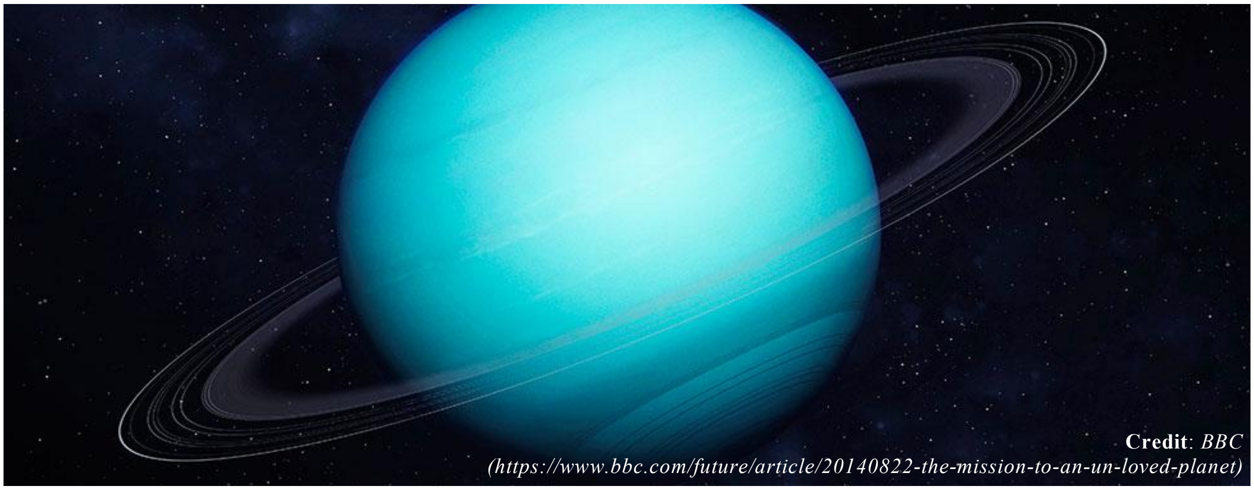

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New Frontiers-class Uranus Orbiter: Exploring the feasibility of achieving multidisciplinary science with a mid-scale mission

Ian J. Cohen[1] (240-584-7261, Ian.Cohen@jhuapl.edu),
[1]The Johns Hopkins University Applied Physics Laboratory (JHU/APL)

Co-authors:
Chloe Beddingfield[2], Robert Chancia[3], Gina DiBraccio[4], Matthew Hedman[3], Shannon MacKenzie[1], Barry Mauk[1], Kunio Sayanagi[5], Krista Soderlund[6], Elizabeth Turtle[1], Elena Adams[1], Caitlin Ahrens[7], Shawn Brooks[8], Emma Bunce[9], Sebastien Charnoz[10], George Clark[1], Athena Coustenis[11], Robert Dillman[12], Soumyo Dutta[12], Leigh Fletcher[9], Rebecca Harbison[13], Ravit Helled[14], Richard Holme[15], Lauren Jozwiak[1], Yasumasa Kasaba[16], Peter Kollmann[1], Statia Luszcz-Cook[17], Kathleen Mandt[1], Olivier Mousis[18], Alessandro Mura[19], Go Murakami[20], Marzia Parisi[8], Abigail Rymer[1], Sabine Stanley[21], Katrin Stephan[22], Ronald Vervack[1], Michael Wong[23], and Peter Wurz[24]

Co-signers:
Tibor Balint[8], Shawn Brueshaber[25], Xin Cao[26], Richard Cartwright[2], Corey Cochrane[8], Alice Cocoros[1], Kate Craft[1], Ingrid Daubar[27], Imke de Pater[23], Chuanfei Dong[28], Robert Ebert[29], Catherine Elder[8], Carolyn Ernst[1], Gianrico Filacchione[19], Jonathan Fortney[30], Daniel Gershman[4], Jesper Gjerloev[1], Matina Gkioulidou[1], Athul P. Girija[31], George Hospodarsky[26], Caitriona Jackman[32], Devanshu Jha[33], Erin Leonard[8], Michael Lucas[34], Alice Lucchetti[35], Heather Meyer[1], Adam Masters[36], Kimberly Moore[37], Sarah Moran[21], Romina Nikoukar[1], Maurizio Pajola[35], Chris Paranicas[1], Wes Patterson[1], Carol Paty[38], Noemi Pinilla-Alonso[39], Gangkai Poh[4], Alena Probst[8], Lynnae Quick[4], Leonardo Regoli[1], James Roberts[1], Sebastien Rodriguez[10], Kirby Runyon[1], Todd Smith[1], Linda Spilker[8], Alan Stern[29], Paolo Tortora[40], Drew Turner[1], Sasha Ukhorskiy[1], Sarah Vines[1], Roland Young[41], and Yongliang Zhang[1]

[2]SETI Institute; [3]Univ. of Idaho; [4]NASA/GSFC; [5]Hampton Univ.; [6]Univ. of Texas at Austin; [7]Univ. of Arkansas; [8]JPL/Caltech; [9]Univ. of Leicester; [10]Paris Diderot Univ.; [11]Paris Observ., CNRS, PSL, France; [12]NASA/LaRC; [13]Univ. of Nebraska-Lincoln; [14]Univ. of Zurich; [15]Univ. of Liverpool; [16]Tohoku Univ.; [17]American Museum of Natural History; [18]Aix Marseille Univ.;[19]National Institute of Astrophysics, Italy; [20]JAXA; [21]Johns Hopkins Univ.; [22]DLR; [23]Univ. of California, Berkeley; [24]Univ. of Bern; [25]Western Michigan Univ.; [26]Univ. of Iowa;[27]Brown Univ., [28]Princeton Univ.; [29]SwRI; [30]Univ. of California, Santa Cruz; [31]Purdue Univ.; [32]Dublin Inst. For Advanced Studies, [33]MVJ College of Engineering, India, [34]Univ. of Tennessee; [35]INAF - Astronomical Observ. Of Padova, Italy; [36]Imperial College London; [37]Harvard Univ.; [38]Univ. of Oregon; [39]Florida Space Inst., Univ. of Central Florida; [40]Univ. of Bologna; [41]United Arab Emirates Univ.

1 Introduction

Uranus presents a compelling case for exploring an Ice Giant system, offering unique opportunities to answer important scientific questions. The Ice Giants, Uranus & Neptune, represent a distinct class of planets within our solar system that has yet to be fully explored. Characteristics of the Uranian system, include: 1) a dynamically full & haphazard ring-moon system; 2) five major satellites - potential ocean worlds with evidence of a rich geologic history[1]; 3) a complex magnetosphere with highly-tilted rotational & magnetic axes[2]; 4) a bulk planetary composition likely dominated by heavier "ices" (e.g., H_2O, CH_4, and NH_3); and 5) a unique atmospheric circulation potentially associated with Uranus' weak internal heat flux. Detailed study of Uranus by an orbiter is crucial to obtain valuable insights into the formation of our solar system and for bounding the possibilities of exoplanetary enviroments[3-4]. **For these reasons and more, the imperative and timely exploration of Uranus will not only enhance our understanding of the Ice Giants but also extends to planetary origins and dynamics throughout the universe.**

The 2013 Planetary Science Decadal Survey[5] states: "*The ice giants are thus one of the great remaining unknowns in the solar system, the only class of planet that has never been explored in detail*". It also recommended "Uranus Orbiter and Probe" as the third-highest priority "large-class" mission. Unfortunately, no Ice Giant mission will be implemented before 2022, which makes it challenging for a mission to make the 2030-2034 launch window needed to take advantage of a Jupiter gravity assist to reach Uranus before it reaches equinox in 2050; **after 2050, the northern hemispheres of the satellites not imaged by *Voyager 2 (V2)* will recede into darkness.** As recognized internationally, the timeliness of a Uranus orbiter mission is a primary motivation for evaluating what science can be done with a lower-cost, faster-turnaround mission within the New Frontiers (NF) class; **this of course requires that the NF target list be expanded to include Uranus.** Both large-scale (Odyssey Pre-Decadal Mission Concept Study (PMCS)[6], 2010[7] & 2017[8] studies) and Discovery (Trident) missions have been explored for the Ice Giants, but, **no comprehensive study has focused on determining the scope and feasibility of a NF-class Uranus orbiter mission.** This paper summarizes one of three concepts submitted to the 2019 PMCS opportunity[9]. **This paper demonstrates the potential for a NF-class orbital mission to address essential scientific questions spanning multiple disciplines of Ice Giant science (plus cross-cutting heliophysics and astrophysics opportunities);** additional science could be achieved via flyby of a Centaur en route to Uranus. To maximize the prospects of meeting launch opportunities by 2034, we omit scientific objectives that are only achievable by an atmospheric probe, and focus instead on the excellence of the achievable science in the broader Uranian system.

***V2*'s brief encounter with Uranus[10] provided a glimpse at the planet's complexity and uniqueness, but motivated more questions than answers.** Our current limited understanding of Uranus is similar to that of other planets prior to orbital missions (e.g., after *Pioneer* & *Voyager* to Jupiter & Saturn).

Orbital missions have flown to every planet in our solar system except for the Ice Giants. At each planet these first orbiters revealed surprises that were missed by the initial flybys: e.g., the Enceladus geyser[11-12], a major discovery of *Cassini,* which was unnoticed by previous flybys. **As our understanding of the Gas Giants was transformed beyond expectations by dedicated orbiter missions (e.g., *Galileo*, *Juno*, *Cassini*) and will further improve with future missions (e.g., *Europa Clipper*, *JUICE*), so too will our knowledge of Uranus expand from the necessary multi-year measurements and orbital investigations.**

2 Science Objectives

Ex. 1 presents a "proto-Science Traceability Matrix" with a broad array of potential science objectives and outstanding mysteries, covering all areas of the Uranus system (rings, satellites, magnetosphere, atmosphere, & interior). An NF-class Uranus orbiter mission is expected to achieve many of these objectives.

2.1 Ring Science

Determine the processes that sculpt & maintain Uranus' ring-moon system. V2 and Earth-based observations have revealed that Uranus hosts a system of dense, narrow rings that lack meaningful spacing, diverse broad and finely-structured dusty rings, and the most tightly-packed system of small moons in the solar system. We still do not understand how the Uranian rings maintain their structure.

The Uranian ring system also boasts ten narrow and oddly-shaped main rings. Four of these are associated with resonances of small moons that likely play a role in shepherding

	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 • 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 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) • 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) • Abundances of hydrocarbons in upper atmosphere

Exhibit 1. *A New Frontiers-class orbiter mission could address many of the outstanding cross-disciplinary mysteries at Uranus.*

them[13]. The mechanisms confining the other ring edges and the nature of their present locations remain a mystery. Uranus also features a complex system of faint dusty rings[14] about which little is known. They likely originate from micrometeoroid bombardment ejecta of the small inner moons and dense rings themselves[15]. Determining the rates and sources of the dusty ring production and distribution within the system will help to determine the lifecycle of ring and moon material.

Thirteen small moons orbit between the main rings and larger classical moons of Uranus[16], within a tight radial range of <18,000 km. This arrangement is unstable on relatively short timescales and depends on the moons' unknown masses[17]. Many of these moons orbit inside Uranus' co-rotation radius. Thus, these moons' tidal interactions with Uranus cause inward migration towards the Roche limit, where they may fragment into new rings or interact with existing rings. They may also be driven outward through strong resonant torques if a more massive ring develops. Determining how the ring-moon system may undergo recycling throughout its lifetime is critical to understand how planetary ring-moon systems operate under myriad configurations.

Determine the composition & origin of Uranus' rings & small satellites. The rings and small moons of Uranus are dark, and their compositions are unknown. Observations[18] have revealed H_2O and CO_2 ice spectral features on Uranus' larger moons, whereas the rings' spectra are flat[19]. Limited observations of the small moons have not revealed if they are more akin to the larger moons or the rings.

2.2 Satellite Science

Determine whether the classical Uranian satellites have signatures indicative of oceans & determine their surface compositions. Uranus has five classical satellites (Miranda, Ariel, Umbriel, Titania, and Oberon). These moons may have common compositional surface ices like those of the Pluto-Charon system (i.e., widespread H_2O ice, CH_4 and other volatiles, hints of NH_3-hydrates and possible tholins[20-21]). However, further investigation of these moons may provide insight to a different icy evolution than Kuiper Belt Objects (KBOs), mainly due to the limited knowledge of CO_2 as a volatile ice at Uranus[22-23], as opposed to CO on KBOs[21]. The widespread evidence for resurfaced terrains on the classical Uranian satellites, hypothesized global heating events, and the possible presence of NH_3-hydrates on their surfaces indicate that these moons are possible ocean worlds[24]. Heat flux estimates for Miranda[25-26] and Ariel[27] indicate that these moons experienced heating events in the past, possibly sustaining subsurface liquid H_2O. Additionally, ground-based spectroscopic observations of the Uranian satellites hint at the presence of NH_3-bearing species on their surfaces[20]. NH_3-rich material in the lithosphere would dramatically lower the interior freezing temperature (vs. pure H_2O ice), assisting in the sustainability of subsurface oceans. If oceans are present in these satellites' interiors, either globally or locally, they may have interacted, or currently interact with the surface in the form of plumes, cryovolcanic flows, and/or tectonic features indicative of nonsynchronous rotation.

Understand what processes formed & modify the surfaces of the classical Uranian satellites. The geologic processes of the Uranian satellites are complex, as indicated by large tectonic and possibly cryovolcanic features imaged by *V2*. These features extend well past the terminator in the *V2* images, as revealed by enhanced nightside "Uranus-shine" processing techniques[28]. Miranda exhibits three unique "coronae", large polygonal shaped regions of surface deformation containing subparallel ridges and troughs that are highlighted by high and low albedos. These are made up of complex sets of tectonic features[29-30] and may contain cryovolcanic flows[31]. Ariel exhibits complex canyon systems thought to be a result of internal processes driving tectonism[32-33], while the formation of the large canyons on Oberon and Titania remain poorly understood[34-35].

2.3 Magnetosphere Science

Understand the fundamental structure & dynamics of Uranus' magnetosphere and the importance of internal vs. external drivers. Uranus' magnetosphere offers a unique configuration that provides an opportunity to understand the drivers of magnetospheric dynamics throughout the solar system. The axis of the approximately dipolar portion of its internal magnet is offset and tilted ~59° from the planetary rotation axis, which itself is inclined by 98° relative to the ecliptic (cf. these two axes are nearly aligned at Saturn). Such an orientation presents an asymmetrical obstacle to the impinging solar wind[36]. Plasma transport within a planetary magnetosphere may be driven by external and/or internal dynamics. The former suggests convection-driven plasma acceleration and circulation[37], whereas the latter would be subjected to centrifugal forces as the plasma is accelerated and energized. The magnetospheres of terrestrial planets with intrinsic magnetic fields (i.e., Earth & Mercury) are primarily driven by solar wind forcing, while the magnetospheres of Gas Giants (Jupiter & Saturn) are driven predominantly by internal plasma sources & fast planetary rotation and a mixture of internal/external processes, respectively. *V2* observations suggest that Uranus may be solar wind-driven[38-39], but it is a mystery why, unlike all other planets, no solar wind alpha particles were seen by observed higher energies[40]. Uranus' fast (~17 hr) rotation forces the magnetic configuration to open and close to the solar wind diurnally; this suggests that internal drivers must play a role, even though solar wind-driven transport can be decoupled near the solstices[41-42]. A mission arriving within a decade of 2049 would observe a different configuration than *V2,* as the alignment of the planet's rotation axis changes seasonally.

Understand what processes generate Uranus' intense electron radiation belt. Planetary radiation belts provide an in-situ laboratory to study the universal process of particle acceleration, providing conditions that are hard to reproduce on Earth and remain inaccessible in astrophysical phenomena. Radiation belts are defined by trapped energetic charged particle populations and their energy density and composition are a fingerprint of a planet's diverse interactions with internal and external drivers. Uranus' radiation belts are especially interesting as *V2* observations did not confirm our expectations. 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 only very slowly. Neither appeared to be the case at Uranus, which possesses a uniquely low-density plasma magnetosphere and where waves result in efficient particle losses. The mystery remains as to why Uranus' electron belts appear so intense[43] (cf. Saturn & Neptune at energies ≲2 MeV) while its ion belts show low intensities, despite sharing physical processes[44].

Uranus' unexpected behavior may stem from its unique magnetospheric configuration resulting in the dominance of surprising processes. For example, whistler mode chorus waves are thought play a role for electron acceleration and loss, but the intensities of these waves measured at Uranus were surprisingly higher than those observed at any other planet[45].

2.4 Interior Science

Understand the configuration & evolution of Uranus' magnetic field. *V2* showed that the intrinsic magnetic field of Uranus is multipolar and non-axisymmetric. However, only the largest scales were resolved, so its detailed configuration remains unknown and its temporal evolution unconstrained. Dynamo region thickness and convective vigor are two hypotheses to explain Uranus' unique magnetic field configuration[46-48], testable by magnetic field measurements resolving both large- and small-scale components and its secular variation. In addition to determining the planet's compositional and thermal structure, gravitational field measurements would further test generation mechanisms by establishing how deep zonal flows extend into the interior[49].

Determine the bulk composition & the distribution of materials within Uranus. Standard three-layer structure models of Uranus infer that the planet consists of ~2 $M_\oplus$ of H-He; although this estimate puts important limits on the planetary metallicity, it is not known which elements dominate the deep interior[50]. Alternative structure models suggest that Uranus could have a density profile without discontinuities[51] and that a large fraction of water is not needed fit the observed properties. It is of particular importance to determine the global ice-to-rock ratio, which can also be used to address Uranus' formation – a long-standing problem for planet formation theory[52]. Beyond the ice-to-rock ratio, the abundances of key species such as He tell us about the environment in which Uranus formed, and bulk enrichments of C, N, and S provide additional information on the planet formation process. However, ground-based attempts to constrain the bulk composition from measurements of atmospheric disequilibrium species (e.g., CO) have been inconclusive[53]; and Uranus' ice-to-rock ratio remains loosely constrained[50-51].

Understand Uranus' global energy balance & internal heat flow. Uranus is the only Giant Planet that is in approximate equilibrium with solar insolation[54]. However, a more precise energy balance determination is necessary because large uncertainties exist in the *V2* bond albedo and thermal emission measurements. This balance presently suggests that Uranus' interior may not be fully convective and/or contains compositional gradients that hinder convection[55], although atmospheric phenomena may also be responsible[56]. If convective inhibition is at play, then Uranus' internal heat flux may vary seasonally, and given that recent ground-based observations reveal many episodic convective events, an orbiter mission arriving during an active period may measure a higher heat flux, especially since episodic convective events have been revealed by recent ground-based observations[57].

2.5 Atmosphere Science

Understand Uranus' atmospheric heat transport mechanisms. Many atmospheric processes cause downward (e.g., solar insolation) and upward (e.g., thermal radiation and cumulus convection) flux of energy. These processes provide local perturbations that shape atmospheric features such as cloud bands and vortices. The connection between local atmospheric events and the global energy balance remains an outstanding mystery. Because the molecular weight of condensable species is heavier than the background H-He atmospheric mixture, moist convection is generally inhibited and tends to happen in episodic bursts[58]. Given this time-variability, a new mission may find that local episodic convection leads to a higher global heat flux.

In the middle and upper atmosphere, our ignorance of heat transport processes is symptomized as the "energy crisis": *V2* stellar occultations revealed that Uranus' thermosphere is hot[59]. Although this "crisis" exists at all four giant planets, it is particularly surprising for Uranus because of its large axial tilt; given that the thermosphere is hot in both summer and winter hemispheres, solar heating cannot be the cause[60]. The vertical temperature gradient may point to the nature of the unknown heating[61], but *V2* data cannot distinguish between candidate heating mechanisms.

Understand Uranus' zonal & meridional circulation patterns. These circulations are critical for understanding vertical heat transport and energy balance, as well as producing a coherent model of atmospheric dynamics. Uranus' zonal wind profile – with retrograde winds at the equator and a single prograde peak in each hemisphere – starkly contrasts with Jupiter and Saturn. Uranus' winds also exhibit a surprising hemispheric asymmetry near the poles[57], which may be seasonally driven. Whereas the cloud bands of Jupiter and Saturn are loosely associated with the zonal jets due to eastward jet peaks acting as transport barriers, Uranian cloud bands are seemingly not tied to the smooth wind structure and associated temperature gradients, which may hint at unresolved peaks in the zonal wind structure[61].

Uranus' overturning meridional circulation structure remains unknown. Methane gas depletion around the poles suggests that Uranus has a single deep circulation cell in each hemisphere, in which air rises from the deep atmosphere at low latitudes, clouds condense out, and dry air is transported to high latitudes where it descends[63]. However, such a pattern is inconsistent with observed cloud distributions, implying that the meridional circulation must be more complex. High-resolution measurements of the wind field may reveal coupling between zonal/meridional circulation via eddies.

Determine the thermodynamics & chemistry of Uranus' clouds and hazes. During the *V2* flyby, Uranus appeared almost featureless. The subsequent presence of unexpected bright storms[63] has revealed that Uranus has an active, temporally dynamic, and poorly understood weather layer. Clouds and hazes occur preferentially at specific latitudes, and the banding pattern of tropospheric hazes is apparently not tied to the zonal wind structure. Vertically, clouds and tropospheric hazes are *not* found at the altitudes predicted by thermochemical equilibrium models[64]; in fact, the compositions of Uranus' upper cloud layers remain unclear[61]. The thermodynamics and chemistry of the clouds have far-reaching implications for connecting the atmosphere to the planet's bulk composition, and for understanding the global energy balance.

V2 and *Spitzer* measurements[65] revealed hydrocarbon densities much lower in Uranus' stratosphere than at any other giant planet due to the stark differences in atmospheric mixing. Hydrocarbons are the main source of photochemical haze, act as EUV continuum absorbers, and trace vertical transport.

3 NF-class Design Considerations

Maintaining balance across the research disciplines described above should be a high priority for a NF Uranus orbiter. Based on work from previous studies, a NF-class orbiter mission should be feasible. For example, the costs in the 2010 study[7] suggest ~$1.1B (FY15$) for Phases A-D for an orbiter mission with a flagship-class payload without an atmospheric probe (assuming 30% reserves) without the launch vehicle costs. Appropriately scoping the payload to accommodate NF-class science would reduce both the payload and spacecraft costs. From a mission design standpoint, the potential use of a solar electric propulsion (SEP) stage with a cruise of ~14 years could reduce the spacecraft's chemical propulsion burden, while still leaving enough Radioisotope Power System (RPS) lifetime for the baseline mission, to be feasible within the NF cost. **A NF Uranus orbiter could be undertaken with current technologies, given appropriate trades in design and scope.**

Power is perhaps the most limiting constraint on a Uranus orbiter mission and addressing power within cost is the primary obstacle to the feasibility of a NF Uranus orbiter mission. Previous Ice Giant mission studies[7-8] have resulted in architectures requiring >350 W-e end-of-life power, which required three or more now-cancelled Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTGs). Owing to the relative inefficiency and significant cost of current RPSs, any design should attempt to reduce the needed end-of-life power; this will have significant impact on both the spacecraft and orbit design as well as the communication subsystem and payload. **Hence, accelerating the development and expanding the efficiency and lifetime (and potentially reducing the cost) of next-generation RPSs would significantly enhance the mission.** For example, the recent Neptune Odyssey mission concept uses three next-generation RPSs[6], suggesting that a NF-class Uranus mission could close with fewer. This of course assumes that a sufficient supply of plutonium is available for future space exploration missions. With current technology (i.e., 14-year MMRTG flight design life), a typical baseline would be a <12-year cruise (potentially with a Centuar flyby) and a 2-year mission at Uranus with a system tour that enables surface mapping of the large satellites as well as spatial coverage of the planet & rings/small moons; this baseline could be significantly lengthened if the lifetime of future RPSs were improved.

Another significant driver is determining the total mass that can be put into Uranus orbit within the NF cost cap. Because significant propellant mass is needed for Uranus orbit insertion, mass efficiency is critical. A realistic ~60-kg payload (e.g., 5 instruments & radio science) using current technologies, would provide closure to numerous mysteries summarized in Ex. 1. **However, cost reduction and increases in capability & availability of launch vehicles (e.g., SLS) could be enabling for a NF-class Uranus orbiter mission launching outside of windows with Jupiter gravity assists.** Lastly, the risk-vs.-benefit of using aerocapture for orbit insertion should be analyzed as it can greatly increase the delivered payload[66-67] and shorten flight times[68].

References

[1] Ahrens+(2020), PS Decadal Survey White Paper

[2] Kollmann+(2020), PS Decadal Survey White Paper

[3] Batalha+(2011), doi:10.1088/0067-0049/204/2/24

[4] Rymer+(2018), arXiv:1804.03573

[5] Nat'l Res. Council(2011), doi:10.17226/13117

[6] Rymer+(2020), Neptune-Triton Odyssey PMCS Report

[7] Hubbard(2010), Mission Study Report for 2013 PS Decadal

[8] Hofstadter+(2017), Ice Giants Mission Study Report

[9] Leonard+(2020), PS Decadal Survey White Paper

[10] Stone&Miner(1986), doi:10.1126/science.233.4759.39

[11] Dougherty+(2006), doi:10.1126/science.1120985

[12] Porco+(2006), doi:10.1126/science.1123013

[13] Porco&Goldreich(1987), doi:10.1086/114354

[14] de Pater+(2006), doi:10.1126/science.1125110

[15] Esposito&Colwell(1989), doi:10.1038/339605a0

[16] Showalter&Lissauer(2006), doi:10.1126/science.1122882

[17] French+(2015), doi:10.1088/0004-6256/149/4/142.

[18] Grundy+(2006), doi:10.1016/j.icarus.2006.04.016

[19] de Kleer+(2013), doi:10.1016/j.icarus.2013.07.016

[20] Cartwright+(2018), doi:10.1016/j.icarus.2018.06.004

[21] Grundy+(2016), doi:10.1126/science.aad9189

[22] Cartwright+(2015), doi:10.1016/j.icarus.2015.05.020

[23] Sori+(2017), doi:10.1016/j.icarus.2017.02.029

[24] Hendrix+(2019), doi:10.1089/asr.2018.1955

[25] Beddingfield+(2015), doi:10.1016/j.icarus.2014.09.048

[26] Ruiz, J.(2005), doi:10.1016/j.icarus.2005.03.021

[27] Peterson+(2015), doi:10.1016/j.icarus.2014.11.007

[28] Stryke&Stooke (2008), 2008 LPSC, abstract #1362

[29] Schenk(1991), doi:10.1029/90JB01604

[30] Pappalardo+(1997), doi:10.1029/97JE00802

[31] Jankowski&Squyres(1988), doi:10.1126/science.241.4871.1322

[32] Peterson+(2015), doi:10.1016/j.icarus.2014.11.007

[33] Croft&Soderblom (1991), in *Uranus*, pp. 561–628

[34] McKinnon 1988), doi:10.1038/333701a0

[35] Janes&Melosh(1988), doi:10.1029/JB093iB04p03127

[36] Cao&Paty (2017), doi:10.1002/2017JA024063

[37] Dungey(1961), doi:10.1103/PhysRevLett.6.47

[38] Mauk+(1987), doi:10.1029/JA092iA13p15283

[39] DiBraccio&Gershman(2019), doi:10.1029/2019GL083909

[40] Krimigis+(1986), doi:10.1126/science.233.4759.97

[41] Selesnick&Richardson (1986), doi:10.1029/GL013i007p00624

[42] Vasyliuñas(1986), doi:10.1029/GL013i007p00621

[43] Mauk&Fox(2010), doi:10.1029/2010JA015660

[44] Mauk(2014), doi:10.1002/2014JA020392

[45] Kurth&Gurnett (1991), doi:10.1029/91JA01819

[46] Holme&Bloxham (1996), doi:10.1029/95JE03437

[47] Stanley&Bloxham(2006), doi:10.1016/j.icarus.2006.05.005

[48] Soderlund+(2013), doi:10.1016/j.icarus.2013.02.014

[49] Kaspi+(2013), doi:10.1038/nature12131

[50] Nettelmann+(2013), doi:10.1016/j.pss.2012.06.019

[51] Helled+(2011), doi:10.1088/0004-637X/726/1/15

[52] Helled&Bodenheimer(2014), doi:10.1088/0004-637X/789/1/69

[53] Cavalie+(2014), doi:10.1051/0004-6361/201322297

[54] Pearl+(1990), doi:10.1016/0019-1035(90)90155-3

[55] Nettelmann+(2016), doi:10.1016/j.icarus.2016.04.008

[56] Gierasch&Conrath(1987), doi:10.1029/JA092iA13p15019

[57] Sromovsky+(2015), doi:10.1016/j.icarus.2015.05.029

[58] Li+(2018), doi:10.1175/JAS-D-17-0257.1

[59] Broadfoot+(1986), doi:10.1126/science.233.4759.74

[60] Stevens+(1993), doi:10.1006/icar.1993.1005.

[61] Sicardy+(1985), doi:10.1016/0019-1035(85)90040-5.

[62] Fletcher+(2020), doi:10.1007/s11214-020-00646-1

[63] de Pater+(2015), doi:10.1016/j.icarus.2014.12.037

[64] de Pater+(1991), doi:10.1016/0019-1035(91)90020-T

[65] Bishop+(1990), doi:10.1016/0019-1035(90)90094-P

[66] Spilker+(2016), NASA PSD Report (JPL D-97058)

[67] Hall+(2005), doi:10.2514/1.4118

[68] Girija+(2020), doi:10.31224/osf.io/bxvgz