The case for a New Frontiers-class Uranus Orbiter: System science at an underexplored and unique world with a mid-scale mission

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Abstract

Current knowledge of the Uranian system is limited to observations from the flyby of Voyager 2 and limited remote observations. However, Uranus remains a highly compelling scientific target due to the unique properties of many aspects of the planet itself and its system. Future exploration of Uranus must focus on cross-disciplinary science that spans the range of research areas from the planet's interior, atmosphere, and magnetosphere to the its rings and satellites, as well as the interactions between them. Detailed study of Uranus by an orbiter is crucial not only for valuable insights into the formation and evolution of our solar system but also for providing ground truths for the understanding of exoplanets. As such, exploration of Uranus will not only enhance our understanding of the Ice Giant planets themselves but also extends to planetary dynamics throughout our solar system and beyond. The timeliness of exploring Uranus is great as the community hopes to return in time to image unseen portions of the satellites and magnetospheric configurations. This urgency motivates evaluation of what science can be achieved with a lower-cost, potentially faster-turnaround mission, such as a New Frontiers (NF)-class orbiter mission. This paper outlines the scientific case for and the technological and design considerations that must be addressed by future studies to enable a NF-class Uranus orbiter with balanced cross-disciplinary science objectives. In particular, studies that trade scientific scope and instrumentation and operational capabilities against simpler and cheaper options must be fundamental to the mission formulation.

1 Introduction

Uranus presents a compelling scientific target, providing a unique opportunity to explore an Ice Giant system with its five classical satellites, potential ocean worlds with drastic surface features, and dynamically full and apparently haphazard system of rings and small moons, in addition to the planetary and magnetospheric effects of its highly-tilted rotational axis being almost in Uranus' orbit plane and its strongly multipolar intrinsic magnetic field. Uranus, and its Ice Giant neighbor Neptune, represents a distinct class of planets in the solar system and beyond. Whereas Jupiter and Saturn are made mostly of hydrogen, the bulk compositions of Uranus and Neptune are dominated by heavier "ices" such as water, methane, hydrogen sulfide, and ammonia. These "Ice Giants" may be representative of similarly-sized planets common throughout the galaxy (Batalha et al. 2011; Wakeford & Dalba 2020), but remain the least-investigated planets in the solar system. The observations from Voyager 2 have left us with many outstanding mysteries about the Uranian system (e.g., Fletcher et al. 2020a; 2020c). As such, the study of the solar system's Ice Giants is a crucial step for providing ground truths for the understanding of Ice Giant-sized exoplanets (Rymer et al. 2018; Fortney et al. 2021; Wakeford & Dalba 2021) as observations show that Neptune-sized planets are the most abundant population of exoplanets (Zhu & Dong 2021).

The 2011 National Research Council Planetary Science Decadal Survey *Vision and Voyages for Planetary Science in the Decade 2013-2022* 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" (National Research Council 2011). Underscoring the importance of studying the Ice Giants, the 2013 Decadal Survey recommended a Uranus Orbiter and Probe as the third-highest priority "large-class" mission (National Research Council 2011). The mission summarized here would explicitly address the design considerations necessary to formulate an orbiter mission to Uranus within a future New Frontiers cost cap (assumed to be approximately $1B USD). A recommendation for a similar mission concept was submitted by the Outer Planets Assessment Group (OPAG) for consideration in the last Planetary Science Decadal Survey (McKinnon et al. 2009), but no such mission was formulated. With potential interest from international partners such as the European Space Agency (European Space Agency 2021), there is potential scope for combining resources from agencies to achieve flagship-level science with more modest missions. This article specifically presents the case for a potential US-only New Frontiers-class mission.

2 *The need for a mid-scale Uranus orbiter mission*

Voyager 2's brief encounter with Uranus provided a tantalizing glimpse of the complexity and uniqueness of the planet and its wider system of rings and satellites, but ultimately supplied many more questions (e.g., Stone & Miner 1986; Arridge et al. 2014; Beddingfield et al. 2021). The currently limited understanding of Uranus is analogous to that of other planets after our initial flyby encounters (e.g., the Mariner missions to Mercury, Venus, and Mars; the Pioneer and Voyager missions to Jupiter and Saturn). Just as our understanding of those planets was transformed after sending dedicated orbiter missions (e.g., MESSENGER (Solomon et al. 2019), Pioneer Venus Orbiter (Colin 1980), the Viking missions (Soffen et al. 1976), Galileo (Johnson et al. 1992), Juno (Bolton et al. 2017), Cassini (Spilker 2019)), so too will our knowledge of Uranus expand tremendously from such long-term measurements and investigations. In particular, magnetospheric and atmospheric conditions can change rapidly compared to interior or surface conditions of the planet and satellites. For example, due to its unique extreme dipole tilt, the entire configuration of the Uranian magnetosphere varies drastically in a single (17.-hr) Uranian day; likewise, many plasma transport processes at play in the magnetosphere occur on the timescales of minutes or hours (e.g., injections, particle drifts, etc.). Furthermore, because observed changes in in-situ conditions may be the result of time-dependent dynamic processes or transition of the spacecraft into a different region of space, flybys are limited to snapshots of a planetary space environment. A similar case can be made for the atmospheric phenomena, which display a range of timescales, from hours (the eruption of convective plumes and interactions with the surrounding zonal winds; de Pater et al. 2015), to weeks (the evolution of rare dark ovals; Hammel et al. 2009), to years (the development of polar aerosol collars and caps, and associated changes in the polar windfield, Sromovsky et al., 2019). The only way to address this issue is with an orbiting spacecraft, as demonstrated by the results from previous orbital missions.

The first orbiters at every other planetary system also revealed many surprises that were not expected from the limited information gleaned by the flyby encounters of their predecessors. For example, one of the greatest discoveries of Cassini was the eruption of material from the subsurface ocean of Enceladus (Dougherty et al. 2006; Porco et al. 2006), a phenomenon unnoticed by the previous flybys of Pioneer 11 and the Voyagers. Future missions should yield similarly surprising results, especially given that the flyby measurements from Voyager 2 at Uranus may not have been representative (Kollmann et al. 2020). Thus, any orbiter mission at Uranus could be expected to provide a substantial advancement in our understanding of the system relative to the Voyager 2 flyby. While a New Frontiers-class Uranus orbiter mission may not result in investigations as comprehensive as larger-class missions like Cassini at Saturn or Galileo at Jupiter, successful and transformative smaller-class missions (e.g., MESSENGER at Mercury and Juno at Jupiter) highlight the significant advancement in understanding of systems that can be obtained by targeted orbital missions.

Additionally, information on whether the classical Uranian satellites are ocean worlds provides direct complements to investigations of the New Horizons, Europa Clipper, and JUICE missions. Finally, perhaps most significantly, a New Frontiers-class Uranus orbiter mission would complement any potential mission to the Neptune system (e.g., Rymer et al. 2021) by providing additional information about both Ice Giant planets and thus enabling comparisons and contrasts between the two planets and their systems. There is also strong interest from the international community for collaboration on such a mission (Arridge et al. 2012; Fletcher et al. 2020a; Blanc et al. 2021; European Space Agency 2021).

It is unclear whether a large-scale strategic mission would be able 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 will gradually recede into darkness and the magnetospheric configuration will again evolve back towards what was observed by Voyager 2. 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 class. To maximize the prospects of meeting launch opportunities by 2034, this mission concept omits scientific objectives that are only achievable by an atmospheric probe (e.g., Orton et al., 2021) and focus instead on the excellence of the achievable science in the broader Uranian system as well as cross-cutting heliophysics and astrophysics opportunities (e.g., Cohen & Rymer 2020).

Previous studies of potential future Uranus missions have been conducted and outlined the broad science that should be targeted by a large strategic mission (e.g., Hofstadter et al., 2019). These provide a solid foundation from which to focus a smaller-class New Frontiers mission, but have made assumptions about multiple aspects of the mission design (i.e., communications, power, orbit and spacecraft design) that may not be applicable or appropriate for a lower-cost mission. To date, no NASA-funded study has explored the trades necessary to construct a mission with high science return for <$1B, though many such concepts have been proposed (e.g., Elder et al. 2018; Jarmak et al. 2020; Leonard et al. 2021).

In 2010, an Ice Giants mission concept study was conducted for the Planetary Science Decadal Survey (Hubbard 2010). The aim of this study was "to define a preferred concept approach along with the risk/cost trade space for a Uranus or Neptune Mission launched in the 2020–2023 timeframe and within a cost range of $1.5B–$1.9B in FY15$". Though the study "developed a concept that can achieve very robust science at Uranus at a cost below flagship mission levels", the target cost range was ~50% higher than the modern NF cost cap. Notably, the use of a Jupiter gravity assist was not considered in this study because of the unfavorable trajectories during the targeted launch window. Ultimately, the study concluded that the identified science objectives could be achieved for $1.894B (FY15$), including an enhanced orbiter payload and six-month satellite tour, use of a solar electric propulsion (SEP) stage, and delivery of a 127-kg atmospheric entry probe. The "Uranus Orbiter and Probe" mission that resulted from this study was ranked as the third-highest-priority large-class mission in the 2011 Planetary Science Decadal Survey (National Research Council 2011).

A more recent Ice Giants Pre-Decadal Survey Mission Study was conducted looking at potential mission architectures to both Uranus and Neptune (Hofstadter et al. 2017; Hofstadter et al. 2019). Unlike its 2010 predecessor, this study targeted launch dates within the purview of the 2023 Planetary Science Decadal Survey (i.e., 2024-2037) and was charged to "[i]dentify missions across a range of price points, with a full life cycle cost not to exceed $2B (FY15$)" with no identified lower cost limit. Although the Science Definition Team explored over thirty architectures, neither a strawman payload was recommended nor was any explicit effort made to explore the New Frontiers trade-space. The lowest-cost option given a fully refined point design was a Uranus flyby that cost nearly $1.5B (FY15$); the Uranus orbiter point design with the lowest cost ($1.7B FY15$) carried an atmospheric probe and only a ~50-kg orbiter payload. Furthermore, the 2018 Decadal Survey mid-term review found "[t]he objectives of the mission concept described in the 2017 ice giants predecadal study have been changed significantly from the original *Vision and Voyages* science objectives", prompting a recommendation that "NASA should perform a new mission study based on the original ice giants science objectives identified in *Vision and Voyages* to determine if a more broad-based set of science objectives can be met within a $2 billion cost cap." (National Research Council 2018).

3 Science Objectives

The "proto" Science Traceability Matrix (STM) in Figure 1 summarizes a broad array of potential science objectives and outstanding mysteries, covering all areas of the system (satellites, magnetosphere, atmosphere, interior, and rings). These potential science objectives generally align with those of the Uranus Orbiter & Probe mission recommended in the 2013 Planetary Science Decadal Survey. Overall, the mission aims to address the overarching science goal to "*Explore the Uranian system to solve known mysteries and address multidisciplinary objectives relevant to the rings, satellites, magnetosphere, interior, and atmosphere."* Measurement types (denoted in matrix form with a key at the bottom) are also provided for each objective.

	Outstanding Mystery	Science Objective *(Relevant V&V Science Goal)*	Potential Observables
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 and geomorphologic structures, tidal flexing, plume activity, physical libration, and thermal anomalies • Topography • Spectroscopic indications of outsourcing from interior • Induced magnetic field and satellite tidal number/degree of compensation
SATELLITES	***Which processes formed the extremely dark and resurfaced terrains of the five classical Uranian satellites?***	Determine the surface compositions of the classical Uranian satellites. *(4)*	• Compositional mapping and associations (or lack) with geologic features/topographic lows • Regional distributions (leading versus trailing hemisphere) of dark material • Compositional trends with distance from Uranus
SATELLITES		Understand what processes formed and modify the surfaces of the classical Uranian satellites. *(4 & 5)*	• Units and surface features/structures • Topography and stratigraphy • Relative age of units and features (estimated from cross-cutting relations and crater density) • Incident plasma and 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 versus external drivers. *(1 & 3)*	• Temporal and spatial variabilities in plasma and magnetic fields • Plasma and energetic ion composition • Particle energization and acceleration • Times, durations and depths of satellite/ring microsignatures
MAGNETOSPHERE	***How does Uranus generate such an intense electron radiation belt?***	Understand what processes generate Uranus' intense electron radiation belt. *(1 & 3)*	• Plasma and low-frequency waves and wave power distributions • Plasma and energetic electron and ion pitch-angle distributions and energy spectra
INTERIOR	***How is Uranus' interior structured below the clouds and how does it behave?***	Understand the configuration and 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
INTERIOR		Determine the bulk composition and 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*) and remote sensing above clouds • Low-degree (<10) even gravitational harmonics • Map and temporal evolution of the intrinsic magnetic field
INTERIOR		Understand Uranus' global energy balance and internal heat flow. *(1)*	• Reflectivity at multiple phase angles and latitudes • Thermal emission at multiple latitudes • Temperature/density profiles • Distribution of absorbers and temperature lapse rate in upper troposphere/stratosphere
ATMOSPHERE	***What mechanisms drive Uranus' large- and small-scale atmospheric dynamics?***	Understand Uranus' atmospheric heat transport mechanisms. *(1 & 3)*	• Mapping of entire planetary "surface" • Upper atmospheric density and wave inventory • Tracking of storms, clouds, and eddies in reflected sunlight • Thermal profile, upward and downward radiative flux – *requires entry probe*
ATMOSPHERE		Understand Uranus' zonal and meridional circulation patterns. *(1 & 3)*	• Temperature and 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
ATMOSPHERE		Determine the thermodynamics and 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
RINGS	***Why is the architecture of the Uranian ring-moon system so dynamically full and haphazard?***	Determine the processes that sculpt and maintain Uranus' ring-moon system. *(1)*	• Ring particle size distribution, planet/moon tidal parameters • Ring internal structures (e.g., density waves and satellite wakes) • Rings' non-circular shapes and pattern speeds • Discovery of new moons and moon shapes, light-curves, and orbital elements • Dusty ring spatial density and periodic structures • Magnetic field orientation, components, and periodicities
RINGS		Determine the composition and origin of Uranus' rings and small satellites. *(1)*	• Spectral absorption in moon and ring spectra • Crater density on small moons • Micrometeoroid impact flux and composition • Radiation belt location and flux

Figure 1. *A summary of the outstanding science mysteries, science objectives (including linkages to the 2013 Planetary Science Decadal Survey goals), and potential observables that could be addressed by a future New Frontiers-class Uranus orbiter mission.*

The science objectives presented here all address at least one of several science goals for giant-planet system or satellite exploration outlined in the 2011 Planetary Science Decadal Survey (National Research Council 2011): 1) *Giant planets as ground truth for exoplanets*; 2) *Giant planets' role in promoting a habitable planetary system*; 3) *Giant planets as laboratories for properties and processes on Earth*; 4) *Formation and evolution of the satellites of the outer solar system*; 5) *Processes controlling the present-day behavior of the satellites of the outer solar system*; and 6) *Processes that result in habitable environments*. Each science objective's relevance to these overarching goals is explicitly identified in Figure 1 along with potential observables.

Science Objective	Potential Measurement Types											
	Imaging/Spectroscopy				Gravity Science	Radio Occultations	Magnetic Field	Plasma	Energetic Particles	Plasma/ low-frequency waves	Dust	In-situ atmospheric probe
	NIR	Thermal IR	Visible	UV								
Determine whether the classical Uranian satellites have signatures indicative of subsurface oceans.		X	X	X	X		X	X				
Determine the surface compositions of the classical Uranian satellites.	X	X	X									
Understand what processes formed & modify the surfaces of the classical Uranian satellites.	X	X	X					X	X		X	
Understand how internal & external drivers generate plasma structures & transport within Uranus' magnetosphere.							X	X	X			
Understand what processes generate Uranus' intense electron radiation belt.							X	X	X	X		
Understand the configuration & evolution of Uranus' magnetic field.		X		X	X		X	X	X	X		
Determine the bulk composition & the distribution of materials within Uranus.		X	X		X	X	X			X		X
Understand Uranus' global energy balance & internal heat flow.	X	X	X		X	X	X					
Understand Uranus' atmospheric heat transport mechanisms.	X	X	X	X		X						X
Understand Uranus' zonal & meridional circulation patterns.	X	X	X	X	X	X	X					X
Determine the thermodynamics & chemistry of Uranus' clouds and hazes.	X	X	X	X		X			X			X
Determine the processes that sculpt & maintain Uranus' ring-moon system.	X		X	X	X	X	X	X	X		X	
Determine the composition & origin of Uranus' rings & small satellites.	X	X	X	X				X	X		X	

Figure 2. *Mapping of the potential science objectives of a New Frontiers-class Uranus orbiter mission to different measurement types. This underscores the broad, cross-disciplinary science that can be achieved given that many instruments can provide observations relevant to multiple aspects of the science investigation.*

Since the Uranian system provides a multitude of outstanding mysteries and unique characteristics to investigate, there are multiple possible complements of instruments that could deliver revolutionary science measurements as showcased in Figure 2. Despite the cost constraints, a New Frontiers-class Uranus orbiter mission is expected to achieve many of the science objectives outlined below.

3.1 Satellite Science

Determine whether the classical Uranian satellites have signatures indicative of subsurface oceans and determine their surface compositions. Uranus has five mid-sized classical satellites (Ariel, Miranda, Umbriel, Oberon, and Titania) in addition to its thirteen small moons. These moons have surface ices of common composition to those of the Pluto-Charon system - i.e., widespread H_2O ice, CH_4 and other volatiles, hints of NH_3-hydrates and the possible detection of tholins (Grundy et al. 2016; Cartwright et al. 2018; Schenk & Moore 2020). However, further investigation of these moons may provide insight on an icy evolution very different than those of Kuiper Belt Objects (KBOs), mainly due to the limited knowledge of CO_2 as a volatile ice at Uranus (Cartwright et al.

2015; 2020a), rather than carbon monoxide on KBOs (Grundy et al. 2020). The widespread evidence for resurfaced terrains from tectonism and cryovolcanism 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 (Hendrix et al. 2019; Schenk & Moore 2020; Ćuk et al. 2020, Beddingfield & Cartwright 2021; Cartwright et al. 2021). Heat flux estimates for Miranda (Beddingfield et al. 2015) and Ariel (Peterson et al. 2015) indicate that these moons experienced heating events in the past (Ćuk et al. 2020), possibly sustaining subsurface liquid water. For example, the estimated heat flux in the past on Miranda is broadly consistent with the heat flux generated by Europa's current orbital resonance (Hussman et al. 2002; Ruiz et al. 2005). In addition, ground-based spectroscopic observations of the Uranian satellites hint at the presence of ammonia-bearing species on the surfaces of these moons (Bauer et al. 2002; Cartwright et al. 2018; 2020b). If present in the lithosphere, ammonia-rich material would dramatically lower the interior freezing temperature (compared to 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. Images of the satellite surfaces can be used to obtain surface compositions indicative of subsurface

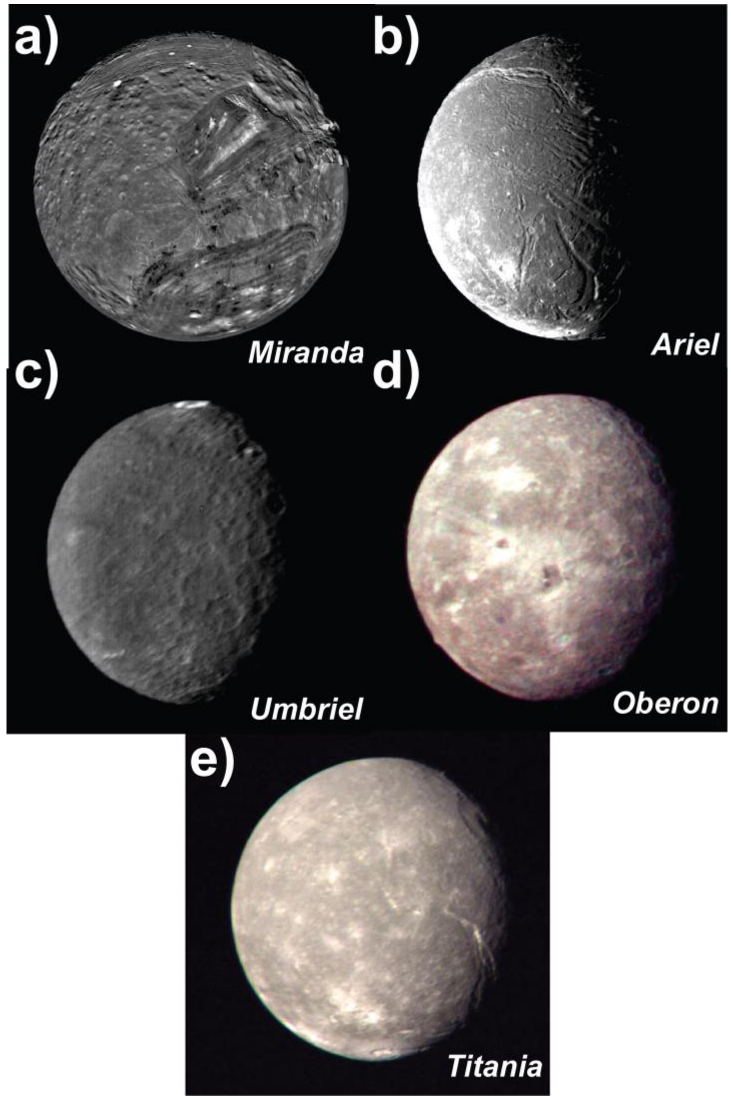

Figure 3. *Voyager 2 images revealed surface features that have raised multiple mysteries regarding the composition, evolution, formation, and structure of the classical Uranian satellites. (Images from NASA/JPL)*

ocean-surface interaction (infrared) and topographic information to investigate tectonics and geodynamics associated with a subsurface ocean, as well as map and analyze geologic units and surface features (visible). Observations of an induced magnetic field associated with any of the moons would also be indicative of a subsurface ocean (e.g., Arridge & Eggington, 2021; Weiss et al. 2021).

Understand what processes formed and modify the surfaces of the classical Uranian satellites. The geologic processes operating on the Uranian satellites are complex, as indicated by large tectonic and possibly cryovolcanic features imaged by Voyager 2 (Schenk 1991; Beddingfield & Cartwright, 2020; 2021; Schenk & Moore 2021). On Miranda and Ariel, tectonic and possibly cryovolcanic features extend well past the terminator in the Voyager 2 imaging dataset, as revealed by enhanced nightside "Uranus-shine" processing techniques (Stryke & Stooke 2008). Miranda (Figure 3a) exhibits three unique "coronae", large polygonal shaped regions of deformed surface containing subparallel ridges and troughs that are highlighted by high and low albedos. These are made up of complex sets of tectonic features (Smith et al. 1986; Schenk 1991; Pappalardo et al. 1997) and may also contain cryovolcanic flows in one corona (Jankowski & Squyres 1988; Beddingfield & Cartwright, 2020) and the large Global Rift System cuts across the ancient cratered terrain. Ariel (Figure 3b) exhibits complex canyon systems, which are thought to be a result of internal processes driving tectonism (Johnson et al. 1987; Croft & Soderblom 1991), and possible cryovolcanic features including lobate flow-like features and double ridges (Beddingfield & Cartwright, 2021). Umbriel, Oberon, and Titania (Figures 3c-e) also exhibit large canyons, similar to those seen on some icy satellites elsewhere. However, the formation of these features is not well understood, and various mechanisms have been proposed (McKinnon 1988; McKinnon et al. 1991; Greenberg et al. 1991; Janes & Melosh 1988; Sori et al., 2017), which can only be tested through investigations such as mapping of surface features, compositions, and cratering densities, and obtaining topographic information from visible images. These images can also be used to map and analyze geologic units and surface features and compare them with weathering patters to be expected from different plasma, particle or dust populations (e.g., Hendrix et al. 2012; Cartwright et al. 2015). They can also be used to perform crater density studies to estimate surface ages. Compositional trends and regolith properties can be investigated using infrared spectra, providing key insight into the origin of the mysterious dark material. Since spectra depend both on surface composition and grain size (e.g., Hapke 2012), independent information on energetic particles is needed that affect grain size (e.g., Raut et al. 2008; Howett et al., 2020) and can drive the chemical formation of the dark material (e.g., Lanzerotti et al. 1984) or other changes in color (e.g., Stephan et al. 2010; Hibbits et al. 2019).

3.2 Magnetospheric Science

Understand how internal & external drivers generate plasma structures and transport within Uranus' magnetosphere. The magnetosphere of Uranus (Stone & Miner 1986; Paty et al. 2020) offers a unique configuration that provides an opportunity to understand the drivers of magnetospheric dynamics throughout the solar system. With the planetary rotation axis tilted by 98° relative to the ecliptic plane and a magnetic field axis tilted by ~59° with respect to Uranus' rotation axis, the orientation of the magnetic field (Figure 4a) presents an asymmetrical obstacle to the impinging solar wind (Cao & Paty 2017; Paty et al. 2020), which changes continuously during the 17.2-h Uranian day. Furthermore, the Uranian magnetic field requires higher-degree multipoles near the planet to adequately model the internal planetary field. This multipolar structure sets Uranus and Neptune apart from the Gas Giants, Jupiter and Saturn (e.g., Stanley & Bloxham 2006; Soderlund & Stanley 2020; Paty et al. 2020).

Plasma transport within a planetary magnetosphere may generally be driven by external and/or internal forces. External forcing would suggest that Uranus' magnetosphere becomes connected to the solar wind, whereas an internally-driven system would be subjected to centrifugal forces as the plasma is accelerated and energized. The magnetospheres of terrestrial planets with an intrinsic magnetic field (i.e., Earth and Mercury) are primarily driven by solar wind forcing, whereas the magnetospheres of gas giants Jupiter and Saturn are dominated by forces driven by internal plasma sources and fast planetary rotation. *Voyager 2* observations suggest that Uranus may be solar wind-driven (Mauk et al. 1987). However, this runs contrary to Voyager 2 observations that revealed an apparent lack of solar wind alpha particles at higher energies (Krimigis et al. 1986); future measurements of suprathermal particle populations may yet reveal them. Given the unique combination of its extreme obliquity and the large offset of its magnetic field, Uranus' magnetic configuration varies between open and closed to the solar wind over a relatively fast (17.2-hr) Uranian day; this suggests that internal drivers must play a role, even though plasma transport due to the solar wind is decoupled from that due to rotation near the solstices (Selesnik & Richardson 1986; Vasyliuñas 1986). Depending where Uranus is in its orbit, the solar wind would approach along the direction of the rotation axis, or perpendicular to it (or somewhere in between) because Uranus' rotation axis is almost aligned with its orbital plane. This will have a strong effect on the interaction of the solar wind plasma with the magnetosphere of Uranus and the resulting current system. A mission arriving within a decade of 2050 would have the chance to observe a very different configuration relative to the solar wind than Voyager 2 as the alignment of the planet's rotation axis changes seasonally, and thus may expect to observed very different magnetospheric dynamics.

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 magnetically trap and energize charged particles around a planet and are as diverse as the planets they encompass. Uranus' radiation belts are especially interesting as Voyager 2 observations did not confirm our expectations (Kollmann et al. 2020; Paty et al. 2020). For the particles to accumulate to high intensities, the radiation belts need to draw from a large reservoir of lower energy plasma (as illustrated in Figure 4b) and/or lose the accelerated particles very slowly. Neither appeared to be the case at Uranus, which features an almost particle-free "vacuum" magnetosphere with little source plasma to be accelerated (McNutt et al., 1987), slow acceleration through radial diffusion (Cheng et al., 1987), and where waves are thought to result mostly in particle losses (Coroniti et al., 1987). Thus,

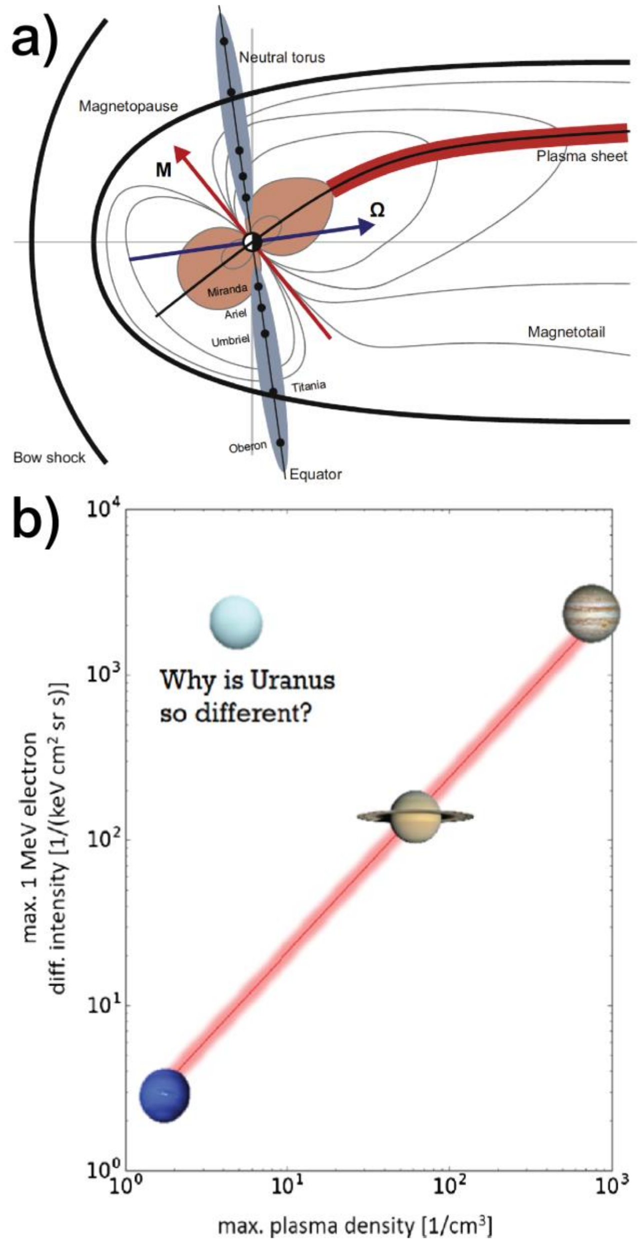

Figure 4. *Uranus' asymmetric magnetosphere (a, from Arridge et al. 2014) presents a unique opportunity to test our understanding of magnetospheric physics. In particular, it remains unclear how and why the relationship between Uranus' 1 MeV electron intensities and the amount of potential source plasma in its magnetosphere stands out so starkly from the rest of the Giant planets (b, from Kollmann et al. 2020).*

it remains a mystery why Uranus' electron belts appear surprisingly intense (e.g., compared to Saturn & Neptune (Mauk & Fox 2010)) whereas its ion belts show low intensities, despite sharing several physical processes (Mauk 2014).

Wave observations may hold the key to a possible explanation, as the whistler-mode hiss and chorus wave intensities that Voyager 2 measured at Uranus were surprisingly higher than those it observed at any other planet (Kurth & Gurnett 1991); this suggests that such waves may play an important role in the system. In general, whistler-mode waves may play a role in both electron acceleration and loss, depending on the specific plasma conditions, a fact that has been of increasing interest (e.g., Thorne et al. 2013; Allison et al. 2019). Past studies at Uranus have suggested that the waves are causing a net loss (Tripathi & Singhal 2008), yet results may be biased by the limited temporal and spatial coverage of the available Voyager 2 measurements. A very different explanation why Uranus may behave so unexpectedly is because its unique magnetospheric configuration results in the dominance of processes that have been observed to play lesser roles at other planets. For example, the non-dipolar field near the planet could trap charged secondaries from cosmic rays hitting the atmosphere, which does not occur in other planets' more dipolar fields (Kollmann et al. 2020).

3.3 Interior Science

Understand the configuration & evolution of Uranus' magnetic field. Voyager 2 showed that the intrinsic magnetic field of Uranus is multipolar (i.e., not dominated by the dipole component) and has no symmetries along any axis (e.g., the dipole is tilted by 59° relative to the rotational axis, as previously mentioned (Figures 4a and 5a; Holme & Bloxham 1996; Soderlund & Stanley 2021)). Magnetic field measurements during the Voyager 2 flyby in combination with auroral observations allowed the large-scale field to be estimated up to spherical harmonic degree l=4 (Herbert 2009); in contrast, the dipole-dominated magnetic fields of Jupiter and Saturn are known to l>10 and surprises such as the north-south asymmetry and temporal variability of the Jovian field were discovered as they were characterized in greater detail (Cao et al. 2019; Connerney et al. 2021). Even more discovery awaits at Uranus (and Neptune) where the magnetic field is more spatially, and likely temporally, complex. Long-term in-situ measurements of the local magnetic field as well as energetic particles tracing global field properties (e.g., location and field strength of the foot points of field lines) will resolve both large- and small-scale fields over time thus enabling characterization of Uranus' dynamo to a level commensurate with Jupiter and Saturn (Cao et al. 2019; Connerney et al. 2021), which would not only test hypotheses for how its multipolar magnetic field is generated but also help explain why the dynamos of gas and ice giant planets differ so substantially. Potential explanations for Uranus' unique magnetic field configuration relate to the presence of a deep stably-stratified layer (e.g., Stanley & Bloxham 2004), the relatively weak influence of rotation on deep convective flows (Soderlund et al. 2013), the interplay of density versus electrical conductivity variations with depth (Soderlund & Stanley 2020), among others. Thus, in addition to characterizing the magnetic field, Uranus' interior structure, composition, heat flow, and dynamics must also be determined in order to resolve the mystery of how the dynamo operates.

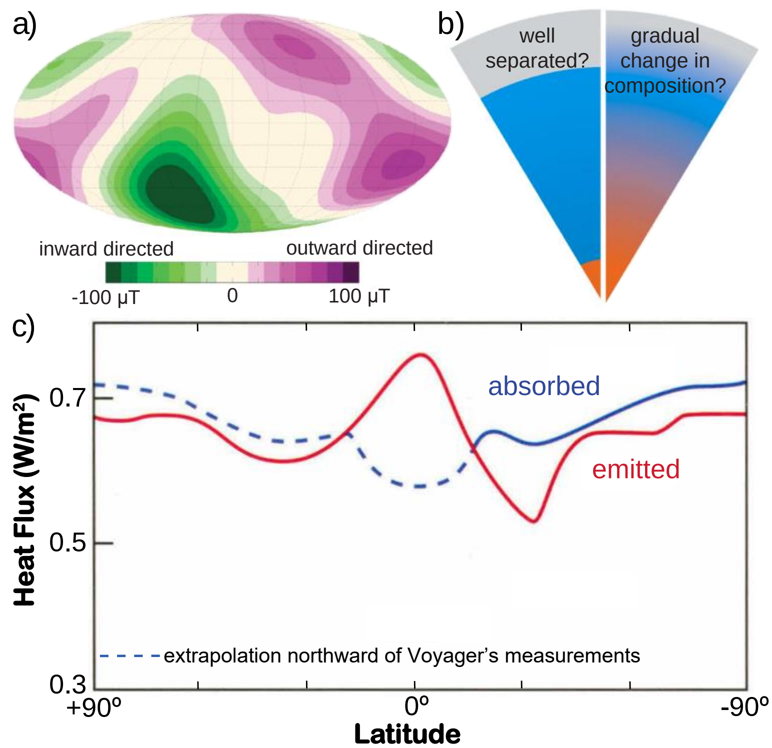

Figure 5. *The peculiarities of Uranus' interior are showcased by the (a) multipolar intrinsic magnetic field, (b) unknown internal structure and bulk composition, and (c) energy balance with comparable absorbed and emitted heat fluxes. Adapted from Soderlund & Stanley (2020), Helled & Guillot (2017), and Ingersoll (1999), respectively.*

Determine the bulk composition and the distribution of materials within Uranus. Standard three-layer structure models of Uranus infer that the planet consists of ~2 Earth masses of hydrogen-helium; although this estimate puts important limits on the planetary metallicity, it is not known which elements dominate the deep interior (Nettelmann et al. 2013; Helled & Fortney 2021; Teanby et al. 2021). Alternative structure models suggested that Uranus could have a density profile without discontinuities (Helled et al. 2011) and that a large fraction of water is not needed to fit the observed properties (Figure 5b). 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 (Helled & Bodenheimer 2014; Helled et al. 2020; Mousis et al 2021). Currently, the ice-to-rock ratio of Uranus remains only loosely constrained (Helled et al. 2011; Nettelmann et al. 2013). It is therefore clear that more accurate measurements of the gravity field and estimates of the depth to the dynamo region from magnetic field measurements (e.g., Tsang & Jones 2020; Connerney et al. 2021; Masters & Soderlund 2022) are required to determine Uranus' bulk composition and its depth dependence.

Abundances of key species such as helium would tell us about the environment in which Uranus formed, and bulk enrichments of carbon, nitrogen, and sulfur would provide additional information on the planet formation process. However, it must again be noted that compositional determination can only be obtained by in-situ observations from an atmospheric probe, which is not considered within the scope of the New Frontiers-class orbiter mission promoted here due to cost cap limitations. Unfortunately, ground-based attempts to constrain aspects of the composition from measurements of atmospheric disequilibrium species (such as CO) have thus far been inconclusive (e.g., Cavalie et al. 2014).

Understand Uranus' global energy balance & internal heat flow. Uranus is the only outer planet in the solar system that is in approximate equilibrium with solar insolation (Pearl et al. 1990; Pearl & Conrath 1991), suggesting that its interior may not be fully convective and/or contains composition gradients that hinder convection (e.g., Nettelmann et al. 2016; Podolak et al. 2019; Scheibe et al. 2019; Vazan & Helled 2020), although atmospheric phenomena may also be responsible (Gierasch & Conrath 1987; Kurosaki & Ikoma 2017). Given the large uncertainties in the Voyager 2 measurements of Uranus' bond albedo and thermal emission, and the potential for temporal variability in the reflectivity and emission, a more precise energy balance measurement is necessary (Figure 5c). This requires mapping the reflectivity at multiple phase angles and latitudes (which can only be done with an orbiting spacecraft), and measuring the thermal emission at multiple latitudes. Furthermore, if convective inhibition is at play, then Uranus' internal heat flux may vary with time, 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.

Interior structure models use gravitational constraints to link planet composition, density, pressure, and temperature as a function of radius, albeit with non-unique solutions including 'hot' and 'cold' Uranus scenarios that may or may not be fully adiabatic (Helled et al. 2011; Nettelmann et al., 2013; Bethkenhagen et al. 2017; Podolak et al. 2019). As a result, improved measurements of the planet's composition, luminosity, and gravity field will reduce the uncertainty in interior heat flow. Moreover, variation of electrical conductivity with depth depends strongly on the planet's temperature structure, leading to potential interactions between the zonal winds and magnetic field in the semiconducting region of the atmosphere (Soyuer et al. 2020). These interactions are expected to produce perturbations in the poloidal magnetic field that may further test modeled temperature profiles (Soyuer & Helled 2021).

3.4 Atmospheric Science

Understand Uranus' atmospheric heat transport mechanisms. Many atmospheric processes cause downward (e.g., solar insolation) and upward (e.g., thermal radiation, cumulus convection, and vertically propagating waves) radiation of energy. These processes provide local perturbations that shape atmospheric features such as cloud bands and vortices. Furthermore, the total upward heat flux in the atmosphere is the sum of such local processes. The connection between local atmospheric events and the global energy balance remains an outstanding question. Because the molecular weight of condensable species is heavier than the background hydrogen-helium atmospheric mixture, moist convection is generally inhibited and tends to happen in episodic bursts (Li & Ingersoll 2015; Friedson & Gonzales 2017; Leconte et al 2017; Li et al. 2018; Guillot 2021). Given this time-variability, a new mission may find that local episodic convection leads to a higher global heat flux. Even if a new mission arrives at a quiescent time, recent work presents specific testable predictions for the thermal stratification in observable layers during an inter-storm period (Li & Ingersoll 2015).

In the middle and upper atmosphere, our ignorance of heat transport processes is symptomized as the "energy crisis"*:* Voyager 2 stellar occultations revealed that Uranus' thermosphere is hot (Broadfoot et al. 1986; Herbert et al. 1987; Stevens et al. 1993), although ground-based studies have revealed that these temperatures are declining over time (Melin, 2021). Although all four giant planets exhibit this "crisis", 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 (Stevens et al. 1993). The vertical temperature gradient may point to the nature of the unknown heating (Clarke et al. 1987; Stevens et al. 1993; Waite et al. 1997; Raynaud et al. 2003), but Voyager 2 occultations cannot distinguish between candidate heating mechanisms. New occultation measurements (including those relatively deep, down to several bars) with modern instrumentation from an orbiter should shed light on this long-standing mystery.

Understand Uranus' zonal and meridional circulation patterns. These circulations are critical for understanding the previously-discussed vertical heat transport and energy balance as well as producing a coherent model of atmospheric dynamics and how they extend into the interior (Hueso et al. 2021). Both Uranus' zonal wind profile (retrograde (westward) winds blowing at the equator and a single prograde (eastward) peak in each hemisphere), and its tropospheric temperatures (cool mid-latitudes contrasted with a warm equator and pole), are in stark contrast to the finely-banded winds and temperatures of Jupiter and Saturn. The penetration depth of these winds is not well constrained, but gravitational and ohmic dissipation models suggest they are limited to within the outermost 10% of the planet (Kaspi et al. 2013; Soyuer et al. 2020) Uranus' winds also exhibit a surprising hemispheric asymmetry near the poles (Sromovsky et al. 2014; Karkoschka 2015), 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 (Fletcher et al. 2020b), which may hint at unresolved peaks in the zonal wind structure. Temporal tracking of cloud features in high-resolution images would reveal any such peaks, as well as any seasonal changes since Voyager 2.

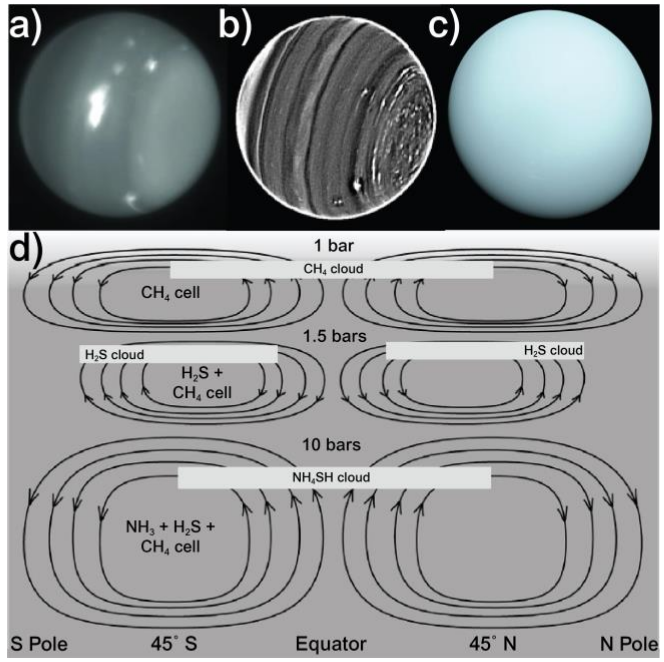

***Figure 6**. Remote observations of Uranus in the (a-b) near-infrared (from de Pater et al. 2015 and Sromovsky et al. 2015, respectively) have shown the Uranian atmosphere to be much more interesting than the (c) classic Voyager 2 image (NASA/JPL). It remains unclear whether (d) a three-layer overturning meridional circulation model accurately describes Uranus' zonal and meridional circulation patterns (adapted from Sromovsky et al. 2014).*

The structure of Uranus' overturning meridional circulation remains unknown. Depletion of gases such as methane (observed in the near-infrared) and H_2S (observed in the microwave) around the poles seems to suggest 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 (Sromovsky et al. 2015). However, such a circulation pattern is inconsistent with observed cloud and temperature distributions in the upper troposphere, implying that the meridional circulation must be more complex, perhaps involving multiple stacked cells (Figure 6d, Fletcher et al. 2020b). High-resolution maps of temperature and key chemical tracers of vertical mixing are necessary to unravel the meridional circulation. As for the Gas Giants, high-resolution measurements of the wind field may reveal coupling between zonal and meridional circulation via eddies (Salyk et al. 2006; Del Genio & Barbara 2012). This can be supported by remote microwave observations of H_2S in the deep Uranian atmosphere (e.g., ALMA, VLA) (de Pater et al. 2021; Molter et al. 2021).

Determine the thermodynamics and chemistry of Uranus' clouds and hazes. During the *Voyager 2* flyby, Uranus appeared almost featureless. The subsequent presence of unexpected bright storms (Figure 5a; de Pater et al. 2015) 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 models (de Pater et al. 1991); in fact, the compositions of Uranus' upper cloud layers remain unclear (Figure 5b; Sromovsky et al. 2015), although ices of H_2S and CH_4 are promising candidates (Irwin et al. 2018). 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 (Moses et al. 2021). A deeper understanding of cloud properties can be achieved with three-dimensional spectroscopic mapping of para-H_2, CH_4, H_2S, and the spatial and vertical distributions of aerosols from near-infrared spectroscopy.

Voyager 2/UVS measurements (Broadfoot et al. 1986; Herbert et al. 1987; Bishop et al. 1990; Stevens et al. 1993) showed that Uranus' upper atmosphere was remarkably "clear", with hydrocarbon densities much lower than those found for any other giant planet (Melin 2021). Deeper in the stratosphere, hydrocarbons derived from methane photochemistry (Moses et al. 2021) are the main source of photochemical haze, act as continuum absorbers in the extreme ultraviolet, and serve as key tracers of vertical transport. For example, the spatial distribution of acetylene gas hints at a coupling between circulation patterns in the troposphere and stratosphere (Roman et al. 2020). Better constraints on their distributions can be determined by solar and stellar ultraviolet occultations (Smith & Hunten 1990; Herbert & Sandel 1998). A future New Frontiers-class orbiter mission could potentially host a breadth of multi-wavelength remote sensing instruments to optimizing its capability to addressing the science objectives in Figure 1.

3.5 Ring Science

Determine the processes that sculpt and maintain Uranus' ring-moon system. Since their discovery (Elliot et al. 1977), scientists have puzzled over how the Uranian rings maintain their narrow and non-circular structures (French et al. 1991) but sometimes also show striking changes (de Pater et al., 2007). Voyager 2 and Earth-based observations have revealed that Uranus hosts a system of dense narrow rings lacking meaningful spacing, diverse broad and finely structured dusty rings, and the most tightly-packed system of small moons in our solar system (Figure 7; Nicholson et al. 2018; Showalter 2021). This "dynamically full" system is known to be unstable and is brimming with interesting interactions and dynamics including overlapping resonant interactions between multiple moons (French et al. 2015). The system is also "full" in the sense that it likely has no room for additional moons, as multiple pairs are probable to cross orbits and collide in the near future - in some cases, possibly as little as just thousands of years (French & Showalter 2012). The ring-moon system contains important information about its formation and evolution, and it can provide clues to the unique dynamical history of Uranus (Ćuk et al. 2020; Hsu et al. 2021).

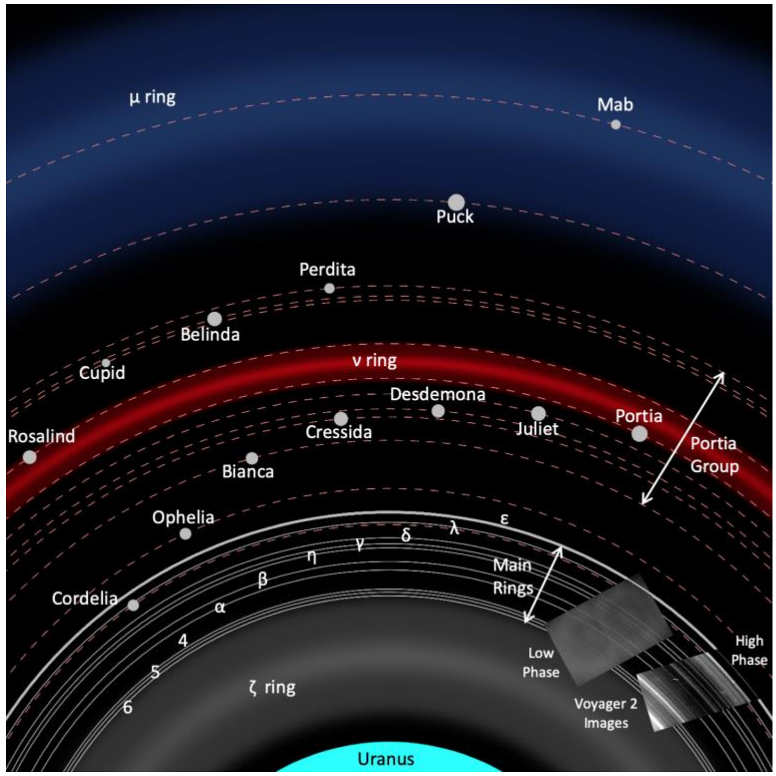

Figure 7. *It remains unclear why the Uranian ring-moon system shown here is so dynamically full and apparently haphazard.*

The most prominent features in the Uranian ring system are the ten narrow and oddly-shaped main rings (French et al. 1988). Four of the main rings are associated with resonances of small moons that likely play a role in shepherding them (Porco & Goldreich 1987; Chancia et al. 2017). The mechanisms confining the remaining ring edges and the nature of their present locations remain a mystery (Esposito et al. 1991). We could further our understanding of how these unique rings function by obtaining high-resolution images and occultation profiles to reveal their detailed structures. These data could provide more precise information on the rings' non-circular shapes, evidence of accretion and/or fragmentation, density waves resulting from satellite resonances or planetary interior oscillations, wakes of nearby satellites, and structures such as the propellers found in Saturn's rings (Tiscareno et al., 2008). There may also be undiscovered small moons we could detect and find to play a role in maintaining the narrow rings (Murray & Thompson 1990, Chancia & Hedman 2016).

Uranus also features a complex system of faint dusty rings (Ockert et al. 1987; de Pater et al. 2006; Hedman & Chancia 2021). We know very little about the structures and properties of these dusty rings. They likely originate from micrometeoroid bombardment ejecta of the small inner moons and the dense rings themselves (Esposito & Colwell 1989). The ejecta then evolves under Uranus' oblateness, electric and various magnetic forces, and radiation pressure that will mostly affect the sub-micron grains (e.g., Juhaz & Horanyi 2002). Understanding the rates and sources of the dusty ring production and distribution throughout the system will help to determine the lifecycle of ring and moon material; this information is needed to understand the formation of the rings, their dynamics, and their current characteristics - including their differences in color (bluish for the μ-ring and reddish for the others). This information requires high-phase-angle images of the dusty rings and high-resolution images of the small moons' surfaces for signs of cratering and accretion.

Thirteen small moons orbit between the main rings and the larger main moons of Uranus (Smith et al. 1986; Karkoschka 2001b; Showalter & Lissauer 2006). Nine of the moons' orbits are radially spaced within under 18,000 km. This arrangement is unstable on relatively short timescales and depends on the moons' unknown masses (Duncan & Lissauer 1997; French & Showalter 2012; French et al. 2015). Many of these moons orbit inside Uranus' corotation 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, like at Saturn (Charnoz et al. 2018. In this way, the ring-moon system may undergo recycling throughout its lifetime (Hesselbrock & Minton 2019). Determining how this process works is fundamental to understanding how planetary ring-moon systems operate under a variety of configurations.

Determine the composition and origin of Uranus' rings and small satellites. The rings and small moons of Uranus are dark, and their compositions are unknown (Karkoscka 2001). Observations (Grundy et al. 2006) have revealed H_2O and CO_2 ice spectral features on Uranus' larger moons, whereas the rings' spectra are flat (de Kleer et al. 2013). Limited observations of the small moons have not revealed if they are more akin to the larger moons or the rings. Thus, improved near-infrared spectra of the small moons and rings are needed to determine both their origins and the darkening mechanism(s) in the system. Observations of Uranus' unique magnetic field and magnetospheric particle environment would provide insight into the interaction between the plasma in Uranus' magnetosphere and the regoliths of its moons and ring particles and its potential to alter their compositions.

4 Required Mission Design Scope and Considerations

Although a New Frontiers-class orbiter mission would by definition likely achieve less science than those targeted by previously-studied large strategic-class missions, such a mission should put an emphasis on maintaining balance across the research disciplines as significant system science should be achievable. Results from previous larger studies suggest the feasibility of a New Frontiers-class orbiter mission to Uranus. For example, the costs in the Hubbard (2010) Decadal study 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 New Frontiers-class science would reduce both the payload and spacecraft costs. From a mission design standpoint, the potential use of a 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 New Frontiers cost cap. Furthermore, a New Frontiers-class Uranus orbiter mission could be implemented with current technologies, given appropriate trades in design and scope; however, multiple technologies under development could enhance and expand the scope and capability of such a mission (e.g., Spilker 2021).

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 New Frontiers-class Uranus orbiter mission. This plays into not only the extent of the payload and spacecraft subsystems, but also the power required for deep-space communications, specifically downlink. Previous Ice Giant mission studies (Hubbard 2010; Hofstader et al. 2017) have resulted in architectures requiring >350 W-e end-of-life power, which required three or more now-cancelled Enhanced Multi-Mission Radioisotope Thermoelectric Generators (eMMRTGs). Owing to the relative inefficiency and significant cost of current RPS, 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 RPS would significantly enhance the mission. For

Instrument Type	Representative Heritage Instrument	Mass (kg)	Power (W)
Wide-angle Camera	MESSENGER/MDIS [Hawkins et al. 2007]	4.6	10.0
Visible/Near-infrared Imaging Spectrometer	New Horizons/Ralph [Reuter et al. 2008] & Lucy/L'Ralph	19.0	7.1
Magnetometer	MESSENGER [Anderson et al. 2007]	4.7 (incl. boom)	4.2
Plasma Spectrometer	MESSENGER/FIPS (ions) [Andrews et al. 2007]	1.4	2.1
	Parker Solar Probe/SPAN-B (electrons) [Kasper et al. 2016]	2.5	2.0
Energetic Particle Sensor	Parker Solar Probe/EPI-Lo [McComas et al. 2017]	3.9	4.3
Ultra-stable Oscillator	New Horizons/REX [Tyler et al. 2008]	0.1	2.1
Narrow-angle Camera	New Horizons/LORRI [Cheng et al. 2007]	9.0	5.5
Ultraviolet Imaging Spectrometer	New Horizons/Alice [Stern et al. 2008b]	5.0	5.8
Thermal Infrared Imager	Lunar Reconnaissance Orbiter/Diviner [Paige et al. 2009]	11.5	18.4
	TOTAL	52.1	62

Figure 8. *Example of an instrument complement that would enable broad, cross-disciplinary science return for New Frontiers-class Uranus orbiter mission. White rows indicate a notional baseline payload that may be feasible given realistic cost and power constraints; gray rows provide additional high-impact instruments that could be included if resources and operations allow. Duty cycles and operations would be dependent on the mission and spacecraft designs.*

example, the recent Neptune Odyssey mission concept uses three next-generation RPS (Rymer et al. 2021), suggesting that a New Frontiers-class Uranus mission could be implemented with fewer. This of course assumes that a sufficient supply of plutonium is available for future space exploration missions, which could potentially be achieved with early enough planning and investment (Zakrajsek 2021). It is also important to emphasize that future RPS needs may come from outside the Planetary Science community – e.g., the Heliophysics concept for an Interstellar Probe mission (Kinnison et al. 2021).

With current technology, a typical baseline New Frontiers-class Uranus orbiter mission would target a less than twelve-year cruise (potentially with a Centaur flyby en route to Uranus) and a two-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, and small moons; this baseline could be significantly lengthened if the lifetime of future RPS were improved. Previous studies (e.g., McAdams et al. 2011) have demonstrated that such short-duration trajectories are feasible.

Another significant driver is determining the total mass that can be put into Uranus orbit within the New Frontiers cost cap given the significant propellant required to achieve orbit insertion (approximately 3 kg of propellant required to deliver 1 kg of payload into orbit) and to maintain pointing for both downlink and targeting of scientific objectives, mass efficiency will be critical. This mission uses chemical propulsion, though an ion engine, like that used on the Dawn mission, could be considered as a potential future trade; the use of a SEP stage, as has been explored by previous studies, could be considered, but would likely be difficult to fit within the New Frontiers cost cap. A realistic ~50-kg payload using current technologies would provide closure to numerous scientific mysteries summarized in Figure 1; however, cost and power limitations of course add additional limitations, though the latter could be addressed with a creative concept of operations that varies instrument duty cycles. A summary of a notional baseline payload and representative heritage instruments is presented in Figure 8. Because of the potential mass limitations, a New Frontiers-class Uranus orbiter is unlikely to have the resources to carry an atmospheric probe of the size and capability proposed by previous studies (e.g., Hubbard 2010; Hofstadter et al. 2017; Hofstadter et al. 2019) and that would fully obtain all of the potential observables listed in Table 1. However, such a mission might be able to consider inclusion of a smaller, more focused atmospheric probe (e.g., Sayanagi et al. 2020), which would likely be able to make a subset of the identified probe potential observables (e.g., thermal profile) in Table 1. Fortunately, cost reduction and increases in the capability and availability of launch vehicles (e.g., SLS) could significantly enhance the deliverable mass and thus scope of a New Frontiers-class Uranus orbiter mission, as well as potentially enabling contributed elements from other agencies, while also adding the capability to launch outside of windows with Jupiter gravity assists. Furthermore, the risk-versus-benefit of using aerocapture for orbit insertion should be analyzed as it can strongly increase the mass of the delivered payload and shorten flight times (Hall et al. 2005; Spilker et al. 2016; Girija et al. 2020; Dutta et al. 2021).

Another primary design driver for a New Frontiers-class Uranus orbiter mission will be limitations on the total mission duration resulting from the nominal fourteen-year flight design life of currently-available RPS (Lee & Bairstow 2015); however, future RPS are targeting and recent pre-Decadal mission studies designed baseline missions based on longer lifetimes (e.g., Howett et al. 2021; Rymer et al. 2021). The preliminary design is a two-year baseline mission in orbit at Uranus with a system tour that enables sufficient surface mapping of the large satellites as well as imaging coverage of the planet, its rings, and the small moons. Furthermore, the mission will be designed to complete its baseline mission by Uranus spring equinox (2050), allowing for imaging of the northern hemispheres of the satellites that were not illuminated during the Voyager 2 flyby. This, of course, constrains the launch vehicle selection and propulsion. The initial assumption is that the spacecraft will be designed to accommodate both three-axis and spin-stabilization to enable simpler operations during the long cruise, as was done on New Horizons (Stern 2008).

As previously discussed, the architecture summarized here does not include any mission critical technologies below TRL6 and baselines high-heritage instrumentation and spacecraft subsystems. However, the mission could benefit from significant enhancement by using aerocapture (TRL~3), which is under current NASA-funded development (Spilker et al. 2018). Likewise, any mission to Uranus will likely require a nuclear power system, though deep-space use of solar power could also be considered (e.g., Piszczor et al. 2008). The baseline mission can use currently-available MMRTGs (Lee & Bairstow 2015). However, the ability to use either the next-generation RTG (NG-RTG; Matthes et al. 2018) or the dynamic RPS (DRPS; Qualls et al. 2018) systems currently under development by NASA with estimated launch availability dates of 2026 and 2030, respectively - which were baselined for the recent Neptune Odyssey mission concept (Rymer et al. 2021) - would provide 20-380% greater end-of-life power than the MMRTGs and significantly enhance the capability of a New Frontiers-class Uranus orbiter.

5 Summary and Conclusion

Uranus presents a unique and tantalizing, yet woefully underexplored, destination due to the unique properties of it and its system and additionally provides an opportunity to explore the currently underexplored category of Ice Giants. Compelling characteristics of the Uranian system that are unlike other planets that have been studied in detail include: 1) five major satellites - potential ocean worlds with drastic surface features; 2) a unique magnetosphere with a dramatic configuration that features highly-tilted rotation and magnetic axes driven by a non-dipole-dominated interior dynamo as well as unexpectedly strong radiation belts and plasma wave activity; 3) a bulk planetary composition thought to be dominated by heavier "ices" (e.g., H_2O, CH_4, H_2S, and NH_3) and a poorly constrained amount of rocky material; 4) climate with unique atmospheric circulation, winds, chemistry, and cloud formation; and 5) a dynamically full and apparently haphazard ring-moon system.

As has been demonstrated by previous missions to other planets, orbiting missions are necessary to truly characterize a world, especially for magnetospheric and atmospheric studies focusing on processes with timescales shorter than or comparable to the duration of a flyby. Likewise, close periapse passes across a wide range of planetary latitudes and longitudes enabled by a sustained orbiter mission are required to intimately probe the interior of Uranus, which may hold keys to understanding the formation of our solar system as well as providing ground truths for the understanding of exoplanets with similar mass and radii, and potentially those with similar chemical enrichments, axial tilts, low-temperature conditions, and higher-order magnetic fields. As such, exploration of Uranus will not only enhance our understanding of the Ice Giant planets themselves but also extends to planetary dynamics throughout our solar system and beyond.

While we are pushing the frontier of exploration further out within our solar system and discover more and more Ice Giant-sized exoplanets, a mission to Uranus is becoming timely. Because of the strong desire to revisit the Uranian system before the unimaged hemispheres of the satellites recede back into darkness (equinox is in early 2050), there is an imperative to explore any and all options. In particular, a mid-cost New Frontiers-class orbiter mission - such as the one described in this article – could achieve many significant and interdisciplinary system science questions with currently-available technology, if appropriate care is taken in the mission design. For example, the technical challenges of flying to and entering orbit around Uranus and sustaining operations at a distance of 20 AU must all be carefully considered and traded against the overall mission feasibility, impact, and cost. As this paper shows, a mid-scale (e.g., New Frontiers-class) mission could achieve significant and high-impact cross-disciplinary science observations using current technology.

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Acknowledgements

Work on this project at APL was funded by internal investment by the APL Civil Space Mission Area within the Space Exploration Sector. LNF was supported by a European Research Council Consolidator Grant (under the European Union's Horizon 2020 research and innovation program, grant agreement No 723890) at the University of Leicester. Parts of this work were carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. RPS details include pre-decisional information – for planning and discussion purposes only.