscious idiosyncrasies that affect how one implements a technique). Data-wise, using a shadow method, laser-based topography, stereo-based topography, or photoclino metric-based topography will all yield different results due to different biases in how each technique returns a depth measurement [3]. Measurement-wise, there are a myriad of different techniques and exact definitions for crater “depth” that all affect the final measurement [3].

For example, one might choose to take a simple profile through topography data along a North-South direction, measuring the peak elevation as the rim and the minimum elevation as the floor. Alternatively, one might measure all locally high points along a rim, the single deepest position in a crater floor, and take an average of the rim points to represent the rim height. Or a maximum. Or an upper quartile. All of these different methods, coupled with individual researcher bias, will return different values for the crater depth, and this type of variability was studied and reported in [3].

With that context, this work focuses on using Pluto and Charon topography data, generated through stero grammometry, as a case study to examine the depths of the visibly best preserved craters on both bodies. We use a few different methods to calculate crater depth and will report on both the variations as well as the results, and place them into context with other work done for other solar system bodies.

Methods: We are in the process of gathering data at this stage, so we report here on the methods we are planning to use in order to understand the variation in crater depth based on those different definitions. To begin with, crater diameter measurement is consistent: We are using best-fit circles based on tracing the crater rims on publicly available mosaics of Pluto and Charon. The rim points are identified visually, recorded in decimal degrees, converted to kilometers from the center using Great Circles, and fit using several different methods that then vote on the most consistent parameters [4].

For crater depth, we are also using the publicly released maps (for shadow length measurements) and publicly released digital terrain models that were generated from stero grammometry [5,6]. We are using the following definitions/methods for measuring crater depth, all of which are described in the review paper by [3]:

- Free Shadowfront [7], as modified by [8] to allow for off-nadir pointing. (Technique only works for simple, bowl-shaped craters.)
- 8 chords drawn from the crater center through the rim, spaced in 45° azimuths starting from the crater center and going due north. Using the maximum minus minimum.
- Extracting all topographic data for the crater and azimuthally collapsing into a merged profile. From this, using different metrics and comparing them to yield floor depths and rim heights. For the floor, this includes: absolute minimum, lowest 10%, searching a histogram for a minimum depth plateau. For the rim, this includes: absolute maximum, highest 10%, average of rim profile, upper quartile of the rim profile.
Work by [3] using most of these methods with laser data for the pristine lunar crater Linné demonstrated a depth range that varied by ±6.6%, which led to a depth-vs-diameter variation of ≈±4.5% from the mean. We expect that this work will yield significantly more variation because of the coarser nature of the data and inclusion of craters which are unlikely to be as well preserved as Linné.

Additionally, the most common method of reporting depth-vs-diameter results is by fitting a power-law through the data. Even that fitting can yield biases and different results based on how the fit is done. The most robust method recommended in [3] is a Deming fit [9], which uses a maximum likelihood approach and can incorporate uncertainty in both crater diameter and crater depth.

But, the data fed into this are also subject to variation: How are the craters selected that will be fit to yield a crater depth-vs-diameter relationship? The 2018 review [3] found practically no standard within the crater community, so we plan to explore a few different techniques. The input data themselves will be for the visibly best preserved craters – those craters that appear to have retained some form of ejecta blanket, have raised rims, and minimum visible infill material. From those, different researchers tend to select either all craters in their sample, or progressively skim the deepest craters, be it the deepest 50%, 10%, 5%, or some other metric. Again, we will explore different values here in order to examine the variation and possibly try to arrive at a statistically meaningful result that does not appear to be arbitrary.

**Preliminary Work:** The first two authors of this abstract have generated preliminary measurements for several dozen craters on Pluto, and the first author has done so for Charon, as well. The method used by the first author for their measurements was an average of the deepest 50% of the crater floor, and an average of the highest 50% of the crater rim. In contrast, the method used by the second author for their measurements was maximum/minimum from chords. The results already vary considerably, with the first author’s data yielding craters approximately 2× deeper than the second; however, when properly propagating uncertainties through the analysis, a fit for each dataset are within ~1σ of each other due to relatively large scatter in both samples. Similarly, the depth-based transition diameter between simple crater and complex crater morphologies varied by a factor of 50% between the first and second authors, depending on both the depth data and the fitting method to those data.

**Future Work:** We are actively working on gathering data as described above, and will report on our results at the meeting in July. These results will also be placed into context with other data throughout the solar system and where Pluto and Charon fit in relation to other bodies.

**References:**

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DWARF PLANETS ARE PLANETS, TOO: PLANETARY PEDAGOGY AFTER NEW HORIZONS:  K. D. Runyon1, P. T. Metzger2, S. A. Stern3 J. Bell4, 1Johns Hopkins APL, Laurel, MD, USA (kirby.runyon@jhuapl.edu). 2University of Central Florida, Orlando, FL, USA. 3Southwest Research Institute, Boulder, CO, USA. School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA.

Introduction: The last two decades have seen a shift in how scientists and the public understand the organization of the Solar System. The discovery of KBOs of comparable size to Pluto, beginning with Eris (erroneously thought at the time to be larger than Pluto) [1,2, 3], have revolutionized our understanding of the size distribution of round worlds. With more than 120 dwarf planets discovered since the early-2000s [4], a paradigm shift is needed regarding how students are taught the organization of the Solar System: it is no longer sufficient to teach students the names of nine (eight) planets’ named after pagan gods and assume that any meaningful science education has occurred. We believe the International Astronomical Union (IAU) has done damage to the public understanding of solar system science with their 2006 vote on the definition of planets [5], which explicitly excludes dwarf planets as a planet category [6]. Taxonomical science is not legitimately advanced by democratic voting, but set by the precedent of a word’s usage. We summarize events since 2006 which counter the IAU’s action and suggest a new paradigm for solar system education to young students.

Geophysical Planet Definition: As proposed by Runyon et al. (2017) and Runyon and Stern (2018), the geophysical planet definition (GPD) states that a planet is 1) Round by self-gravity; 2) Has never undergone nuclear fusion; and 3) Matches the above criteria regardless of its orbit.

This definition classifies all dwarf planets and the solar system’s 19 known round satellites as planets. Furthermore, this broad and inclusive definition highlights the diversity of planets and the many subcategories, which include 1) Terrestrial planets; 2) Giant planets (Gas giant planets and Ice giant planets); 3) Dwarf planets (Kuiper belt planets and one asteroid belt planet); 4) Satellite planets. This planetary categorization is implicit in the peer reviewed literature, is common in professional verbal usage, and is based on precedent rather than voting, unlike the IAU’s planet definition [5,6]. Further, just as there is no formal lower-size cut-off for giant planets, we simply suggest that dwarf planets be defined as being smaller than Mercury, rather than whether they have “cleared their orbits,” as the IAU suggests as the main dwarf planet criterion [5,6].

Anachronistic Reclassification of Asteroids as Non-Planets: Metzger et al. [7] demonstrated through a thorough literature review that asteroids were considered a class of planet until the 1950s, despite their numbering in the thousands and their mutual orbit-sharing. The change was heralded by the realization that different formation processes resulted in asteroids being geophysically distinct from larger planets. This is at odds with the supposedly historically-precedented IAU planet criterion that a planet must have cleared its orbit [6], or, informally, be otherwise gravitationally dominant [5].

Ignoring the IAU: (Il)legitimacy of Voting: The peer reviewed literature is replete with examples (at least 129) of professional planetary scientists implicitly use the GPD—not the IAU definition—when referring to round worlds. In such papers, authors commonly substitute the word “planet” for the body’s proper name. We have found examples applying to Pluto, Titan, Europa, Earth’s Moon, Ganymede, Ceres, Triton, Io, and other dwarf and satellite planets dating from both before and after the IAU’s 2006 planet definition vote. This precedent amounts to ignoring the IAU and the orbital dynamics criterion. This professional precedent of using a liberal planet definition in the peer-reviewed literature is one that space-interested members of the general public and students should feel free to use. The taxonomical voting of the IAU [5,6] is thus undermined in its legitimacy and no action by the IAU is needed.


In our experience, a very common conversation will go something like the following: “I’m a planetary scientist, and I explore lots of worlds in the solar system, including Pluto.” “Is Pluto a planet again?” “Well, I consider Pluto a planet, along with more than 120 other similarly-sized planets in the solar system.” “Good! I like keeping Pluto as a planet.” The good-will engendered by such exchanges is consistent with the public sentiment and human intuition that small, round worlds, even as small as Pluto, should be categorized as planets. The broad diversity the GPD categorization implies, such as from tiny satellite planets like Enceladus, small...
terrestrial planets such as Mercury, to gas giant planets like Saturn, teach us the fascinating complexity and diversity of nature. This parallels stellar diversity between, e.g., red dwarf stars and blue supergiant stars—both are stars, but differ by multiple orders of magnitude in size, mass, and lifetime.

**Planetary Pedagogy for Teachers and Parents:**
Our impression is that many children’s books and curricula blithely teach a seemingly small, simple solar system composed of the Sun and eight or nine planets. Then, a few facts about each planet (only eight or nine planets) are presented. As a new pedagogical framework, we suggest that students learn three zones of the Solar System, with different types of planets in each zone with different bulk compositions. This stands in contrast to teaching a long list of planet names. This new paradigm is analogous to the teaching of the periodic table of the elements: rather than memorizing a list of names, the natural organizational structure should be emphasized (Figure 1).

**Zone 1: The Inner Solar System:** Terrestrial planets with metallic cores formed close to the Sun in the warm inner solar system. Mercury, Venus, Earth, the Moon, Mars, and Ceres are terrestrial, satellite, and dwarf planets in the inner solar system.

**Zone 2: The Middle Solar System:** Giant planets with massive gaseous envelopes with rocky/metallic cores swept up large amounts of material during planetary formation. All are orbited by often multiple satellite planets, each of which has significant water and other ices on their surfaces, indicative of the cold conditions at these solar distances. The middle solar system giant and satellite planets are Jupiter (Io, Europa, Ganymede, Callisto), Saturn (Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Iapetus), Uranus (Miranda, Ariel, Umbriel, Titania, Oberon), and Neptune (Triton).

**Zone 3: The Outer Solar System:** At distances greater than 30 AU from the Sun, even “supervolatiles” are often frozen as ices, sometimes in vapor pressure equilibrium with tenuous atmospheres. While there are over 120 dwarf planets in the 3rd zone, the 10 largest are Pluto, Eris, Makemake, 2007 OR10, Haumea, Charon (also a satellite planet with Pluto), Quaoar, Sedna, Orcus, and 2002 MS4 [4]. Notably, Pluto and Charon form the only double planet in the solar system because the system’s barycenter is between both planets. This organizational structure highlights the great planetary diversity within a unified framework showcasing the processes of planetary formation and solar system evolution. Curricula and textbooks should reflect this.

**Conclusion:** The memorable phrase, “Ignore the IAU; dwarf planets are planets, too,” captures the sentiment presented here and is justified from geophysical arguments and from the long precedent set in the professional literature. Teaching the zones and the diversity of the types of planets to students and the general public will better serve planetary science education, aligning what is taught to what is practiced by planetary scientists.

**Figure 1.** Teaching the zones of the solar system with the diversity of the types of planets in each zone will give students and members of the public a clearer picture of the natural organization and processes found in nature rather than memorizing eight or nine planet’s names.

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Introduction: New Horizons revealed surprising geologic diversity across the surface of Pluto (Stern et al., 2015; Moore et al., 2016). Pluto’s terrains range from young regions with few-to-no craters to ancient more heavily cratered areas (Robbins et al., 2017; Singer et al., 2019) (Fig. 1). Erosion and resurfacing of various forms plays a strong role in the appearance of craters on Pluto. There are few ejecta blankets visible across Pluto and few craters that look very fresh. One form of crater modification occurs by sublimation and re-deposition of volatile ices (N₂, CO, CH₄) across Pluto on seasonal cycles or million year obliquity/precession cycles (Earle and Binzel, 2015; Grundy et al., 2016). This both erodes terrains and the craters on them and creates deposits or mantles of various thicknesses across Pluto (Moore et al., 2016; Moore et al., 2017). On Pluto, nitrogen ice flows like a terrestrial glacier, and extant glaciers are observed emanating from the highlands to the east of Sputnik Planitia onto the plain itself (Moore et al., 2016; Howard et al., 2017). Past glacial erosion is also likely responsible for some of the landforms and degraded terrains observed on Pluto today (Howard et al., 2017; White et al., 2017). Craters also reveal underlying subsurface structure (layering of dark and bright material) in some areas.

Crater sizes and morphologies: The basin underlying Sputnik Planitia, Sputnik basin, is likely the largest impact feature identified to date on Pluto. It’s dimensions are ~1300 by 900 km, and the mountain blocks found within it along the western side may be related to an interior ring (McKinnon et al., 2017). The surface around Sputnik basin is raised up to 1 km compared with Pluto overall and is consistent with an ejecta blanket (Schenk et al., 2018). At ~250 km in diameter, Burney basin is the next largest impact feature and also shows a complex interior with one or more rings. Central morphologies including peaks, lumps are observed, and one possible central pit crater has been identified. Initial crater depth measurements (Schenk et al., 2018b) indicate that fresh unmodified craters on both Charon and Pluto are consistent with g⁻¹ scaling of both complex crater depths and transition diameters (Fig. 2).

Size-frequency Distributions: Craters on Pluto show the same distinct downturn in size-frequency distribution (SFD) power-law slope that is seen on Charon for craters smaller than ~10-15 km (Fig. 3). For larger craters (D > 15 km) the differential slope has an average value of approximately -3. For smaller craters (D > 10 km) the distributions all have a shallow differential slope less than approximately -2. Because this slope break appears on all Pluto terrains and also on Charon in approximately the same location
(noting that Charon does not have an atmosphere and does not show the same crater modification as on Pluto), this slope break is thought to be a characteristic of the impactor population and geologic processes on Pluto create an additional effect (Singer et al., 2019). The slope break location and the slope for the smaller craters varies with terrain on Pluto, showing the influence of the different dominant geologic actions on each terrain. For example, the shallowest slope on Pluto is found in the northern terrains where mantling from atmospheric deposition is strongly apparent.

Figure 2. Depth/diameter plot comparing unmodified crater depths on Pluto (large dots) and Charon (large squares) to those on Ganymede (best-fit line) and Dione and Tethys (small points) [from 12].

Terrain ages: The crater populations have been compared to models of the impact flux over time onto Pluto (Greenstreet et al., 2015; Greenstreet et al., 2016; Singer et al., 2019). The existing model outputs are relevant to the larger craters on Pluto ($D > 10$ km) because the additional break in SFD slope (for $D < 10$ km craters) was not known until after the New Horizons flyby. Similar to the results for Charon (Singer et al., 2019), the more heavily cratered terrains on Pluto are estimated to be quite old, 4 Ga or older. The eroded highlands of Eastern Tombaugh Regio are the one region that could interpreted as “middle-aged”, having a few larger but heavily eroded craters still visible. There are also several different terrain types on Pluto with few-to-no obvious craters of any size (e.g., Sputnik Planitia and the area around Wright and Piccard Montes). These terrains are more difficult to date with the small number statistics but we will present updated impact flux models (with an additional slope break included) and estimates for ages of middle-aged and younger terrains at the meeting.

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As we look back four years since New Horizons captivated the world with its revelations of Pluto, we also celebrate the 50th anniversary of humankind’s first steps on the Moon and the 89th anniversary of Clyde Tombaugh’s discovery of Pluto. Such reflections offer the opportunity to review successes and lessons learned from the past while planning for the future.

The Apollo Moon landings, for instance, offers a classic example of sequential, multi-stage exploration of the Moon, including naked eye observations, telescopic observations, flyby missions, orbiting missions, unmanned landers, and manned landers. The earliest of these observations involved ancient sky watchers simply looking up and noticing differences in the Moon’s shading, a handful of large surface features, and its orbital motion. By the 1600’s many of the craters, rilles, and other diminutive surface features could be seen thanks to the advent of the telescope for celestial viewing. Three and a half centuries later, the United States and Soviet Union began sending a variety of unmanned spacecraft that collectively flew by, orbited, and landed on the Moon. These led up to the manned landings from Apollo 11 in 1969 through Apollo 17 in 1972. Each level of exploration revealed previously unknown characteristics of the Moon. Perhaps most significantly, thanks to the manned missions that saw astronauts collect rocks and return them to Earth, scientists finally determined a highly plausible scenario for the Moon’s formation.

As for Pluto, if we want to really understand and properly characterize its features, we are still in the early stages of exploration. Pluto is not visible to the unaided eye so was not observed until Clyde Tombaugh detected it in 1930. That means scientists have only been able to study it for less than a century, compared to four centuries of lunar studies through telescopes. Some of this disparity is equalized by the fact that technology has advanced so quickly in the 20th century, allowing scientists to speed up the process of learning. Still, for the first several decades after Pluto’s discovery its characteristics remained little-understood. Scientists estimated basic parameters such as its orbit and mass, but physically it remained from our perspective little more than a dot in the sky, a celestial needle in the haystack. The Hubble Space Telescope allowed for the creation of crude albedo maps of Pluto’s surface, but not until the New Horizons flyby and its mesmerizing images and scientific results did scientists really start to get an idea of how dynamic a world it is. Yet, how much of Pluto will we know if the exploration ends there? We may well compare that to our knowledge of the Moon had we never sent orbiters or landers there. If we are to comprehensively characterize Pluto, and, by extension, any other planetary body, we must continue the quest for knowledge with continued multi-stage exploration.

Pluto, Apollo, and the Case for Space Exploration. K.S. Schindler, Lowell Observatory, 1400 W. Mars Hill Rd., Flagstaff, AZ 86001, kevin@lowell.edu.

Pluto System After New Horizons 2019 (LPI Contrib. No. 2133)
Methane stratification on Pluto inferred from New Horizons LEISA data

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Abstract

In this talk we demonstrate that the relative intensity of the CH₄ band depth reflect a stratification of CH₄, either in the CH₄ concentration in N₂-rich ice and/or in the relative abundance between the N₂-rich:CH₄:CO and CH₄-rich ices, depending on the area. The stratification of CH₄ is shown to result from the differential sublimation between N₂ and CH₄ which tends to concentrate CH₄ in N₂ ice grains and, produces a CH₄-rich phase that accumulates on the surface.

1. Introduction

The diurnal, seasonal and astronomical cycles on Pluto trigger sublimation-transport-condensation cycles of the volatile ices (N₂, CH₄, CO) with different amplitudes and time constants at the surface. Evidence of vertical stratification has been put forward by Douté, Schmitt et al. [1] using the spectral shift of the CH₄ bands. Their stratified model also better fitted their high spectral resolution disk integrated observations. This was further confirmed by several authors from spectral analysis and modeling of new observations [2, 3]. In addition to differential sublimation of the surface CH₄:N₂ ices, other processes were proposed to explain such a vertical stratification. For example Grundy and Stansberry proposed a process of solar gardening in which sublimation preferentially remove N₂ from a little below the surface, not exactly at the surface, and thus enrich that layer in CH₄ [4].

Following the Pluto flyby by the New Horizons spacecraft the qualitative distribution of the two major volatile ice phases identified on the surface of Pluto, N₂-rich:CH₄:CO ice and CH₄-rich ice, has been mapped by Schmitt et al. (2017) [5] and the spatial transitions between the predominant zone of these phases have been highlighted. The first quantitative composition map has been derived by Protopapa et al. (2017) [6].

2. The CH₄ maps

Different CH₄ qualitative abundance maps have been obtained from several CH₄ bands (Fig 1). These maps display relatively different spatial distributions, but with regular evolutions at a given location from the weakest to the strongest CH₄ bands (Fig. 2).

In this talk we demonstrate that these band depth changes reflect a stratification of CH₄, either in the CH₄ concentration in N₂-rich ice and/or in the relative abundance between the N₂-rich:CH₄:CO and CH₄-rich ices, depending on the area. For this we use in addition our 'CH₄ state index' that allow to separate between N₂-rich and CH₄-rich phases based on the spectral position of the CH₄ bands and a new N₂ ice distribution map including the area where the N₂ ice band is too weak to be observed directly. These various indicators help to decipher between stratification and grain size effects as large variations have been found across Pluto surface [6].

We will show that several different configurations appear to exist at the surface of Pluto according to the latitude, and that they may be the witness of different stages in the sublimation-condensation cycles or of different timescales. The CH₄ band ratio maps are particularly interesting to map these different configurations (Fig. 3). The stratification of CH₄ is shown to mostly result from the differential sublimation between N₂ and CH₄ which tends to concentrate CH₄ in N₂ ice grains and, according to the phase diagram, produces a CH₄-rich phase that accumulates on the
But other situations may exist where the stratification may be reversed due to CH₄-poor N₂-rich ice condensation. We will discuss the meaning of the different band depth variations seen across the CH₄ bands, for the different types of CH₄ configurations, in terms of relative effects of grain size, methane concentration and vertical stratification.

Figure 3: The map of the 1950 nm / 1700 nm CH₄ band groups evidencing at least 3 major types of CH₄ configurations (north polar regions (pale yellow), mid-northern latitudes (blue) and area surrounding Cthulhu Regio and East of Tombaugh Regio (red-yellow).

3. Summary and Conclusions

The occurrence of the different configurations of vertical CH₄ distribution on Pluto witness different thermal and sublimation history of the ices. The CH₄ concentration and the depth of these stratified terrains could be interesting quantitative indicators of the strength of the sublimation process, as they can be correlated with the nitrogen sublimation fluxes obtained by volatile transport models (Bertrand et al. 2018) [7]. A layered medium radiative transfer modeling of the LEISA spectra will be necessary to confirm these stratifications and to extract this information.

Acknowledgements

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References


**THE LONG-TERM EVOLUTION OF PLUTO’S ATMOSPHERE AND ITS EFFECT ON CHARON’S SURFACE THOLIN FORMATION**

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**Introduction:** After the New Horizons’ flyby observation of the Pluto-Charon system in July 2015, we have a better understanding of these far away objects.\(^1\) Sputnik Planitia (SP) is one of the most important discoveries of this mission, which is located at the northern mid-latitude hemisphere in the antipodal position to Charon and contains a large quantity of ice.

In this work, we use a coupled treatment to compute the long-term evolution of Pluto’s surface temperature and pressure. The time variation of the orbital parameters of Pluto was obtained by N-body integration and modified from the prior numerical results. Based on the energy balance equation, we build a Pluto thermal model with Clausius-Clapeyron equation and thermal conduction when Pluto revolves around the sun in its variable eccentric orbit with special attention to the sublimation process of the nitrogen ice stored in the SP over the past three million years. Furthermore, we also applied DSMC (Direct Simulation Monte Carlo) method to explore the corresponding escape dynamics of Charon’s tholin-like materials which were seasonally transported from Pluto.

**Pluto’s Orbital Cycles Model:** In order to build the long-term thermal model with the orbital evolution of Pluto, we computed the Pluto’s orbital parameters which were modified from \(^2\) to fit the current observational data. The variation of Pluto’s orbital parameters in the past three million years \(^3\) is shown in Figure 1. (a).

On the other hand, Figure 1 (b) illustrates the three unit components, \(x, y, z\) which represent the vector of Pluto’s rotation axis. The reference frame is centered at Pluto’s spring equinox with the \(x\)-axis pointing towards the sun and the \(z\)-axis being vertical to the orbital plane.

**Thermal Model of Nitrogen Ice on Pluto:** According to the New Horizons observations, Pluto’s atmosphere is likely controlled by the seasonal sublimation of the SP’s ice.\(^4\) The Pluto thermal model is derived by a study of Leighton and Murray\(^5\), which first described the sublimation of ice plays an important role in the thermal process of SP. The energy balance equation of surface can be written as:

\[
F_\odot (1-A_\odot) \ r_h^{-2} \ \cos \theta = e \sigma T^4 + Z(T)L(T) + \kappa (\partial T/\partial z)
\]

The first term on the right-hand-side represents the solar insolation on the surface of SP. Where \(F_\odot\) is the solar constant, \(A_\odot\) is the visual geometric albedo, \(r_h\) is the heliocentric distance and \(\theta\) is solar zenith angle. Figure 2 shows the solar flux which Pluto’s and SP’s surface receive in current epoch and Figure 3 shows the mean variation of SP’s solar flux in the past three million years. The right-hand side represent the energy loss and conduction on SP. The first term \(e \sigma T^4\) is the black body emission term. The second term describes the latent heat of sublimation by nitrogen ice on SP. The vapor pressure of nitrogen is controlled by the
average solar insolation and infrared emissivity. It can be derived by \[6\]: 
\[
\log_{10} P = 17.5901 - 435.37/T - 3.88851 \log_{10} T + 0.0063423 T,
\]
where \(P\) is in \(\text{pa}\) and \(T\) is in Kelvin. The surface pressure of Pluto is very close to being in the vapor-pressure equilibrium of nitrogen gas, so the heat change of the nitrogen phase transition is zero in this model. \[7\] The last term is the thermal conduction which can be derived from the 1-D thermal conduction equation \(\rho c (\partial T/\partial t) = \kappa (\partial^2 T/\partial x^2)\) with \(\kappa\) for thermal conductivity, \(\rho\) for density , and \(c\) for specific heat capacity. Thermal inertia, \(I\), is the key parameter to control the thermal conduction with unit \(m^2 K^{-1} s^{-1/2}\): 
\[
I = \sqrt{\rho c \kappa}.
\]

**Pluto-Charon system:** We assume an escape rate of \(5 \times 10^{25}\) molecules/s. The collisions between gas molecules only occur near the exobase of Pluto. Therefore, the gas molecules travel as a vortex-like stream line on the rotational frame. Due to the gravitational effect, there is a higher density region on the trailing side of Charon. The DSMC result also shows 3.6% of escaping \(\text{CH}_4\) molecules will impact with the surface of Charon.

**Figure 4.** An example of Jean’s escape on the upper atmosphere of Pluto.

**Figure 5.** \(\text{CH}_4\) gas distribution and flow line on \(XY\)-plane with an exobase of 2750.

**DSMC in Pluto-Charon System:** Because of the large variation of Pluto’s orbit, the seasonal influence of exobase will be significant. By using a DSMC calculation, we can calculate the gas transport between Pluto and Charon. Figure 4 shows the Jean’s escape on a exobase of 2750 km from the center of Pluto. The motion of gas particle is by the gravitational force of Pluto and Charon.

**Figure 5.** shows the number density distribution of escaping \(\text{CH}_4\) molecules on the rotational frame of Pluto-Charon system.
ROTATION STATES OF PLUTO'S SMALL MOONS AND THE SEARCH FOR SPIN-ORBIT RESONANCES. M. R. Showalter1, S. B. Porter2, A. J. Verbiscer3 M. W. Buie2, and P. Helfenstein4, 1SETI Institute (mshowalter@seti.org), 2Southwest Research Institute, 3U. Virginia, 4Cornell University.

During the New Horizons flyby of Pluto, it was observed that the four small moons, Styx, Nix, Kerberos and Hydra, have very unusual spin states. Whereas we might have expected the moons to be tidally locked, they are in fact all spinning at rates markedly faster than their mean motions. Also, all of the moons’ rotation poles are misaligned with their orbital poles; several moons have obliquities near 90°. It has been speculated that these states may be the result of spin-orbit resonances driven by the large, regular perturbations from the central “binary planet” comprising Pluto and Charon. However, to date, no such resonances have been associated with the moons’ rotations.

We are currently in the second year of a Hubble Space Telescope observing program focused on the photometry and dynamics of the Pluto system. The most recent data set, combined with earlier HST images obtained during 2010–2015, provides a very long baseline for determining the rotation state of each small moon. The analysis, however, is complicated by the presence of marked year-by-year variations in the amplitudes of the light curves. These are the result of polar precession, which causes each moon’s orientation toward the Earth to vary on time scales of a few years.

We will present the initial results of new data analysis and 3-D modeling that enable us to recover the polar precession rate and orientation of each moon. Preliminary results show that these rates are compatible with New Horizons data, but much more precise. We note that the model of high-obliquity moons that are both spinning and precessing explains the photometry better than the earlier hypothesis by Showalter and Hamilton[1] that these moons are in chaotic rotation.

With the new results in hand, we will revisit the question of whether any spin-orbit resonances are active. Because of the large obliquities and polar precession, the standard formulas do not apply. Instead, each resonance is defined by three periods: the rotation period, the polar precession period, and the synodic orbital period with Charon. The resonant spin rates derived from this new formulation are very different what one would expect if polar precession is ignored, as it has been in previous searches for resonances. As a result, the question of whether the unusual rotation states are defined by spin-orbit resonances remains open.


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**STELLAR OCCULTATIONS BY PLUTO: 2017-2018.**

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**Introduction:** Pluto’s atmosphere was first detected in the 1980s, via stellar occultations [1–2]. Given the distance, size, and tenuous nature of the atmosphere, it is not easy to study, and occultations provide one of the best ground-based methods. Additional occultation measurements were made in 2002 and from 2006 onward: notable findings include the discovery of waves in the upper atmosphere [3–4], an increase in atmospheric pressure between 1988 and 2016 (e.g. [5–7]), and an evolution in the shape of the occultation light curves that is suggestive of a changing thermal gradient, possibly combined with extinction-generating events, in the lower atmosphere (e.g. [8–9]). Volatile transport models have been developed to better understand and predict Pluto’s atmospheric evolution (e.g. [10–12]). Some models indicated that Pluto’s atmosphere should collapse over a period of years; however, recent results are consistent with models that have no atmospheric collapse, stemming from high thermal inertia and a permanent, northern ice cap. Further observations, post the New Horizons flyby, are important to continue monitoring Pluto’s atmosphere.

**Observations:** Here, we report results from five stellar occultations by Pluto that were observed in 2017 and 2018. A single chord was observed at each epoch.

**2017 August 07.** This event had a shadow path over the Pacific Ocean. The star was Gaia magnitude $G=15.3$, with relative velocity of 20.8 km s$^{-1}$. Observations were made using NASA’s 3-m Infrared Telescope Facility in Hawai’i. Data were taken as visible-wavelength images at 0.4 Hz with MORIS (MIT Optical Rapid Imaging System [13]) and as low-resolution, near-infrared spectra at 0.33 Hz with SpeX [14].

**2018 April 09.** This event had a shadow path over the western United States. The star was Gaia magnitude $G=17.7$ and had relative velocity of 6.4 km s$^{-1}$. Visible-wavelength images, at 10 Hz, were taken from the 4.3-m Discovery Channel Telescope in Arizona with a POETS (Portable Occultation Eclipse and Transit System [15]).

**2018 August 15.** This event also had a shadow path over the western United States. The star was Gaia magnitude $G=12.9$ and had relative velocity of 19.7 km s$^{-1}$. Visible-wavelength images were taken at 1.67 Hz from the 0.6-m Astronomical Telescope of the Univ. of Stuttgart at Sierra Remote Observatories in California with an Andor iXon camera and at -0.33 Hz with the guide camera on a 1-m telescope of Las Cumbres Observatory (LCO) at McDonald Observatory in Texas.

**2018 October 01.** This event had a shadow path over Africa. The star was Gaia magnitude $G=17.3$ and had relative velocity of 1.5 km s$^{-1}$. Visible-wavelength images were taken from Sutherland, South Africa at 0.4 Hz using the 74-in telescope with SHOC (Sutherland High-speed Optical Camera [16]) and at -0.06 Hz using the guide cameras on the 1- and 0.4-m telescopes of LCO.

**2018 November 01.** This event had a shadow path over southern Africa. The star was Gaia magnitude $G=15.0$ and had relative velocity of 16.0 km s$^{-1}$. Visible-wavelength images, at 3.33 Hz, were taken from the 74-in telescope in Sutherland with SHOC.

**Results:** An atmosphere was detected in all observations. The 2017 data have a steeper slope on immersion and emersion, while the light curves are bowl-shaped by mid-2018. This evolution in light-curve shape indicates a change in the lower-atmosphere temperature profile and/or haze over the relatively short timescale of one year. Initial analyses of the atmospheric size and pressure show that the levels are on the same order as those observed post 2002.

**References:**

Introduction: The flyby of NASA’s New Horizons spacecraft [1] past Pluto on 14 July 2015 yielded robust data sets that permitted geological analysis for more than 50% of its surface. The encounter hemisphere of Pluto was imaged at a pixel scale equal to or better than 890 m/pixel, revealing an unexpectedly diverse range of terrains and implying a complex geological history [2,3]. A digital elevation model constructed for the encounter hemisphere [4] is an essential dataset for assessing the relief and relative elevations of Pluto’s various terrains. The remaining >25% of the imaged surface is the anti-encounter hemisphere, imaged at pixel scales coarser than 2.2 km/pixel, typically allowing only surface features on a scale of tens of kilometers to be discerned for this hemisphere. This presentation reviews the primary processes that are thought to drive Pluto’s geology, and constructs a narrative of its geological history.

The Source of Pluto’s Geological Diversity: Pluto’s geological provinces are often highly distinct, and can exhibit disparate crater spatial densities [3,5,6]. Pluto’s geology displays evidence for having been affected by both endogenic and exogenic energy sources (including internal heating and insolation/climatic effects). The geology’s complex nature is caused by combinations of these influences governing the distribution and behavior of different surface compositional suites to strongly varying degrees across even small lateral distances. Most surprisingly, large-scale surface renewal in response to internal heating is ongoing through the present day, as demonstrated compellingly by the sprawling, convecting N2 ice plains of Sputnik Planitia [7-11]. This landform, which dominates the encounter hemisphere, has likely been one of the most influential features on Pluto’s geological and atmospheric evolution for much of its history. Sputnik Planitia has been the subject of investigation on its role in Pluto’s tectonism and polar orientation [12-15]. At both global and local scales, mobilization and transport of volatiles across Pluto on geological timescales appear to have played a prominent role in determining the appearance and distribution of Pluto’s highly varied landscapes, as shown by climate modeling [16-24]. Mapping and landform evolution modeling studies have sought to decipher the nature and origins of individual terrain types on Pluto, which frequently reveal the importance of N2 ice glaciation and surface-atmosphere interactions throughout Pluto’s history [3,4,25-33]. Aside from features influenced by the atmosphere, Wright and Piccard Montes may represent cryovolcanic edifices and if so they may yield information about Pluto’s thermal history [3,34].

Pluto’s Geological History: The N2 ice of Sputnik Planitia is mostly contained within an elongate depression measuring 1200 by 2000 km wide [4], interpreted to be an impact basin that likely dates to >4 Ga [3]. This basin represents a powerful cold trap for volatiles [15], and modeling of volatile behavior in response to topography has shown that infilling of the basin with all available surface N2 ice would be complete by tens of millions of years after its formation [23], meaning that Sputnik Planitia has existed on Pluto’s surface for the majority of its history, and has undergone continual resurfacing via convection, glacial flow, and sublimation/recondensation since its formation. Uplands to the north and west of Sputnik Planitia have been erosional-ly sculpted into a variety of dissected terrains with dendritic valley networks, interpreted to have been carved by the flow of glacial N2 ice [30], and the infilling of Sputnik Planitia would have been accompanied by recession of N2 ice glaciation from these areas, with profound geological consequences. The washboard and fluted terrain on the northern rim of Sputnik Planitia is interpreted to be refractory debris entrained in the glacial N2 ice that was deposited on the landscape after its recession [25]. The northwestern rim of Sputnik Planitia appears to be a convergence zone of two large-scale fracture systems, including a complex, eroded, north-south-oriented ridge-trough system ~300-400 km wide and extending >3200 km long (and which may pre-date the Sputnik basin) [4], and the younger, more sharply-defined, segmented grabens informally named Inanna, Dumuzi, and Virgil Fossae. The blocky mountain ranges that line Sputnik Planitia’s western edge are interpreted to have formed via glacial N2 ice receding from the uplands intruding this tectonically fractured and brecciated H2O ice crust, with crustal fragments breaking form tilted blocks that are now grounded in the denser N2 ice of Sputnik Planitia [30].
eccentric seasons and climate zones [18-20], a consequence of its high obliquity that varies between 103° and 127° on a 2.76 million year cycle [35]. The sequence of dark maculae that extend along Pluto’s equatorial regions exist within Pluto’s permanent diurnal zone, and experience the “mildest” climate of any region on Pluto. The low albedo is interpreted to be caused by atmospheric deposition of complex molecules called tholins upon the landscape [22]. The maculae have not been affected by geological processes, in particular seasonal mobilization of volatile ices [20], that would disrupt the continuous mantle of tholins since their deposition, and therefore are likely amongst the oldest landscapes on Pluto. The informally named Cthulhu Macula, the largest of the maculae, includes regions that display very high densities of large and relatively unmodified craters [3,5,6], another testament to the great age of these landscapes. The tholin mantle becomes discontinuous and then dissipates completely north of 37°N, the northern boundary of the diurnal zone oscillation range. This north polar zone always experiences arctic seasons, with up to century-long summers and winters during each orbit, and so should experience pronounced volatile cycling in response to the extreme temperature variations across a Plutonian year, yielding younger surface ages than for the non-Sputnik permanent diurnal zone. Evidence for volatile mobilization outside the permanent diurnal zone includes the informally named Piri Rupes, interpreted to be a recessional scarp where a volatile surface layer has sublimated above a refractory substrate [3], and the mantled uplands northeast of Sputnik Planitia, which appear to be covered by smooth-surfaced deposits that may be derived from slow atmospheric vapor condensation, and some of which have been modified by sublimation pitting [31].

The bladed terrain of Tartarus Dorsa east of Sputnik Planitia is amongst the highest elevation terrain on Pluto and consists of rounded, elongate swells reaching hundreds of kilometers long, the surfaces of which show a rippled texture of narrow, aligned, linear ridges separated by a few kilometers and reaching hundreds of meters high. The terrain is interpreted to be a massive deposit of CH₄ ice that preferentially precipitated at low latitude and high elevation early in Pluto’s history, with subsequent excursions in Pluto’s climate partially eroding the deposits via sublimation into the present blades [28]. No unambiguously recognizable craters appear on the bladed terrain, indicating that the processes creating the blades must be ongoing into the relatively recent past. The western portions of the bladed terrain transition to the bright, pitted uplands of east Tombaugh Regio, which are presently experiencing deposition of N₂ ice fed by sublimation from Sputnik Planitia [30], with the N₂ ice subsequently reentering Sputnik Planitia via sublimation. These uplands may therefore represent a glacially modified portion of the bladed terrain [28].

South of Sputnik Planitia, the twin edifices of Wright and Piccard Montes reach >150 km in diameter and >4 km high, with large central depressions reaching tens of km across, and which are deeper than the edifices are high. Tentatively interpreted as cryovolcanic in origin [3,34], these structures exhibit very few superposed craters, and so potentially represent evidence for endogenic heating having been sufficient to facilitate the eruption of cryolavas onto Pluto’s surface relatively late in its history (possibly ~1 Ga or later).

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Introduction: Chaos terrain is formed by disruption of preexisting surfaces into irregularly shaped blocks with a “chaotic” appearance [e.g., 1-3]. This typically occurs through fracturing and can be induced by a variety of processes. The subsequent evolution of these blocks after fractures form can follow several paths. If the blocks are completely destabilized and free from the surface below they may rotate, translate, or potentially even float in a liquid or solid with sufficient density contrast [2,3]. Alternatively, the blocks may remain in place and the fractures around them may be deepened over time by erosion [4]. These distinctive areas of broken terrains are most notably found on Jupiter’s moon Europa, Mars, and Pluto.

Several models for chaos formation have been proposed, and comparing across bodies may yield extra constraints on the formation and evolution of this enigmatic terrain type [e.g., 1,2,4,5]. This work focuses on providing a morphological comparison of the blocks that make up chaoses on Pluto, Europa, and Mars by measuring block diameters, heights, and axial ratios. In addition, we also provide a comparison between martian chaos blocks near Xanthe Terra and fretted terrain blocks in the Ismenius Lacus Quadrangle.

Mapping Method: Chaos terrain blocks were mapped on Pluto across mountain ranges extending from the NW to SW extent of the Sputnik Planitia (SP) using New Horizons ~315 m px⁻¹ base mosaics and a 240 m px⁻¹ stereo digital elevation model (DEM). Images from the Galileo mission’s regional mapping campaign (East and West RegMaps) were used to map chaos blocks across regions on Europa, using 210-220 m px⁻¹ base mosaics and DEMs [6], and 180 m px⁻¹ base mosaics and DEM for Conamara. Base mosaics from the THEMIS (global daytime daytime IR) instrument on Mars Odyssey at 100 m px⁻¹, and a 200 m px⁻¹ global DEM product from the MOLA instrument on Mars Global Surveyor were used to map blocks across all regions studied on Mars.

Chaos terrain blocks were mapped in ArcGIS using polygons to outline the perimeter of each block along their apparent base, using visual and topographic mapping. A general visual diameter cutoff was assigned to improve accuracy of measurements due to resolution constrains (see Figs. 2-4 for respective cutoffs). The apparent height of each block was determined by subtracting the average base elevation of the perimeter of the polygon from the highest elevation point within each polygon. To derive a measure of the mountain block size (diameter) we used the geodesic area of the feature to calculate an equivalent circular diameter. The axial ratio of each block was derived by creating a rectangle of the smallest area enclosing the block.

Results and Observations: The size vs. height distribution of blocks mapped across all regions of study are presented in Figs. 1,2,3,4.

Figure 1. Size-height distribution of measured blocks across all regions studied. Pluto and Mars blocks exhibit a positive linear relationship, whereas blocks on Europa generally show a “flat” trend. Mars fretted blocks display a wider diameter range compared to chaos, and lower heights for larger blocks.

Figure 2. Pluto. Blocks in Tenzing Montes generally appear taller for the same effective diameter compared to other regions, which matches their “spiky” visual appearance. Some blocks in Tenzing Montes are tilted to varying degrees (~5-10°). Tilting alone may not be responsible for taller blocks, as tilted blocks are found throughout all regions.
Implications for Crustal Lithology:
The size and height distributions of chaotic mountain blocks could provide information about the lithologic structure of the crust. If the blocks are all the same height or reach a maximum height and level out (i.e., cease to increase in height with increasing diameter), then this could yield information about the layer thickness of the fractured unit. The block heights in Conamara have been previously used by [7] to estimate a 0.2-3 km thickness of the icy lithosphere assuming the blocks were floating and reached an isostatic level. The same analysis as [7] using our typical untilted block heights on Europa (Fig. 3) of ~0.1-to-0.2 km and less extreme compositions [6] leads to ice shell thickness predictions of ~1-to-4 km, and up to ~5-to-9 km for the taller blocks (~0.5 km) in the West RegMap.

On Pluto, it is possible the chaotic blocks could have been partially or fully floating icebergs in the nitrogen ice sheet of SP, which would assist with destabilization or breakup/tilting [8-9]. Pure water ice and nitrogen ice may have a density contrast of >5% at Pluto’s surface temperatures, however other components are likely present as well (e.g., CH₄, CO, tholins; [e.g., 10-13]). However, the distribution in Fig. 2 does not match what is expected of floating blocks. It is possible that the very largest blocks on Pluto may be reaching a maximum height of ~4 km, but there are insufficient data points to infer if this could be indicative of layer thickness. Additionally, using the same calculations as [7] to calculate the minimum root depth required for SP blocks to be floating in isostacy yields a minimum root depth of >50 km. Unless the blocks are much less dense than H₂O ice it is unlikely that the blocks are floating at the present time, as SP is estimated to be ~7-9 km deep [14,15] and is likely more shallow near the edges (assuming an impact origin of SP).

For Mars a different process could lead to an estimate of layer thickness. The competence of lithologic layers could influence the maximum height of blocks, as different layers are more resistant to erosional or deformational processes such as erosional downcutting, faulting and fracturing. The “surface tops” of martian blocks commonly matches the same high elevation as the surrounding plateau [2], and the maximum height of blocks in a region could be used to infer the relative layer thickness of a lithologic layer because erosional processes could have carved the weaker surface layers down to a more resistant layer. In certain regions blocks generally do not exceed above 1-1.5 km in height, compared to blocks in other regions reaching up to ~2 km in height (Fig. 4). Regional variation in the maximum height of blocks could be the result of e.g., subsidence [2], spatial variability in the competence of lithologic layers and/or differential exposure to erosional processes over time.

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BEYOND PLUTO: THE NEW HORIZONS ENCOUNTER WITH KUIPER BELT OBJECT 2014 MU69.
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Introduction: At 05:33:22 UT on January 1st 2019, the New Horizons spacecraft passed 3538 km from Kuiper Belt object (KBO) 2014 MU₆⁹, nicknamed “Ultima Thule”, giving us our first close-up look at a small KBO [1] and fulfilling the 2003 Decadal Survey’s recommendation [2] that mission to Pluto should also include an exploration of the broader Kuiper Belt of which Pluto is a part. New Horizons data on MU₆⁹ achieved a best resolution of 33 m/pixel for panchromatic images (though effective resolution was lower due to smear and low SNR), 330 m/pixel for color images, and 1.8 km/pixel for near-IR spectroscopy. Extensive UV, microwave thermal emission, plasma, dust, and satellite and ring search data were also obtained.

Context: MU₆⁹ was discovered by the Hubble Space Telescope in June 2014, as part of a 4-year intensive search for New Horizons flyby targets beyond Pluto [3]. Based on its semi-major axis (a = 44.2 AU), low orbital eccentricity (e = 0.038), and low inclination (i = 2.4°), and its albedo and color (below), MU₆⁹ is almost certainly a member of the dynamically cold, non-resonant “cold classical” population of Kuiper Belt objects (CCKBOs), and probably a member of the tightest orbital clustering of CCKBOs known as the “kernel” [4]. Because there is no known mechanism for producing this cold orbital distribution after the dispersal of the protoplanetary nebula, and because of the low temperatures and low impact rates [5] in the Kuiper Belt, CCKBOs are thought to be the most dynamically and physically primitive known population of small bodies in the solar system.

Global Appearance: MU₆⁹ is a contact binary, composed of two sharply distinct components which make contact at a bright, narrow, “neck” (Figure 1). The largest component is nicknamed “Ultima”, and the smaller one “Thule”. Both are flattened, with their smallest axes aligned, and their contact point is close to the longest axis of both bodies. This configuration strongly suggests that the two components formed independently, and orbited each other in a tidally-locked configuration before coming gently together. The current rotation period of 15.92 hours is slow enough that for reasonable densities, the two bodies must have lost significant angular momentum after contacting each other.

The rotational pole was oriented only 29 degrees from the sun and 39 degrees from New Horizon’s approach direction during the encounter, so only a little over one hemisphere was visible to the spacecraft during the flyby.

On both components, the surface is generally smooth, though pits are seen near the terminator, and bright spots away from the terminator may also be bright-floored pits. These features have a shallow size/frequency distribution similar to that of small craters in the Pluto system, and, if impact-generated, indicate a surface age of at least 4 Ga.

Ultima: Ultima is highly flattened, with approximate dimensions 20.6 x 19.9 x 9.4 km: the shortest dimension is the least certain. It appears to be divided into half a dozen similar-sized sub-units, distinguished by surface texture and/or separated by linear scarps or bright linear albedo features (Fig. 1). Dark features that appear to be low hills and ridges are unevenly distributed across the surface. The sub-units may provide evidence for assembly of Ultima from smaller bodies, though the continuity of some surface texture units across some of the bounding linear features argues for some of the unit boundaries being relatively young rather than primordial.

Thule: Thule is closer to spherical than Ultima, with approximate dimensions 15.4 x 13.8 x 9.8 km (again, the shortest dimension is the least certain), and is markedly different in appearance (Fig. 1). It is dominated by a large depression, nicknamed “Maryland”, 7 km in diameter and 0.5 – 1.0 km deep, which is likely to be an impact feature. The rest of the surface is characterized by bright and dark albedo markings that often have strikingly sinuous boundaries, possibly due to sublimation erosion of variable-albedo thin surface layers.

Color and Composition: Color images reveal a red surface very consistent with typical colors of Cold Classical KBOs for both components. The bright neck, and one other surface unit on Ultima that is otherwise similar to neighboring regions, are slightly less red. In the near-IR, both components show a similar spectrum with a flat continuum, a weak signature of H₂O, and a 2.3 µm band tentatively ascribed to methanol (CH₃OH). The visible/NIR spectrum is similar to the former KBO Pholus [6], though MU₆⁹ is less red in the visible.

Limits on Satellites, Rings, and Outgassing: No satellites or rings were discovered during the flyby. At the time of writing, satellite searches excluded
satellites > 150 meters diameter to radii of ~3,000 km, and > 3 km diameter out to the Hill sphere radius of ~40,000 km, assuming photometric properties comparable to MU69 itself. Rings with I/F > 2 x 10^-7 in backscattered light and > 10^-6 in forward-scattered light, i.e. fainter than Jupiter’s main ring, were also excluded. No UV emission or absorption from molecular or atomic species, and no disturbance to the solar wind, was seen during the flyby, consistent with expectations for an object that has occupied a stable orbit for > 4 Ga.

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Figure 1. Cross-eyed stereo pair image of 2014 MU₆₉, taken by the New Horizons Long-Range Reconnaissance Imager (LORRI). The “Ultima” component is at the top and the “Thule” component is at the bottom. Left image: Range = 27,860 km, phase = 12.9°, 138 m/pixel. Right image: Range = 6,650 km, phase = 32.5°, 33 m/pixel.
**Introduction:** *Exploring the Planets* (http://explanet.info) [1] is a free online college textbook covering the basic concepts of planetary science, and the character and evolution of the planetary bodies in the Solar System (including the planets, important moons, asteroids, and Kuiper Belt Objects). The latest edition (3rd edition) was published online in 2007 by Eric H Christiansen. Earlier paper editions were published by Prentice Hall in 1990 and 1995.

*Exploring the Planets* approaches an introductory study of the solar system mainly through basic geological principles. Compared with other introductory planetary geology texts, such as *Planetary Sciences* by de Pater and Lissauer [2], *Introduction to Planetary Science* by Faure and Mensing [3], *The New Solar System* by Beatty, Petersen, and Chaikin [4] or *Earth, Evolution of a Habitable World* by Lunine [5], this is the only book with a basic geology approach. It is intended to be used as a primary or supplementary source in introductory science courses (geology or astronomy).

The MS thesis project of the lead author was to update the section for Pluto using all the new data from New Horizons. We describe the main sections included and the reasons for focusing on those for the intended audience.

**Significance:** The modern results based on recent investigations of Pluto are critical for our understanding of the nature and history of this body, icy bodies, and the Solar System as a whole. Pluto is an end member in a spectrum of planetary objects in the Solar System. Pluto is cold, icy, distant from the sun, and a representative object of the vast Kuiper Belt, and is unlike the terrestrial bodies of the inner Solar System. This body refines models of how icy planets evolve over time, and how our Solar System has evolved.

For these reasons, it is important to update *Exploring the Planets* to summarize the current understanding of the geology of Pluto. This way, students can better understand the formation and evolution of small icy bodies and the implications for the evolution of our Solar System.

**Objectives:** We completed our main objective of producing a pedagogically and scientifically sound chapter for *Exploring the Planets*, on Pluto. The chapter is comprehensive in scope, accurate, and easy to understand, and contains helpful figures and animations to facilitate learning. Instructors and students will be able to use this book as a resource in introductory college courses for non-science majors. The next edition of *Exploring the Planets* will be freely available at explanet.info. Anyone who desires to learn more about the planets of the Solar System will find this book helpful.

![Figure 1. Pluto as imaged by New Horizons at its closest approach in July of 2015. (A) A semi-true color image of Pluto, similar to what the naked eye would see. (B) A color enhanced image reveals a geologically diverse planet that has undergone many geologic processes, with some still continuing today. Perhaps the most spectacular part of the image is Sputnik Planitia, a basin filled with a large ice sheet at the heart of Pluto. This image shows the location of the areas that are discussed in the chapter. (NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute).](image)

**Methods:** In order to produce instructive chapters about Pluto, we used effective pedagogical principles of transfer [7], cognitive learning [8], and cognitive apprenticeship [9] to organize, construct figures, and write text. We implemented these principles to help students recall previous information, present new information, guide students in developing critical thinking skills, and elicit and assess performance.

**Chapter Sections:** The Planet Pluto and the Kuiper Belt discusses the physical characteristics of Pluto along with a discussion of the definition of a planet, Pluto’s place in the Solar System, and the Kuiper Belt. A section on Pluto’s Spin and Climate follows and describes how the axial tilt of Pluto affects the planets unique climate of long summers and winters, and overall patterns of sublimation and deposition of volatile ices. Pluto’s Ices outlines the major ices and tholins observed on the surface of Pluto and their distributions. The section on the Atmosphere describes the composition of the atmosphere and its relationship to the sublimation of the volatile surface ices. Geological Provinces lays out the major geologic regions of Pluto and the geologic processes that occur in each region. This section includes an extensive discussion about Sputnik Planitia and Tombaugh Regio.
Impact Craters are an important part of any planetary body. The most interesting fact about the craters on Pluto is the lack of them seen on Sputnik Planitia, indicating recent resurfacing of the basin. The only type of Tectonic Features imaged on Pluto were extensional. These grabens and rifts formed by expansion as the water on Pluto froze. Two possible Volcanic Features have been identified on Pluto. These are large mounds with central depressions that reveal that there must be internal planetary heat. Pluto’s Internal Structure is similar to the icy moons of the outer planets, with a rocky core, a liquid water layer, a water-ice mantle, with a surface veneer of volatile ices. There are five Moons of Pluto with most of the information gathered for Charon, the main moon of Pluto. This body is now geologically dead but it has experienced cryovolcanism, extensional tectonics, and tholin deposition. The Geologic Evolution of Pluto (and Charon) is similar to other small icy bodies. It began with accretion of ices and silicates and perhaps a major collision that formed Charon and the other icy moons. Pluto differentiated quickly, with the rocky material sinking to the center of the planet, followed by cooling of Pluto that caused a thickening of the lithosphere and extensional tectonics.

Conclusion: Exploring the Planets is a valuable textbook for explaining basic geological and planetary concepts to college students and so, it is important to keep the textbook updated. To provide a complete up-to-date and free resource on the planets, we have updated the chapter on Pluto by summarizing the new scientific literature on this planet by rewriting the chapters and introducing new images/figures.

**Pluto’s Far Side.** S.A. Stern¹, H.A. Weaver², L.A. Young¹, C.B. Olkin¹, J.M. Moore³, W.M. Grundy⁴, W.B. McKinnon⁵, T.R. Lauer⁶, D.P. Cruikshank³, J.R. Spencer³, G.R. Gladstone⁵, K. Ennico⁵, and the New Horizons Team. ¹Southwest Research Institute, 1050 Walnut St. Suite 300, Boulder, CO 80302 (astern@boulder.swri.edu), ²Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, ³NASA Ames Research Center, Moffett Field, CA 94035, ⁴Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001, ⁵Dept. Earth and Planetary Sciences, Washington University, St. Louis, MO 63130, ⁶National Optical Astronomy Observatory, Box 26732, Tucson, AZ 85762, ⁷Southwest Research Institute, 6220 Culebra Road, San Antonio, TX 78238.

**Introduction:** Owing to the slow, 6.38 day-long rotation of Pluto on its axis, and the New Horizons flyby of the Pluto system at 14 km sec⁻¹, this flyby was only able to study one hemisphere of Pluto at high resolution. As a result, the planet’s “far side” hemisphere was only imaged at much lower resolutions. Nonetheless, many valuable datasets were obtained on Pluto’s far side, greatly extending our knowledge of these portions of Pluto beyond what Earth-based and Earth orbital observatories could achieve. These datasets most notably included Ralph/MVIC and LORRI panchromatic and color imaging measurements over far side terrains; marginally resolved Ralph/LEISA compositional spectroscopy was also obtained.

Images of Pluto obtained by New Horizons during the planet’s final rotation as the spacecraft approached in July 2015. The planet’s far side is seen primarily in the images in the top half of this set of LORRI images.

In this presentation, we will present an overview of New Horizons results on Pluto’s far side and we will compare these results to near side data.

Specifically, this presentation will review shape, albedo, color, composition, atmospheric, and geologic information about the far side hemisphere. The presentation will conclude with a look at how both next-gen large ground-based and space-based telescopes, and a Pluto Orbiter, will benefit studies of the far side over the next few decades.

**Acknowledgements.** This work was funded by NASA through the New Horizons project. We thank the Deep Space Network, JPL, KinetX Aerospace, and the entire present and past New Horizons team for making the flyby of the Pluto system successful.
2014 MU69 in Context. T. Stryk\textsuperscript{1}, J.M. Moore\textsuperscript{2}, J.R. Spencer\textsuperscript{3}, C.B. Olkin\textsuperscript{3}, H.A. Weaver\textsuperscript{4}, S. A. Stern\textsuperscript{3}, and the New Horizons Geology and Geophysics Team. \textsuperscript{1}Roane State Community College, Oak Ridge, Tennessee, United States 37830 (strykt@roanestate.edu), \textsuperscript{2}NASA Ames Research Center, Mountain View, \textsuperscript{3}Southwest Research Institute, Boulder, \textsuperscript{4}Applied Physics Laboratory, Laurel

Introduction: The New Horizons flyby of 2014 MU69 “Ultima Thule” provided a close-up view of a pristine cold-classical binary Kuiper belt object \cite{1}. The goal of this poster is to put the size and shape of 2014 MU69 in context with other trans-Saturnian objects of similar size, the six comet nuclei visited by spacecraft as well as the dozens of other objects of similar size that have been explored by spacecraft in other regions of the solar system.

Context: New Horizons imagery revealed 2014 MU69 to consist of two objects with mean radii of 9.73 and 7.2 km respectively \cite{1}. This makes it comparable in size to Pluto’s small moons and some small moons of Uranus and Neptune (Figure 1). It is thought that it may have similarities to Jupiter family comets prior to entering the inner solar system as well as longer period comets, so a comparison with these objects is certainly in order \cite{2}. And this poster will also put it in context with rocky asteroids with radii under 40 kilometers.

Goals: The addition of the relatively pristine 2014 MU69 “Ultima Thule” to the growing menagerie of small world that have been studied close up gives us import context for both the modified versions of worlds like itself as well as a useful comparison for other worlds in its size range. This poster will illustrate this with the best available imagery.

References:
\cite{1} MacKinnon, W. B.(2019) \textit{LPS L}, Abstract #2767. \cite{2} Weaver, H. A. (2019) \textit{LPS L}, Abstract #2982

Figure 1: All members of the solar system with mean radii less than 4 kilometers for which we have disk resolved imagery shown to scale. Data for Pluto’s moons (Styx, Nix, Kerberos, Hydra) and 2014 MU69 “Ultima Thule” courtesy NASA/SWRI/APL, Data for Naiad (Neptune), Belinda (Uranus), and Cordelia (Uranus) from Voyager 2 courtesy NASA/JPL.
Introduction: The observations obtained by the New Horizons spacecraft flyby of Pluto on July 14, 2015 have provided a watershed for our understanding of the composition of Pluto’s atmosphere [1]. The key observations that provided compositional information during the flyby were the Radio Experiment (REX) instrument, that performed uplink X-band radio occultations, the Alice instrument, that carried out extreme- and far-ultraviolet solar occultations, and the Long Range Reconnaissance Imager (LORRI) and the Multispectral Visible Imaging Camera (MVIC) [2].

These observations, along with chemical and thermal models, have provided a coherent and consistent picture of the vertical distribution of nitrogen and methane, as well as temperature, in Pluto’s atmosphere from the surface to upper atmosphere at nearly ~1500 altitude [3]. In addition, Alice measured ultraviolet absorption due to the minor constituents C2H2, C2H4, C2H6, and HCN from which their abundances have been determined in the lower and middle atmosphere (below ~400 km).

These observations have also revealed a global haze layer extending from the ground to over 500 altitude [4]. The haze distribution is complex, with numerous individual thin haze layers embedded within the background haze. The formation of this haze is intimately tied to the distribution of the condensable species that were detected by Alice, including C2H2, C2H4, C2H6, and HCN [5], as well as the temperature structure. Thus the haze provides indirect information on the distribution of photochemically produced species that complement the Alice measurements.

In this review we will discuss the key observations that have given us this understanding of the compositional structure of Pluto’s lower (< 30 km), middle (30-400 km) and upper (> 400 km) atmosphere, along with the associated compositional measurement uncertainties [2,6]. We will also discuss how the compositional information informs our understanding of chemical, dynamical and thermal processes controlling the chemical structure of the atmosphere. And finally, we will identify important and yet unanswered questions that require new and/or better laboratory measurements and models needed to improve our understanding of Pluto’s atmospheric composition.

ORIGIN OF CHARON’S RED POLES: NEW INSIGHTS FROM EXOSPHERIC MODELING AND SOLID METHANE PHOTOLYSIS. Ben Teolis1,2, Ujjwal Raut1,2, Joshua A. Kammer1, Carly A. Howett3, Kurt D. Rutherford1,2 and G. Randall Gladstone 1,2. 1Southwest Research Institute, San Antonio, TX 78238, ben.teolis@swri.org, 2Department of Physics and Astronomy, University of Texas at San Antonio, TX 78249, 3Southwest Research Institute, Boulder, CO, 80302

Introduction: The stunning color images of Charon captured by the Multispectral Visible Imaging Camera (MVIC) revealed that the northern polar region is tainted with a distinct reddish hue. This color has been attributed to tholin-like refractory material resulting from interplanetary Lyman-α (IPM Ly-α) photolysis of solid methane, which accretes onto Charon’s cold winter polar region following escape from Pluto [4]. This proposition, if confirmed, would constitute a seminal discovery of the New Horizons mission that advances our understanding of the synergism of planet-satellite gas transfer and photolytic processes active in the Pluto-Charon system and the role of these cooperative processes in the origin of the observed red polar cap.

Here we present preliminary results from our Charon exospheric model and laboratory experiments on Ly-α photolysis of solid methane. The goal is to estimate the contribution of the IPM Ly-α photolysis of methane cold-trapped on Charon’s poles to the observed reddish color, and to better constrain the following processes:

1) Spatial/temporal variability of the methane accretion rate onto Charon’s surface.
2) Photo-conversion rate of methane into refractories, especially in conditions of simultaneous CH₄ accretion and Ly-α irradiation that occur on Charon.
3) Optical constants of these refractories in the MVIC spectral range which is the color determinant.

Our work is intended to provide the required latitude dependent cold-trapping rates, photolytic refractory yield and optical constants needed for a comprehensive understanding of the origin of Charon’s prominent polar albedo marking.

Charon Exosphere model: The discovery by the New Horizon’s spacecraft of significant methane escape rates from Pluto’s atmosphere [4] has shed new light on the physics of Charon’s possibly seasonal exosphere. As Charon orbits through Pluto’s outflowing methane cloud, CH₄ arriving at Charon’s surface will thermally equilibrate and form a gravitationally bound Charon exosphere. This putative Charon exosphere – although insufficiently abundant for direct detection [7] – is likely to be highly seasonal owing to the Pluto-Charon system’s high inclination. The distribution, flux and accretion rate of exospheric CH₄ to/from Charon’s winter polar terrain, varies drastically with position and time, as the surface temperature responds to the seasonally rising and setting sun. Methane accretion rates will evolve differently in the north versus the south, as the Pluto/Charon system’s distance to the sun differs substantially between northern and southern summer, depending Pluto’s orbital eccentricity and precession over geologic time. Our Charon Monte Carlo exospheric model is intended to quantify the distribution and evolution of exospheric and condensed methane at Charon.

Figure 1: Predicted photolytic refractory thickness produced from condensed CH₄ on Charon surface over 1 Pluto orbit as estimated from our Charon exospheric model. The three cases shown are for different CH₄-to-refractory conversion efficiencies.

The model considers the CH₄ flux onto Charon [6], Charon’s rotation and the combined gravity field of Charon and Pluto, and (3) seasonal methane adsorption/desorption to/from the poles. With the photolysis cross sections emerging from our laboratory experiments, we will integrate condensed methane photodestruction and refractory synthesis by Ly-α photons into the model, including the dependence of these parameters on the methane accretion rate. We will use the exospheric model (together with lab experiments) to estimate the distribution of photolytic refractory material across Charon’s polar latitudes (Figure 1), and compare to the distribution observed by MVIC.
**Solid Methane Photolysis:** While there have been several previous studies on UV irradiation of methane ice, the reported CH$_4$ destruction cross sections differ up to a factor of 15 [1], [3]. This disagreement most likely stemmed from the use of uncalibrated UV sources; Ly-$\alpha$ output can vary from 5-75%, depending on the operational configuration of the microwave discharge lamp. We have optimized our UV source to emit dominantly in the Ly-$\alpha$ (> 75%) as per the recipe provided in Ref. [2]. Additionally, the required measurements of the color evolution vs. dose and optical constants of photolyzed methane films are lacking.

![Ly-$\alpha$ Irradiation of a 260 nm thick CH$_4$ film at 10 K](image)

**Figure 2 –** Spectral reddening in Ly-$\alpha$ processed methane film irradiated to the indicated fluence. The reflectance is increasingly suppressed towards smaller wavelengths.

We show in Figure 2 the change in the UV-Vis-NIR reflectance (encompassing the MVIC spectral range) of a solid methane film condensed onto a gold-coated quartz crystal microbalance at 10 K (Charon’s winter pole T) and irradiated with Ly-$\alpha$ processed to the indicated fluence. The oscillations are due to interference of light reflected by the CH$_4$ ice-vacuum and CH$_4$ ice-gold interfaces.

We observe spectral reddening as the CH$_4$ film is processed to higher dose; the reflectance is increasingly suppressed at shorter wavelengths as a result of photoprocessing (indicated by the arrows in Figure 2). Future efforts will focus on deriving the imaginary refractive index k of the refractories that cause strong UV-Vis absorption to induce the reddening. Similar measurements will be performed under Charon like conditions where methane ice is irradiated during the winter accretion phase.

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ON THE EQUILIBRIUM STATE OF PLUTO’S SURFACE ICE.  L. M. Trafton¹, S. Tan², J. A. Stansberry³. ¹University of Texas at Austin, Austin, TX, ²Planetary Science Institute, Tucson, AZ, ³Space Telescope Science Institute, Baltimore, MD

Pluto’s surface volatile inventory is dominated by the gaseous and solid phases of N₂ and CH₄. Simulation of the composition of these phases under 3-phase thermal equilibrium (i.e., between the gaseous and two solid phases) results in an atmospheric CH₄ mixing ratio far less than observed. For example, between 37K and 40K, the surface pressure under thermal equilibrium would vary from 11.5 to 62 μbar, and the atmospheric CH₄ mixing ratio from 0.0048% to 0.0102% [1]. This is compared to the observed values of 12.8 μbar and 0.3% [2, 3]. The equilibrium CH₄ mixing ratio is far less than observed over the plausible range of temperatures set by the global radiative balance of the N₂-rich ice with insolation [4, 2]. Under 2-phase equilibrium, in the case where the N₂-rich solid phase is absent, a temperature of 42.5 is required at the observed pressure of 12.8 μbar for the mixing ratio to reach the observed value. This would be 4-5K warmer than the regulated N₂-rich regions, [2]. However, the N₂-rich regions appear to be significantly undersaturated [5, 6], which is inconsistent with a surplus atmospheric CH₄ mixing ratio under thermal equilibrium.

The thermodynamics of these two ice regions are connected globally through interaction with the atmosphere. Unlike 3-phase equilibrium, which is fixed by just the temperature or pressure, 2-phase equilibrium requires two thermodynamic variables to fix the state of the ice, such as pressure and mole fraction [7, 1]. We investigate the contradiction between the excess atmospheric CH₄ concentration and the apparent lack of saturation in the N₂-rich ice in terms of the composition of a thin, CH₄-rich boundary layer on the N₂-rich ice surface near thermal equilibrium.

References:
LIMITS ON X-RAY LUMINOSITY FROM PLUTO’S H₂ CORONA. O. J. Tucker1, R. E Johnson2, J. Bell1, M. R. Collier1, W. M. Farrell1, A. Glocer1, R. M. Killen1, P. Saxena1, 1NASA GSFC (8800 Greenbelt Rd., 20771, orenthal.j.tucker@nasa.gov), 2University of Virginia (Thorton Hall, P.O. Box 400259, Charlottesville, VA 22904-4259, rej@virginia.edu).

**Introduction:** Recent observations of Pluto’s upper atmosphere revealed the thermal structure is more complex than previously considered [1,2]. New Horizons (NH) found Pluto’s upper atmosphere to be cooler and more contracted than model predictions before the mission (pre-NH) [3,4]. Seemingly contrary, the Chandra space telescope observed X-ray luminosities from Pluto larger than some JFCs more consistent with a significant extended atmosphere [5]. Previous studies have focused on the thermal escape of N₂ and CH₄ in the upper atmosphere [5,6]. However, most planetary bodies possess diffuse hydrogen coronas, and photolysis of CH₄ on Pluto will result in the production of H₂. Here we examine the effect of diffusion and escape of H₂ on the thermal structure of Pluto’s upper atmosphere, and potential limits on its contribution as a source X-ray emission from Pluto’s corona.

**Background:** For the first time NH directly measured the abundance of N₂ and CH₄ in the upper atmosphere and sparse populations of C₂H₆ hydrocarbons. Like Titan, molecular hydrogen is expected to be a significant photochemical product in the atmosphere. Krasnopolsky and Cruikshank (1999) [7] estimate that almost every absorbed photon result in the production of H and/or H₂. Molecular hydrogen may have a significant influence on the thermal structure of the upper atmosphere because it will escape significantly. Further, depending on its production rate it may be the dominant atmospheric component in the extended corona.

NH observation of a was cooler the upper atmosphere (~68 K compared to predictions of ~80 K) [7,8] is surprising because the CH₄, principal heating agent, fraction in the atmosphere is relatively consistent with that used in the pre-NH estimates. Radiative emissions by CO and HCN are molecular cooling agents, however they are not abundant enough to explain the observations. Recent work by Zhang et al. (2017) [9] indicate radiative cooling by hazes may be important. Here we build on previous work on the energy balance in the upper atmosphere by examining the effect of cooling due to molecular escape of H₂ in the upper atmosphere. Tucker et al. (2013) [10] showed that thermal escape of H₂ from Titan cools the bulk atmosphere at high altitudes in the absence of the significant escape by N₂ or CH₄.

In Titan’s lower thermosphere H₂ has a mixing ratio on the order of 0.1 %, however above the exobase it becomes the dominant atmospheric species [10]. Here we predict the density distribution of H₂ from just below the exobase out to several Pluto radii. At these altitudes solar wind charge exchange (SWCX) reactions between high charge state solar wind ions and exospheric neutrals are known to produce X-ray emissions from the excited ions [11]. Chandra observed X-ray emissions from Pluto’s exosphere that were similar to that observed from the comas of the comet 2P/Encke [5]. In fact, Pluto’s X-ray luminosity was determined to be (~2.0 × 10¹⁵ ergs/s) 5 times larger than comet 2P/Encke [5]. The observations occurred near the time of the New Horizons encounter, 1¼ year prior to the encounter and approximately one month after. The cooler temperatures inferred from the NH observations indicative of thermal escape rates of ~ (3 – 7) × 10²² N₂/s and (4 – 8) × 10²⁵ CH₄/s. Collectively, these escape rates are 2 orders of magnitude lower than estimated for 2P/Encke (~7 × 10艇⁷ molecules/s). The brighter emissions occurring from Pluto’s more tenuous atmosphere (assuming density ~1/r² similar to a comets) would seem to suggest solar wind induced X-ray emission occurs more efficiently at Pluto ~33 AU than for JFCs within 1AU [5]. However, Lisse et al. (2016) [5] proposed that Pluto may have a neutral torus about its orbit because due to long lifetime against photoionization of ~100 years compared to days near 1 AU. To this end, we will present estimates X-ray luminosity from the extended atmosphere for comparison.

**Methodology:** We use Direct Simulation Monte Carlo (DSMC) techniques to model thermal structure N₂, CH₄ and H₂ in the upper atmosphere, and the thermal escape, similar to that done in Tucker et al. (2013) [10]. DSMC is a numerical approach used to simulate non-equilibrium rarefied gas flow. Here we show results from 1D radial simulation at altitudes from ~900 km out to 10,000 km. The thermal flux from the lower boundary for N₂ and CH₄ is taken from NH observations [1], and for H₂ it is constrained by the CH₄ photo-destruction and recent photo-chemical models of Pluto’s atmosphere [1].

**Results:** An example result is shown in Figure 1 of temperature and density profile. Here the H₂ mixing fraction is artificially set to be ‘Titan like’ on the 0.1% level at z ~ 950 km. The results show cooling due to escape, and how rarefaction results in the gas...
distribution not being in thermal equilibrium in at altitudes below the exobase. Molecular hydrogen has a Jeans parameter (gravitational energy/thermal energy) that approaches ~ 1.5 at the lower boundary. Hence, much of the thermal energy of H₂ is converted to bulk outflow energy limited by diffusion through the heavier atmospheric gases. For this case we obtain an escape rate of ~10²⁷ H₂/s⁻¹, however the true escape rate must be constrained by CH₄ photo-destruction and H₂ production rates derived for Pluto’s atmosphere.

Figure 1: Example DSMC result of density (top) and temperature (bottom) for N₂, CH₄ and H₂ in Pluto’s atmosphere.


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CRYOVOLCANISM ON PLUTO: VARIOUS THEORETICAL CONSIDERATIONS. O. M. Umurhan\textsuperscript{1,2} and D. P. Cruikshank\textsuperscript{1,2}. \textsuperscript{1}SETI Institute, Mountain View, CA orkan.m.umurhan@nasa.gov, \textsuperscript{2}NASA Ames Research Center, Moffett Field, CA (dale.p.cruikshank@nasa.gov)

Introduction: The existence of high-standing relatively young structures like Wright Mons and Picard Mons has been postulated to be the result of cryovolcanic activity [1-3]. The observation of entrained tholin materials in the base of troughs and channels like Virgil and Inanna Fossae has recently been suggested to be the result of material deposition from NH\textsubscript{3} laden H\textsubscript{2}O cryovolcanic flow, both explosive and seeping [4]. Similarly, cryovolcanism has been invoked to explain both the remarkable smoothness and the occasional presence of several foundered crustal blocks observed of Charon’s Vulcan Planum [5].

Aims: In this study we consider the shape and scope of what cryovolcanic flow would look like for conditions typical of Pluto’s surface. We consider a series of theoretical calculations assuming cylindrically symmetric flow of NH\textsubscript{3} rich H\textsubscript{2}O slurry with and without additional methanol based on published rheological studies [6]. We construct a simple flow model to assess the competing process times between cooling and flow front advance (see Fig. 1).

We assess various timescales associated with initial surface crusting driven by rapid NH\textsubscript{3} sublimation. We compare that against the time it takes the flow to extend before the flow head freezes (Fig. 2). We take these basic theoretical considerations and numerically construct cylindrically symmetric mounds and compare them with surface textures observed from New Horizons acquired data and subsequently derived Digital Elevation Models.

Some Results: We assess the distance over which flows can reach before freezing over surfaces of a given initial slope. We find that for conditions representative of Pluto’s surface NH\textsubscript{3} laden H\textsubscript{2}O cryoflow over a surface with a mean slope angle of $\theta$=1-10 degrees can extend between 1 and 3 km before the flow front freezes (e.g., Fig. 3). More general results will be presented at the meeting. If time permits, we will also present full landform evolution modeling of cryovolcanic seeping flow in a model channel configuration.

THE PLUTO SYSTEM AT TRUE OPPOSITION.  A. J. Verbiscer\textsuperscript{1}, M. R. Showalter\textsuperscript{2}, M. W. Buie\textsuperscript{3}, and P. Helfenstein\textsuperscript{4} \textsuperscript{1}University of Virginia, Charlottesville, VA 22904, USA; \textsuperscript{2}SETI Institute, Mountain View, CA 94043, USA; \textsuperscript{3}Southwest Research Institute, Boulder, CO 80302, USA; \textsuperscript{4}Cornell University, Ithaca, NY 14853 USA.

At opposition in 2018, the Pluto system was visible at the smallest solar phase angles in 87 years. The system was at true opposition on 12 July 2018 when it crossed the line of nodes and, as seen from Pluto, the Earth transited the solar disk. Such rare planetary alignments enable the characterization of the global small-scale surface texture and porosity of Pluto and its moons as well as the direct measurement of their geometric albedos, rather than estimations of their values by interpolating photometric models. Any variation among the regolith properties of Pluto’s moons tests the hypothesis that ejecta exchange between the moons has altered their surfaces \cite{Stern09}.

Here we report the results of a Hubble Space Telescope (HST) program to observe the Pluto system at true opposition and characterize the phase curves of Pluto, Charon, Nix, Hydra, Styx, and Kerberos at small phase angles.


\textbf{Acknowledgements:} Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555.

Introduction: The Pluto system is comprised of the Pluto and Charon binary pair and four much smaller satellites: Styx, Nix, Kerberos, and Hydra, in order of increasing distance from Pluto [1]. In this invited talk, we review the properties of the small satellites and how they inform our understanding of the origin of the Pluto system.

Orbital and Rotational Properties: The orbits of the small satellites are remarkable in that the orbit planes are nearly coincident with Pluto’s equatorial plane, and their orbital periods (20.16 d, 24.85 d, 32.17 d, 38.2 d) fall nearly in the 3:4:5:6 mean motion resonances (MMRs) with Charon [2]. Although the MMRs are regions of dynamical stability, attempts to model the orbital evolution of the small satellites from formation in a presumably more compact (around Pluto) configuration to their current locations (with orbital semi-major axes of 42,660 km, 48,694 km, 57,780 km, 64,738 km) have been largely unsuccessful [3]. While Pluto and Charon are in synchronous rotation (period=6.4 d) and have rotational poles aligned with their orbital poles, all of the satellites have rotational periods (3.2 d, 1.83 d, 5.3 d, 0.429 d) much shorter than their orbital periods and rotation poles oriented nearly perpendicular to their orbital planes, suggesting that impacts may have dominated their rotational properties.

Physical Properties: Nix and Hydra are approximately the same size, with effective spherical diameters of ~35 km. Styx and Kerberos are much smaller, with effective spherical diameters of ~10 km for both. All of the small satellites are highly aspherical (Fig.1), with primary axes ratios ranging from 1.6 to 2.4 [4]. All of the small satellites have highly reflective surfaces, with V-band geometric albedos in the range 0.5-0.9 [1]. The phase curves of Nix and Hydra are similar and modeling suggests relatively smooth, forward-scattering surfaces [5]. The masses derived from dynamical models [6] are highly uncertain (~50-100%), but using the nominal mass values for Nix and Hydra, and the latest shape models [4], the bulk densities are ~1.9 g/cm for Nix and ~2.3 g/cm for Hydra, suggesting they are not highly porous objects and/or a significant amount of rocky material has been incorporated into their interiors.

Color and Composition: The surfaces of Nix and Hydra have mostly neutral (i.e., solar-like) colors [1], but Hydra’s surface is slightly bluer than Nix’s. The large crater on Nix is slightly (~10%) redder than the rest of the surface (Fig. 1), perhaps revealing either previously buried material, or retained impactor material that has different properties than the typical surface material. Near infrared spectra of Nix and Hydra [7; see Fig. 2] reveal deep water ice absorption bands, mostly crystalline in nature, and another band near 2.21 μm that may indicate the presence of an ammoniated material (e.g., ammonium chloride, ammonium nitrate, or ammonium carbonate, but not ammonia hydrate). Perhaps significantly, the strength of the ammonia-containing material appears to be weakest at the location of the slightly reddish large crater on Nix [7]. Weak spectral bands near 2.42 μm and 2.45 μm may due to absorption by hydrocarbon or tholins [7].

Origin: The dynamical, physical, and compositional properties of the small satellites are consistent with a giant impact origin of the system [8], in which two Pluto-sized objects experienced a glancing collision producing the Pluto-Charon binary and a debris disk in their equatorial plane where the small satellites subsequently formed. The debris disk was likely comprised primarily of mantle material from the two large, and probably partially differentiated impactors, which could explain why the small satellites have bright, icy surfaces and relatively low bulk densities. The retention of high albedo surfaces over the age of the solar system also suggests that impacts on the small satellites were primarily destructive (i.e., resulted in a net loss of material, including that of the impactors) and that the small satellites have icy material throughout their interiors. The properties of the small satellites of the Pluto system can inform our understanding of other KBO satellite systems that also resulted from giant impacts. But we do not expect the properties of Pluto’s small satellites to be similar to those of the typical small KBOs (i.e., objects that are not satellites of Dwarf Planets).

Fig. 1: Resolved images of Pluto’s four small moons taken during the New Horizons flyby in July 2015. Celestial north is up and east is to the left. All images were deconvolved to recover the best available resolution. Panchromatic LORRI images were used for Styx, Kerberos, and Hydra, while an enhanced color image combining both MVIC and LORRI data was used for Nix. Some surface features on Nix and Hydra are impact craters. The largest crater on Nix is slightly darker and redder than the rest of Nix’s surface. (Adapted from [1].)

Acknowledgments: This work was supported by NASA’s New Horizons project, and most of the data discussed here were obtained by New Horizons. We thank the Deep Space Network, JPL, KinetX Aerospace, and the entire present and past New Horizons team for making the flyby of the Pluto system successful.

Fig. 2: New Horizons LEISA near-infrared spectra of Nix (top) and Hydra (bottom). Both spectra (black symbols with error bars) show deep absorption bands centered near 1.5, 1.65, and 2 μm associated with crystalline water (H2O) ice. The over-plotted red curves are from model fits that include only crystalline water ice. The residuals (plotted below the main spectra) show that both Nix and Hydra have an additional absorption feature near 2.2 μm that may be associated with an ammonia-bearing species. (Adapted from [7].)
WASHBOARD AND FLUTED TERRAINS ON PLUTO AS EVIDENCE FOR ANCIENT GLACIATION.
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Introduction: The 2015 flyby of the Pluto system by NASA’s New Horizons spacecraft revealed that the landscape to the northwest and west of Sputnik Planitia (Fig. 1) has been eroded into a variety of dissected terrains, including what has been termed “washboard” and “fluted” terrains (WFT) [1,2]. These consist of low, parallel to sub-parallel ridges that emboss portions of the uplands here. Through mapping and spatial analysis of the ridges, we have argued that they represent crustal debris that were buoyant in pitted glacial nitrogen ice that formerly covered this area, and which were deposited after the nitrogen ice receded via sublimation early in Pluto’s history [3]. This presentation reviews this and alternative hypotheses for their origin.

Observations: Washboard terrain consists of parallel to sub-parallel sets of mostly ENE-WSW-trending low ridges and troughs that are spaced ~1-2 km crest-to-crest (Fig. 2a). This terrain occurs in level topographic settings within upland plateaus and valley floors to the northwest and west of Sputnik Planitia, as well as exterior to and within Burney crater. Fluted terrain (Fig. 2b) consists of similar ridge and trough sets, spaced ~2-3 km crest-to-crest [2], that are seen on high relief (~2 km), generally high albedo spurs and massifs that separate basins and valleys to the northwest of Sputnik Planitia. The ridges and troughs are oriented downgradient on hillslopes that reach up to 20° [2]. A notable type of fluted terrain is the “fluted craters” (Fig. 2c), the walls of which display a pattern of radially aligned, downslope-oriented ridges and troughs. WFT ridges occur across an an elevation range of ~4.8 km, from -2.9 km to +1.9 km, concentrate at low elevations (mean of -0.5 km ± 0.9 km), and are never seen in topographic settings that are both high relief and high elevation. The albedo of washboard and fluted ridges matches that of nearby non-ridged terrain, and is higher in upland plateau and massif settings than in valley floor settings. The ridges generally parallel each other, and rarely branch.

Interpretation: Both washboard and fluted ridges predominantly trend ENE-WSW, and we interpret the broader range of azimuths displayed by fluted ridges to result from their occurrence within higher relief topographic settings with steeper slopes. We therefore regard fluted and washboard terrain as being different manifestations of the same landform-evolving process that produces these ridges. We consider WFT to represent a deposit that has been emplaced, with deposition within high relief, steep-sloped settings tending to cause the ridges to diverge from a natural ENE-WSW orientation. We disfavor an aeolian hypothesis as the scale of the ridges is too large for them to be dunes formed by winds in Pluto’s thin atmosphere, and because fluted ridges are seen to occur on convex, high-
relief topography, which is not a plausible setting for dune formation. An origin as an exhumed compressional tectonic fabric is also disfavored as the WFT coverage should not be elevation- and relief-dependent if this were the case. In addition, the source of the NNW-SSE-aligned compressive stress is not apparent, especially as WFT occurs within the context of extensional tectonism consisting of large-scale normal faults. Instead, we hypothesize that WFT originate from past, expanded nitrogen ice glaciation [3]. WFT mostly concentrates within a system of deep basins and sinuous valleys extending radially outwards from the northwest margin of Sputnik Planitia. This section of Sputnik Planitia’s perimeter is where elevations are lowest and slopes leading into the uplands are gentlest (on a scale of hundreds of kilometers). These basins and valleys form part of a 3200-km-long, north–south-oriented tectonic system seen in global topography between the 145° E and 165° E meridians, which intersects the perimeter of Sputnik Planitia [4]. The coincidence of WFT with the large tectonic system can explain why the ridges are restricted to the uplands northwest of Sputnik Planitia and not seen in other areas bounding Sputnik Planitia that might have formerly hosted glaciation. The tectonism would have fragmented the water ice crust, allowing portions of it to be dislodged and ascend to the surface of the denser nitrogen ice, where they can be manipulated by glacial flow. After recession of the formerly extensive glaciation by sublimation, the buoyant debris would have been deposited to form the WFT ridges. Formation of the Sputnik Planitia basin early in Pluto’s history would have instigated recession of nitrogen ice across Pluto, as the basin represented a powerful cold trap that the nitrogen ice migrated to [5,6]. Based on cratering rates estimated for Pluto [7], a crater size-frequency distribution derived for the WFT corresponds to an age of ~4 Gyr [3].

The consistent ENE-WSW azimuth of the ridges, regardless of latitude or location relative to Sputnik Planitia, suggests that they are not former margins of the nitrogen ice glaciation, which would be expected to conform more to local topography and Sputnik Planitia’s boundaries. As such, they are not analogous to the morphologically similar De Geer glacial moraines on Earth [8], which have been interpreted as marking former ice-margin positions where sediment is deposited or pushed up during brief stillstands or minor readvances. Fields of elongated sublimation pits are seen at low latitudes in Sputnik Planitia [9], the patterning and scale of which resemble the WFT. We hypothesize that sublimation of nitrogen ice that formerly covered the WFT region produced a pitted texture comparable to what is seen in southern Sputnik Planitia today, and that during sublimation, the buoyant crustal debris covering the ice would move downslope and concentrate within these elongate pits, leaving the parallel ridges of debris as a record of the sublimation texture after recession of the nitrogen ice. The cause of the common alignment of the ridges is uncertain, but may be related to structural anisotropies in the nitrogen ice (i.e. stress fields associated with flow paths) that caused the pits to align and join together [9].

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### Introduction:
The three volatiles present as ices on Pluto’s surface, N₂, CO, and CH₄, are also present in its atmosphere. These are in a state of disequilibrium, because of disparate insolation across the surface, differing altitudes, and the history of the surface-atmosphere interaction and subsurface processes on timescales of hours to millions of years. Spatial segregation of species is seen on Pluto; vertical layering probably also exists.

### Equilibrium states of N₂, CO, CH₄:
Recent work has been done on the state of these species in thermodynamic equilibrium [1, 2]. A key to this work is the mutual solubility of solid N₂ and CH₄. While CO can be mixed in N₂ in any dilution in the binary solution below 40 K, the same is not the case for CH₄ in N₂ [3]. For example, at 40 K, N₂-rich ice is saturated with 4.9% CH₄, and CH₄-rich ice is saturated with 6.3% N₂. Considering only the binary mixture, CH₄ and N₂, this leads to the remarkable result that the partial pressures of N₂ and CH₄ for intermediate mole fractions of N₂ and CH₄ in equilibrium with the gas depend only on temperature, and are independent of the solid mole fraction. In equilibrium, once CH₄ is saturated in N₂-rich ice, adding more CH₄ to the system while keeping the temperature constant will lead to more CH₄-rich ice that is saturated with N₂, but not to a higher partial pressure of CH₄. Table 1 gives the N₂ and CH₄ partial pressures, calculated according to [1].

### Table 1 CH₄ and N₂ vapor pressures in equilibrium

<table>
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<tr>
<th>T, K</th>
<th>xᵦCH₄(y)</th>
<th>xN₂(y)</th>
<th>PₖN₂(y)</th>
<th>PₖCH₄(y)</th>
<th>yᵦCH₄(y)</th>
<th>yCH₄(y)</th>
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<td>3802</td>
<td>2482</td>
<td>0.0653</td>
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</tr>
</tbody>
</table>

(a) Saturation mole fraction of CH₄ in N₂:CH₄ ice or N₂ in CH₄:N₂ ice.
(b) Partial pressure. Note N₂ is in μbar, CH₄ is in nbar.
(c) CH₄ gaseous mole fraction

### Observations of Pluto in disequilibrium:
Both the surface and atmosphere of Pluto are seen to be in disequilibrium. The N₂ surface pressure is observed to be consistent with vapor-pressure equilibrium over Sputnik Planitia from the REX radio ingress, with near-surface temperatures of 38.9 ± 2.1 K and surface pressure of 12.8 ± 0.7 μbar [4]. In contrast, the atmospheric CH₄ mixing ratio is ~0.3% [5], 10-100x higher than predicted for vapor-pressure equilibrium at that temperature. In the surface, dilution of CH₄ in N₂-rich terrains within Sputnik Planitia is not ~4%, as expected. Instead, the CH₄ mole fraction is only ~0.3% [6], a value more consistent with equilibrium at much colder temperatures (at which temperatures N₂ would be in α phase) [3], and similar to values derived from ground-based observations of Pluto [7].

### Drivers of disequilibrium:
In general, volatiles sublime from those areas on Pluto that absorb more sunlight, and condense on less-illuminated areas. Direct evidence for Pluto’s diurnal sublimation/condensation cycle is seen in the REX observations over Sputnik Planitia at dusk, where the subliming N₂ forms a cold boundary layer. Net sublimation or condensation implies local disequilibrium. For pure N₂ at Pluto’s surface pressure, the departure from equilibrium is very small. For the binary system (N₂, CH₄), things become complex quickly (and the tertiary N₂, CH₄, CO is still more complex). For example, net sublimation leads to a CH₄-rich ice surface (as the N₂ ice preferentially sublimes), and net condensation results in a N₂-rich ice surface (as the N₂ rich atmosphere is forced to condense) [1]. Thus the cycles of sublimation and condensation can lead to segregation by latitude, with bands of CH₄-rich, N₂-rich, or volatile-free surface elements [6, 8]; or altitude, with N₂ dominating at low-elevations (including Sputnik Planitia) and CH₄ dominating at high elevations (including the bladed terrain) [9, 1].

Disequilibrium is likely to also lead to vertical structure or layering (Fig 1). Vertical structure can complicate interpretation of infrared spectra [6], since the infrared absorption is likely to occur below the topmost layers that are involved with the surface-atmosphere interaction. The layering affects rates of sublimation and condensation as well. A simple picture of a homogenous surface in equilibrium with a gas (Fig. 1A) predicts atmospheric CH₄ ratios [10, 1] that...
are much lower than observed [5]. CH₄ abundance can be raised by a very thin molecular layer of CH₄-rich ice in balance with the atmosphere (Detailed Balance model [11], Fig 1B), which resets the relative equilibrium vapor pressures of CH₄ and N₂ in the solid solution according to their surface mole fractions. This would throttle the N₂ surface pressure by orders of magnitude, which is not seen at Pluto or Triton. If the N₂ at depth can communicate with the atmosphere, then thick CH₄ patches can build up by sublimation (Fig 1C, [12]). These can be warm, and supply CH₄ into the atmosphere through turbulent diffusion. Essentially the CH₄-patch model is used in recent volatile transport models [Fig 1B, 13] to predict atmospheric CH₄ mixing ratios similar to observations. Still more complex vertical structure is likely through solar gardening (Fig 1D, [14]), wherein sunlight is absorbed many cm within the surface, and thermal photons are emitted from much closer to the surface.

Relaxation timescales. There are multiple drivers to disequilibrium. The relaxation timescales for equilibrating the partial pressure above a surface is very short, only a few minutes [11], and local concentrations of atmospheric CH₄ (for example, over CH₄ patches) relax to the global average with a timescale of ~4 months [15]. The relaxation timescale within the solid is much longer. It is also less well known and more difficult to model, since compositional gradients can be muted by solid state diffusion, or by transport in the gas phase within inter-grain voids. These relaxation timescales can be compared to the drivers toward disequilibrium: the 6.4-day Pluto rotation, its 248-year orbit, and the ~3 million-year obliquity cycle.

Conclusions: Important new theoretical predictions on the equilibrium state of volatile ices on Pluto have yet to confirmed in the lab. Experiments under relevant Pluto conditions [12] could also investigate the effect of sublimation and condensation on the state and composition ices, such as the presence of CH₄-enriched grains, their effective size, and the CH₄ concentration. Volatile transport models can be and have been used to test manifestations of disequilibrium. What is needed is more lab experiments and more modeling efforts, and a close collaboration between the two.

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References: