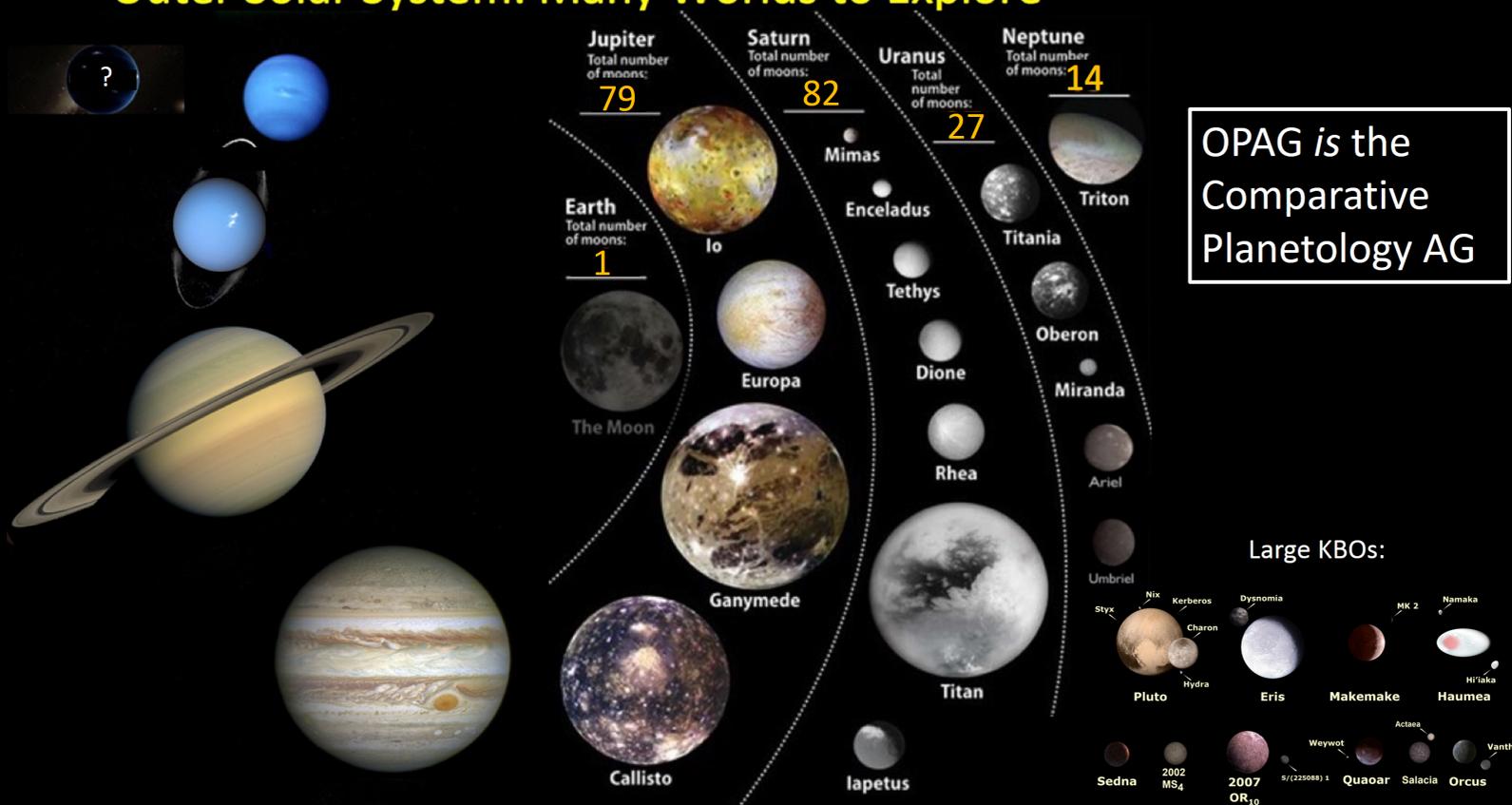


OPAG Update to the Planetary Science Advisory Committee (PAC)

Jeff Moore, OPAG Chair, NASA ARC, PAC Meeting, 10 March 2020

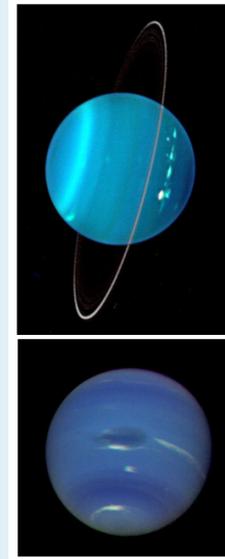
Outer Solar System: Many Worlds to Explore



Outer Planets Assessment Group (OPAG) Charter

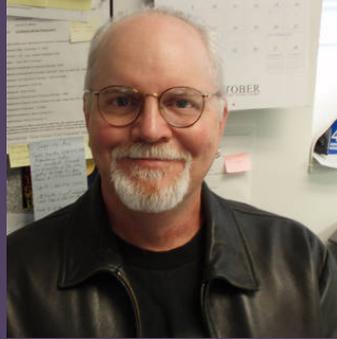
<https://www.lpi.usra.edu/opag/>

- NASA's community-based forum to provide science input for planning and prioritizing outer planet exploration activities for the next several decades
- Evaluates outer solar system exploration goals, objectives, investigations and required measurements on the basis of the widest possible community outreach
- Meets twice per year, summer and winter
 - Next meeting: tentatively 1-3 Sept 2020 in Seattle, WA
- OPAG documents are inputs to the Decadal Surveys
- OPAG and Small Bodies Assessment Group (SBAG) have Joint custody of Pluto system and other planets among Kuiper Belt Objects



KBO planets

OPAG Steering Committee



Jeff Moore
OPAG Chair
Ames Research Center



Linda Spilker
OPAG Vice-Chair
Jet Propulsion Lab

* =New Member



Alfred McEwen
University of Arizona



Lynnae Quick*
NASA Goddard



Kathleen Mandt*
Applied Physics Laboratory

OPAG Steering Committee



Morgan Cable*
Jet Propulsion Lab



Britney Schmidt
Georgia Institute of Technology



Kunio Sayanagi
Hampton University



Tom Spilker*
Consultant



Abigail Rymer*
Applied Physics Lab

* =New Member

OPAG Steering Committee



Scott Edgington
Jet Propulsion Lab



Amanda Hendrix
Planetary Science Institute



Mark Hofstadter
Jet Propulsion Lab



Terry Hurford
Goddard Space Flight Center



Carol Paty
Georgia Institute of Technology

Recent and Upcoming OPAG-related Meetings

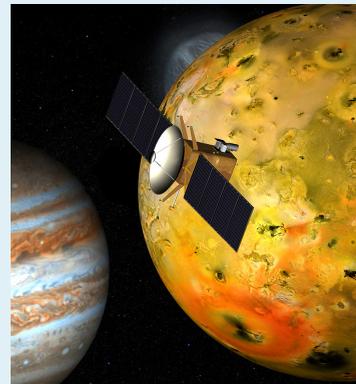
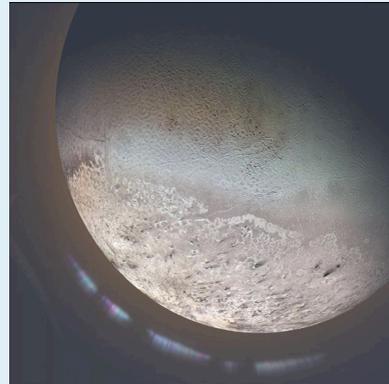
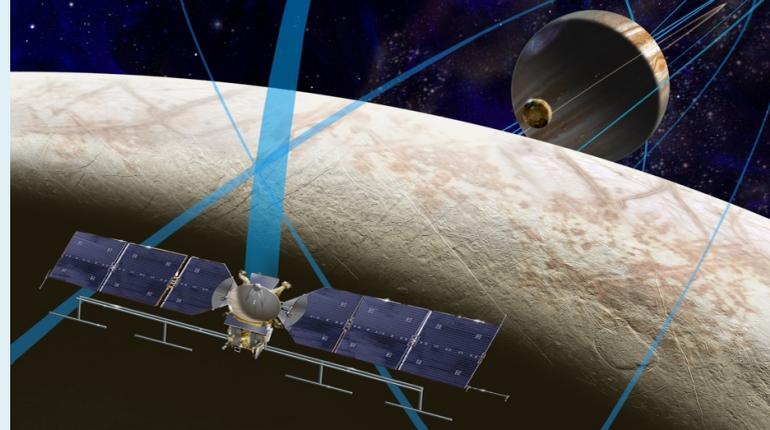
- **OPAG Meeting** (3-4 February 2020) Lunar and Planetary Institute, Universities Space Research Association (USRA) 3600 Bay Area Blvd, Houston, TX
- **Joint VEXAG/OPAG/ExoPAG meeting** (4-7 February 2020), Lunar and Planetary Institute, Houston, TX

Upcoming Meetings:

- ***Outer Planets Assessment Group (OPAG) Town Hall***, Lunar and Planetary Science Conf. noon, 18 March 2020, The Woodlands, Houston, TX: **CANCELED (possible remote broadcast TBD)**
- **OPAG Meeting** (tentatively 1-3 September 2020) Seattle, WA, possibly held at University of Washington

Some Key Activities since Last PAC Meeting

- Io Volcano Observer (IVO) selected for further Discovery Mission study. Alfred McEwen (PI)
- TRIDENT selected for further Discovery Mission study. Louise Prockter (PI)
- Juno Probe Completed 25th Orbit of Jupiter
- Europa Clipper completed PDR progressing towards launch NLT 2025
- JUICE progressing towards 2022 launch
- 3 Outer Planet mission studies for the Decadal Survey selected via ROSES
- **OPAG Committee White Paper posted**



New Frontiers has been good for exploration of Outer Planets

- Missions from the 1st Decadal survey:
 - New Horizons
 - Juno
- Approved candidate missions in 2nd Decadal (V&V) to outer solar system:
 - Saturn Probe
 - Ocean Worlds: Enceladus and Titan
 - Dragonfly to Titan selected for NF-4
- OPAG supports keeping Io Observer and Ocean Worlds in NF-5, along with Saturn Probe
- If IVO is selected for Discovery, then there might be no Io Observer proposals submitted to NF-5, similar to what happened with the Trojan mission after Lucy was selected.
- Although Dragonfly was selected for NF-4, OPAG supports keeping Enceladus as an option for NF-5



Dragonfly



OPAG Goals Document: 2019 (consistent with our just-posted White Paper)

- First draft written in 2006, recently posted update: August 2019
- Revised Introduction
 - Ocean Worlds emphasis, but not the only emphasis
- Recent sections:
 - Planets in the Kuiper Belt
 - Ocean Worlds and the Search for Life
 - OPAG Relevance to Worlds not in the Outer Solar System
 - Telescopic Observations
 - Workforce Issues
 - Summary Recommendations for Next Decadal Survey
- OPAG science priorities address the relevant subset (8/10) of the key questions from Vision and Voyages
- Document posted: <https://www.lpi.usra.edu/opag/goals-08-28-19.pdf>

Scientific Goals for Exploration of the Outer Solar System

Explore Outer Planet Systems and Ocean Worlds

EXECUTIVE SUMMARY

1.0 INTRODUCTION

1.1 The Outer Solar System in Vision and Voyages

1.2 New Emphasis since the Decadal Survey: Exploring Ocean Worlds

2.0 GIANT PLANETS IN OUR SOLAR SYSTEM

2.1 Jupiter and Saturn

2.2 Uranus and Neptune

3.0 GIANT PLANET MAGNETOSPHERES

4.0 GIANT PLANET RING SYSTEMS

5.0 GIANT PLANETS' MOONS

5.1 Pristine/Primitive (Less Evolved?) Satellites' Objectives

5.2 Ganymede Science Objectives

5.3 Europa Science Objectives

5.4 Io Science Objectives

5.5 Enceladus Science Objectives

5.6 Titan Science Objectives

5.7 Triton Science Objectives

6.0 PLANETS IN THE KUIPER BELT

7.0 OCEAN WORLDS AND THE SEARCH FOR LIFE

7.1 Ocean Worlds: Understanding Oceans and Habitability Worlds

8.0 OPAG RELEVANCE TO WORLDS NOT IN THE OUTER SOLAR SYSTEM

9.0 TECHNOLOGY

10.0 TELESCOPIC OBSERVATIONS

11.0 WORKFORCE ISSUES

12.0 SUMMARY RECOMMENDATIONS FOR NEXT DECADAL SURVEY

Key References

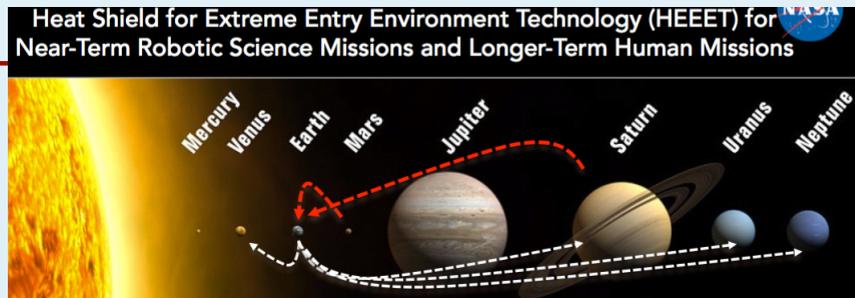
New Sections in Green

Purposes of OPAG Goals Document

- Describes the science objectives for exploration of outer solar system
- Consistent with the 2013 Decadal Survey “Vision and Voyages” but kept up-to-date as new missions are approved, new discoveries are made, models evolve, our understanding of solar system processes changes, and new questions are posed.
- Will be used as a resource for defining technology development directions and needed laboratory experiments, modeling, and other research
- Resource for mission and instrument science objectives
- Guides our preparation for the outer solar system portion of the next decadal survey
 - Including mission studies being done in preparation for that survey.
- *The emphasis for future exploration of the outer solar system is to understand giant planet systems and ocean worlds*

Priority Technologies for OPAG

- Current or recent programs are advancing instrumentation:
 - Instrument Concepts for Europa Exploration (ICEE), Homesteader, ColdTech, ICEE-2 (for Europa Lander), in addition to PICASSO and MatisSE
- **Technology development for electric power is a high priority to OPAG**
 - NASA has suspended development of the eMMRTG, the power source baselined in multiple recent studies of outer solar system mission concepts; development continues on the NextGen RTG
 - In V&V Decadal Survey, the highest priority for multi-mission technology investment was a more efficient radioisotope power (was ASRGs, then eMMRTG; now NextGen RTG)
 - High efficiency LILT solar cells can decrease area and mass for all solar missions.
 - Lightweight solar array structures help at Jupiter (and potentially Saturn)
 - Roll-Out Solar Arrays (ROSA) recently demonstrated on Space Station
- **Technology development is urgently needed for potential Ocean Worlds Missions** such as Europa Lander
 - Including **miniaturization and new life detection instrumentation**
- **Continue developing the technologies needed for Ice Giant mission** – HEEET; low power, high data rate Ka-band Telecommunication systems; and NextGen RTG, on a schedule consistent with published launch opportunities to Neptune via a Jupiter gravity assist



OPAG Findings February 3-4, 2020 Meeting

1. Europa Clipper. OPAG applauds the progress the Europa Clipper team is making toward its Critical Design Review (CDR) this coming August, and the transparency shown by the team that mission development's cost reserves are running very low. The reserve, quantified as Unallocated Future Expenses, reached 12% in November 2019 even though it met the JPL-required 25% as of June 2019. The project team has been able to reconstitute some of the reserve amount required ahead of its CDR, but there is danger that this savings effort will fall short, threatening the mission's science. NASA should recognize the scientific importance of the entire Europa Clipper payload, and strive to fly the full science instrument suite to best achieve the mission objectives.

Finding 1.

OPAG is concerned about the fast drain on the cost reserves. OPAG recognizes the scientific importance of flying the entire Europa Clipper science payloads, and urges NASA to minimize the impact of the low cost reserves on the science investigations.

OPAG Findings February 3-4, 2020 Meeting

2. Icy Satellite Technology support. OPAG strongly supports technology development programs that invest in future Ocean Worlds in situ exploration (similar in scope to the ICEE program). OPAG understands that the FY2020 congressional budget includes funding for Icy Satellite technology development. OPAG would like to know the operating plan for this budget line item.

Finding 2.

OPAG supports investment in future Ocean Worlds in situ technology development. OPAG would like a report on the operating plan for the Icy Satellite technology development line item listed in the FY2020 congressional budget.

OPAG Findings February 3-4, 2020 Meeting

3. Expanding RCN to other areas of planetary science. OPAG commends NASA for the outstanding impact that programs like the NASA Astrobiology Institute and the new Research Coordination Networks (RCN) have for building up a strong astrobiology community that is actively advancing the search for life in the solar system and beyond. These efforts have led to the development of groundbreaking mission concepts and have benefitted a diverse community of researchers eager to answer the question of whether we are alone in the universe. OPAG encourages NASA to build on this success by expanding RCN opportunities to other planetary science communities. In particular, a Giant Planet System Science RCN would provide opportunities for interdisciplinary coordination among members of the OPAG community who have explored the Jupiter and Saturn systems on missions like Galileo, Cassini, and Juno, and who are eager to conduct research (Voyager data analysis, theoretical research, and laboratory studies) relevant to future exploration of the Ice Giant systems.

Finding 3.

OPAG commends the outstanding success of NASA Astrobiology programs for building a strong interdisciplinary community advancing the search for life in the universe. OPAG encourages NASA to expand on this model by creating a new RCN for Giant Planet System Science.

OPAG Findings February 3-4, 2020 Meeting

4. Dual-anonymous review. OPAG applauds NASA's exploration of the dual-anonymous review process to address diversity/bias issues. OPAG notes that technology programs, particularly instrument development opportunities, are a particular challenge for Principal Investigators from diverse and intersectional backgrounds. For example, all of the PI's selected for the ICEE-2 instrument development program were male with limited representation along other axes of diversity, which gives an appearance of bias. OPAG encourages NASA to test the dual-anonymous review process on an instrument program as the next test program to provide a stronger dataset to evaluate the effectiveness of this review strategy. As examples of programs that receive a large number of proposals and represent good testing grounds of dual-anonymous review process, we point to the PICASSO and Applied Information Systems Research programs.

Finding 4.

OPAG commends NASA's efforts to test dual-anonymous review for R&A programs. OPAG encourages NASA to test dual-anonymous review on an instrument development program in the near future because this is a class of programs that can be perceived as lacking in diversity of selected PIs.

OPAG Findings February 3-4, 2020 Meeting

5. EDI Demographic and Climate Surveys. OPAG applauds the volunteer work being done by the Equity, Diversity and Inclusion (EDI) Working Group with participation from all planetary AGs. We fully support the letter sent by the EDI Working Group to NASA HQ on 28 January 2020 which is also available on the OPAG website.

Finding 5.

We encourage implementation of the two recommendations in the letter in time to inform the Decadal Survey, namely: 1) The community has a need for a survey across all of SMD that will enable analysis of multi-dimensional demographics data to understand the diversity aspects of our population, including data that goes beyond gender ratios and includes disciplines; and 2) NASA should commission regular (yearly), professionally-designed climate surveys so that we can fully identify the equity and inclusion issues within our community, and ensure those climate surveys consider relevant axes of power and career structures.

OPAG Findings February 3-4, 2020 Meeting

6. Advanced Radioisotope Power Systems (RPS) Program Availability Schedule. OPAG thanks June Zakrajsek of the NASA RPS Program for her briefing. We understand that the development of the eMMRTG has been suspended, and that the NextGen RTG is scheduled to be flight qualified in 2028, with flight unit production starting only after qualification is completed. Previous studies of outer solar system missions that baselined the eMMRTG, such as the recent ice giant missions studies [1], are now obsolete. Since the MMRTG is not a viable option for most long-duration missions [2], the NextGen RTG is the only remaining RPS option currently under development. A lengthy schedule for the NextGen RTG's flight availability could have significant negative impacts on the schedules for some Discovery, New Frontiers, and ice giant flagship mission concepts already studied by NASA and other institutions.

Finding 6.

OPAG requests a further presentation by NASA regarding the schedule for the NextGen RTG development, qualification, flight unit fabrication, testing and delivery for launch, to enable a more detailed discussion at the next OPAG public meeting.

1. Hofstadter, M.D., Simon, A., Ice Giants Pre-Decadal Survey Mission Study Report, JPL D-100520, p. 2-2, 2017 June; available at https://www.lpi.usra.edu/icegiants/mission_study/Full-Report.pdf
2. *ibid*, p 1-8, 2-8.

OPAG Committee White Paper

- **Organized around Big Questions**

- What is the distribution and history of life in the solar system?
- What is the origin, evolution, and structure of planetary systems?
- What present-day processes shape planetary systems, and how do these processes create diverse outcomes within and across different worlds?

With a fourth Cross-Divisional theme: How can solar system bodies inform our understanding of bodies in exoplanetary systems?

- **Strategic Approach**

- Research and Analysis (R&A)
- International Partnership

- **Technology and Supporting Strategic Investment (including)**

- Orbital vs. *In situ* in Exploration
- Aerocapture
- Earth-based Astronomy
- Laboratory Measurements

OPAG Committee White Paper Conclusions

- For **large directed missions**, our top recommendation is to complete Europa Clipper. Our top recommendation for a new start is an **Ice Giant Systems mission**. Flying to either ice giant is scientifically compelling, but Neptune is preferred since Triton is a higher-priority Ocean Worlds target than Ariel or the other Uranian satellites. This re-affirms the importance given to such a mission in the just-previous Decadal Survey. We note that no new technology efforts (aside from finishing efforts already underway) are needed for this mission to proceed.

OPAG Committee White Paper Conclusions **cont'**

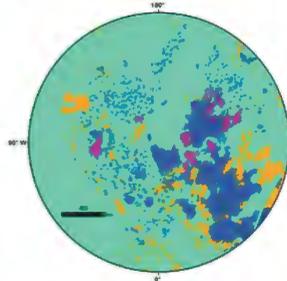
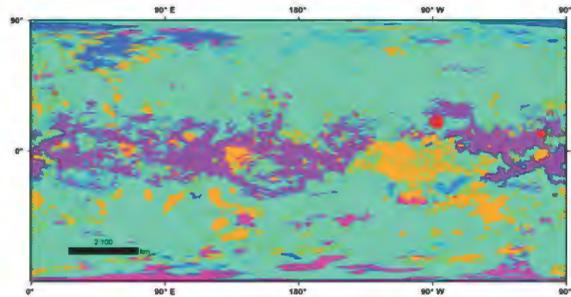
- Our next large directed mission priority is a mission to search for life or biosignatures on an ocean world, most likely Europa or Enceladus. We believe that life detection technology development could prove essential to either mission, so we strongly support the ongoing technology development efforts. The decadal mid-term review recommended that Europa Lander be considered for a new start in the next full decadal survey, rather than beginning sooner. However, a Europa Lander pre-project has been funded and could get a new start. If a Europa Lander mission is approved, then OPAG will certainly support that mission. We recommend that NASA study an Enceladus life-search mission. Concurrently, we strongly recommend that the next Decadal Survey include a Priority Question about actual life or biosignature detection rather than just the study of habitability.

OPAG Committee White Paper Conclusions **cont'**

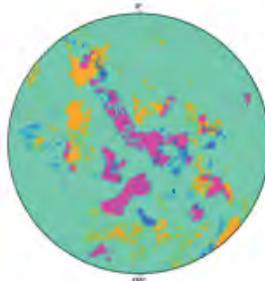
- For **New Frontiers** class missions, OPAG supports opening competition to all solar system destinations, as recommended by the National Academies in 2008. In particular, we support the inclusion of Enceladus and Titan ocean worlds missions along with Io Observer and Saturn probes. Other concepts deserve consideration as well, such as a mission to KBO planets. OPAG strongly recommends that the next Decadal Survey be less restrictive in the number of allowed destinations for New Frontiers missions than in the past Surveys. The outer solar system has a great abundance of interesting worlds to explore, so such restrictions are a particularly onerous restriction on future exploration.



Global Geomorphologic Map of Titan



North Pole



South Pole



The first global geomorphologic map of Titan has been published. The map combined all the available datasets from Cassini (RADAR, VIMS, ISS). Correlations between datasets enabled mapping even where datasets were incomplete. The spatial and superposition relations between major geomorphologic units reveals the likely temporal evolution of the landscape and provide insight into the interacting processes driving its evolution.

The map shows that Titan's surface is dominated by sedimentary or depositional processes with a clear latitudinal variation, with dunes at the equator, plains at mid-latitudes and labyrinth terrains and lakes at the poles. Plains are the most widespread unit on Titan, covering 65% of the surface. Dunes cover 17% while the hummocky unit, the oldest on the surface, cover 14% and is thought to be the remnant of the ice shell. Other units cover only small areas.

(Lopes et al., 2019, Nature Geosciences
<https://doi.org/10.1038/s41550-019-0917-6>)

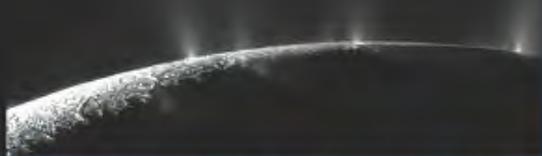


Enceladus' Low Mass Organics

Precursors for biologically-relevant compounds!

Data from NASA's Cassini spacecraft reveal low-mass organic compounds in ice grains from Saturn' moon Enceladus. These are:

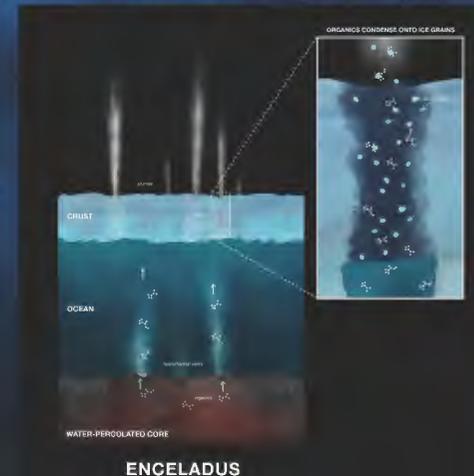
- Reactive Oxygen-, Nitrogen-bearing, and aromatic compounds.
- In Earth's hydrothermal systems, these soluble compounds are known precursors for the synthesis of biologically-relevant organic molecules, such as amino acids.
- Originating from the depths of Enceladus' ocean. These then evaporate when reaching the water surface and quickly adsorb onto ice grains within the Tiger Stripe crustal cracks.
- It's still unknown if amino acids are needed for life beyond Earth, but finding the molecules that form them is an important piece of the puzzle.



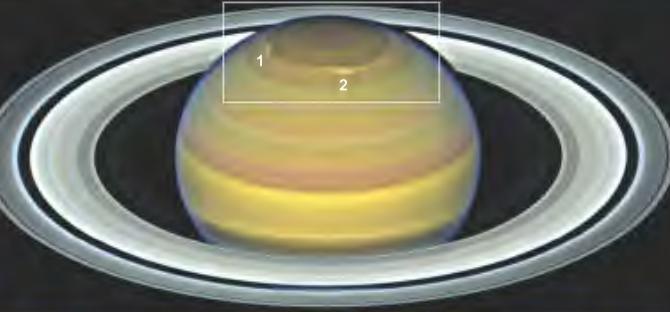
Jets of water ice, complex organics and other contaminants are jettisoned into the space environment surrounding Enceladus (above). The illustration to the *right* shows how the newly detected soluble organics present inside Enceladus' water-percolated hydrothermally active hot core can react to form e.g. amino acids. Then they rise upward through the ocean, adsorb onto water ice grains, and are expelled into space to be tasted by Cassini.

"Low-mass nitrogen-, oxygen-bearing, and aromatic compounds in Enceladean ice grains", Khawaja, *et al.*, MNRAS, 489, 2019.
doi:10.1093/mnras/stz2280

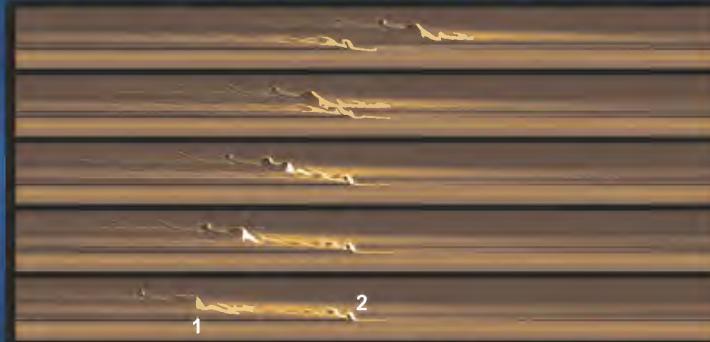
The presence of the detected reactive compounds, along with liquid water and hydrothermal activity, bolsters the hypothesis that Enceladus' ocean may be a habitable environment for life.



Discovering Saturn's New Polar Storms



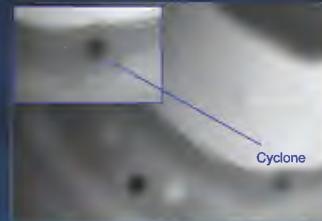
Hubble Space Telescope image showing storms 1 and 2 on June 6, 2018



Numerical simulations of the interaction and evolution of two storms

A. Sánchez-Lavega, E. García-Melendo, J. Legarreta, R. Hueso, T. del Río-Gaztelurrutia, J. F. Sanz-Reguena, S. Pérez-Hoyos, A. A. Simon, M. H. Wong, M. Soria, J. M. Gómez-Forellad, T. Barry, M. Delcroix, K. M. Sanyal, J. J. Blalock, J. L. Gunnarson, U. Dyudina and S. Ewald, A complex storm system in Saturn's north polar atmosphere in 2018, Nature Astronomy (2019).

On the night of March 29, 2018, amateur astronomers captured the presence of a small, but bright, white storm on the disk of the ringed planet, Saturn, near its north pole. Within a few days the spot grew in size, reaching about 4,000 km in length becoming the most remarkable detail on Saturn's disk. About two months later a second storm appeared, northwards of it on the planet. In the following months a third and a fourth spot, emerged much closer to the polar region, on the edge of the famous hexagon wave. The interaction between them generated a new planetary scale disturbance, extending along a latitude band that was something never observed before.



The first storm arose inside a cyclonic vortex first seen in images obtained by the Cassini spacecraft before its destruction in September 2017, and months prior to the 2018 discovery.

Cassini ISS image showing the precursor cyclone on 7 March 2017

Numerical models that simulate these storms showed that their energy is intermediate between the small scale storms (about 1,000 km) and the giant ones, known as Great White Spots (GWS), a huge and rare type of storms whose head reach more than 10,000 km and expand rapidly East and West around the planet. The GWS phenomenon has been reported six times on Saturn with the last event having occurred in 2010 at mid-latitudes. It was studied in detail with Cassini instruments. The energy released by moist convection at the [deep water](#) clouds pump all these storms. The storm system observed in 2018 has emerged in the northern hemisphere, as the GWS, and seems to have followed their formation rate cycle of one every 30 or 60 years.

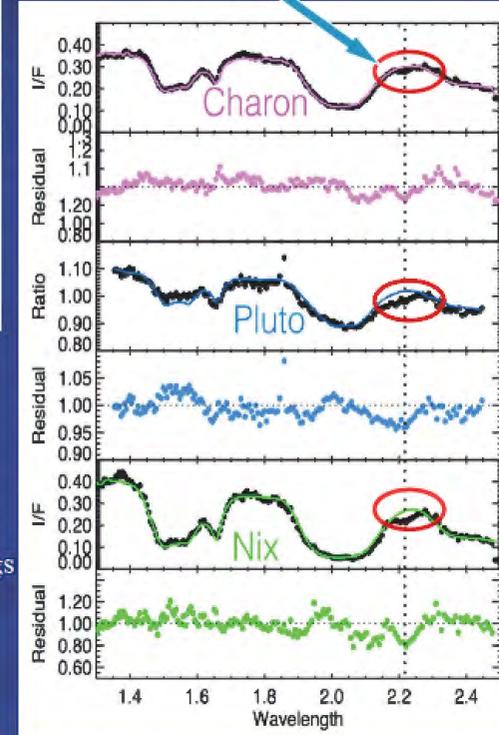
Ammonia spectral band on Pluto and cryovolcanism

New Horizons discoveries:

- Exposures of red-colored H₂O ice show absorption band of NH₃ hydrate or ammoniated compounds (possibly a salt).
- Exact identification is ambiguous, owing to limited spectral data.
- This absorption band is also seen on Charon and Nix (both rich in H₂O ice).
- Nearly all exposures of H₂O ice on Pluto are colored and carry NH₃ spectral signature
- Some exposures of colored, ammoniated H₂O ice suggest effusion from subsurface source(s)



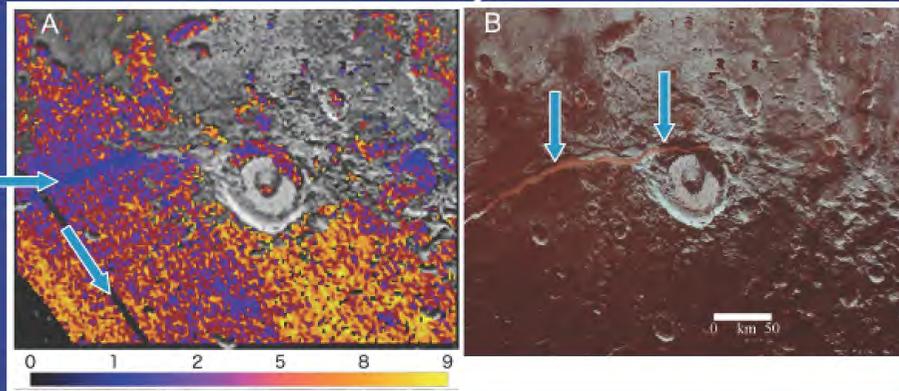
Ammonia spectral band on Charon, Pluto, and Nix



Ammonia absorption (colors) in H₂O ice.

Strongest

Band weakens away from Virgil Fossae trough



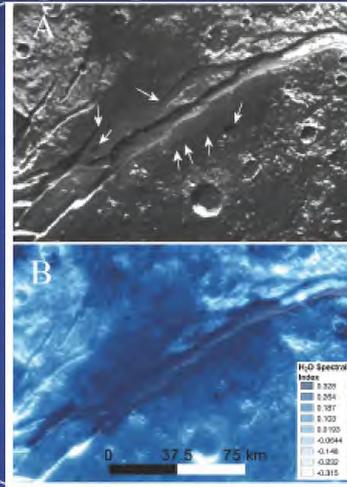
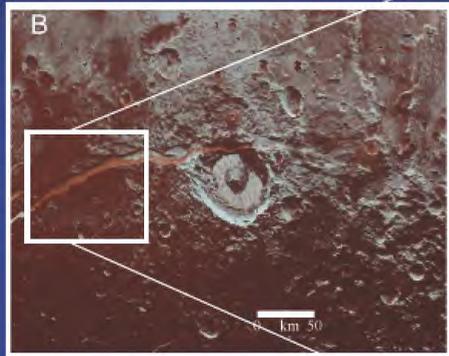
Ultra-red material in trough and surroundings

Strong NH₃ concentration Weaker

New Horizons LEISA spectra

- NH_3 is destroyed at an unknown rate in Pluto's environment, but the presence of its spectral band suggests relatively recent cryovolcanism.

- Muted topography and the distribution of the ammoniated H_2O are consistent with cryoclastic fountains originating from the fault on the wall of the trough.



- The color of the ammoniated H_2O is taken to indicate a complex organic component (tholin) formed by thermal processes in the subsurface reservoir.

- This view is supported by lab experiments and by geochemical modeling.

- This fluidized tholin is a third source of complex organic material on Pluto's surface, together with tholins formed in the atmosphere and in ices on the surface.



Outer Solar System: Many Worlds to Explore



OPAG is the Comparative Planetology AG

