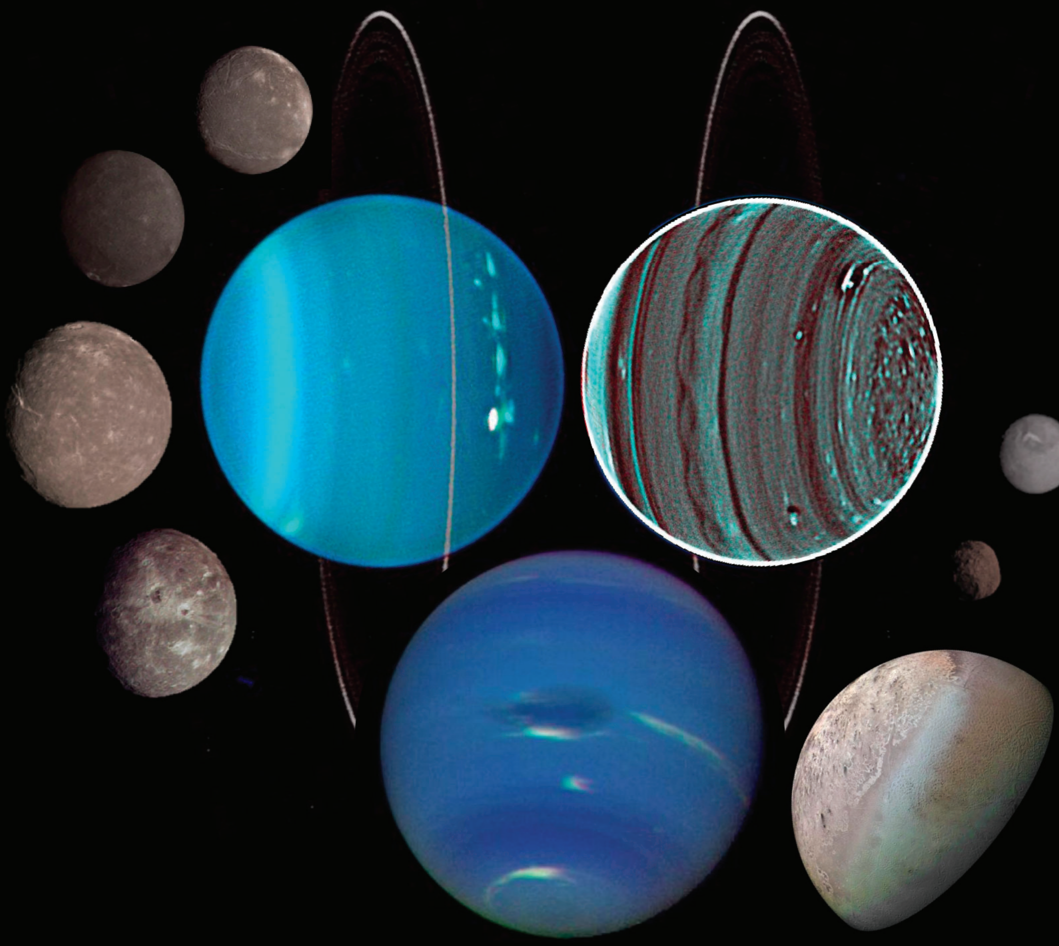
Ice Giant Systems 2020

Discussion Meeting at the Royal Society, London

Programme Book



Plenary at Royal Society: January 20th-21st
Posters: January 20th
Parallel Splinters at Burlington House: January 22nd

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Plenary Programme

Day One: January 20th 2020

Session 1 09:00-12:30: Ice Giant Planets

- 09:15-09:45 *Origin, evolution, and internal structure of the ice giants,* Professor Ravit Helled, University of Zurich, Switzerland
- 09:45-10:15 *Interior structure and energy balance on the Ice Giants,* Dr Jonathan Fortney, University of California, Santa Cruz, USA
- 10:15-10:30 Discussion - interiors objectives
- 10:30-11:00 Coffee break
- 11:00-11:25 *Atmospheric dynamics and cloud structure of the ice giants,* Dr Ricardo Hueso, University of Bilbao, Spain
- 11:25-11:50 *Photochemistry in the atmospheres of Uranus and Neptune,* Dr Julianne Moses, Space Science Institute, USA
- 11:50-12:15 *The upper atmospheres of the ice giants,* Dr Henrik Melin, University of Leicester, UK
- 12:15-12:30 Discussion 2 - Atmospheric objectives

Session 2 13:30-15:00: Ice Giant Magnetospheres

- 13:30-13:55 *Dynamos of ice giant planets,* Dr Krista Soderlund, University of Texas at Austin, USA
- 13:55-14:20 *Ice giant magnetospheres,* Dr Carol Paty, University of Oregon, USA
- 14:20-14:45 *Ice giant auroras,* Dr Laurent Lamy, Observatoire de Paris, PSL, CNRS, France
- 14:45-15:00 Discussion - magnetic field objectives
- 15:00-15:30 Tea break

Session 3 15:30-17:00: Agency Perspectives

- 15:30-16:00 *US Perspectives on ice giant missions,* Dr Mark Hofstadter, JPL/Caltech, USA
- 16:00-16:30 *ESA perspectives on ice giant missions,* Dr. Fabio Favata and Dr. Luigi Colangeli
- 16:30-17:00 Discussion - individual agencies and mission proposals

Poster Session 17:00-18:30

Day Two: January 21st 2020

Session 4 09:00-12:30: Cross-disciplinary perspectives

- 09:00-09:25 *Lessons learned from (and since) the Voyager 2 flybys of Uranus and Neptune,* Dr Heidi Hammel, Association of Universities for Research in Astronomy, USA
- 09:25-09:50 *The exoplanet perspective,* Dr. Hannah Wakeford, Space Telescope Science Institute, USA
- 09:50-10:15 *Cross-NASA divisional relevance of an ice giant mission,* Dr Abigail Rymer, JHU-APL, Maryland, USA
- 10:15-10:30 Discussion - summary of knowledge gaps
- 10:30-11:00 Coffee

Session 5 11:00-12:30: Ice Giant Systems

- 11:00-11:25 *The rings and inner satellites of Uranus and Neptune,* Dr Mark Showalter, SETI Institute, USA
- 11:25-11:50 *The Uranian satellite system,* Dr Elizabeth Turtle, JHU-APL, Maryland, USA
- 11:50-12:15 *Triton and the Kuiper Belt connection,* Dr Michele Bannister, Queen's University Belfast, UK
- 12:15-12:30 Discussion - Satellite/rings objectives

Session 6 13:30-17:00: Enabling technologies

- 13:30-13:55 *Mission design prospects,* John Elliot, JPL, USA
- 13:55-14:20 *Enabling technologies for ice planet exploration,* Dr Thomas R Spilker, Independent Consultant, USA
- 14:20-14:45 *The development of European radioisotope space nuclear power systems,* Dr Richard Ambrosi, University of Leicester, USA
- 14:45-15:00 Discussion - technologies
- 15:00-15:30 Tea
- 15:30-16:00 *Strategy for coordination 2020+,* Dr Amy Simon, NASA Goddard Spaceflight Center, USA, and Dr Mark Hofstadter, JPL/Caltech, USA
- 16:00-17:00 Panel discussion

Splinter Programme

Ice Giant Planets - Origins, Interiors, and Atmospheres (Royal Astronomical Society)

Talks are 15 minutes unless otherwise stated - plan for 12 minutes with 3 minutes of Q&A and handover. Please bring slides to the Session Chair in advance of your session.

Session 1: Origins and Interiors (10:00-12:00)
Chair: Olivier Mousis

- 10:00-10:15: Introduction (Chair)
- 10:15-10:30: Atreya et al. - Science and Measurements Critical to Unravel the Origin and Migration of the Icy Giant Planets
- 10:30-10:45: Mousis et al. - Key Atmospheric Signatures for Identifying the Source Reservoirs of Volatiles in Uranus and Neptune
- 10:45-11:00: Mandt et al. - Determining the Origin of the Ice Giants' Building Blocks Based on Analog Measurements from Comets
- 11:00-11:15: Millot et al. - Laser-driven shockwave compression to explore new states of matter at planetary interior conditions
- 11:15-11:30: Reinhardt et al. - Bifurcation in the history of Uranus and Neptune: the role of giant impacts
- 11:30-11:45: Kegerreis et al. - Knocking Over an Ice Giant: High-Resolution Simulations of Collisions and their Consequences
- 11:45-12:00: Hill et al. - Double-diffusive convection models of Uranus and Neptune

Lunch & Posters (Geological Society, 12:00-13:00)

Session 2: Atmospheres I (13:00-14:45)
Chair: Ricardo Hueso

- 13:00-13:15: Guillot et al. - Uranus and Neptune are key to understand planets with hydrogen atmospheres
- 13:15-13:30: Tortora et al. - Gravity and Atmospheric Science at Ice Giants through Radio Tracking from Earth
- 13:30-13:45: Cavalié et al. - Ice Giant atmospheric chemistry and dynamics: from tropospheres to ionospheres
- 13:45-14:00: Teanby et al. - Is Neptune Really an Ice Giant?
- 14:00-14:15: Moses et al. - Chemical Consequences of a Large Cometary Impact on Neptune
- 14:15-14:30: Simon et al. - Hubble OPAL Observations of Uranus and Neptune: 2014-2019
- 14:30-14:45: Sánchez-Lavega et al. - Numerical simulations of Neptune's Dark Spots

Afternoon Break (14:45-15:15)

Session 3: Atmospheres II (15:15-17:00)
Chair: Amy Simon

- 15:15-15:30: Irwin et al. - Exploring clouds and composition of Ice Giants in the visible/near-IR.
- 15:30-15:45: Roman et al. - Mid-IR imaging of Neptune from VLT-VISIR, 2008-2018: stratospheric changes and comparison to Uranus
- 15:45-16:00: Orton et al. - Mid-Infrared Through Submillimeter Observations of Uranus and Neptune
- 16:00-16:15: Toledo et al. - Microphysical simulations of methane clouds in the atmosphere of the ice giants
- 16:15-16:30: Rowe-Gurney et al. - Longitudinal Variations in the Stratosphere of Uranus from the Spitzer Infrared Spectrometer
- 16:30-16:45: Sinclair et al. - Spatial structure in Neptune's 7.90-µm stratospheric CH_4 emission, as measured by VLT-VISIR
- 16:45-17:00: Martin-Torres et al. - Non-Local Thermodynamic Equilibrium model for the mid-infrared emissions in the atmospheres of Uranus and Neptune

Ice Giant Systems - Magnetospheres, Auroras, Satellites and Rings (Geological Society)

Session 1: Ice Giant Magnetospheres (10:00-12:00)
Chair: Chris Arridge

- 10:00-10:15: Introduction (Chair)
- 10:15-10:40: Kollmann et al. - Magnetospheric Studies: A requirement for addressing interdisciplinary mysteries in the Ice Giant systems
- 10:40-11:00: Masters et al. - A More Viscous-Like Solar Wind Interaction With the Ice Giant Planets
- 11:00-11:20: Griton et al. - Magnetohydrodynamic simulations of a Uranus type rotating magnetosphere at equinox and solstice
- 11:20-11:40: Cohen et al. - The Ice Giant Radiation Belts
- 11:40-12:00: Manners et al. - Ultra-Low-Frequency Waves throughout the Solar System: Implications for the Ice Giant

Lunch & Posters (Geological Society, 12:00-13:00)

Session 2: Ice Giant Systems (13:00-14:45)
Chair: Adam Masters

- 13:00-13:15: Hsu et al. - Composition Mapping the Rings and Moons of Ice Giants
- 13:15-13:30: Arridge et al. - Detectability of Induction Signatures from Subsurface Oceans at Uranus' Main Satellites
- 13:30-13:45: Dunn et al. - Soft X-ray Imaging for the Ice Giants: Satellite Composition and the Global Magnetosphere
- 14:00-14:15: Kramer et al. - Alternate Radioisotope Heat Sources for Icy Moons Exploration

- 14:15-14:30: Bertrand et al. - Climate modeling on Triton with a hierarchy of models
- 14:30-14:45: Smith et al. - Neutral Tori: Potential key insight into Ice Giant Magnetospheres

Afternoon Break (14:45-15:15)

Session 3: Ice Giant Auroras and Plasmas (15:15-17:00)
Chair: Ian Cohen

- 15:15-15:30: Moore et al. - The "H3+ Problem" at Neptune
- 15:30-15:45: Melin et al. - Near-infrared observations of Uranus: spatially resolving of the H3+ ionosphere
- 15:45-16:00: Ebert et al. - Plasma Instruments for Magnetospheric Science at Uranus and Neptune
- 16:00-16:15: Jones et al. - Plasma Instrumentation for an Ice Giants Mission
- 16:15-16:30: André et al. - An Energetic Particle Monitor for Ice Giant Atmospheric Probes
- 16:30-16:45: Sulaiman et al. - The Scientific Potential of a Radio and Plasma Wave Experiment on an Ice Giant Mission
- 16:45-17:00: Discussion (All)

Poster List

Posters to be displayed on Monday January 20th at the Royal Society (17:00-18:30).

1. André et al. - An Energetic Particle Monitor for Ice Giant Atmospheric Probes
2. Andrews et al. - A radio and plasma wave experiment for the ice giants
3. Apéstigue et al. - INTA's Mars miniature sensors: synergies for Ice Giants exploration
4. Aslam et al. - Net Flux Radiometer for Ice Giant Probes
5. Atkinson et al. - Possible Payload for Future Ice Giant Entry Probe Missions
6. Blanc et al. - Science Goals and Mission Objectives for the Future Exploration of Ice Giants Systems: A Horizon 2061 Perspective
7. Brozović et al. - Know before you go: status of the ephemerides and physical parameters in the Uranus and Neptune systems
8. Cohen et al. - New Frontiers-class Uranus Orbiter: Exploring the feasibility of achieving multidisciplinary science with a mid-scale mission
9. Dalba et al. - Adding Context to the Exoplanet Case for In Situ Exploration of the Ice Giants
10. de Pater et al. - Ice Giant Research at UC Berkeley
11. DiBraccio et al. - Voyager 2 Constraints on Plasmoid-based Transport at Uranus
12. Dobinson et al. - Breaking Neptune's Methane/Haze Degeneracy
13. Ebert et al. - Plasma Instruments for Magnetospheric Science at Uranus and Neptune
14. Friedson et al. - Nonradial oscillations of Uranus
15. Gershman et al. - Alfvénic Mach Number Variations in the Outer Solar System: Implications for Uranus and Neptune
16. Greathouse et al. - The Alice/UVS Line of Instruments: Uniquely Equipped for Ice Giant System Studies
17. Hadid et al. - Polarization electrostatic field in the presence of negatively charged grains: implications for dust levitation near Saturn's F ring
18. Hedman et al. - Using the rings of Ice Giants to probe their planets' interiors, magnetospheres and moons.
19. Izraelevitz et al. - Feasibility of an Ice Giant Deep Probe (1kbar)
20. Jones et al. - Plasma Instrumentation for an Ice Giants Mission
21. Lamy et al. - A modern digital High Frequency Receiver to explore the Ice Giants radiosources
22. Leonard et al. - Tectonic resurfacing on Ariel, a Uranian satellite
23. Lopes et al. - Cryovolcanism in the Outer Solar System
24. Morooka et al. - Science opportunities with the Langmuir probe experiment for the Icy Giants
25. Nixon et al. - The CIRS-Lite Infrared Fourier Transform Spectrometer for missions to the Ice Giants
26. Nordheim et al. - Cosmic ray ionization of Ice Giant atmospheres
27. Probst et al. - IPED: Study on the Impact of the Entry Zone on the Trajectory and Design of a Planetary Entry Probe
28. Sayanagi et al. - SNAP: Small Next-generation Atmospheric Probe
29. Scheibe et al. - Thermal Evolution of Uranus and Neptune
30. Soyuer et al. - Constraining the Depth of the Winds in Uranus and Neptune
31. Venkatapathy et al. - Enabling Entry Technologies for Ice Giant Missions

Posters to be displayed at the Geological Society during lunch on Wednesday January 22nd:

1. Colyer et al. - Semi-grey radiative modelling of giant-planet atmospheres
2. Brueshaber et al. - Polar Vortex Dynamics on Gas and Ice Giant Planets
3. d'Ollone et al. - Radiative modelling of the Ice Giant atmospheres – A first step toward Global Circulation Models
4. Nordheim et al. - Digital elevation modelling of Uranian moons using Voyager 2 images
5. Atkinson et al. - Measurements of Ice Giant Atmospheric Dynamics and Composition from Radiometric Tracking of an Entry Probe

Plenary Abstracts & Speakers

The following abstracts are organised according to the order of the plenary sessions.

Contributed Abstracts

The following abstracts are organised by sub-theme and surname of the lead author.

Origins

Science and Measurements Critical to Unravel the Origin and Migration of the Icy Giant Planets

S.K. Atreya (University of Michigan), M.H. Hofstadter (JPL-Caltech), O. Mousis (Aix Marseille Université), K.R. Reh (JPL-Caltech), M.H. Wong (University of California, Berkeley)

Uranus and Neptune are the missing pieces of the outer solar system formation puzzle. They are also the only analogs for half of all confirmed exoplanets with known radii. Their comprehensive exploration is thus both timely and essential. This abstract focuses on the question of their formation. The findings of the Voyager flybys were instrumental in showing that elemental abundances are key to unmasking the mystery of the origin of the giant planets, and only entry probes are capable of measuring most of them. That was the scientific rationale for the Galileo Probe at Jupiter. The Probe's findings fundamentally altered our view of the formation of Jupiter. Juno is well on its way to filling in the remaining gap – the oxygen elemental abundance – at Jupiter. For the Icy Giants, most critical measurements are the abundances and the isotopic ratios of the noble gases, He, Ne, Ar, Kr and Xe, together with the depth profiles of the condensibles CH_4, H_2S, NH_3 and H_2O. Entry probes deployed to 5-10 bar level can accomplish most of this. Orbiter data on atmospheric structure, disequilibrium species such as CO, and the interior would be highly complementary to the probe data.

Further Reading:

[1] *S.K Atreya et al. (2020)* Deep Atmosphere Composition, Structure, Origin, and Exploration, with Particular Focus on Critical in situ Science at the Icy Giants, Sp. Sci. Rev. Online link expected by the time of this meeting.
[2] *O. Mousis et al. (2020)* Key Atmospheric Signatures for Identifying the Source Reservoirs of Volatiles in Uranus and Neptune, Online link expected by the time of this meeting.
[3] *M. Hofstadter et al (2019)* Uranus and Neptune Missions: A Study in Advance of the Next Planetary Science Decadal Survey, Planet. Space Sci. https://doi.org/10.1016/j.pss.2019.06.004.
[4] *S.K. Atreya et al. (2019)* The Origin and Evolution of Saturn, with Exoplanet Perspective, pp5–43 in *Saturn in the 21st Century* (eds. K. Baines, et al.), Cambridge University Press.

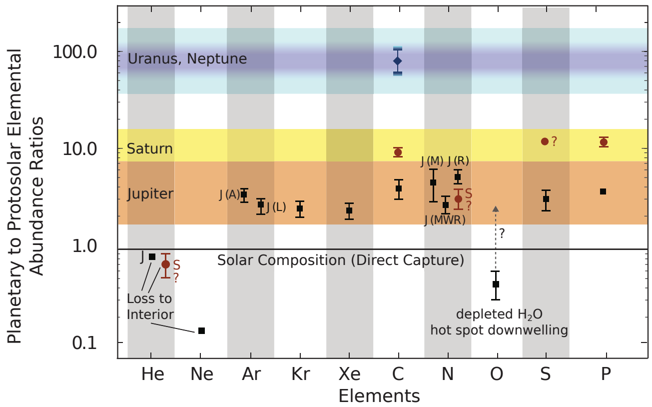

Figure 1 Elemental abundances of the giant planets. "N" in Jupiter represents values obtained from ammonia measurements of the Galileo probe mass spectrometer [J(M)], probe radio signal attenuation [J[R}] and the Juno microwave spectrometer [J(MWR)], whereas "Ar" values are shown using both Asplund et al. [J(A)] and Lodders [J(L)] solar values (values generally agree for other elements). Saturn's He and N are labeled S. N/H of Saturn is a lower limit, and S/H is highly questionable. Only C/H is determined for Uranus and Neptune from ground-based CH_4 observations. See Atreya et al. (2019) and references therein for all relevant details.

Adding Context to the Exoplanet Case for In Situ Exploration of the Ice Giants

P.A. Dalba (@Paul_Dalba, University of California Riverside)

Uranus and Neptune are members of a class of planet that is common throughout our galaxy. Partly due to their high occurrence rate, ice giant exoplanets will shape our understanding of how all planetary systems form and evolve. Yet, our inability to visit these exoplanets will always present a challenge to their characterization. We can overcome this obstacle by using in situ observations of Uranus and Neptune to inform our exoplanet investigations. I intend for this poster presentation to expand upon the exoplanet motivation behind sending a mission to Uranus or Neptune. Collaboration with astrophysics is beneficial to an ice giant mission and is bolstered by an understanding of the context from the exoplanet side. This includes substantial discoveries made from ice giant exoplanets so far, as well as the set of measurements, data, and tools we expect to have at our disposal in the coming years. This presentation also highlights areas where the planetary and exoplanetary science goals currently overlap and other areas where such overlap may be increased in the future.

Knocking Over an Ice Giant: High-Resolution Simulations of Collisions and their Consequences

Jacob Kegerreis (Durham University), Vince Eke (Durham University), Pedro Gonnet (Google Switzerland), Don Korycansky (University of California, Santa Cruz), Richard Massey (Durham University), Matthieu Schaller (Leiden Observatory) Luís Teodoro (NASA Ames).

Uranus spins on its side, presumably the result of a giant impact. We model collisions onto the young Uranus to test which impact scenarios can explain the planet's tilted rotation, and what the other consequences of this violent event would be. We confirm that a wide range of impacts can reproduce the spin for an impactor at least twice the mass of the Earth. Using hydrodynamical simulations with over 100 times higher resolution than the current standard, we also determine that previous simulations produced numerically unconverged results. Our converged simulations rule out some scenarios that were thought to be plausible. Some grazing collisions deposit significant impactor material in a hot, high-entropy shell, which might create a thermal boundary layer to help explain Uranus' low luminosity and lack of heat flow from the interior. Significant ice and rock can be scattered into orbit and be available for inner satellite formation. Most of the atmosphere survives the impact, but over half can be ejected beyond the Roche radius. This new generation of fast, fully public simulation tools offers great opportunities to connect models of early accretion and impacts to the long-term interior and satellite evolution of ice giant systems.

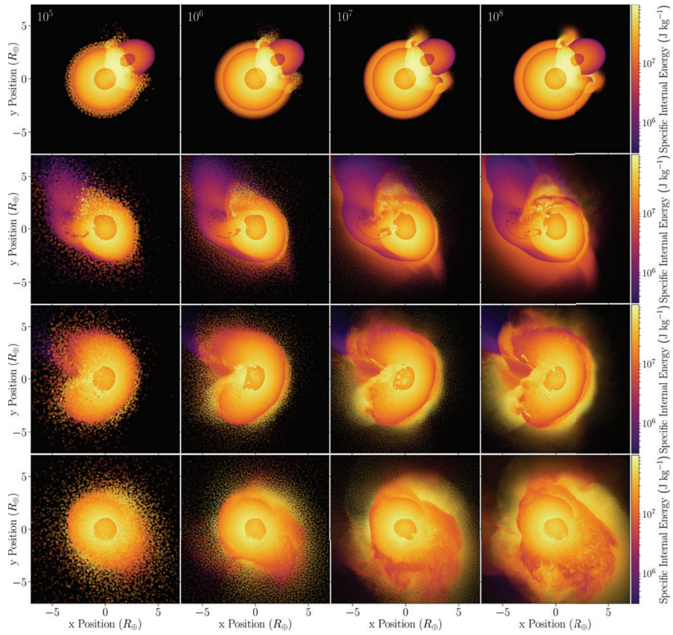

Figure 2 Snapshots in the early stages of the same giant impact on Uranus at the same times from simulations with the ~10^5 SPH particles (left panels) typical in the literature up to the 10^8 (right panels) in our simulations, using the open-source code SWIFT. This reveals unprecedented detail in the evolution of the interior and the debris and, crucially, confirms numerical convergence.

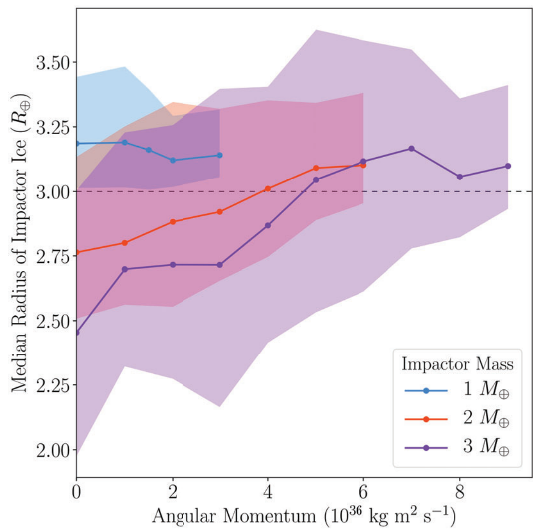

Figure 3 The radial deposition of the impactor's material inside the final planet for different collision scenarios, with implications for the creation of composition gradients and thermal boundary layers for Uranus' long-term evolution. The shaded regions show the 1σ percentile range of the material distribution. The dashed line shows the approximate radius of the ice-atmosphere boundary in the proto-Uranus targets.

Optional Further Reading:
Kegerreis et al. MNRAS, 487:4, August 2019:
arxiv.org/pdf/1901.09934.pdf
Kegerreis et al. ApJ, 861:52, July 2018:
arxiv.org/pdf/1803.07083.pdf
Animation:
icc.dur.ac.uk/giant_impacts/uranus_1e8_anim.mp4

Determining the Origin of the Ice Giants' Building Blocks Based on Analog Measurements from Comets

K.E. Mandt (@mommascientist, JHU Applied Physics Laboratory), O. Mousis (Laboratoire d'Astrophysique de Marseille), S. Treat (JHU Applied Physics Laboratory/University of Maryland)

The abundances of the heavy elements and isotopic ratios in the giant planet atmospheres can be used to trace the composition of volatiles that were present in the icy solid material that contributed to their formation. The first definitive measurements of noble gas abundances and isotope ratios at comet 67P/Churyumov-Gerasimenko (67P/C-G) have important implications for the formation conditions of the 67P/C-G building blocks. We evaluate how these results can improve understanding of the formation conditions of the building blocks of the Ice Giants and discuss how future measurements of Ice Giant atmospheric composition can be interpreted partially illustrated by Fig. 1. We determine the best approach for comparing comet observations with giant planet composition, and would be the current composition of the Ice Giant atmospheres based on four potential sources for their building blocks as illustrated in Fig. 2. The primary constraints for building block composition are the bulk abundance of carbon relative to nitrogen, the noble gases relative to carbon and to nitrogen, Kr/Ar, Xe/Ar and the xenon isotopes. In situ measurements of these quantities by a Galileo-like entry probe in the atmosphere(s) of Uranus and/or Neptune should place important constraints on the formation conditions of the Ice Giants.

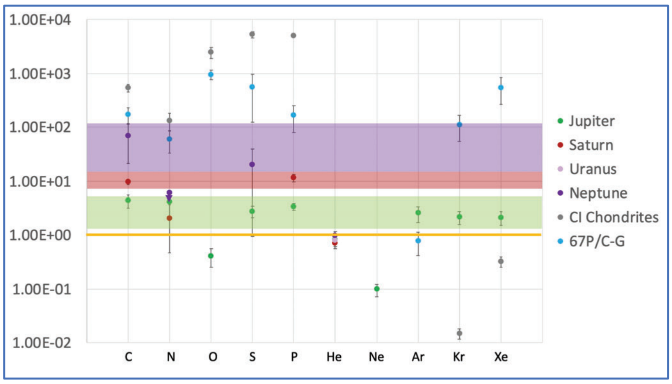

Figure 4 Illustration of the elemental abundances relative to hydrogen, X/H, scaled to solar hydrogen $(X/H)_{Observed}/(X/H)_{Solar}$. The colored bars show the predicted range of enhancement of the heavy elements assuming that the building blocks for Jupiter (green), Saturn (red), and Uranus and Neptune (purple) were solar composition. The nitrogen estimate for Uranus and Neptune is an upper limit.

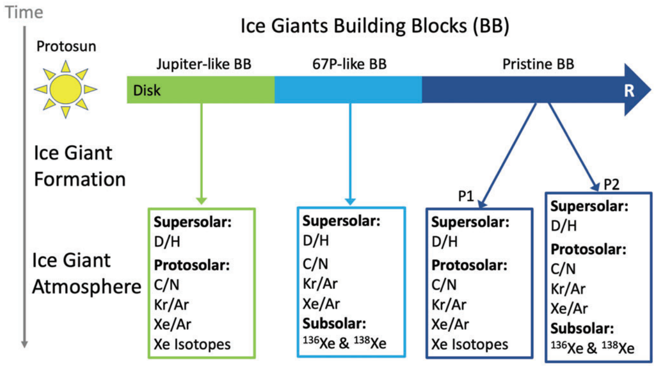

Figure 5 Illustration of four scenarios for the origin of the Ice Giants building blocks based on the composition of their current atmospheres. All of the building blocks would have a supersolar D/H from water ice enriched in D/H. Jupiter-like and the 1st category of pristine building blocks, P1, would have protosolar values for all other constraints and represent the end members of reprocessing in the PSN. The 67P-like building blocks would be similar in all constraints to the observations made for 67-P/C-G and represent the partially reprocessed pristine building blocks, P2, which would be protosolar in all constraints except for the xenon isotopes, which would be like those observed in 67P/C-G.

Laser-driven shockwave compression to explore new states of matter at planetary interior conditions

M. Millot, F. Coppari, S. Hamel and J.H. Eggert (Lawrence Livermore National Laboratory), J.R. Rygg (University of Rochester, NY)

Laser-driven dynamic compression can now recreate the extreme conditions existing deep inside large planets and exoplanets to explore how elevated pressure and temperature modify the properties of the constituent materials and contribute to an improved understanding of planetary formation and evolution.

We will present the first experimental evidence for superionic water ice obtained through a combination of advanced shock compression schemes including ultrafast optical diagnostics and *in-situ* x-ray diffraction (XRD). In these experiments, we used shock-waves to simultaneously compress and heat liquid water samples to 100-400 GPa and 2,000-3,000 K, near the conditions expected in the deep interior of Uranus and Neptune. The ultrafast XRD measurements show that water solidifies into nanometer-sized ice grains within a few nanoseconds and provide unambiguous evidence for a crystalline lattice of oxygen in superionic water ice. Further, the XRD data allow us to document ice's compressibility at unprecedented conditions and unravel a temperature- and pressure-induced phase transformation from a body-centered-cubic ice (likely ice X) to a new face-centered-cubic, superionic ice that we named ice XVIII.

The new data suggest a possible physical explanation for the thin-shell dynamo geometry hypothesis for the ice giants. Part of this work was performed at LLNL under Contract DE-AC52-07NA27344. LLNL-ABS-797459.

Further Reading:

Experimental evidence for superionic water ice using shock compression,
Millot, et al., Nature Physics **14**, 297–302 (2018)
https://www.nature.com/articles/s41567-017-0017-4
Nanosecond X-ray diffraction of shock-compressed superionic water ice,
Millot, Coppari et al., Nature **569**, 251–255 (2019)
https://www.nature.com/articles/s41586-019-1114-6

Key Atmospheric Signatures for Identifying the Source Reservoirs of Volatiles in Uranus and Neptune

O. Mousis (Aix Marseille Univ), A. Aguichine (Aix Marseille Univ), D.H. Atkinson (JPL-Caltech), S.K. Atreya (University of Michigan), T. Cavalié (Univ. Bordeaux), J.I. Lunine (Cornell University), K.E. Mandt (APL-JHU), T. Ronnet (Lund Observatory)

We investigate the enrichment patterns of several delivery scenarios of the volatiles to the atmospheres of ice giants, having in mind that the only well constrained determination made remotely, i.e. the carbon abundance measurement, suggests that their envelopes possess highly supersolar metallicities, i.e. close to two orders of magnitude above that of the PSN. In the framework of the core accretion model, only the delivery of volatiles in solid forms (amorphous ice, clathrates, pure condensates) to these planets can account for the apparent supersolar metallicity of their envelopes. In contrast, because of the inward drift of icy particles through various snowlines, all mechanisms invoking the delivery of volatiles in vapor forms predict subsolar abundances in the envelopes of Uranus and Neptune. Alternatively, even if the gravitational instability mechanism remains questionable in our solar system, it might be consistent with the supersolar metallicities observed in Uranus and Neptune, assuming the two planets suffered subsequent erosion of their H-He envelopes. Because current technologies do not enable entry probes to reach levels deeper than a few dozens of bars in the atmospheres of giant planets, subsequent probe measurements should focus on the determination of the abundances of the noble gases since these latter never condense in the envelopes of Uranus and Neptune and are expected to be well mixed, even in the top layers at the ~1-bar level. Because these species are highly sensitive to the considered mechanism of volatiles delivery, they should be considered in the top priority of the measurements to be made by an ice giant entry probe.

Optional Further Reading:

[1] *O. Mousis et al. (2020)* Key Atmospheric Signatures for Identifying the Source Reservoirs of Volatiles in Uranus and Neptune, Space Science Reviews, submitted. [2] *S.K Atreya et al. (2020)* Deep Atmosphere Composition, Structure, Origin, and Exploration, with Particular Focus on Critical in situ Science at the Icy Giants, Space Science Reviews, accepted. [3] *D.H. Atkinson et al. (2020)* Model Payload for Ice Giant Entry Probe Missions, Space Science Reviews, submitted.

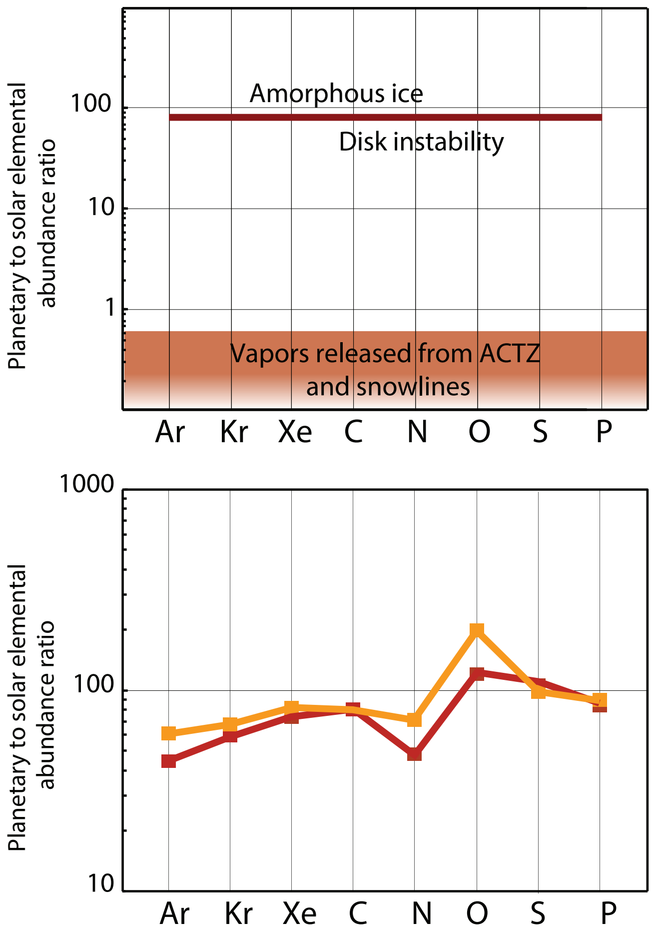

Figure 6 Signatures of the different scenarios of volatiles delivery in the envelopes of Uranus and Neptune, assuming homogeneous mixing and that the measured C abundances are representatives of the bulk values. Calibration is done on a C abundance assumed to be 80 times protosolar. Top panel: volatiles delivered via disk instability or amorphous planetesimals in the framework of the core accretion model display significant supersolar and homogeneous volatiles enrichments, compared to their protosolar abundances. Volatiles delivered as vapors desorbed from the ACTZ or resulting from the sublimation of pure condensates at their respective snowlines display subsolar abundances in the envelopes. Bottom panel: atmospheric signatures of volatiles accreted in the ice giants in forms of pure condensates (red lines) or clathrates (orange lines).

Bifurcation in the history of Uranus and Neptune: the role of giant impacts

Christian Reinhardt, Alice Chau, Joachim Stadel, Ravit Helled

Despite many similarities, there are significant observed differences between Uranus and Neptune: while Uranus is tilted and has a regular set of satellites, Neptune's moons are irregular. Also, Neptune seems to have an internal heat source, while Uranus is in equilibrium with solar insulation. Finally, structure models based on gravity data suggest that Uranus is more centrally condensed than Neptune. We perform a large suite of high-resolution SPH simulations to investigate whether these differences can be explained by giant impacts. For Uranus, we find that an oblique impact can tilt its spin axis and eject enough material to create a disk where the regular satellites are formed. Some of the disks are massive and extended enough, and consist of enough rocky material to explain the formation of Uranus' regular satellites. For Neptune, we investigate whether a head-on collision could mix the interior, and lead to an adiabatic temperature profile, which may explain its larger flux and higher moment of inertia value. We find that massive and dense projectiles can penetrate towards the centre and deposit mass and energy in the deep interior. We conclude that the dichotomy between the ice giants can be explained by violent impacts after their formation.

Further Reading:

Our work has been recently accepted and can be found under https://doi.org/10.1093/mnras/stz3271

Relevant previous works:

Stevenson 1986:
http://articles.adsabs.harvard.edu/pdf/1986LPI....17.1011S

Podolak and Helled 2012:
https://arxiv.org/pdf/1208.5551.pdf

Kurosaki and Inutsuka 2018:
https://arxiv.org/pdf/1811.05234.pdf

Kegerreis et al 2018:
https://ui.adsabs.harvard.edu/link_gateway/2018ApJ...861...52K/PUB_PDF

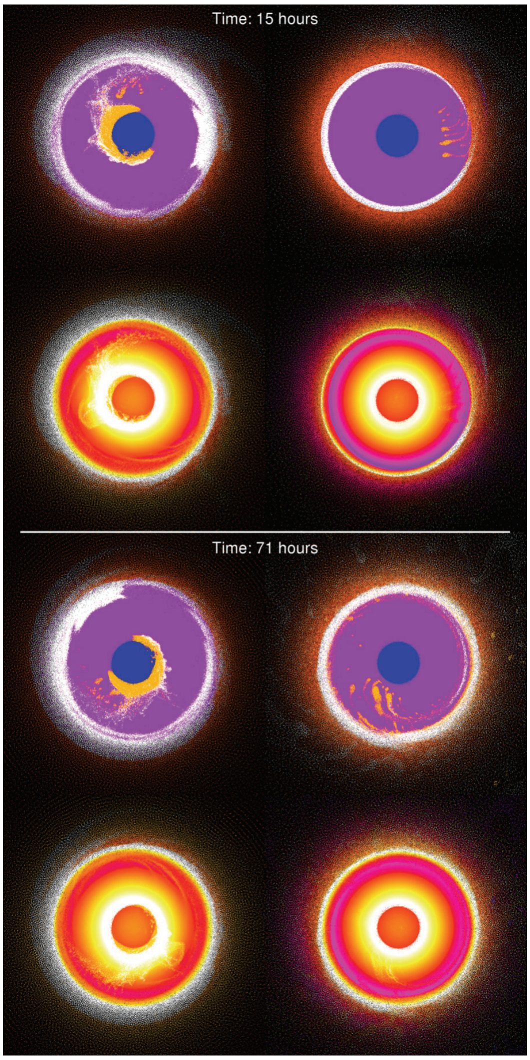

Figure 7 ***The planet's interior after a head-on (left) and a grazing (right) collisions.*** *Shown are the results for a giant impact on Neptune (differentiated 2 $M_\oplus$ impactor, $N = 5 \times 10^6$ particles, $v_\infty = 5$ km s^{-1}) for b = 0.2 (head-on, left) and b = 0.7 (grazing, right) 15 h (top panel) and 71 h (bottom panel) after the impact. The size of an individual snapshot is 8 $R_\oplus \times$ 8 $R_\oplus \times$ 1 $R_\oplus$. The top panels shows the origin of the material (target core: blue, mantle: violet, atmosphere: orange and impactor core: yellow, mantle: white). The bottom figures show the internal energy of the particles between 0 erg g^{-1} (black) and 10^{12} erg g^{-1} (white). For the head-on collision the projectile's core and part of its mantle penetrates deeply into the target. The atmosphere but also the planet's interior are substantially heated. In case of the grazing collision, during the the initial impact (top panel) the projectile only interacts with the target's atmosphere and upper mantle so it survives the first encounter. Much less material and energy is deposited in the planet and most of it remains in the atmosphere and upper mantle. The impactor remains bound to the planet and re-impacts two days later. This second collision is more head-on but since the projectile's core is eroded during the tidal encounter it can not impact the planet's core and the rock is distributed in the mantle. In both cases ~10% of the original H-He is ejected because of the impact.*

Interiors and Atmospheres

Polar Vortex Dynamics on Gas and Ice Giant Planets

Shawn Brueshaber (@DrVortex24, Western Michigan University), Kunio Sayanagi (Hampton University), Timothy Dowling (University of Louisville)

We present a shallow-water numerical model that reveals a mechanism governing the polar atmospheric dynamics of the giant planets. Exploration of the polar regions has produced surprisingly diverse results, from several tightly packed cyclones surrounding a central cyclone offset from the poles at Jupiter, to a single, intense, compact polar cyclone centered on each pole of Saturn. Observations suggest Uranus and Neptune have dominant, single polar cyclones too. These discoveries raise questions about the mechanism that differentiates these polar atmospheric dynamical regimes. The model is forced by small-scale stochastic mass pulses that parametrically represent cumulus storms. The effects of four parameters, the planetary Burger number, Bu = $(L_d/a)^2$ (L_d is the Rossby deformation radius, a is the planetary radius), input storm strength, s, the storm fraction ratio (proportion of cyclonic and anticyclonic storms injected into the domain), α, and storm size are systematically investigated. Bu emerges to be the most important, able to distinguish between four distinct dynamical regimes, which from large to small Bu matches observations of Jupiter, Saturn, and the Ice-Giants. By applying this correlation with respect to Bu in reverse, an observation of a particular polar regime could in principle used to constrain L_d.

Ice Giant atmospheric chemistry and dynamics: from tropospheres to ionospheres

T. Cavalié (Laboratoire d'Astrophysique de Bordeaux, University of Bordeaux, CNRS), M. Dobrijevic (Laboratoire d'Astrophysique de Bordeaux, University of Bordeaux, CNRS), J. Leconte (Laboratoire d'Astrophysique de Bordeaux, University of Bordeaux, CNRS), V. Hue (Southwest Research Institute), O. Venot (Laboratoire Interuniversitaire des Systèmes Atmosphériques, CNRS)

Uranus and Neptune atmospheres remain mysterious in terms of composition and dynamics. Deep composition is key to constrain internal and formation processes but is difficult to measure with remote sensing techniques because of the condensation into various cloud layers of several key volatiles. Chemical complexification initiated by solar UV and magnetospheric electrons, as well as contamination by external sources (dust, comets, ring and satellite material), all occurring in the upper atmosphere but diffusing downward, can further complicate the situation because of the mixing of these various components caused by dynamics.

In this context, an atmospheric entry probe to measure key volatiles (e.g. noble gases, C, N, S, P) in the upper troposphere is highly desirable and would benefit from direct observational support from an orbiting spacecraft, as well as contextual ground-based supporting observations. All these measurements are essential to constrain the chemistry models we develop to better understand the composition and dynamics in the Ice Giant atmospheres. With a coherent set of models, ranging from 1D thermochemical and diffusion models for the tropospheres to 2D time-dependent photochemical models for the stratospheres and ionospheres, we will contribute to a better understanding of the Ice Giant composition and dynamics.

Further Reading:
We develop thermochemical models to constrain deep composition in the Ice Giants from observations and to support a future atmospheric probe mission.
Relevant papers are: Leconte et al. (2017, https://arxiv.org/abs/1610.05506), Cavalié et al. (2017, https://arxiv.org/abs/1703.04358), Mousis et al. (2018, https://arxiv.org/abs/1708.00235), Venot et al. (2019, https://arxiv.org/abs/1902.04939).
We also develop photochemical models (1D time-dependent and 2D seasonal) that account for neutral, ionic and isotopic chemistry. Relevant papers are: Dobrijevic et al. (2020, https://doi.org/10.1016/j.icarus.2019.07.009), Hue et al. (2018, https://arxiv.org/abs/1802.08697).

Semi-grey radiative modelling of giant-planet atmospheres

Greg Colyer (University of Oxford), Chin-Min Liu (University of Oxford), Peter Read (University of Oxford), Roland Young (UAE University)

We consider semi-grey radiative schemes for the giant-planet atmospheres, that are suitable for use within idealized radiative-convective model (RCM) and general circulation model (GCM) codes. In particular, building on the Oxford Jupiter model (Young et al. 2019) and on the work of Robinson and Catling (2012), we develop optical depth parameterizations for the ice giants. In radiative balance, formal solutions for the temperature profile are obtained in our general case, and exact analytic solutions are possible for useful classes of parameterization. These radiative balance results are applicable to the upper atmosphere where small-scale convection and large-scale circulation are absent or weak. We investigate their surprisingly rich properties at the top of the atmosphere, and consider the implications for boundary conditions when deployed in RCM and GCM codes.

We also propose a related parameterization scheme for radiatively active clouds. Finally, we consider the possibility of generalizing this approach to multiple frequency bands.

Further Reading:

1. R.M.B. Young, P.L. Read and Y. Wang, Icarus 326 (2019) 225, doi.org/10.1016/j.icarus.2018.12.005
2. T.D. Robinson and D.C. Catling, Ap. J. 757 (2012) 104, doi.org/10.1088/0004-637X/757/1/104

Ice Giant Research at UC Berkeley

Imke de Pater, J. Tollefson, E. Molter, M.H. Wong, P. Gao, E. Redwing, C. Moeckel, C. Goullaud, D. DeBoer, S. Paradis, A. Zorzi (University of California, Berkeley), S.Luszcz-Cook (Columbia University, New York), M. Showalter (SETI)

Cutting edge science is conducted at UC Berkeley on the Ice Giant systems (atmosphere, rings, and satellites of Uranus and Neptune).

Atmospheres: At radio wavelengths, using ALMA and the VLA (with R. Sault and B. Butler), we constrain the H2S and NH3 abundances down to ~50 bar on both planets, as a function of latitude. Using Keck and HST data, taken simultaneously with VLA data in Aug-Sep 2015, we model the clouds and hazes. On Neptune we look at winds, dark spots, and latitudinal variations over time using the entire archival HST dataset. With L. Sromovsky and P. Fry we continue to monitor cloud features, in particular near the north pole.

Rings: The rings of both planets have been observed with the Keck telescope at near-IR wavelengths. Thermal emission from Uranus' rings was detected at mm wavelengths with ALMA. Our most recent data on Uranus' rings will be used to investigate the opposition effect.

Small satellites: An analysis of 2015 Keck data shows an increase in the I/F since the Voyager era of all small moonlets (hemispheric difference?); Mab resembles Miranda in composition rather than Puck.

We will summarize a few recent results on our poster.

Breaking Neptune's Methane/Haze Degeneracy

J. Dobinson (University of Oxford), P. Irwin (University of Oxford), L. Fletcher (University of Leicester), G. Orton (JPL, CalTech, USA), N. Teanby (University of Bristol), D. Toledo (National Institute for Aerospace Technology, Spain).

This study presents observations that map haze and methane abundance in Neptune's atmosphere using the VLT's SINFONI instrument together with adaptive optics. At most near-IR wavelengths, there is a degeneracy between haze and methane. However, the H+K band available to the SINFONI instrument not only includes methane absorption features, but also strong collision induced absorption from H_2-H_2 and H_2-He interactions. This breaks the haze/methane degeneracy enabling both to be mapped at the same time, and potentailly provides insight into the source of excess methane in Neptune's tropopause.

Uranus and Neptune are key to understand planets with hydrogen atmospheres

T. Guillot (Observatoire de la Côte d'Azur/University of Tokyo)

Uranus and Neptune are the last unexplored planets of the Solar System. I show that they hold crucial keys to understand the atmospheric dynamics and structure of planets with hydrogen atmospheres. Their atmospheres are active and storms are believed to be fueled by methane condensation which is both extremely abundant and occurs at low optical depth. This means that mapping temperature and methane abundance as a function of position and depth will inform us on how convection organizes in an atmosphere with no surface and condensates that are heavier than the surrounding air, a general feature of gas giants (see figure). Using this information will be essential to constrain the interior structure of Uranus and Neptune themselves, but also of Jupiter, Saturn and numerous exoplanets with hydrogen atmospheres. Owing to the spatial and temporal variability of these atmospheres, an orbiter is required. A probe would provide a reference profile to lift ambiguities inherent to remote observations. It would also measure abundances of noble gases which can be used to reconstruct the history of planet formation in the Solar System. Finally, mapping the planets' gravity and magnetic fields will be essential to constrain their global composition, structure and evolution.

Further Reading:

Guillot, T. (2019). Uranus and Neptune are key to understand planets with hydrogen atmospheres. ESA White paper. [arXiv:1908.02092]

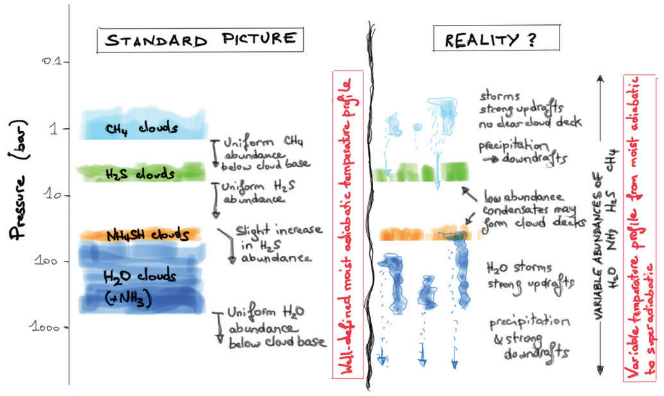

Figure 8 Sketch of possible cloud structures in Uranus and Neptune. The left side shows the standard picture which assumes that small-scale mixing maintains relatively well-defined cloud decks and a temperature profile close to a moist adiabat (accounting for the condensation of the different species). Any latitudinal variation may be explain by meridional circulation. The right side shows an alternative model in which, for abundant condensing species such as methane and water, storms occur. This implies strong updrafts, but also strong downdrafts due to rainout and evaporative cooling. On the other hand, less abundant species such as H_2S and NH_4SH may form relatively well-defined cloud decks. In this case, large temperature variations, from moist-adiabatic to super-adiabatic are to be expected.

Nonradial oscillations of Uranus

A.J. Friedson (Jet Propulsion Laboratory, California Institute of Technology)

A Doppler imager has been recommended for inclusion on an ice giant mission (*Ice Giants Pre-Decadal Final Report*, NASA, 2017). It would look for planetary-scale oscillations whose properties reveal aspects of internal structure. Currently, the proposed instrument is defined more by its science goals rather than its actual measurement objective, serving as a placeholder for any instrument capable of measuring oscillating velocities of aerosols, or periodic temperature or pressure variations. To inform a selection among competing measurement approaches, I am performing numerical calculations of the properties of Uranus' normal modes, including their periods, spatial structure, ability to penetrate to upper tropospheric or higher levels, and their relative influence on the external gravity field. Mode types to be studied include f-modes, g-modes, i-modes, and r-modes. Their amplitudes cannot be calculated from first principles without knowledge of the excitation mechanism. However, given a mode type and amplitude, one can assess the best way to measure an oscillation by scaling the model mode amplitude until the velocity, temperature, pressure, or gravitational perturbation exceeds its minimum measurement requirement defined by current technology. The most easily measured variable, within mission and other constraints, then indicates the optimal measurement objective and associated instrument design criteria.

Exploring clouds and composition of Ice Giants in the visible/near-IR

P.G.J. Irwin (@PatrickIrwin1), J. Dobinson, A. James, A. Braude (University of Oxford), L.N. Fletcher (University of Leicester), N.A. Teanby (University of Bristol), D. Toledo (National Institute for Aerospace Technology, Spain), G.S. Orton (Jet Propulsion Laboratory, Caltech, USA), B. Bézard (Observatoire de Paris).

Uranus and Neptune, known as the 'Ice Giants', are amongst the most mysterious planets in our Solar System. Their extremely cold temperatures at the cloud tops means that their main bulk constituents, thought to be rock and normally 'icy' materials such as H_2O and NH_3 are condensed well below their main visible cloud decks. In this presentation we will describe ground- and space-based observations of these planets that:

A) show that gaseous H_2S is present above the main cloud decks of these planets at a pressure ~ 3 bar, indicating that that these clouds almost certainly contain H_2S ice [1, 2] and that the abundance of H_2S must exceed that of NH_3 at the condensation level of ammonium hydrosulphide (NH_4SH);

B) show that the abundance of CH_4 at the cloud tops changes greatly with latitude (Fig. 1), with abundances of ~4% seen at equatorial latitudes, reducing to ~2% near the poles [3], consistent with previous HST/STIS determinations [4, 5]; and

C) show that the polar 'cap' or hood of Uranus (region of higher reflectivity seen pole-wards of 40 - 50° N) can at least be partly explained by the lowering of methane abundance at polar latitudes [6].

Further Reading:

[1] Irwin, P.G.J., et al.: Detection of hydrogen sulfide above the clouds in Uranus's atmosphere. Nature Astronomy 2, 420 – 427, 2018 (https://ora.ox.ac.uk/objects/uuid:8ef4459a-29ec-4420-87af-e149c4f35c73).
[2] Irwin, P.G.J., et al.: Probable detection of hydrogen sulphide (H_2S) in Neptune's atmosphere. Icarus 321, 550 – 563, 2019 (https://arxiv.org/abs/1812.05382).
[3] Irwin, P.G.J., et al.: Latitudinal variation in the abundance of methane (CH_4) above the clouds in Neptune's atmosphere from VLT/MUSE Narrow Field Mode Observations. Icarus 331, 69 – 82, 2019 (https://arxiv.org/abs/1905.03516).
[4] Karkoschka, E., Tomasko, M., The haze and methane distributions on Uranus from HST-STIS spectroscopy. Icarus 202, 287–309, 2009.
[5] Karkoschka, E., Tomasko, M.G., The haze and methane distributions on Neptune from HST-STIS spectroscopy. Icarus 211, 780–797, 2011.

[6] Toledo, D. et al.: Uranus's northern polar cap in 2014. Geophys. Res. Lett. 45, 5329-5335, 2018. (https://ora.ox.ac.uk/objects/uuid:dec0dfb0-ab72-45d5-b376-1beab99992ae).

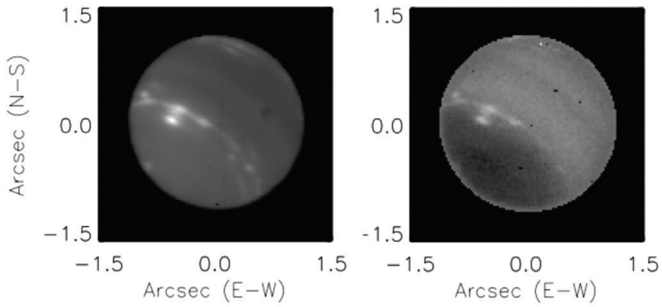

Figure 9 Left Panel - mean brightness of Neptune at 800 - 860 nm recorded by VLT/MUSE in 2018, showing discrete methane clouds overlying uniform H2S cloud base. Right Panel - Principal Component Analysis of MUSE data showing the distribution of a component that captures methane abundance variations, showing lower methane abundance in south polar region.

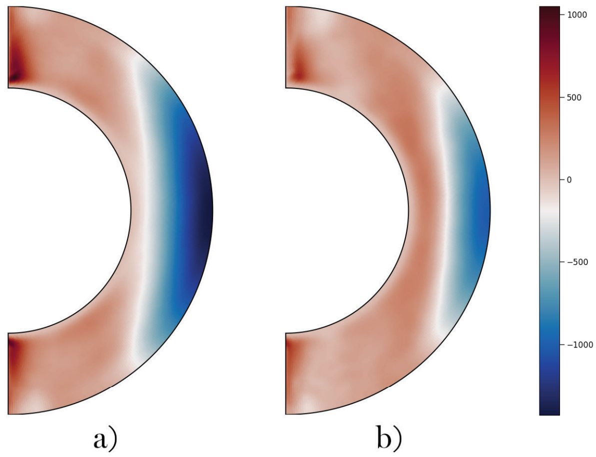

Figure 10 Time and azimuthally averaged toroidal component of the velocity field, roughly corresponding to the zonal winds at the surface for a) thermal convection and b) double-diffusive convection. Red indicates the prograde direction, while blue indicates the retrograde direction. Note, both cases produce a retrograde equatorial band, surrounded by prograde winds at the mid-latitudes, though the winds at the equator are somewhat slower in the double-diffusive case with the prograde bands appearing at lower latitudes, also, compared to the thermally-driven case.

Double-diffusive convection models of Uranus and Neptune

D.J. Hill (@DustinJayHill, Drexel University)

Uranus and Neptune are believed to consist primarily of ices, such as water, ammonia, and methane. Under conditions that exist in the deep interior of these planets, mixtures of these ices are predicted to undergo chemical processes that may release hydrogen. The hypothesis that we are testing is if chemical processes can reproduce dynamics observed in Uranus and Neptune. To test this, fluid dynamical simulations in a rotating spherical shell are completed, containing both thermally-driven—analogous to the more luminous Neptune—and double-diffusive—analogous to the less luminous Uranus—convection. Two of the observed properties that can be compared with our models are the banded zonal winds, that are dominated by equatorial winds that move in a retrograde direction and the intrinsic luminosity associated with each planet. Initial results indicate that the double-diffusive models can account for these properties. If this extends over a greater range of parameters, this may indicate that a chemical process occurs within Uranus that tends to destabilize the interior to convection, despite its low intrinsic luminosity.

Non-Local Thermodynamic Equilibrium model for the mid-infrared emissions in the atmospheres of Uranus and Neptune

Javier Martin-Torres (Twitter: @GroupofAtmosph1; Facebook: @groupofatmosphericscience Luleå University of Technology, Luleå, Sweden/Instituto Andaluz de Ciencias de la Tierra (CSIC-UGR), Armilla, Granada, Spain), Glenn Orton (Jet Propulsion Laboratory, Pasadena, CA, USA)

A non-Local Thermodynamic Equilibrium (non-LTE) model for the mid-infrared emissions in the atmospheres of Neptune and Uranus is presented. The model is an updated version of the methane model by Martín-Torres et al (1998) with an improved and extended collisional scheme. The new version includes the calculation of the vibrational excitation of CO2 and the main hydrocarbons in Uranus and Neptune. Level populations are computed for stationary conditions, and stimulated emission and scattering are neglected, given the atmospheric temperatures and the wavelength of the transition considered for these species. The model includes exchanges of energy by vibrational-translational (V-T) and vibrational-vibrational (V-V) processes, as well as by radiative processes. Radiative processes include spontaneous emission, direct absorption of solar radiation, and the exchange of photons among the atmospheric layers.

The model has been applied to the retrieval of temperature and the abundances of the main atmospheric species in Uranus after mid-infrared spectral observations acquired with the Infrared Spectrometer (IRS) on the Spitzer Space Telescope (Orton et al., 2015a; Orton et al., 2015b). We will present the values of the non-LTE source function to Planck function ratio (J/B), and their uncertainties, for the main species emitting in the mid-IR in Uranus and Neptune.

Optional Further Reading:

- *Martin-Torres et al., 1998* https://www.sciencedirect.com/science/article/pii/S1364682698001084?via%3Dihub
- *Orton et al., 2014a* https://www.sciencedirect.com/science/article/abs/pii/S0019103514003765
- *Orton et al., 2014b* https://www.sciencedirect.com/science/article/abs/pii/S0019103514003789

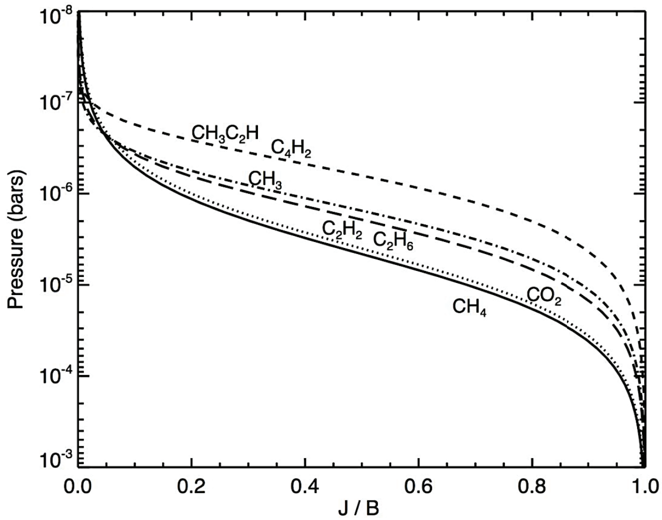

Figure 11 Ratio of the source function to the Planck function, J/B, for the main mid-infrared emitters in Uranus. This ratio for CH4 is shown by the solid line and for CO2 by the dotted line. The ratios for C2H2 and C2H6 are indistinguishable and are shown by the long-dashed line. Similarly, the ratios for CH3C2H and C4H2 are indistinguishable and are shown by the short-dashed line. The ratio for CH3 is shown by the alternating dot-dashed line. (Figure from Ortin et al., 2014b)

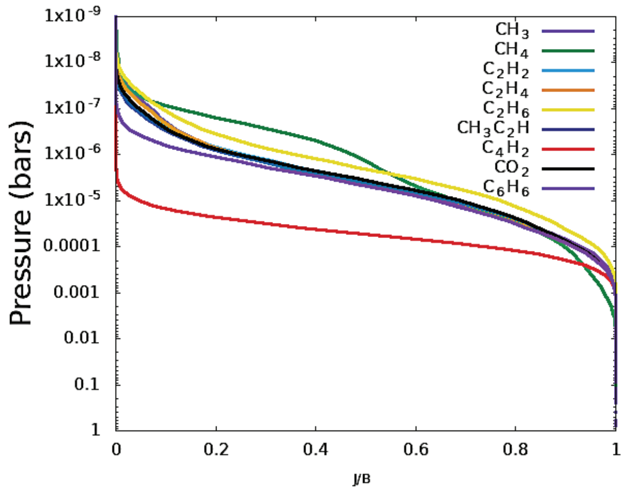

Figure 12 Ratio of the source function to the Planck function, J/B, for the main mid-infrared emitters in Neptune.

Chemical Consequences of a Large Cometary Impact on Neptune

J.I. Moses (Space Science Institute), S.H. Luszcz-Cook (American Museum of Natural History)

Millimeter and sub-millimeter observations from ground-based telescopes have revealed the presence of an unexpectedly large amount of carbon monoxide in Neptune's stratosphere that may have been delivered during a large cometary impact that occurred a few hundred years ago (e.g., *Lellouch et al. 2005)*. The comet-impact hypothesis could also explain the current presence of HCN and CS in Neptune's stratosphere (e.g., *Marten et al. 1993; Moreno et al., 2017)*. We use a 1D photochemical model to track the fate of gas-phase species introduced into Neptune's upper atmosphere from this putative cometary impact. The results regarding the coupled hydrocarbon and oxygen chemistry will be presented here. We will describe how the vertical profile of the comet-derived species vary with time, how the comet-derived species affect hydrocarbon abundances, and how comet-derived CO can complicate the derivation of the deep oxygen abundance on Neptune from indirect methods (e.g., *Cavalié et al. 2017)*.

Further Reading:

Cavalié, T., et al. (2017), Icarus 291, 1 <link >
Lellouch, E., et al. (2005), A&A 430, L37 <link>
Marten, A., et al. (1993), ApJ 406, 285 <link>
Moreno, R., et al. (2017), A&A 608, L5 <link>
Moses, J.I. & Poppe, A.R. (2007), Icarus 297, 33 <link>

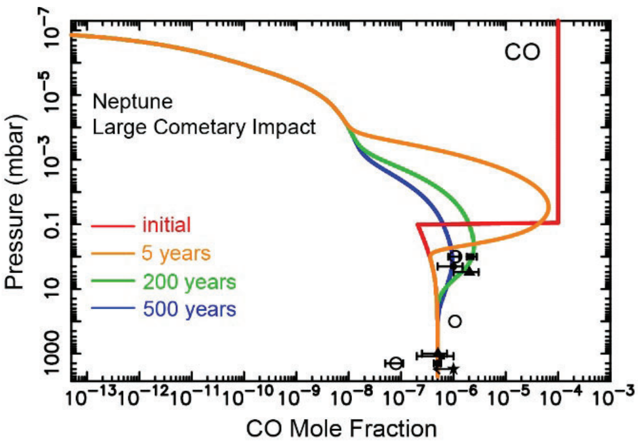

Figure 13 Vertical profile of comet-derived material as it varies with time after being delivered by a large cometary impact.

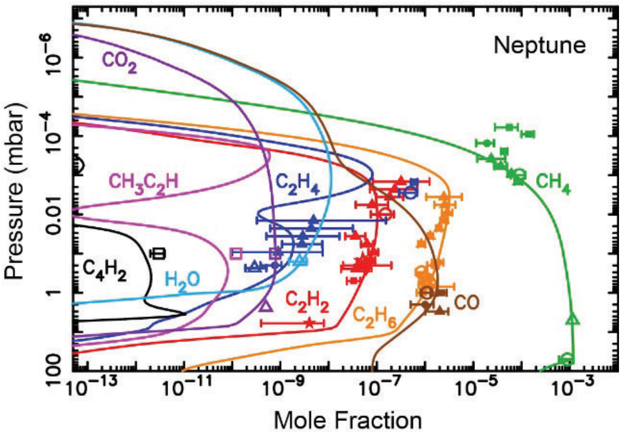

Figure 14 Vertical profiles of several atmospheric species on Neptune in a model that includes dust ablation and a recent cometary impact (Figures from Moses & Poppe, 2017).

Cosmic ray ionization of Ice Giant atmospheres

T. A. Nordheim (Jet Propulsion Laboratory, California Institute of Technology), K. L. Aplin (University of Bristol), J. A. Sinclair (Jet Propulsion Laboratory, California Institute of Technology), J. M. Jasinski (Jet Propulsion Laboratory, California Institute of Technology).

Galactic cosmic rays (GCRs) represent a major ionization source in planetary atmospheres, particularly within deeper layers that are largely unaffected by solar UV and charged particle precipitation. When GCR particles undergo inelastic collisions with atmospheric nuclei they create large numbers of secondary interactions, resulting in extensive nuclear and electromagnetic particle cascades. In thick atmospheres, such as those of the giant planets, these cascades can develop much more extensively than what is the case at Mars and Earth. Furthermore, GCRs are strongly modulated by the heliosphere, and therefore GCR fluxes are significantly higher at the Ice Giants than in the inner Solar System. Intriguingly, observations of Uranus and Neptune show brightness variations that appear to be associated with GCR variability (Aplin et al. 2016;2017).

Using a full 3D Monte Carlo particle physics code, we have carried out the first detailed study of cosmic ray ionization within the atmospheres of Uranus and Neptune. We will show preliminary results of this study and discuss the possible importance of GCR ionization to atmospheric chemistry and atmospheric electricity. We will also discuss the effect of GCR shielding by the planetary magnetic fields of Uranus and Neptune.

Radiative modelling of the Ice Giant atmospheres – A first step toward Global Circulation Models

J. Vatant d'Ollone (@PlanetoJVO, University of Leicester), L.N. Fletcher (University of Leicester), S. Guerlet (LMD/IPSL, Sorbonne University, Paris), M.T. Roman (University of Leicester)

One-dimensional modelling efforts for Ice Giant atmospheres have been performed in the past, from pioneering works *[1]* to more recent comprehensive studies *[2]*. Circulation patterns inferred from observations and models have been discussed in *[3]*, but few fully three-dimensional models of Ice Giants have ever been presented.

Among the differences between these studies are the estimated radiative time constants and the consequences for the atmospheric circulation on Uranus and Neptune. For instance, comparing VLT images to Voyager data, *Roman et al. [4]* pointed out that the Uranian atmosphere underwent almost no changes in terms of thermal structure, pointing out that either the radiative time constants are much longer than estimated by *Li et al. [2]*, or there is a very efficient energy redistribution by global circulation.

Here, following what has been previously done for Saturn *[5]* and Jupiter *[6]*, 1-D radiative-convective equilibrium modelling is performed with a radiative-transfer code based on a correlated-*k* method. We utilise modern estimates of gaseous opacities provided by photochemical models *[7]*. We explore the response to seasonal solar forcing along with the sensitivity to aerosols, which are poorly observationally constrained and therefore source of uncertainties for radiative models.

We present a comparison with previous works, discussion of time constants and aerosol sensitivity, and pave the way to a fully 3-D circulation model for the Ice Giants. Such a model will be useful for interpreting future observations of Uranus and Neptune from the James Webb Space Telescope and new missions to these distant worlds.

Further Reading:

[1] Conrath et al., 1990 ; https://doi.org/10.1016/0019-1035(90)90068-K

[2] Li et al., 2018 ; https://arxiv.org/pdf/1806.02573.pdf
[3] Fletcher et al., 2019 ; https://arxiv.org/pdf/1907.02901.pdf
[4] Roman et al., 2020 ; https://arxiv.org/pdf/1911.12830.pdf
[5] Guerlet et al., 2014 ; https://doi.org/10.1016/j.icarus.2014.05.010
[6] Guerlet et al., 2019 : https://arxiv.org/pdf/1907.04556.pdf
[7] Moses et al., 2018 ; https://arxiv.org/pdf/1803.10338.pdf

Mid-Infrared Through Submillimeter Observations of Uranus and Neptune

G.S. Orton (Jet Propulsion Laboratory, California Institute of Technology), L.N. Fletcher (University of Leicester), M.T. Roman (University of Leicester), J.A. Sinclair (Jet Propulsion Laboratory, California Institute of Technology)

Observations of thermal emission from Uranus and Neptune have been made over a wide range of wavelengths from ground-based platforms, airborne observatories, Earth-proximal spacecraft and from the Voyager-2 flybys in the 1980s. Observations since the Voyager flybys have included long-wavelength observations of disk-averaged radiances from the Earth-proximal Infrared Space Observatory and the Herschel Space Observatory covering the far-infrared to millimeter range. Airborne observations from SOFIA covered 17-35 µm, and Akari and Spitzer have covered shorter wavelengths down to 7 µm, below which contributions from reflected sunlight and potential auroral emissions may confuse the signature of thermal emission. Ground-based filtered imaging and spectroscopy at 8-10m telescopes have enabled spatially resolved measurements, complementing those of Voyager IRIS. Several specific examples of these are presented at this meeting. The critical insights into the structure, chemistry and dynamics of the atmospheres of these Ice Giants attest to the need for significant parts of this spectral region to be included in the instrument capabilities missions to these planets. A vigorous program of Earth-based observations in the accessible spectral range should accompany the spacecraft capability in order to track potential seasonal and non-seasonal variability. The latter would include mid-infrared observations from the James Webb Space Telescope.

Further Reading:

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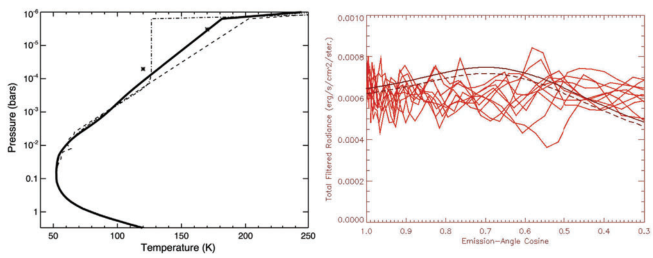

Figure 15 Testing temperature profiles of Uranus with spatially resolved observations. Left: Alternative global-mean temperature profiles that are consistent with Spitzer IRS spectra (Orton et al. 2014b). The spectra cannot distinguish between the nominal profile (solid line) and the alternative model given by the dash-dotted line. Right: Equatorial center-to-limb behavior of stratospheric C_2H_2 emission. Predictions of emission from a vertical distribution of C_2H_2 by Orton et al. (2014a) that is consistent with the nominal (solid) or

alternative (dashed) profiles. The data (red) are not consistent with the mild limb darkening predicted by the models. This suggests that an even more extensive isothermal region is required in order to match the lack of limb darkening observed, although this is inconsistent with temperatures implied by the analysis of Voyager UV occultation data (asterisks) by Herbert et al. (1987, JGR 92, 15093). It also requires a steeper inversion of temperatures in the lower stratosphere to match the overall Spitzer spectrum

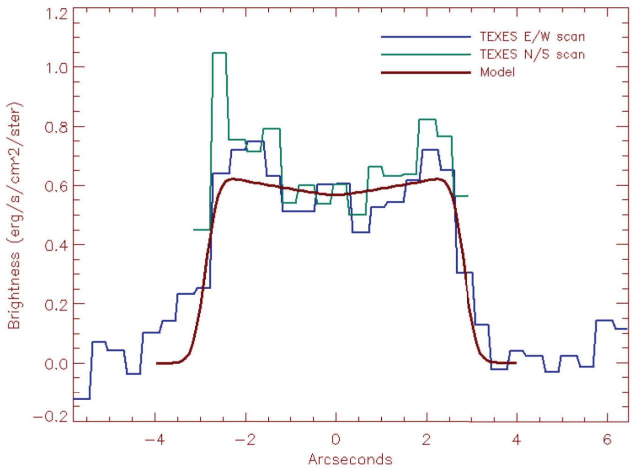

Figure 16 Spatially resolved scans of Uranus with the TEXES instrument at $\lambda/\Delta\lambda$~55,000 from the Gemini North Telescope on 22+27 October 2007. Scans of the H_2 quadrupole line in either north-south or east-west orientations show a limb brightening that is higher than predicted by the nominal model shown in the left panel (solid black line in both panels). This requires the temperature inversion in the lower stratosphere to be steeper, consistent with the requirement for a broader isothermal region required to match the C_2H_2 center-to-limb behavior.

Longitudinal Variations in the Stratosphere of Uranus from the Spitzer Infrared Spectrometer

N. Rowe-Gurney (@NRoweGurney, University of Leicester), L. N. Fletcher (University of Leicester), G. S. Orton (Jet Propulsion Laboratory, California Institute of Technology), M. T. Roman (University of Leicester), A. Mainzer (Jet Propulsion Laboratory, California Institute of Technology), J. I. Moses (Space Science Institute), I. de Pater (University of California at Berkeley), and P. G. J. Irwin (University of Oxford).

NASA's Spitzer Infrared Spectrometer (IRS) acquired mid-infrared (5-37 µm) disc-averaged spectra of Uranus very near its equinox on 16th to 17th of December 2007. A global-mean spectrum was constructed from observations of multiple longitudes, spaced equally around the planet, and have provided the opportunity for the most comprehensive globally-averaged characterisation of Uranus' temperature and composition ever obtained (Orton et al., 2014 a, b).

In this work, we analyse the disc-averaged spectra at four separate longitudes to shed light on the discovery of longitudinal variability occurring in Uranus' stratosphere during the 2007 equinox. We detect a variability of up to 15% at stratospheric altitudes sensitive to methane, ethane, and acetylene (~ 0.1 mbar). The tropospheric hydrogen-helium continuum exhibits a negligible variation, constraining the phenomenon to the stratosphere.

The full optimal estimation inversions (using the NEMESIS retrieval algorithm, Irwin et al., 2008) have allowed us to suggest the observed variations are that of temperature and are possibly linked to meteorological features that have been observed with ground-based telescopes (Sromovsky et al., 2009; de Pater et al., 2011; Roman et al., 2019). High-resolution forward models produced using the low-resolution retrieval results fit well to the newly reduced data longwards of 12 µm.

Further Reading:

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Roman et al., 2019, arxiv.org/abs/1911.12830
Orton et al., 2014, [a] doi:10.1016/j.icarus.2014.07.010;
[b] doi:10.1016/j.icarus.2014.07.012
Sromovsky et al., 2009, doi:10.1016/j.icarus.2009.04.015

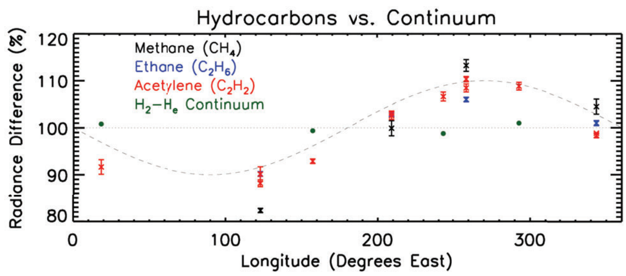

Figure 17 Percentage radiance difference from the global average of hydrocarbon species and the hydrogen-helium continuum across 360° of Uranus. Standard errors and a 10% reference sinusoid are displayed.

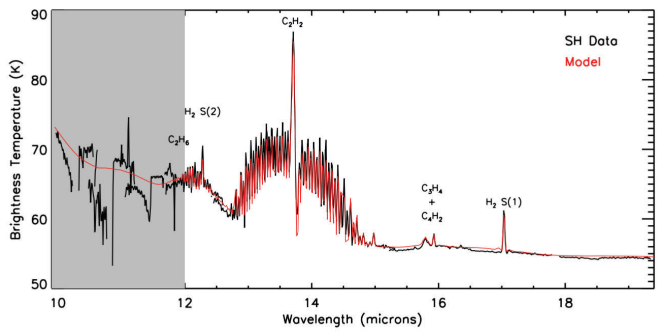

Figure 18 Global average Short-High (SH) module data (black) compared to output from forward model using retrieved values for temperature and gas profiles (red). This shows a good fit to data longwards of 12 µm. Data has been newly reduced using the most up-to-date pipeline software and techniques.

Mid-IR imaging of Neptune from VLT-VISIR, 2008-2018: stratospheric changes and comparison to Uranus

M.T. Roman (University of Leicester), L.N. Fletcher (University of Leicester), G.S. Orton (Jet Propulsion Laboratory/California Institute of Technology), J.A. Sinclair (Jet Propulsion Laboratory/California Institute of Technology), N. Rowe-Gurney (University of Leicester)

With its long seasons, Neptune's stratosphere experiences solar forcing and expected photochemistry that slowly changes over decades, even as it caps an exceptionally dynamical troposphere below. In this study, we investigate potential trends in mid-infrared emission from the stratosphere and upper troposphere of Neptune between 2008/2009 and 2018 using spatially resolved images from the VISIR instrument at the Very Large Telescope (VLT). We find that Q-band images (18.7µm and 19.5 µm), sensitive to temperatures in the upper troposphere (~200 mbar), show no significant changes between 2008 and 2019 and remain consistent with temperatures inferred from 1989 Voyager-IRIS measurements. However, 12.2-µm images sensitive to emission from stratospheric ethane (around 1 mbar) show a decrease in the northern hemisphere, with brightness temperatures falling ~2 K between 2009 and 2019. Likewise changes at 7.7 µm suggest changes in the latitudinal trend of emission from stratospheric methane. Together, these changes suggest that the lower stratosphere experiences intra-seasonal changes that may be coupled to dynamical forcing or variable mixing from the troposphere. We contrast this apparent temporal variability and the observed meridional trends in Neptune's stratospheric emission to recent findings from similar observations of Uranus, where vertical mixing is thought to be weaker.

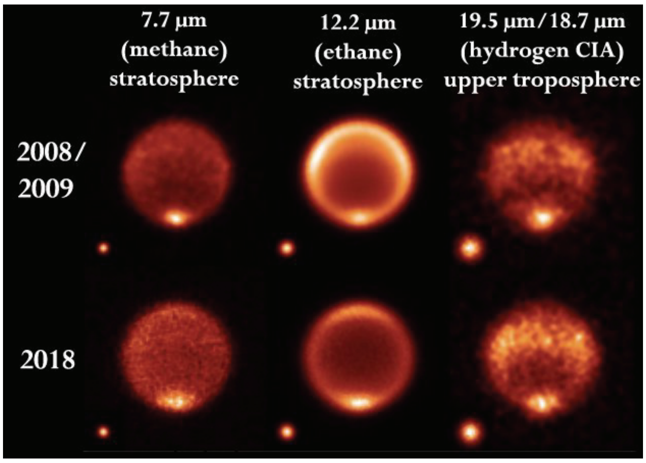

Figure 19 A comparison of mid-infrared images of Neptune dating from 2008/2009 and 2018. Images are shown in three different filters, with the bright south pole down in the images. The 7.7 µm images shows emission associated with stratospheric methane (~1 mbar). Between 2009 and 2018, the emission in the southern hemisphere appears to have increased. In contrast, the 12.2 µm emission from stratospheric ethane significantly increased in the northern hemisphere over the same period. However, there were no significant changes between the 19.5 µm image and the 18.7 µm –both sensitive to tropospheric temperatures at ~200 mbar—over the same period.

Numerical simulations of Neptune's Dark Spots

A. Sánchez-Lavega (University of Basque Country UPV/EHU), J. Legarreta (University of Basque Country UPV/EHU), R. Hueso (University of Basque Country UPV/EHU

Since the discovery of the first dark spots (DS) in Neptune in 1989 by the Voyager 2 spacecraft, six different DSs have been reported in the planet on different years at a variety of latitudes and with different sizes. Presumably, these features are anticyclones whose low albedo clouds are deeper than their surroundings. The DSs are often accompanied by bright clouds located higher in the atmosphere and produced by ascending motions associated to their dynamics. We present a numerical study of the DSs motions, their stability and overall evolution from a comparison of all the observed cases of DSs with numerical simulations using the EPIC atmospheric model (Explicit Planetary Isentropic-Coordinate, Dowling et al., Icarus 1998). Our aim is to constrain the properties of these anticyclones (potential vorticity) and those of Neptune's troposphere. We find that in order for the vortices to maintain their stability in the observed time scales we need in some cases modifications of the meridional wind profile as observed at cloud level. The meridional drift rates observed in some vortices can be retrieved under specific atmospheric conditions.

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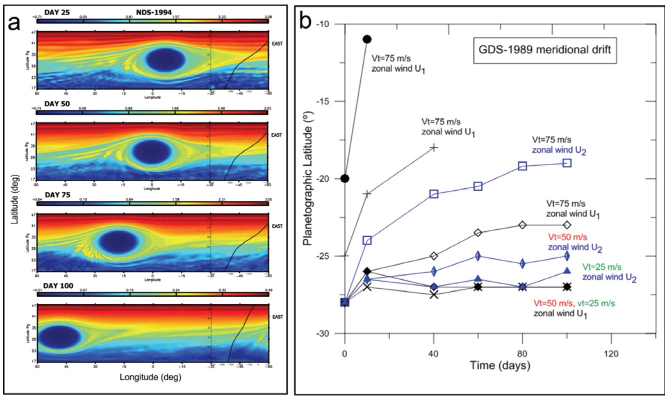

Figure 20 (a) Simulations of Neptune's Dark Spot called NDS-1994 (Northern hemisphere and first observed in 1994) located at 32°N. Its lifetime was 4-6 years. The zonal wind meridional profile we employed is shown at right; (b) Drift of the Great Dark Spot GDS-1989 for different tests of the zonal wind profile (U1 and U2) and different periphery velocity of the vortex (Vt).

Thermal Evolution of Uranus and Neptune

L. Scheibe (Universität Rostock), N. Nettelmann (University of California, Santa Cruz; Deutsches Zentrum für Luft- und Raumfahrt Berlin), R. Redmer (Universität Rostock)

Uranus and Neptune have highly different intrinsic heat fluxes. This is surprising since they share a large number of similar observed values such as mean density, surface temperature and atmospheric composition. Moreover, previous evolution calculations fail to reproduce the present-day luminosity of Uranus, or - equivalently - yield too long cooling times [1,2]. This is a topic of current interest [3].

Here we investigate how different equations of state for H/He and for water affect the luminosity of assumed adiabatic models. We find that application of H/He-REOS.3 [4] yields shorter cooling times for the ice giants compared to the previously used H/H-REOS.1 [5] and Sesame 7150 EOS [6]. This trend is confirmed if we apply the recent EOS by Mazevet et al. for water [7] and by Chabrier et al for H/He [8]. As a result, adiabatic Neptune appears too bright for its known age.

Furthermore, we also present work in progress on non-adiabatic models including a thermal boundary layer. For that purpose we have developed a new tool based on the well-known Henyey method for stellar structure and evolution calculations.

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DOI: https://doi.org/10.1051/0004-6361/201936378
arXiv: https://arxiv.org/abs/1911.00447

Hubble OPAL Observations of Uranus and Neptune: 2014-2019

A.A. Simon (NASA Goddard Space Flight Center), M.H. Wong (UC Berkeley), G.S. Orton (Caltech/JPL)

The Hubble Outer Planet Atmospheres Legacy (OPAL) program is a yearly monitoring program for the giant planets. Each planet is observed every year, with coverage over two rotations to allow tracking of cloud feature motions. The program began with Uranus in 2014 and Neptune in 2015, already providing 5 to 6 years of coverage for the ice giants. All data are immediately public and high-level science products, in the form of calibrated global maps, are made available through a dedicated archive website: http://dx.doi.org/10.17909/T9G593 The yearly cadence of global map pairs has allowed for studying changes in zonal wind profiles, cloud motions and convective activity levels, large storm development and dissipation (Neptune), and brightening polar hazes (Uranus). They also provide a temporal baseline and context for future ice giants missions. We will present a summary of the observations and results to date from this program.

Spatial structure in Neptune's 7.90-µm stratospheric CH_4 emission, as measured by VLT-VISIR

J. A. Sinclair (Jet Propulsion Laboratory/California Institute of Technology), G. S. Orton (Jet Propulsion Laboratory/California Institute of Technology), L. N. Fletcher (University of Leicester), M. Roman (University of Leicester), I. de Pater (University of California, Berkeley), T. Encrenaz (L'Observatoire de Paris), H. B. Hammel (Association of Universities for Research in Astronomy), R. S. Giles (Southwest Research Institute, San Antonio), T. Velusamy (Jet Propulsion Laboratory/California Institute of Technology), J. I. Moses (Space Science Institute), P. G. J. Irwin (University of Oxford), T. W. Momary (Jet Propulsion Laboratory/California Institute of Technology), N. Rowe-

Gurney (University of Leicester), F. Tabataba-Vakili (Jet Propulsion Laboratory/California Institute of Technology).

We present a comparison of VLT-VISIR images and Keck-NIRC2 images of Neptune, which highlight the coupling between its troposphere and stratosphere. VLT-VISIR images were obtained on September 16th 2008 (UT) at 7.90 µm and 12.27 µm, which are primarily sensitive to 1-mbar CH_4 and C_2H_6 emission respectively. NIRC2 images in the H band were obtained on October 5th, 6th and 9th 2008 (UT) and sense clouds and haze in the upper troposphere and lower stratosphere. At 7.90 µm, we observe enhancements of CH_4 emission in axisymmetric bands at latitudes of approximately 25°S and 48°S (planetocentric). These enhancements are latitudinally-coincident with bands of bright (presumably CH_4 ice) clouds in the upper troposphere and lower stratosphere evidenced in the H-band images. This suggests the Neptunian troposphere and stratosphere are coupled in these specific regions. This could be in the form of 1) 'overshoot' of strong, upwelling plumes and advection of CH_4 ice into the lower stratosphere, which subsequently sublimates into CH_4 gas and/or 2) generation of waves by plumes impinging from the tropopause below, which impart their energy into the lower stratosphere and accelerate zonal winds.

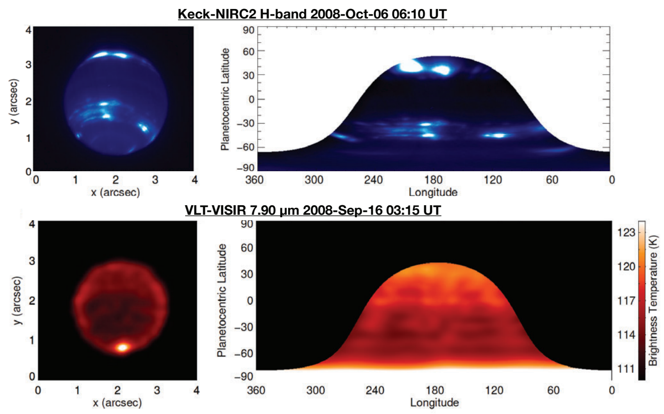

Figure 21 the top row shows Keck-NIRC2 H-band images of Neptune measured on October 6th 2008. The left-hand image is the original and the right-hand is the corresponding cylindrical projection with a centre-to-limb correction applied. These are shown in normalized brightness units, with white regions demonstrating the presence of tropospheric/lower stratospheric clouds. The bottom row similarly shows VLT-VISIR 7.90-µm (bottom row) images of Neptune's stratospheric CH_4 emission measured on September 16th 2008 following deconvolution using a standard star as the point-spread function. The image is shown in brightness temperature according to the right-hand colourbar. Enhancements of CH_4 emission, indicating either enhanced stratospheric temperature and/or CH_4 abundances, are observed at mid-southern latitudes and at similar latitudes as clouds.

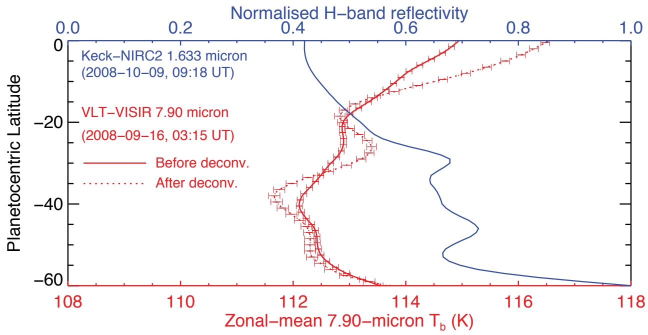

Figure 22 Zonal-mean 7.90-µm CH_4 emission brightness temperature (red) as a function of latitude before (solid, error bars) and after (dotted, error bars) image deconvolution. The zonal-mean H-band reflectivity is shown in solid, blue according to the axis at the top of the panel. This demonstrates that latitudes of enhanced CH_4 emission are observed at similar latitudes as those with more tropospheric/lower stratospheric CH_4 ice clouds. We suggest the upwelling CH_4 ice clouds sublimate upon reaching the stratosphere, enhancing the abundance of stratospheric CH_4 gas.

Constraining the Depth of the Winds in Uranus and Neptune

Deniz Soyuer (University of Zurich), Ravit Helled (University of Zurich)

Determining the depth of atmospheric winds of outer planets is a topic of rigorous investigation in planetary science. Constraints on winds' depth in gas giants were presented by Liu et al. 2008 (Icarus, 196). It was suggested that the induced toroidal magnetic field, arising from the interaction between the poloidal magnetic field and the toroidal flow, produces an associated poloidal current. Ohmic dissipation associated with this current cannot exceed the planetary net luminosity and depends heavily on electrical conductivity of materials involved in the flow. Recently, the depths of the winds in Jupiter and Saturn were constrained from Juno and Cassini gravity data, and found to be consistent with the Ohmic constraint.

Here we investigate whether the same mechanism applies to Uranus and Neptune. This formulation is more challenging in this case due to the non-axisymmetric, multipolar nature of their magnetic fields, and ambiguities in their interior structures and bulk compositions. We determine the Ohmic limit on ice giants for various interior models, and interpret the relation between them in order to determine the maximum penetration depth. We next suggest that the Ohmic constraint can be used to exclude certain structure models and explore various truncation mechanisms for the winds.

Further Reading:

Constraints on Deep-seated Zonal Winds Inside Jupiter and Saturn: Liu et al. 2008: https://arxiv.org/abs/0711.3922

Is Neptune Really an Ice Giant?

N. A. Teanby (University of Bristol), P. G. J. Irwin (University of Oxford), J. Moses (Space Science Institute)

A current interpretive trend in planetary sciences is to refer to Neptune (and Uranus) as "ice-giants", including for this workshop, where their interiors are presumed to be heavily enriched in oxygen by up to 400x solar abundances. However, under further scrutiny the evidence for this seems somewhat dubious and stems primarily from grossly simplified step-type CO profiles derived from non-unique spectroscopic observations. To explain the deep tropospheric CO abundance inferred from these profiles, extreme oxygen enrichment must be invoked, hence "ice giant". However, this potential over-interpretation requires Neptune to be built from unusual ice-rich planetesimal that are depleted in deuterium compared to the present-day comet population or in fact anything else in the modern Solar System. Here we present an alternative interpretation and we will try to persuade you that a "rock giant" Neptune is more consistent with the available evidence. In this model Neptune would contain more rock than ice, with a relative rock:ice abundance of around 75:25, similar to Pluto and KBOs. New observations from the Herschel space observatory are used to retrieve more consistent constraints on Neptune's CO profile that do not require extremely oxygen rich interiors.

Further Reading:

Teanby et al. (2019) *"Neptune's carbon monoxide profile and phosphine upper limits from Herschel/SPIRE: Implications for interior structure and formation"*, Icarus, **319**, 86-98. https://doi.org/10.1016/j.icarus.2018.09.014

Microphysical simulations of methane clouds in the atmosphere of the ice giants

D. Toledo, V. Apéstigue, L. Gómez, I. Arruego, M. Yela (National Institute for Aerospace Technology), P. Irwin (University of Oxford), P. Rannou (University of Reims), L.N. Fletcher (University of Leicester)

Ice giants have a dynamic atmosphere and undergoes a cycle of seasons. Different images of these planets have revealed the presence of discrete clouds at different locations and time periods [1,2]. Based on the altitude of these clouds and the saturation vapour pressure curves of several possible condensates, it has been possible to infer that these clouds were made of methane (CH_4) ice particles. However, as a result of the limitation of ground-based telescopes (or observations from telescopes in orbit around the earth) and the complex cloud structure of the ice giants the detection and analysis of the composition and properties of those clouds is a big challenge. According to the gas abundances in both atmospheres and the T-P profile, a variety of cloud compositions can be found: clouds made of methane (CH_4), hydrogen sulphide (H_2S) [3], ammonia (NH_3), ammonium hydrosulphide (NH_4SH) or water (H_2O) (see Figure 1 for Uranus case). In this work, we will make use of cloud microphysics to constrain particle size, density, vertical distribution and time scale of methane clouds that may be present in the atmosphere of the ice giants. These simulations will provide key information for determining the possible cloud scenario expected during the entry of the probe and thus improve the science return derived from the future observations.

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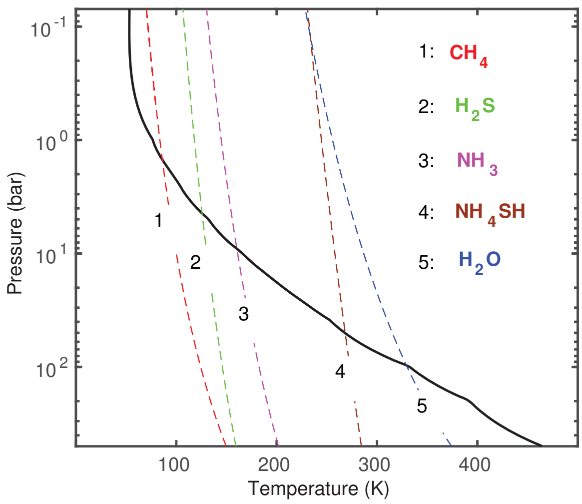

Figure 23 Vertical temperature profile in the atmosphere of Uranus (continuous black line) and the saturation vapor pressure curves for several possible condensates (dashed lines). The cloud base of each specific condensate is given by the point where the two curves cross.

Magnetospheres and Plasma

Detectability of Induction Signatures from Subsurface Oceans at Uranus' Main Satellites

C.S. Arridge (@chrisarridge, Department of Physics, Lancaster University, Lancaster, UK), J. Eggington (Department of Physics, Lancaster University, Lancaster, UK; now at Imperial College, London, UK)

Europa and Enceladus both harbour subsurface oceans and the induced magnetic signature from Europa's ocean has received significant attention. The icy satellites Oberon and Titania at Uranus have been discussed as possible hosts to subsurface oceans and any conducting layers might be passively sounded using Uranus' asymmetric magnetospheric magnetic field. In this paper we present a highly simplified model for the magnetospheric magnetic field of Uranus and use this to estimate the spectrum of magnetic field variation at Uranus' main satellites and then estimate the strength of any induced signatures. Focusing particularly on Oberon and Titania, we show that subsurface oceans could be detectable in the uranian system.

The Ice Giant Radiation Belts

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Planetary radiation belts are regions of space where high-energy charged particles are magnetically trapped. As net products of processes acting on the ions and electrons throughout the magnetosphere, study of their composition, energy content and spatial profiles can relate certain processes back to the global distribution of gas and dust as well as wave-particle interactions. Uranus' radiation belts are especially interesting as Voyager 2 observations1 did not confirm our expectations. In order for the particles to accumulate to high intensities, the radiation belts need to draw from a large reservoir of lower energy plasma and/or lose the accelerated particles very slowly. Neither appeared to be the case at Uranus, which possesses a vacuum magnetosphere2 and where waves intense whistler mode chorus waves were observed3, which result in efficient acceleration and particle losses4. It remains a mystery why Uranus' electron belts appear surprisingly intense (e.g., compared to those of Saturn & Neptune5) whereas its ion belts show low intensities5. Uranus may behave so unexpectedly because its unique magnetospheric configuration results in the dominance of processes that have been observed to play lesser roles at other planets.

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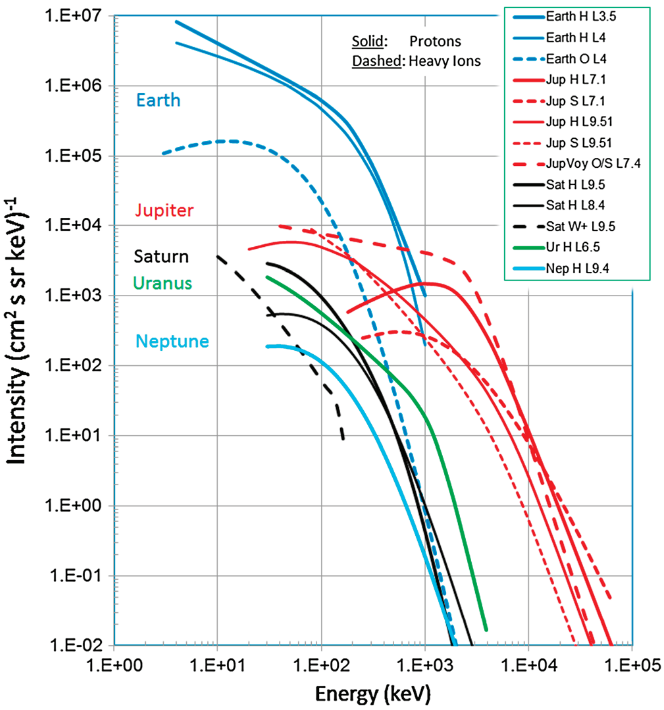

Figure 24 Energetic ion spectra sampled within the ring current regions of the five strongly magnetized planets of the solar system with best fits. The spectra are the most intense observed within these systems specifically at 100 keV and 1 MeV, or both. Solid line spectra are protons, and dashed line spectra are heavy ions (O, S, or Water Group [W+]). From Mauk [2014].

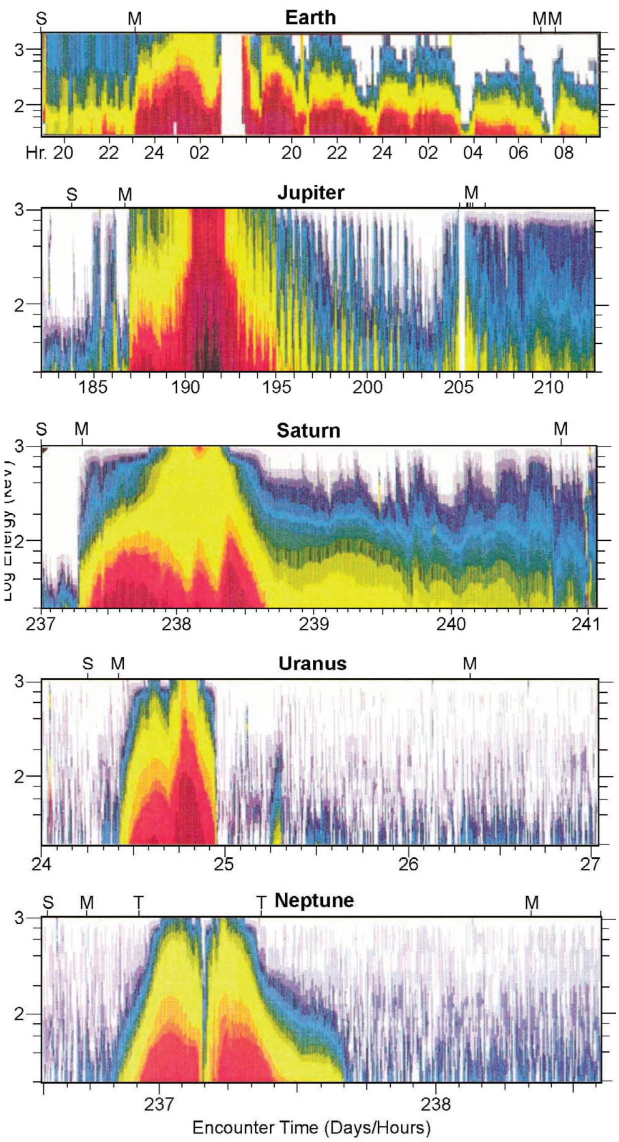

Figure 25 Spectrograms of energetic electron intensities (color scale) versus energy (vertical scale) and time (horizontal scale). The Earth data were obtained by the International Sun Earth Explorer (ISEE) mission, and the other data were obtained by the Voyager encounters of the various outer planet magnetospheres. The time scales encompass both inbound and outbound magnetopauses ("M" character above each plot). Energy spans roughly 20 keV to ~1 MeV. The intensity scale is fixed for all of the panels (intensities between planets can be compared). From Mauk & Fox [2010].

Voyager 2 Constraints on Plasmoid-based Transport at Uranus

G.A. DiBraccio (NASA GSFC) and D.J. Gershman (NASA GSFC)

The analysis of high-resolution magnetic field data during the 1986 Voyager 2 flyby of Uranus has revealed the presence of a loop-like plasmoid within the magnetotail of Uranus – the first to be detected within an Ice-Giant magnetosphere. This plasmoid exhibited classic features including a decrease in the total field magnitude, suggesting the presence of trapped plasma from the central plasma sheet, which was aligned with the inflection point of a bipolar signature. Further analysis of the bipolar signature indicated that this structure was traveling away from the planet. The plasmoid was observed at a downtail distance of ~54 R_U (radius of Uranus), providing an observational constraint of the tail reconnection X-line location that is consistent with previous modeling results. A post-plasmoid plasma sheet was identified following the plasmoid structure, indicating the continuation of reconnection between the open fields in the tail lobes. We determine that the plasmoid was likely ~8-16 R_U in diameter. Plasmoid-based transport estimates suggest a mass loss rate of ~0.007±0.004 kg s^{-1} at Uranus, corresponding to ~35±20% of the atmospheric proton production rate. These results implicate that both internal and external forces play a role in magnetospheric dynamics at Uranus. Plasmoids may be a dominant mass-loss mechanism at Uranus, which suggest similar effects may be take place within the magnetosphere of Neptune.

Soft X-ray Imaging for the Ice Giants: Satellite Composition and the Global Magnetosphere

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X-rays provide irreplaceable insights into the composition of planetary surfaces and the dynamics of magnetospheres.

X-ray fluorescence uniquely characterises elemental composition. *Messenger* leveraged X-ray fluorescence to revolutionise understanding of Mercury's surface composition and *BepiColombo's MIXS* will further this with global abundance maps. The *Chandra X-ray Observatory* has identified characteristic fluorescence lines of oxygen, sulphur and sodium from the Galilean satellites and Saturn's rings. Europa also presented tantalising hints of lines from additional constituents, which have key astrobiological implications for the sub-surface oceans. An orbiter would collect orders of magnitude more photons than Chandra can from Earth orbit, removing sensitivity issues and providing complete mapping of elemental abundances and identification of key trace species. For bodies such as Triton, Miranda and Ariel and the rings of Uranus and Neptune this capability will map elemental composition.

Terrestrial and Jovian X-ray aurorae have provided fundamental magnetospheric insights. Magnetospheric X-ray capability for the Ice Giants could be provided by a low mass, wide-field soft X-ray imager of the kind flying on the ESA-CAS *SMILE* mission (launch 2023). Through X-ray observations of solar wind charge exchange with Earth's exosphere, SMILE will image Earth's magnetosheath and cusps. For Uranus and Neptune's unusual tilted magnetospheres, imaging of the magnetopause and cusp will characterise the global magnetospheric response to the solar wind.

Limitations on sensitivity and spatial resolution for Earth orbiting observatories mean that to fully explore this rich multi-faceted science provided by X-rays we must visit the Ice Giants with in situ X-ray instrumentation.

Alfvénic Mach Number Variations in the Outer Solar System: Implications for Uranus and Neptune

D.J. Gershman (NASA GSFC) and G.A. DiBraccio (NASA GSFC)

The interaction between the solar wind and a planetary magnetosphere is often parameterized in terms of the upstream Alfvénic Mach number (M_A). Interplanetary M_A scales as the ratio of solar wind dynamic pressure to magnetic pressure. The lower M_A in the inner heliosphere leads to increased plasma depletion and magnetic flux pileup at the magnetopause boundary, enabling enhanced reconnection rates. Consequently, in the outer heliosphere, higher upstream M_A is theorized to limit the rate of magnetopause reconnection. Here we analyze data from Helios 1 & 2, Voyagers 1 & 2, and Pioneers 10 & 11 to quantify the variation in M_A throughout the solar system from 1972-2007. We find that solar cycle variations in solar wind magnetic pressure lead to wide ranges of upstream M_A at Jupiter, Saturn, Uranus, and Neptune. Voyager 2's flyby of Uranus during solar minimum in 1986 resulted in a very high upstream M_A of ~20. However, solar maximum conditions lead to an increased solar wind magnetic pressure, and the outer heliosphere M_A can become almost Mercury-like (i.e., ~4). This variation suggests that magnetopause reconnection may play an increasingly important role in all giant planet magnetospheres during solar maximum, particularly Uranus and Neptune.

Magnetohydrodynamic simulations of a Uranus type rotating magnetosphere at equinox and solstice

L. S. Griton (@froginthestars, IRAP, CNRS, Toulouse, France), F. Pantellini (Lesia, Observatoire de Paris, France)

Uranus and Neptune present an opportunity to explore dynamic planet-star magnetized interaction. As proven by measurements at Uranus and Neptune, the magnetic dipole axis and planetary spin axis can be off by a large angle exceeding 45°. The magnetosphere of such an (exo-)planet is highly variable over a one-day period and it does potentially exhibit a complex magnetic tail structure. The dynamics and shape of rotating magnetospheres do obviously depend on the planet's characteristics but also, and very substantially, on the orientation of the planetary spin axis with respect to the impinging, generally highly supersonic, stellar wind.

On its orbit around the Sun, the orientation of Uranus' spin axis with respect to the solar wind changes from quasi-perpendicular (solstice) to quasi-parallel (equinox). We present here a detailed analysis of the magnetosphere of a fictitious Uranus-like planet plunged in a supersonic plasma (the stellar wind) at equinox and solstice. A simulation with zero wind velocity is also presented in order to help disentangle the effects of the rotation from the effects of the supersonic wind in the structuring of the planetary magnetic tail.

Further Reading:

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2) Griton et al., *Journal of Geophysical Research*, 2018, https://doi.org/10.1029/2018JA025331
3) Ice Giant Systems: The Scientific Potential of Missions to Uranus and Neptune (ESA Voyage 2050 White Paper) https://arxiv.org/abs/1907.02963

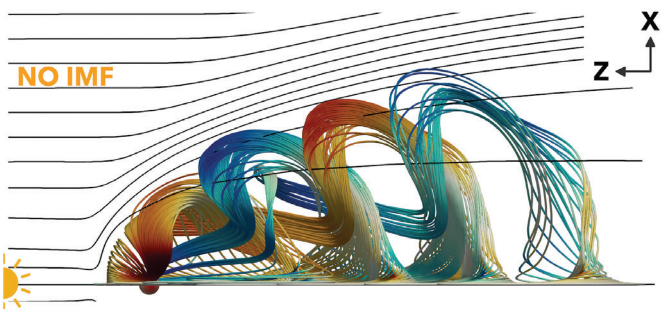

Figure 26 Sample magnetic field lines for a simulation of an Uranus-like magnetosphere at equinox, plunged in a supersonic solar wind with no interplanetary magnetic field. Colour code indicates whether the magnetic field has positive or negative radial component Br. Sample stream lines are shown in black.

Polarization electrostatic field in the presence of negatively charged grains: implications for dust levitation near Saturn's F ring

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Central University, Taiwan) A. M. Persoon (University of Iowa, USA) S-Yi Ye, W. S. Kurth (University of Iowa, USA).

It is well known that in the magnetosphere of Saturn, a polarization electrostatic field develops along the field lines (E ||) to maintain the charge neutrality of the plasma. It is also well established that certain regions of the Saturnian system (ionosphere, moons, rings) are populated by significant amount of nm and µm charged grains. Hence, in order to estimate this electrostatic field, it is important to take into account the dusty plasma as well. In the present work, we derive a more general form of E || by including the dominance of negatively charged grains. Moreover, using the Cassini RPWS Langmuir Probe data, we calculate E || by focusing on one case study near the F ring. We show that in the region close the ring plane the additional gravitational and ion drag forces of the momentum equation amplify E || at least 2 orders of magnitude ($\sim 2 \times 10^{-5}$ V/m) larger than the classical case without the charged grains ($\sim 10^{-7}$ V/m). Moreover, we show that E || is asymmetrical on either side of the magnetic equator (larger underneath it). Eventually we discuss how this has a direct consequence on confining the electrons to the ring plane and levitating the negatively charged dust from each side of the magnetic equator.

Magnetospheric Studies: A requirement for addressing interdisciplinary mysteries in the Ice Giant systems

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Uranus and Neptune are surrounded by unique magnetospheres that are a critical piece in the puzzle how planetary properties are related to their space environments and how feedback between parts of the planetary system work. We will discuss various scientific mysteries, where we cannot explain concrete observations from the Ice Giants.

A magnetospheric mystery is for example how Uranus can have similarly intense electron radiation belts as Jupiter even though it does not have a large reservoir of plasma and loses already accelerated particles fast. In the case of Neptune, we did not observe how its magnetosphere sheds the plasma that Triton is producing. This is critical to determine if that mechanism changes depending on the distance of a planet to its star.

Missions at other planets provide examples of how magnetospheric measurements can contribute to non-magnetospheric science. One landmark example is the discovery of a sub-surface ocean on Europa from observations of magnetic field perturbations. Magnetospheric measurements can help resolve mysteries not related to space physics, for example if planetary magnetic fields protect atmospheres from solar wind erosion, aurora plays a role in Uranus' too high ionospheric temperature, or how long subsurface oceans of moons exist before freezing out.

Further Reading:
Details can be found in a White Paper with the same title that is prepared for NASA's next planetary decadal survey (https://www.lpi.usra.edu/opag/). We are still looking for contributions from more co-authors.

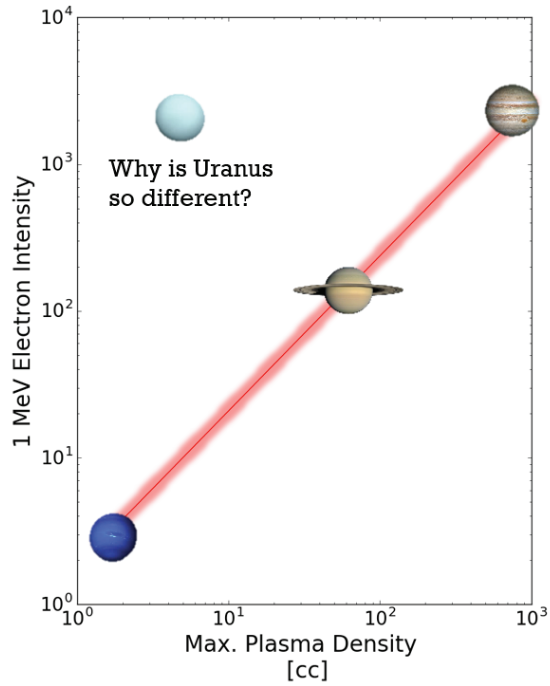

Figure 27 Correlation between observed 1 MeV electron intensities (Mauk & Fox, 2010) and the maximum magnetospheric bulk plasma densities of the Giant Planets (Selesnick et al., 1987; Richardson et al., 1991; Thomsen et al., 2010; Bagenal et al., 2016). Uranus' electron radiation belts stand out because they are comparable to Jupiter's in intensity, even though Uranus has less material available to be energized (shown), strong losses (Coroniti et al., 1987; Tripathi and Singhal, 2004), and inefficient acceleration (Cheng et al., 1987).

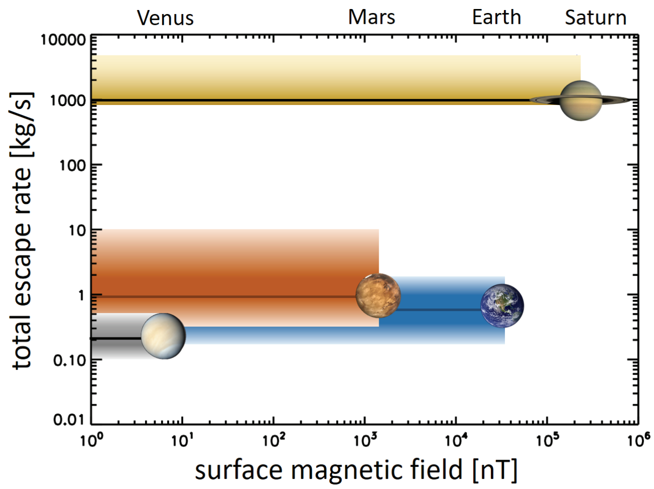

Figure 28 Total present-day atmospheric escape rates (Lammer et al., 2008; Borovsky et al., 2008; Jakosky et al., 2018; Tseng et al., 2013) and their relative variability or uncertainty, shown as a function of surface magnetic fields (Zhang et al., 2016; Acuña et al., 1999). The zeroth-order expectation is that planetary atmospheres are eroded more easily in the presence of weak magnetic fields. As it can be seen, this expectation is not met. Additional observations from the Ice Giants will help determine how escape efficiencies should be normalized to planetary parameters. The Ice Giants are better suited for such a study than Saturn and Jupiter because the Ice Giant moons are relatively weak plasma sources.

Ultra-Low-Frequency Waves throughout the Solar System: Implications for the Ice Giant Magnetospheres

H. Manners (Imperial College London)

Ultra-low-frequency (ULF) waves have been observed in the magnetospheres of each of the magnetized planets in the solar system. These waves make an essential contribution to magnetospheric dynamics and are key to a full understanding of energy redistribution throughout the system, and in some cases periodic modulations over a broad range of timescales. Data gathered during the transit of Voyager 2 through the magnetospheres of Uranus and Neptune show evidence of ULF activity in these systems, though to what extent remains unclear. The unorthodox properties of these magnetospheres present an opportunity to test existing theories in unexplored parameter space, notably ULF-wave-production mechanisms and subsequent wave-wave and wave-particle interactions. ULF waves are also likely to play a role in the near-constant dynamic reconfigurations of these magnetospheres imposed by their obliquity and magnetic dipole offsets.

We will discuss the observations of ULF waves gathered thus far in the context of their implications for system-wide dynamics, and how a new understanding of ULF waves at the Ice Giants may improve our understanding of magnetospheres throughout the solar system.

A More Viscous-Like Solar Wind Interaction with the Ice Giant Planets

A. Masters (Imperial College London)

Identifying and quantifying the different drivers of energy flow through a planetary magnetosphere is crucial for understanding how each planetary system works. The magnetosphere of our own planet is primarily driven externally by the solar wind through global magnetic reconnection, while a viscous-like interaction with the solar wind involving growth of the Kelvin-Helmholtz (K-H) instability is a secondary effect. Here we consider the solar wind-magnetosphere interaction at all the magnetized planets, exploring the implications of diverse solar wind conditions and focusing on the most distant ice giants. We show that with increasing distance from the Sun the electric fields arising from reconnection at the magnetopause boundary of a planetary magnetosphere become weaker, whereas the boundaries become increasingly K-H unstable. Our results support the possibility of a predominantly viscous-like interaction between the solar wind and both Uranus and Neptune, in stark contrast with the solar wind-magnetosphere interaction at Earth.

Near-infrared observations of Uranus: spatially resolving of the H_3^+ ionosphere

Henrik Melin (University of Leicester), L. N. Fletcher (University of Leicester), T. S. Stallard (University of Leicester), S. Miller (University College London), L. Moore (Boston University), J. O'Donoghue (JAXA), L. M. Trafton (University of Texas, Austin), E. M. Thomas (University of Leicester)

Observations of emission from the molecular ion H3+ allows us to monitor the ionosphere of Uranus from the ground. The emission has been observed form Uranus at semi-regular intervals from 1992, but a concerted effort was undertaken after 2010 to increase the cadence of these observations. Since then we have built a large catalogue of at-least-yearly observations from a number of telescope facilities, which together show that the long-term cooling present in the ionosphere has been continuous since 1992. In 2016 the iSHELL high resolution near-infrared spectrographs was commissioned on the NASA Infrared Telescope Facility (IRTF), which presented a paradigm shift in the quality of the observations. Here, we describe this programme and its findings. We also present the very latest iSHELL observations obtained in October and November of 2019.

The "H_3^+ Problem" at Neptune

L. Moore (Boston University), H. Melin (University of Leicester), and J.I. Moses (Space Science Institute)

As H_3^+ is a major component of giant planet ionospheres, its emissions have been incredibly fruitful for studies of the upper atmospheres Jupiter, Saturn, and Uranus. They can be used to remotely monitor thermospheric temperatures and ionospheric plasma densities, and they provide key insights into magnetosphere-ionosphere coupling processes and auroral emissions. To date, however, no H_3^+ emissions have been detected at Neptune. Recent observations place an upper limit on H_3^+ column densities of ~10^{13} m^{-2} – at least a factor of 5 lower than the most conservative model estimates. Here, we present a range of model simulations in order to further quantify the discrepancy between modelled and observed column densities. The current lack of H_3^+ detection at Neptune could be indicative of an extended period of heightened exogenous dust influxes and/or vertical mixing, both of which can lead to reductions of H_3^+ via charge-exchange.

Further Reading:

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Neutral Tori: Potential key insight into Ice Giant Magnetospheres

H. T. Smith (Johns Hopkins University Applied Physics Laboratory)

Neutral Tori are generally a result of particles escaping from a planetary atmosphere, its rings or satellites through internal source mechanisms or interactions with the magnetosphere. These particles then form a population of co-orbiting neutral particles that provide a source of plasma to the magnetosphere as well as drive dynamics and chemistry. Thus, understanding neutral tori provides key (sometimes unique) insight into planetary magnetospheres, moon source characterization and understanding, and ultimately can provide insight to past, present and future of magnetospheres. Current increased neutral torus research had provided significant insight into Saturn and Jupiter's magnetosphere and gas giants in general. These results indicated great potential for improving our understanding the magnetospheres of Uranus and Neptune whose orientations offer the possibility of magnetospheric configurations not previously observed. Here, we will discuss how the Gas Giant neutral torus state of understanding and significantly increased and may provide an analogy for what we may expect from studying these features on Ice Giants.

Satellites and Rings

Climate modeling on Triton with a hierarchy of models

T. Bertrand (NASA Ames Research Center), E. Lellouch, F. Merlin, B. Sicardy (Observatoire de Paris - LESIA), F. Forget (Université Pierre et Marie Curie – LMD)

The high-resolution images of the south pole of Triton seen by Voyager 2 revealed hints of atmosphere dynamics, with dark NE-oriented surface wind streaks and dark plumes blown away by 8-km westward horizontal winds [1]. In addition, ground-based observations as well as modeling effort have been performed in the last decades, leading to different scenarios for the volatile and non-volatile surface ice distribution [2-5], and a record of atmospheric pressure [6-7] and CH_4 and CO column densities [8]. We investigate the volatile transport of N2, CH4 and CO over the last decades and the atmosphere dynamics on Triton in 1989 in light of what we learned on Pluto with New Horizons and using two Pluto-validated climate models:

- The 2D LMD Volatile Transport Model, which simulates the volatile cycles over millions of years [9-10].
- The 3D LMD Global Climate Model (GCM), which contains the full 3D dynamics, cloud formation, turbulence, radiative transfer etc. [11]

We compare the results with available observations to understand the surface ices distribution and evolution and the possible atmospheric circulation regime of Triton. In particular, our results suggest a reduced North polar cap and CH4-rich deposits near the edge of the South polar cap.

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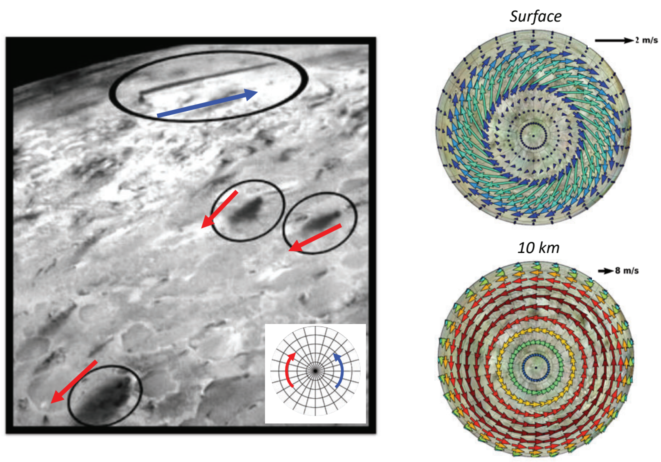

Figure 29 Left : the south pole of Triton seen by Voyager 2 revealed N-E retrograde surface wind streaks (red arrows) and N-W prograde 6-10 km altitude plumes (blue arrows). Right : surface and 10 km horizontal winds as simulated with the Triton GCM. The GCM reproduces this trend only when a small northern polar cap is assumed.

Know before you go: status of the ephemerides and physical parameters in the Uranus and Neptune systems

M. Brozović (Jet Propulsion Laboratory, California Institute of Technology), R.A. Jacobson (Jet Propulsion Laboratory, California Institute of Technology)

We summarize the current status of the satellite ephemerides of Uranus and Neptune, including the values and uncertainties of physical parameters such as the GMs, pole orientations, and gravity field coefficients. We recently updated the satellite ephemerides for all but inner satellites of Uranus and these solutions are available on JPL's Horizons on-line solar system data and ephemeris computation service, https://ssd.jpl.nasa.gov/horizons.cgi. We determined the GMs of Triton, Naiad, and Thalassa in the Neptune system, the GMs of Ariel, Umbriel, Titania, Oberon, and Miranda the Uranus system, and the first two zonal harmonics for both planets. It is unlikely that the higher order gravity coefficients will become measurable without an orbiter. The moment of inertia g of Uranus remains elusive due to the planet's pole precession rate of only ~1.3 mas/yr which is too small to be detected. However, g may become measurable with the availability of <1 mas precision absolute satellite astrometry, or an orbiter with low altitude Uranus periapsis passages. The moment of inertia of Neptune may be easier to determine due to Triton's relatively rapid precession rate. We plan to do periodic ephemerides updates as more Earth-based, Hubble Space Telescope, and ring occultations data are acquired.

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Using the rings of Ice Giants to probe their planets' interiors, magnetospheres and moons.

M.M. Hedman (University of Idaho)

Planetary rings are exceptionally sensitive probes of their environments, so detailed measurements of the rings around the Ice Giants can provide useful information about their planets' interior, magnetosphere and moons. For example, recent studies of historical observations of one of Uranus' rings yielded constraints on the mass of one of Uranus' small moons. Meanwhile, Cassini observations of Saturn's rings have revealed structures driven by oscillations in the planet's interior and asymmetries in its magnetosphere. Similar structures may exist in the rings around the Ice Giants and so could help constrain the internal structures of those planets.

Composition Mapping the Rings and Moons of Ice Giants

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The origin and evolution of ice giants' ring-moon systems cannot be understood without their composition information. A modern dust analyzer equipped with a mass spectrometer provides a viable and robust measurement method to perform composition mapping of rings and moon surfaces in planetary systems. Dust grains, like photons, carry information from the environment where they were formed and interacted with. These effectively "information capsules" are transported by various processes, such as impact ejecta production from meteoroid bombardment and/or non-gravitational forces, and can be measured by an orbiting spacecraft to produce a composition map along the spacecraft ground track. This has been impressively demonstrated with CDA onboard Cassini in the Saturnian system and is the major task of SUDA onboard Europa Clipper. In addition, in situ dust measurements are highly sensitive to diffuse populations as well as localized sources (e.g., a cryo-volcanic eruption), providing complementary information to imagery, spectroscopy, and field-and-particle datasets for the study of rings, moons, and their interactions with the magnetosphere and host planet.
Here we will provide an update about the capability of a modern dust instrument as well as the potential scientific contribution for the study of the ring-moon systems of ice giants.

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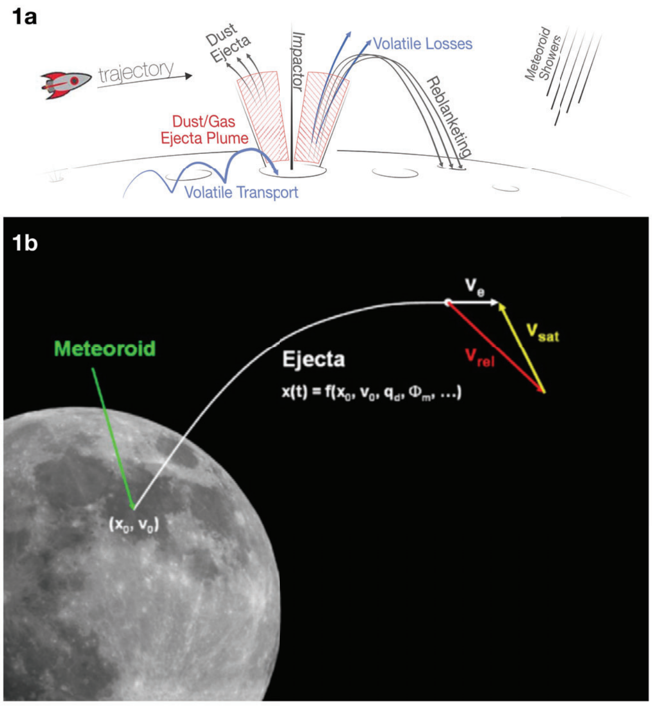

Figure 30 Ejecta produced by meteoroid impacts could be detected in orbit to provide localized surface composition information along the spacecraft ground track using a high-resolution dust mass spectrometer. By tracing the trajectory back to the surface compositional maps of the surface are generated (Fig. 1b from Postberg et al., 2011).

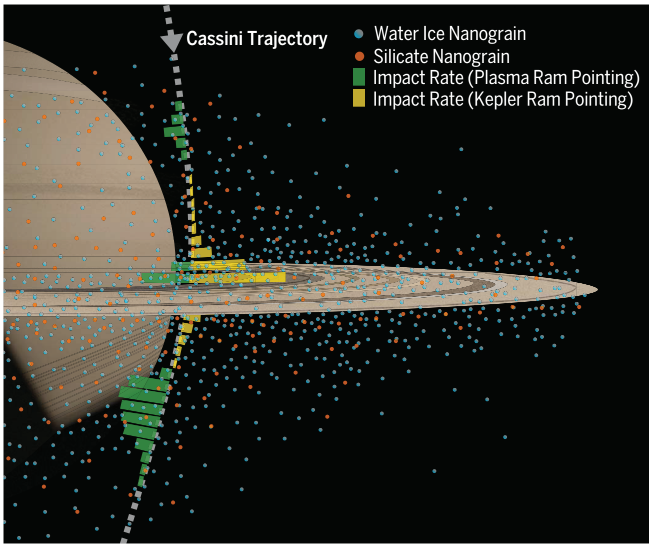

Figure 31 Schematic view of the nanometer-sized ring ejecta environment measured by the Cassini Cosmic Dust Analyser (CDA) during the Cassini Grand Finale mission. Grains with two composition types were detected: water ice and silicates. The measured particle flux profiles show influences of Saturn's gravitational and electromagnetic fields, and suggest Saturn's main rings as the source.

Tectonic resurfacing on Ariel, a Uranian satellite

E. J. Leonard (Jet Propulsion Laboratory, California Institute of Technology), D. A. Patthoff (Planetary Science Institute)

Voyager 2 encountered the Uranian system in 1986 and returned images of all of the major moons in the system. Ariel, the second major moon from Uranus, was imaged at ~3 km/pixel [1]. The lack of large (>10 km diameter) identifiable craters on Ariel's surface implies that the satellite has resurfaced (Figure 32) [2]. This resurfacing is also evidenced by the chasmata, or large (>5 km wide) canyons, that extend for 10s of kilometers and are located near the equator of the moon (in the limited images obtained by Voyager). Previous work on the chasmata hypothesizes that they are cryovolcanic features and evidenced by the smooth material that fills these canyons [3]. In this work, we examine whether the chasmata could form through tectonic processes by investigating extension in a two-layer physical analogue model (Figure 33) [4, 5] and modelling potential stress mechanisms [6] including diurnal and obliquity stresses. Our results have consequences for the depth to a potential liquid layer and orbital history of the satellite.

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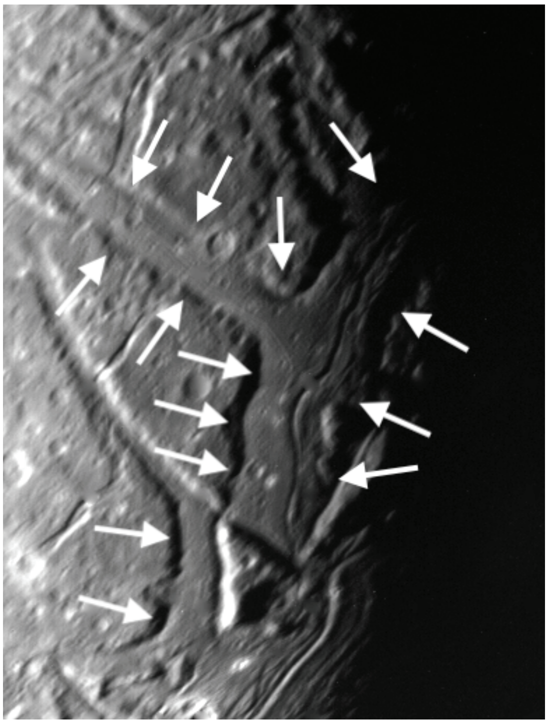

Figure 32 Chasmata (indicated by white arrows) on Ariel's surface, as imaged by Voyager 2 (PIA01356, resolution ~ 2.4 km/px).

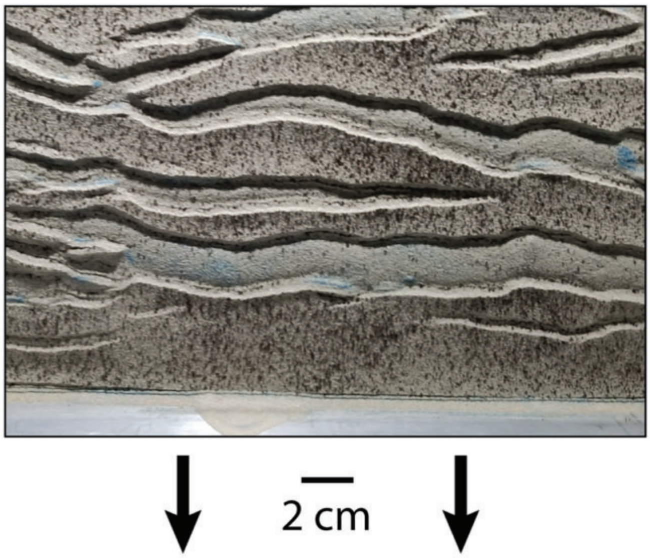

Figure 33 Example of a physical analogue experiment run with a 1 cm brittle layer underlain by 2 cm of putty with a total strain of ~30% at a strain rate of 10^{-6} s^{-1}. The resulting horst and graben system in the experiments have similar morphology to the chasmata on Ariel including: (1) flat-topped ridges, (2) broad troughs, and (3) slight bowing-up of the material within the troughs [3].

Cryovolcanism in the Outer Solar System

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The surfaces of the icy satellites in the outer solar system exhibit a wide range of ages and terrains, from ancient and impact-scarred, to youthful and actively resurfaced. Endogenic geologic activity on these moons may manifest as tectonism and cryovolcanism (i.e., icy cold volcanism) at their surfaces. Neptune's moon Triton was the first object where active plumes were observed by Voyager 2 in 1989. Since then, spacecraft data have revealed evidence of global oceans beneath the icy shells of a variety of icy bodies. In some cases, these subsurface oceans could supply the requisite protection, key elements, and energy sources to provide habitable conditions for, and facilitate the development of, simple lifeforms on these ocean worlds. Communication between the ocean and the surface in the form of cryovolcanism might therefore provide an essential pathway for biosignatures originating in the ocean to be delivered to the surface where they could be detected by spacecraft instruments searching for signs of extraterrestrial life. This paper will review the range of cryovolcanic features that have been observed on icy bodies and what we know about their origin.

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Digital elevation modelling of Uranian moons using Voyager 2 images

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The Voyager 2 flybys of Uranus and Neptune provided the first, and to date only, imaging of their respective moons, revealing a host of fascinating geological features, the presence of plumes on Triton and possible cryovolcanic deposits on Miranda and Ariel. Miranda's resurfaced and deformed terrain hints at a past period(s) of intense tidal heating. Exploration of these potential ocean worlds may be a key motivation for future missions. Imaging coverage by future flyby missions may be limited, and an orbiter mission might not observe regions of the moon surfaces imaged by Voyager 2 due to different lighting conditions. The Voyager 2 flyby datasets therefore continue to be one of the most important tools for understanding ice giant moons. Digital elevation models (DEMs) constructed from flyby and orbital imagery are a basic tool used to study planetary bodies, allowing for the evaluation of quantities such as past tidal stresses and thermal histories. For the ice giant satellites, DEM generation is challenging due to the low image quality, limited coverage, and limited stereopairs of the Voyager 2 images. Here we present DEMs of regions on Ariel and Miranda that were generated using a workflow optimized for the challenging Voyager 2 dataset.

Missions and Instrumentation

An Energetic Particle Monitor for Ice Giant Atmospheric Probes

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The Voyager 2 flybys of Uranus and Neptune provided limited measurements of energetic particles in their magnetospheres. The energetic particle instrument onboard the spacecraft detected significant fluxes of energetic electrons and protons in the regions of their magnetosphere where these particles could be stably trapped. We will review these observations and discuss the need for a more detailed modeling of their particle environment for their future exploration.

An Ice Giant Atmospheric Probe will provide a unique platform in order to measure energetic particles in the innermost regions of their magnetospheres – within a few radii of the cloud tops – and into the upper atmosphere, as was done with Galileo Probe EPI at Jupiter and during the Cassini Grand Finale at Saturn.

We will propose an instrument onboard an Ice Giant Atmospheric Probe in order to provide omnidirectional as well as sectored measurements of electrons (30 keV – 1 MeV) and ions (30 keV – 6 MeV) in their magnetospheres. The foreseen instrument will operate during the pre-entry phase of the Probe and provide unique measurements to understand the innermost magnetospheric structure, dynamics, and electrodynamical coupling between the dust, rings, moons, and atmosphere of Uranus and Neptune that cannot be achieved with an orbiter.

A radio and plasma wave experiment for the ice giants

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We describe a consolidated and compressed package of radio and plasma wave instruments for inclusion on a future mission to Uranus or Neptune. Proceeding from a set of scientific goals, we identify specific sensors and sub-systems necessary for the investigation. We consider trade-offs involved in both orbital and fly-by mission scenarios. We demonstrate that a radio and plasma wave package is required to address many of the major open science questions concerning these planetary systems, and that even measurements from a relatively constrained payload are capable of providing fundamental new insights to the Ice Giants. Building on shared heritage and re-use from similar instrument suites on Cassini, BepiColombo, and experience gained during the development of the RPWI system on JUICE, we present outline concepts for a streamlined payload for the tightly constrained mass, volume and telemetry envelope likely to be realised for a potential future mission to the outer solar system.

Net Flux Radiometer for Ice Giant Probes

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A Net Flux Radiometer (NFR), for inclusion as a payload on a future Ice Giants Probe mission, is described. The NFR will measure the upward and downward radiation flux, in seven spectral bands, spanning the range from solar to far infra-red wavelengths, each with a 5° field-of-view and in five view angles (±80°, ±45°, and 0°) as a function of altitude. NFR measurements within either Uranus or Neptune's atmospheres, using dedicated spectral filter bands will help derive radiative heating and cooling profiles, and will contribute to our understanding of the planet's atmospheric heat balance and structure, tropospheric 3-D flow, and compositions and opacities of the cloud layers. The NFR uses seven non-imaging Winston cones integrated to thermopile detectors, with individual bandpass filters, housed in a diamond windowed vacuum micro-vessel. The focal plane thermopile detector signals are read out in parallel mode, amplified and processed by a multi-channel digitizer application specific integrated circuit under field programmable gate array control. The vacuum micro-vessel rotates providing chopping between upward and downward radiation fluxes. The unique design allows for small net flux measurements in the presence of large ambient fluxes and rapidly changing ambient temperatures during the Probe descent to ≥10 bar pressure.

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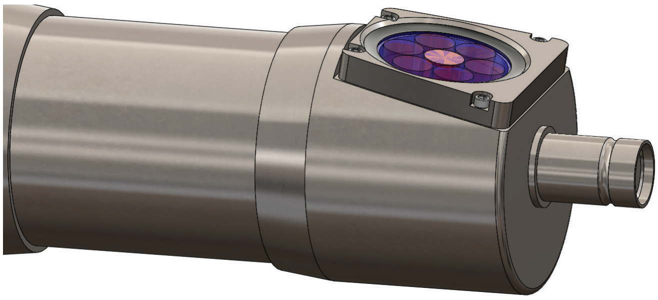

Figure 34 NFR vacuum micro-vessel (13 cm in length) which houses the seven Winston cones and thermopile detector focal plane assembly. The Winston cone field-of-view's (highlighted) transmit through a diamond window.

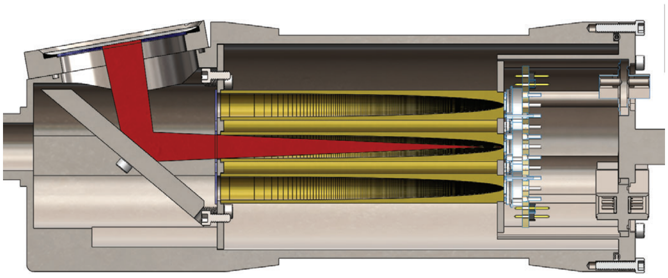

Figure 35 Half-section of the NFR vacuum micro-vessel showing a F#/11.3 (~5° full angle) beam, fold mirror, Winston cones and detector focal plane assembly.

INTA's Mars miniature sensors: synergies for Ice Giants exploration

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INTA's Space Sensors Engineering Area (AISE) has been involved in Martian exploration during the last decade, developing four different radiometers [1-4], one magnetometer [1], one nephelometer (in cooperation with INAF, Italy)[5] and one dust sensor (together with University Carlos III, Spain)[6] for different missions (MetNet penetrator, Schiparelli Lander, Mars 2020 Rover and ExoMars 2020 Surface Platform).

That is the result of a long-term strategy established ten years ago, named InMARS [7], devoted to the development of high performance, low power, miniature sensors capable of operating in the extreme Martian atmospheric conditions. Within this program we have developed an intensive selection, qualification and screening activity (CERES - Compact Electronic Resources for the Exploration of Space) that allowed us to acquire key enabling technologies, components (including ASICs [8][9]), materials and procedures.

Taking advantage of the experience and heritage accumulated during this decade, we propose an early concept of a lightweight radiometer for future probes to Ice Giants or other moons with rich atmospheres for the study of the suspended aerosols scattering properties, the particles number density, constraining the aerosol shape, size and opacity. The limited resources that our technology demands from the platform allow it to be used as a complement to other atmospheric instrumentation included in future missions.

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[9] S. Sordo-Ibáñez et al. IEEE Transactions on Magnetics, vol. 51, pp. 1-4, 2015.

Measurements of Ice Giant Atmospheric Dynamics and Composition from Radiometric Tracking of an Entry Probe

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The dynamics of planetary atmosphere including winds, waves, tides, and turbulence is a tie-point between multiple aspects of planetary structure and processes, including atmospheric composition and compositional gradients, thermal and energy structure, and the location and properties of the clouds. Radiometric tracking of an ice giant entry probe provides the only direct measurements of the atmospheric dynamics along the probe descent path, as well as measurements of the abundance of microwave absorbing molecules along the probe relay signal raypath, expected to be primarily ammonia (NH_3) or hydrogen sulfide (H_2S).

Doppler tracking of a descent probe has been demonstrated at Jupiter with the Galileo Jupiter and Huygens Titan probes. Using ultrastable oscillators, the time variation of the measured relay signal frequency provides a direct measure of the line of sight component of probe speed. Careful analysis of the Doppler residuals can provide the signature of atmospheric waves, convection, and turbulence, along with other probe dynamical effects such as probe spin and pendulum motion.

Measurements of the received signal strength would provide a profile of atmospheric absorbers along the probe radio signal raypath, complementing probe mass spectrometer composition measurements.

Possible Payload for Future Ice Giant Entry Probe Missions

D.H. Atkinson (Jet Propulsion Laboratory, California Institute of Technology), O. Mousis (Aix Marseille Université, CNRS), T.R. Spilker (Independent Consultant)

Descent probes make essential measurements of atmospheres beyond the reach of remote sensing, including the abundances of noble gases and key isotopes, and the thermal and dynamical structure beneath the cloud tops. Measurements are defined as Tier 1, indicating threshold science required to justify the probe mission, and Tier 2 indicating valuable science that significantly complements and enhances the threshold measurements, but are not enough to justify the probe alone.

Tier 1 measurements comprise atmospheric abundances of noble gases including helium, key isotopic ratios, and atmospheric thermal structure. Tier 1 instrumentation includes a mass spectrometer and helium abundance detector, and an atmospheric structure instrument.

Tier 2 science includes lower priority atmospheric structure and processes including atmospheric dynamics, atmospheric net radiative transfer of upwelling thermal infrared and downwelling visible fluxes, cloud locations and properties, and the abundances of key disequilibrium species. Potential Tier 2 instrumentation includes a nephelometer, net flux radiometer, accelerometers, and telecomm ultrastable oscillators to enable Doppler wind measurements.

Carrying Tier 1 and possibly Tier 2 instrumentation, a shallow probe would measure abundances of noble gases, key isotopes, heavier elements and disequilibrium species, and deeper atmospheric thermal structure, dynamics, and other processes not measurable by remote sensing.

Science Goals and Mission Objectives for the Future Exploration of Ice Giants Systems: A Horizon 2061 Perspective

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We will present the unique place of Ice Giants in the "Planetary Exploration, Horizon 2061" foresight exercise (e.g., http://horizon2061.cnrs.fr/) and the key measurements needed to address its key science questions:

a) Origin of ice giant systems:
In-situ measurements of elemental composition and isotopic ratios of Ice Giants atmospheres will allow to unravel the scenarios of their origin;

b) Diversity of planetary systems architectures:
An in-depth exploration of giant planets systems by an orbiter missions is needed to understand the diversity of their architectures;

c) Diversity of Solar System objects:
This exploration will allow us to compare ice giants with other solar system planets and with "hot Neptunes";

d) How do ice giants work?
A synergistic combination of in-situ and orbiter observations is needed to understand their internal structure and dynamics, the generation of their magnetic fields, and how their magnetospheres and aurorae work;

e) Moons and potential habitats:
A comprehensive study of satellite systems will provide clues to their origins and potential habitability.

In conclusion, we will present a science traceability matrix connecting the five science objectives to the key measurements needed to address them and will discuss the specific advantages of a space exploration of the two Ice Giants.

New Frontiers-class Uranus Orbiter: Exploring the feasibility of achieving multidisciplinary science with a mid-scale mission

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Uranus presents a compelling scientific target and provides a unique opportunity to explore Ice Giant system science. Characteristics of the Uranian system include: 1) a dynamically full and haphazard ring-moon system; 2) five major satellites - potential ocean worlds with drastic surface features; 3) a dramatically configured magnetosphere with highly-tilted rotational and magnetic axes; 4) a bulk planetary

	Outstanding Mystery	Science Objective *(Relevant V&V Science Goal)*	Potential Observables
RINGS	*Why is the architecture of the Uranian ring-moon system so dynamically full & haphazard?*	Determine the processes that sculpt & maintain Uranus' ring-moon system. *(1)*	• Ring particle size distribution, planet/moon tidal parameters • Ring internal structures (e.g., density/satellite wakes) • Rings' non-circular shapes & pattern speeds • Discovery of new moons & moon shapes, light-curves, & orbital elements • Dusty ring spatial density & periodic structures • Magnetic field orientation, components, & periodicities
		Determine the composition & origin of Uranus' rings & small satellites. *(1)*	• Spectral absorption in moon & ring spectra • Crater density on small moons • Micrometeoroid impact flux & composition • Radiation belt location & flux
SATELLITES	*Do any of Uranus' classical satellites sustain a subsurface ocean?*	Determine whether the classical Uranian satellites have signatures indicative of subsurface oceans. *(6)*	• Tectonic & geomorphologic structures, tidal flexing, plume activity, physical libration, thermal anomalies • Topography • Spectroscopic indications of outsourcing from interior • Induced magnetic field & satellite tidal number/degree of compensation
	Which processes formed the extremely dark & resurfaced terrains of the five classical Uranian satellites?	Determine the surface compositions of the classical Uranian satellites. *(4)*	• Compositional mapping & associations (or lack) w/ geologic features/topographic lows (cold traps) • Regional distributions (leading vs. trailing hemisphere) of dark material • Compositional trends w/ distance from Uranus
		Understand what processes formed & modify the surfaces of the classical Uranian satellites. *(4 & 5)*	• Units & surface features/structures • Topography & stratigraphy • Relative age of units & features (estimated from cross-cutting relations & crater density) • Incident plasma & energetic particle spectra (moon-magnetosphere interactions)
MAGNETOSPHERE	*How does plasma transport work in Uranus' unique magnetospheric configuration?*	Understand the fundamental structure and dynamics of Uranus' magnetosphere and the importance of internal vs. external drivers. *(1 & 3)*	• Temporal & spatial variabilities in plasma & magnetic fields • Plasma & energetic ion composition • Particle energization & acceleration • Times, durations & depths of satellite/ring microsignatures
	How does Uranus generate such an intense electron radiation belt?	Understand what processes generate Uranus' intense electron radiation belt. *(1 & 3)*	• Plasma & low-frequency waves & wave power distributions • Plasma and energetic electron & ion pitch-angle distributions & energy spectra
INTERIOR	*How is Uranus' interior structured below the clouds and how does it behave?*	Understand the configuration & evolution of Uranus' magnetic field. *(1 & 3)*	• Map of the intrinsic magnetic field, including spherical harmonic coefficients • Temporal evolution of the intrinsic magnetic field • Low-degree (<10) odd and high degree (>10) even gravitational harmonics • Internal heat flux as a function of latitude
		Determine the bulk composition & the distribution of materials within Uranus. *(1 & 2)*	• Noble gas abundances (incl. He) – *requires entry probe* • Bulk enrichments of C, N, and S (*requires entry probe*) & remote sensing above the clouds • Low-degree (<10) even gravitational harmonics • Map & temporal evolution of the intrinsic magnetic field
		Understand Uranus' global energy balance & internal heat flow. *(1)*	• Reflectivity at multiple phase angles & latitudes • Thermal emission at multiple latitudes • Temperature/density profiles • Distribution of absorbers & temperature lapse rate in upper troposphere/stratosphere
ATMOSPHERE	*What mechanisms drive Uranus' large- & small-scale atmospheric dynamics?*	Understand Uranus' atmospheric heat transport mechanisms. *(1 & 3)*	• Mapping of entire planetary "surface" • Upper atmospheric density & wave inventory • Tracking of storms, clouds, and eddies in reflected sunlight • Thermal profile, upward & downward radiative flux – *requires entry probe*
		Understand Uranus' zonal & meridional circulation patterns. *(1 & 3)*	• Temperature & ortho/para-H_2 mapping • Tracking of clouds • 3D maps of key volatiles and tracers (e.g., CH_4, H_2S, NH_3, H_2O, CO, para-H_2; *enhanced* by *entry probe)* • 2-cm brightness temperature
		Determine the thermodynamics & chemistry of Uranus' clouds and hazes. *(1 & 3)*	• Aerosol structure mapping • 3D maps of key volatiles and tracers (e.g., CH_4, H_2S, NH_3, H_2O, CO, para-H_2; *enhanced entry probe)* • Abundances of hydrocarbons in upper atmosphere

Figure 36 "Proto-Science Traceability Matrix" outlining the outstanding mysteries and potential science objectives that could be addressed by a New Frontiers-class Uranus orbiter mission, along with the potential observables and measurements required for closure. Cohen et al.

composition that is unknown, but expected to be dominated by heavy elements such as silicates, H_2O, CH_4, and NH_3; and 5) a unique wind pattern and unknown circulation structure. Detailed study of Uranus by an orbiter is crucial not only for valuable insights into the formation of our solar system but also for providing ground truths for the understanding of Ice Giant-sized exoplanets. For these reasons and more, the imperative and timely exploration of Uranus will not only enhance our understanding of the Ice Giant planets but also extends to universal study of planetary dynamics.

Flybys only provide limited snapshots of a planetary space environment at a given location and time. It is challenging, if not impossible, to characterize a system with such a limited *in situ* dataset. The only way to comprehensively understand Uranus is with an orbiting mission.

Plasma Instruments for Magnetospheric Science at Uranus and Neptune

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The magnetospheres of Uranus and Neptune remain virtually unexplored. Studying these environments is necessary for a complete understanding Solar System magnetospheres and extrapolation to exoplanets. Science questions related to magnetospheric structure and dynamics, plasma sources, and satellite- and solar wind-magnetosphere interactions have been prioritized in the 2013 – 2022 Planetary Science Decadal Survey and Ice Giant pre-decadal mission study. To address these questions, measurements from a suite of instruments are desired, including plasma. The Southwest Research Institute has a proven track record of delivering high-quality plasma instruments for planetary missions. Here, we introduce the Jovian Auroral Distributions Experiment (JADE) [McComas et al. 2017] and Compact Dual Ion Composition Experiment (CoDICE) [Desai et al. 2016] as candidate instruments for Ice Giant missions. JADE is a suite of electron and ion sensors, with large energy and angular coverage, that are currently measuring plasma distributions in Jupiter's magnetosphere on Juno. CoDICE, which is part of the Interstellar Mapping and Acceleration Probe mission, combines plasma, pickup ion, and energetic particle measurements into one sensor package that can be optimized for magnetospheric observations. Details of their instrument capabilities are provided with an emphasis on how they help address important science questions for Uranus and Neptune.

The Alice/UVS Line of Instruments: Uniquely Equipped for Ice Giant System Studies

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Future missions to the Uranus and/or Neptune systems will likely study the structure and evolution of their atmospheres, satellite exospheres, satellite surfaces, rings, and magnetospheres. Remote sensing via ultraviolet spectroscopy can be applied to all of these sources to learn about their composition, structure and magnetospheric interactions. The Alice/UVS line of heritage instruments (Rosetta-Alice, New Horizons-Alice, LRO-LAMP and Juno-UVS) have been used to 1) measure rarefied gases around comet 64P/Churyumov-Gerasimenko and Earth's Moon, 2) retrieve the vertical structure of the atmospheres of Pluto and Jupiter through stellar and Solar occultations, 3) find surficial ice deposits in the moon's permanently shadowed regions, and 4) image Jupiter's auroral emissions to provide context for how in-situ particle measurements connect to the global magnetospheric dynamics at Jupiter. We describe 1) previous studies using the Alice/UVS line of instruments, 2) the capabilities of the next two UVS instruments in production (JUICE-UVS and Europa-UVS), and 3) current design requirements and capabilities of a future Ice Giant UVS exhibiting high heritage and proven reliability.

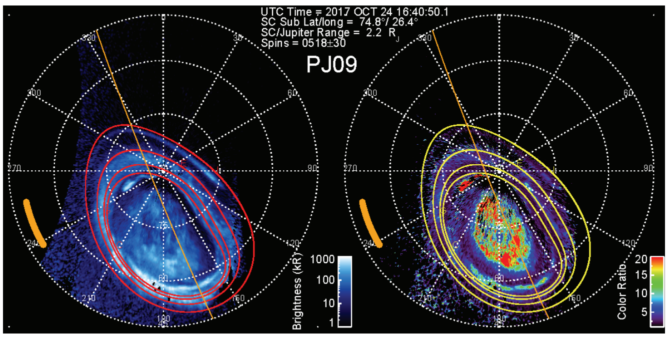

Figure 37 Juno-UVS regularly images the northern aurora of Jupiter (shown here). Auroral emissions can provide a way to monitor plasma dynamics occurring throughout the 3-D magnetosphere around Jupiter and other Giant Planets. This image from the 9th orbit of the Juno mission shows UV auroral brightness on the left and color ratio on the right. Higher color ratio indicates larger CH_4 column abundance above the prompt UV emissions caused by auroral electron impact. This affect is generally assumed to indicate higher electron energy in the auroral electrons, allowing them to penetrate deeper into Jupiter's atmosphere. The four red traces on the left and yellow traces on the right image are the predicted ovals of the footprints of the Galilean Moons. The orange line in both images

represents the terminator, and the position of the Sun is shown by the thick orange crescent on the left of both images.

Feasibility of an Ice Giant Deep Probe (1kbar)

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Access to depths beyond 100bar pressure is traditionally considered infeasible for Ice Giant missions. In this manuscript, we attempt to bridge this feasibility gap by outlining the design for a small, focused-science deep (1kbar pressure) probe for Uranus. Specific objectives would be to measure temperature, pressure, and concentrations of CH_4, NH_3, H_2O, H_2S in vapour form in order to (1) constrain models of atmospheric chemistry, cloud formation, and dynamics, and (2) help constrain models of Ice Giant formation. We discuss instrument selection, communications architecture, thermal and pressure-vessel requirements, and sampling inlet methods for a probe of 12 litre internal volume. The deep probe would deploy from a shallower larger probe that doubles as the data relay. We identify unaddressed risks and technology hurdles. Such hurdles were not deemed infeasible, indicating that in-situ science at depths from 100bar to 1kbar should be considered in future Ice Giant mission studies.

The research described in this paper was funded by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Further Reading:
AGU Abstract on Uranus orbiter mission, which would include probes:
https://agu.confex.com/agu/fm19/meetingapp.cgi/Paper/607916

Figure 38 Pill-shaped deep probe (~27cm x 41cm, 110kg) an insulated pressure vessel of 12 litre internal volume. Shown with deployed dipole antennae.

Plasma Instrumentation for an Ice Giants Mission

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Voyager 2 showed that Uranus and Neptune's magnetospheres are both fascinating environments unlike those surrounding other planets. The offset and tilted magnetic dipoles at both drive extremely unusual solar wind interactions, and internal magnetospheric plasma processes vary on planetary rotational and orbital cycles. The presence and effects of significant internal plasma sources are currently unconstrained, together with the composition of neutral and plasma components. There are relatively intense electron radiation belts at both planets, but the proton belts need to be probed by extended missions. We need to address our lack of understanding of these magnetospheres, and their interactions with the planets' moons and rings, by observing the electron, proton, negative and proton populations in both systems. We present instrument concepts capable of addressing the above topics, based on the extensive heritage at University College London's Mullard Space Science Laboratory. MSSL has previously played leadership roles in, or has contributed to, ion and electron spectrometers for missions such as Giotto-JPA, Cluster-PEACE, Cassini-CAPS, and current/upcoming contributions to Solar Orbiter-SWA, JUICE-PEP, and Comet Interceptor-DFP. These instruments can address specific topics such as particle acceleration, positive and negative ion pickup, planetary wind, the identification of plasma sources and sinks, plus many other processes.

Alternate Radioisotope Heat Sources for Icy Moons Exploration

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Voyager 2 (launched in 1977) made its closest encounter with Uranus in 1986, and with Neptune in 1989. It is still the only spacecraft to have visited either of these ice giant systems. As Voyager 2 leaves the solar system, it is still providing information to the scientific community thanks to the electrical power produced by its three Multi-Hundred Watt radioisotope thermoelectric generators (MHW-RTG). For over fifty years, all U.S. RTG powered spacecraft have utilized the radioisotope plutonium-238 as the heat source material.

While plutonium-238 has been an outstanding radioisotope for a number of U.S. exploratory space missions, it has a relatively low thermal output (~0.5 W_{th}/g). This characteristic will likely severely restrict its potential for an icy moon subsurface endeavour. The emphasis of this research focuses on evaluating other radioisotopes for an icy moon probe considering factors such as: thermal output, half-life, materials compatibility, etc. Recent work suggests that curium-244 (initial thermal output ~2.8 W_{th}/g) has several promising properties as a heat source for a future icy moon probe. Since any new radioisotope heat source will require extensive technical/safety investigations, the timeframe is short to initiate these activities if it is required for Icy Planet missions in the 2030s/2040s.

Further Reading:

D.P. Kramer, et al., "*Nuclear Heat Source Considerations for an Icy Moon Exploration Subsurface Probe*," Proceedings of the Nuclear and Emerging Technologies for Space (NETS2019), Richland, WA, February 2019. Available online at: http://anstd.ans.org/NETS-2019-Papers/Track-1--Emerging-Technologies-in-Space/Track-1--Emerging-Technologies-in-Space.html

A modern digital High Frequency Receiver to explore the Ice Giants radiosources

L. Lamy, B. Cecconi, M. Dekkali, P. Zarka, M. Moncuquet, X. Bonnin, P.-L. Astier, D. Dias, C. Louis (LESIA, Observatoire de Paris/PSL, CNRS)

Among the known planetary magnetospheres, those of Uranus and Neptune display very similar radio environments so that they have early been referred to as 'radio twins'. They produce a variety of electromagnetic radio waves ranging from ~0 to a few tens of MHz similar to - although more complex than - those of Saturn or the Earth (Desch et al., 1991, Zarka et al., 1995). These include the well known Uranian/Neptunian Kilometric Radiations (UKR/NKR) below 1MHz or the Uranian/Neptunian Electrostatic Discharges (UED/NED) beyond, which remain only known from Voyager 2 radio observations. Here, we present a modern concept of digital High Frequency Receiver (HFR) within the frame of a general Radio and Plasma Wave (RPW) experiment retained in various mission concepts toward Uranus and Neptune (e.g. Hess et al., 2010 ; Arridge et al., 2011, 2013, 2014 Christophe et al., 2011; Masters et al., 2013; Hofstadter at al., 2019). The presented HFR concept, based on the heritage of Cassini/RPWS/HFR, Bepi-Clompobo/PWI/Sorbet, Solar Orbiter/RPW and JUICE/RPWI/JENRAGE is aimed at providing a light, robust, low-consumption versatile instrument capable of goniopolarimetric and waveform measurements from a few kHz to ~20MHz, devoted to the study of auroral and atmospheric radio and plasma waves or dust impacts.

Science opportunities with the Langmuir probe experiment for the Icy Giants

M. W. Morooka, D. J. Andrews, J.-E. Wahlund, N. J. T. Edberg, A. I. Eriksson, J. Bergmann (IRF Uppsala, SE)

The Icy Giants and their moons and ring systems offer various exciting science opportunities for space physics and aeronomy. Both planets have haze atmospheric layers and surrounded by rings mostly composed of tiny dust grains. Neptune's moon Triton is geologically active underneath the water cluster surface. Uranus' moons, Miranda and Ariel, also have an icy surface with structure made by the tidal forces. The planetary rotational axis that is highly inclined to their orbital plane, as well as the oddly placed magnetic axis, affects the atmospheric seasonal structures, magnetospheric structures, and moon's environment. These characteristics are unique but there are similarities to the Gas giant systems. A Langmuir probe (LP) measures in-situ plasma density and temperatures of the ionosphere as well as the electron density of the magnetosphere, the key parameters for the dynamical plasma structures in the Icy Giants systems. With a double probe system, the DC electric field and the plasma flow, which is crucial to determine the subsurface activities of the icy moons can be provided. With the scientific heritage from the Cassini mission to Saturn and the JUICE mission to Jupiter icy moons, we will discuss the science objectives that the LP can provide the answer.

The CIRS-Lite Infrared Fourier Transform Spectrometer for missions to the Ice Giants

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The Voyager 2 IRIS Fourier Transform Spectrometer (FTS) built at NASA GSFC provided the first close-up thermal spectra and compositional information of the ice giants, Uranus (1986) and Neptune (1989). Its successor, Cassini CIRS provided much higher spatial and spectral resolution (0.5 cm^{-1} versus 4.3 cm^{-1}; 0.273 mrad versus 4 mrad) and sensitivity while mapping Jupiter (2000) and Saturn (2004-2017), and provided further spectacular new discoveries about their atmospheric composition and dynamics – including the detection of ethylene and the thermal mapping of the 'dragon' storm outburst - and the systems of rings and moons. The next evolution of this instrument series, CIRS-Lite, currently under development, will shrink the instrument relative to CIRS in size, weight and power, while providing increased sensitivity and versatile spectral resolution needed to make new discoveries for the cold atmospheres of the ice giant planets and their rings and moons.

Further Reading:
CIRS-Lite NASA Technical Report (Brasunas et al. 2012): https://ntrs.nasa.gov/search.jsp?R=20120016986
SPIE Paper (Pasquale et al. 2010, institutional access required): https://www.spiedigitallibrary.org/conference-proceedings-of-spie/7652/76520Q/Optical-design-for-the-Composite-InfraRed-Spectrometer-Lite-CIRS-Lite/10.1117/12.879044.full

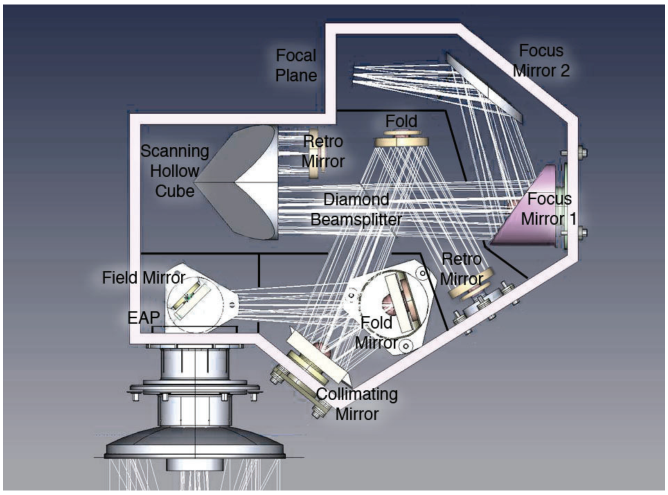

Figure 39 Optical and mechanical layout of CIRS-Lite. CIRS-Lite is more compact than CIRS, having only a single FTS pathway, and using new technology such as diamond beamsplitter to work throughout the thermal infrared, from 5 to 300 microns and beyond.

IPED: Study on the Impact of the Entry Zone on the Trajectory and Design of a Planetary Entry Probe

A. Probst, L. Spilker, T. Spilker, D. Atkinson, O. Mousis, M. Hofstadter, A. Simon

The IPED (Impact of the Probe Entry Zone on the Trajectory and Probe Design) study is a two to three-year NASA Postdoctoral Program research opportunity at JPL (kick-off September 2019) to investigate the impact of entry point selection on the design of the interplanetary and approach trajectory as well as on the probe design. Target bodies considered are Saturn, Uranus, and Neptune, with a slightly stronger focus on Saturn.

The impact will be shown by performing a trade-off between science return and mission design criteria based on a decision matrix which will be developed for three characteristic entry interface zones (EIZs) of each planet. The objective is to provide a baseline for entry site selection by comparing mission scenarios for different science cases.

This paper will present possible EIZs based on the outcome of an international survey on the science research foci of atmospheric sciences with respect to the Outer Planets. Two science maps are shown, outlining the main characteristic regions of the planets' atmosphere with respect to atmospheric science. Example mission scenarios are explained and a first assessment of entry design affecting parameters are shown.

Acknowledgements: Alena's research was supported by an appointment to the NASA Postdoctoral Program at the Jet Propulsion Laboratory, California Institute of Technology, administered by Universities Space Research Association under contract with National Aeronautics and Space Association.

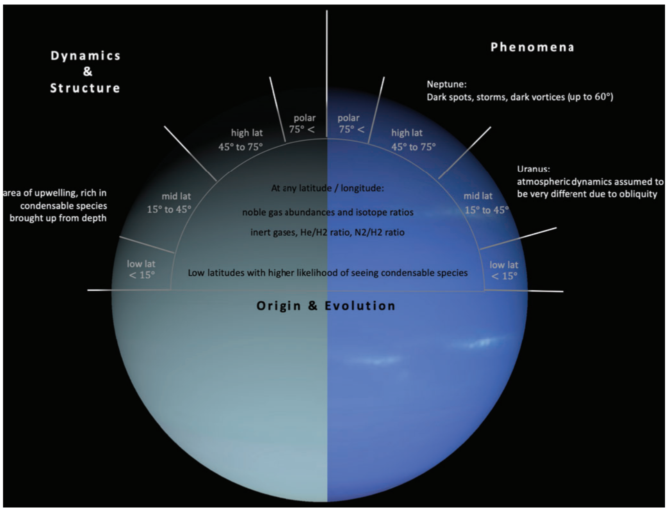

Figure 40 Science Map for Uranus and Neptune. The planets are divided into four latitude zones: low, mid, high, and polar latitudes. Relevant science topics targeting the dynamics and structure (left), origin and evolution (centre) and other phenomena (right) of the upper atmospheres of both planets are defined within each latitude zone. For the purposes of this map, it is assumed that the overarching science topics are identical for both planets. It is additionally assumed that for each planet the northern and southern hemispheres are identical.

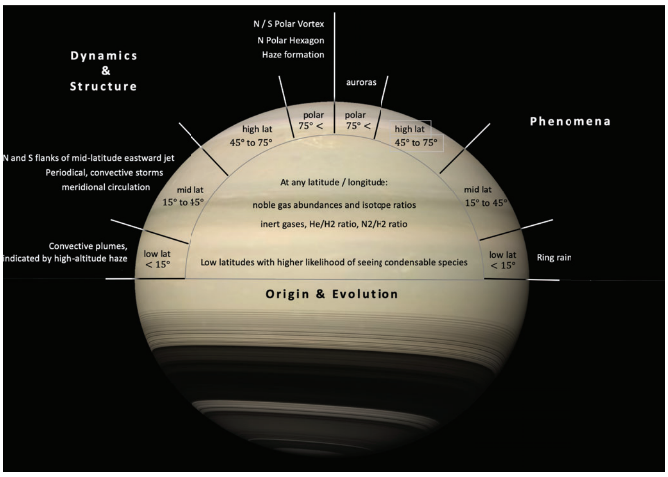

Figure 41 Science Map for Saturn. The planet is divided into four latitude zones: low, mid, high, and polar latitudes. Relevant science topics targeting the dynamics and structure (left), origin and

evolution (centre) and other phenomena (right) of the atmosphere are defined within each latitude zone. Again, for the purposes of this map, it is assumed that the northern and southern hemispheres are identical.

SNAP: Small Next-generation Atmospheric Probe

K. M. Sayanagi (Hampton University), R. A. Dillman (NASA Langley Research Center), D. H. Atkinson (JPL-Caltech), J. Li (NASA Ames Research Center), S. Saikia (Purdue University), A. A. Simon (NASA Goddard), T. R. Spilker (Planetary Flight Architect), M. H. Wong (University of California, Berkeley), A. Arora (Purdue University), S. Bowen (NASA Langley Research Center), A. Bowes (NASA Langley Research Center), J. Brady (NASA Langley Research Center), W. C. Edwards (NASA Langley Research Center), R. Fairbairn (NASA Langley Research Center), D. Goggin (NASA Langley Research Center/AMA), D. Hope (NASA Langley Research Center), S. Horan (NASA Langley Research Center), S. Infeld (NASA Langley Research Center/AMA), J. P. Leckey (NASA Langley Research Center), T. Marvel (NASA Langley Research Center), R. M. McCabe (Hampton University), A. Parikh (NASA Langley Research Center), D. Peterson (NASA Langley Research Center), S. Primeaux (NASA Langley Research Center), A. Scammell (NASA Langley Research Center), K. Somervill (NASA Langley Research Center), L. Taylor (NASA Langley Research Center), C. Thames (NASA Langley Research Center), H. Tosoc (NASA Langley Research Center), L. Tran (NASA Langley Research Center)

We present a concept for a small, atmospheric probe that could be added to future missions to a giant planet, which we call the Small Next-generation Atmospheric Probe (SNAP). SNAP's main scientific objectives are to determine the vertical distribution of clouds and cloud-forming chemical species, thermal stratification, and wind speed as a function of depth at a location distinct from a large primary probe. As a case study, we present the advantages, cost and risk of adding SNAP to the future Uranus Orbiter and Probe flagship mission. In combination with the mission's main probe, SNAP would perform atmospheric in-situ measurements at a second location, and thus enable and enhance the scientific objectives recommended by the 2013 Planetary Science Decadal Survey and the 2014 NASA Science Plan to determine atmospheric spatial variabilities. Out study demonstrates that the science objectives can be achieved with a 30-kg entry probe that reaches 5-bar pressure-altitude and returns data to Earth via the carrier spacecraft. As the baseline instruments, the probe will carry an Atmospheric Structure Instrument (ASI) that measures the temperature, pressure and acceleration, a carbon nanotube-based NanoChem atmospheric composition sensor, and an Ultra-Stable Oscillator (USO) to conduct a Doppler Wind Experiment (DWE).

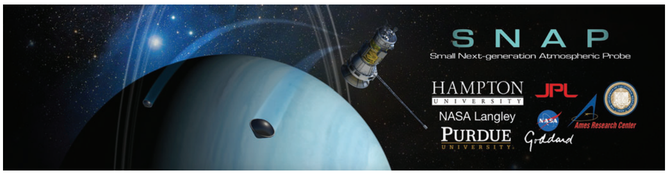

Figure 42 Artist's conception of a future multi-probe mission to Uranus. Small Next-generation Atmospheric Probe (SNAP) will enable future multi-probe mission to the Ice Giant Planets.

The Scientific Potential of a Radio and Plasma Wave Experiment on an Ice Giant Mission

A. H. Sulaiman (University of Iowa), W. S. Kurth (University of Iowa), G. B. Hospodarsky (University of Iowa), M. Imai (University of Iowa)

With the capabilities of a radio and plasma wave instrument, it will be possible to perform a broad range of (cross-disciplinary) studies that include the following:

(i) **Radio emissions**: The magnetized planets are sources of radio emissions, which are important both because of the basic plasma processes involved, and because they provide a valuable remote sensing tool.

(ii) **Waves and plasmas**: The role of plasma waves is recognized as being of fundamental importance for the transfer of energy and momentum between the magnetosphere, ionosphere, and satellites of a gas giant. Further, the electron number density and temperature are among the most important parameters of a plasma. However, they are also difficult to measure. Plasma wave measurements provide a powerful and very accurate technique for determining such basic plasma parameters.

(iii) **Lighting**: Lighting is a fundamental process in atmospheres, usually associated with convective storms, and have been found to occur at Uranus and Neptune.

(iv) **Dust**: The distribution of dust particles in the ice giants systems can be studied by using dust impact detection techniques.

The University of Iowa has a long heritage with radio and plasma wave instruments on outer planet missions that includes the Voyagers, Galileo, Cassini, and Juno.

Gravity and Atmospheric Science at Ice Giants through Radio Tracking from Earth

P. Tortora, M. Zannoni, A. Bourgoin, L. G. Casajus (University of Bologna)

Several mission concepts were proposed in the last few years for the in-situ exploration of the Ice Giants, both by NASA and ESA. A radio science experiment can characterize the internal structure and the atmosphere of both the planet(s) and their largest moons.

A high inclination orbital phase with a very low pericenter distance (as for Juno and Cassini proximal orbits) would enable a detailed mapping of the planet gravity field, through two-way Doppler tracking of the spacecraft.

Moreover, while the spacecraft would be occulted by the planet atmosphere as seen from the Earth, using radio links the physical properties of the occulting atmosphere can be studied, probing both its neutral and charged components.
In addition, multiple close flybys of the Ice Giants' major satellites can be used to determine their gravity fields and search for atmospheres, this latter requiring a one-way radio frequency system.

This talk will give an overview of the achievable gravity and atmospheric science objectives in potential Ice Giants mission concepts, through a careful design of the spacecraft radio frequency system and the analysis of the tracking data acquired both on the ground and on-board.

Further Reading:
Geophysical Research Abstracts
Vol. 21, EGU2019-13227, 2019
EGU General Assembly 2019
"Probing Ice Giants' Gravity Fields and Atmospheres through Radio Tracking from Earth"
By Paolo Tortora et al.
https://site.unibo.it/radioscience-and-planetary-exploration-lab/en/publications/conferences/tortora-ice-giants-v1-0.pdf/@@download/file/Tortora%20ICE%20GIANTS%20v1.0.pdf

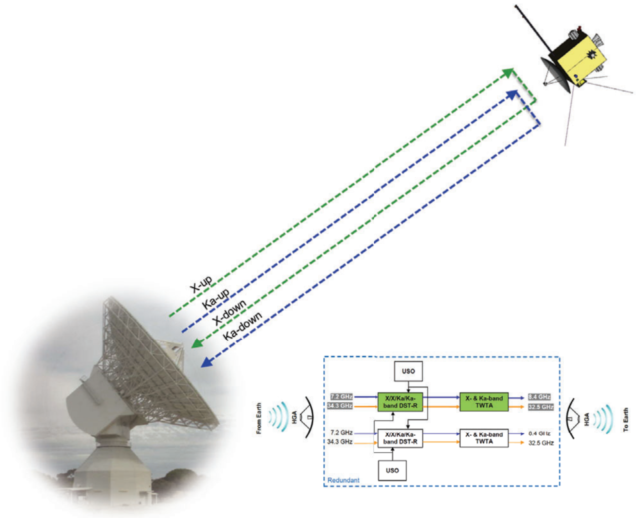

Figure 43 Schematic representation of the tracking configuration required for precision gravity science through the multi-frequency link technique. The green components are "active" in the gravity science mode. The S/C concept is borrowed from the Uranus Pathfinder proposal, submitted in response to ESA's 2014 Call for M-class Mission Proposals.

Enabling Entry Technologies for Ice Giant Missions

E. Venkatapathy, A. Austin, A. Cassell, D. Ellerby, P. Gage, D. Prabhu and P. Wercinski

The proposed poster highlights NASA developed entry technologies that are enablers for Ice Giant Missions. They are: (1) Heatshield for Extreme Entry Environment Technology (HEEET), and (2) ADEPT, a mechanically deployable entry system. HEEET development is complete and is at TRL 6. HEEET is ready for Ice Giant in situ probe missions, and HEEET is an enabler for either direct ballistic entry or entry from Orbit. NASA intends to sustain the HEEET capability as it is needed for other extreme entry environment missions in addition to Ice Giant Missions.

The emerging recognition among the scientific community that by delivering the probe from orbit will allow for simultaneous in-situ and orbital measurement can be enabled by aerocapture using ADEPT. The drag modulated aerocapture (DMA) with ADEPT is the simplest approach that can deliver an orbiter and probe together and without the significant penalty associated with propulsive insertion. Studies performed by JPL and NASA Ames teams point to this very promising possibility. Numerous DMA with ADEPT studies point to its applicability to small spacecraft missions as well as Ice Giant missions.

The poster will present the current state of readiness of HEEET, ADEPT and DMA.

Further Reading:

On HEEET:
https://www.lpi.usra.edu/opag/meetings/feb2018/presentations/Venkatapathy.pdf

The following presentations :
Technology Readiness Assessment for HEEET TPS_GAGE.pdf
from https://pub-lib.jpl.nasa.gov/docushare/dsweb/View/Collection-1933

On DMA-ADEPT:
https://www.lpi.usra.edu/opag/meetings/apr2019/posters/Prabhu.pdf

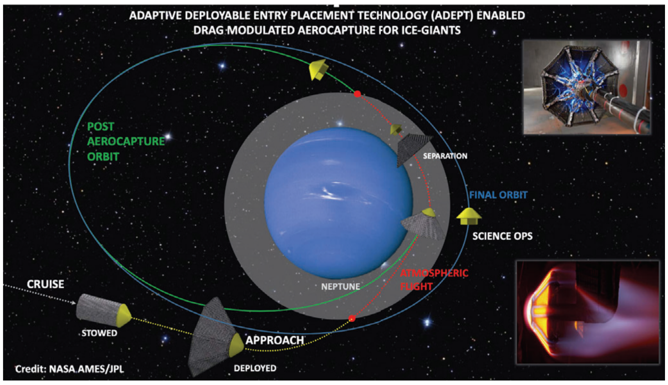

Figure 44 Benefit utilizing Drag Modulated Aerocapture (DMA) with ADEPT can deliver large spacecraft along with Probes into Neptune (or Uranus) Orbit.

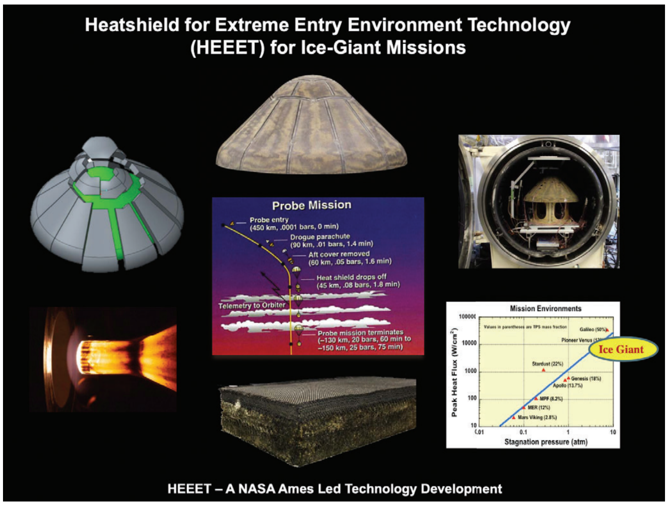

Figure 45 Heatshield for Extreme Entry Environment Technology is a 3-D Woven ablative TPS system demonstrated at TRL 6 and capable of Ice Giant Probe missions.