New Frontiers-class Uranus Orbiter: A Case For Exploring The Feasibility of Achieving Multidisciplinary Science With a Mid-scale Mission. I. J. Cohen[1], C. B. Beddingfield[2], R. O. Chancia[3], G. A. DiBraccio[4], M. M. Hedman[3], S. M. MacKenzie[1], B. H. Mauk[1], K. M. Sayanagi[5], K. M. Soderlund[6], E. P. Turtle[1], E. Y. Adams[1], C. J. Ahrens[7], C. S. Arridge[8], S. M. Brooks[9], E. J. Bunce[10], S. Charnoz[11], G. B. Clark[1], A. Coustenis[12], R. A. Dillman[13], S. Dutta[13], L. N. Fletcher[10], R. A. Harbison[14], R. Helled[15], R. Holme[16], L. M. Jozwiak[1], Y. Kasaba[17], P. Kollmann[1], S. Luszcz-Cook[18], O. Mousis[19], A. Mura[20], G. Murakami[21], M. Parisi[9], A. M. Rymer[1], S. Stanley[22], K. Stephan[23], R. J. Vervack[1], M. H. Wong[24], P. Wurz[25], [1]JHU/APL (11100 Johns Hopkins Road, MS 200-E254, Laurel, MD 20723; Ian.Cohen@jhuapl.edu), [2]SETI Institute, [3]Univ. of Idaho, [4]NASA/GSFC, [5]Hampton Univ., [6]Univ. of Texas at Austin, [7]Univ. of Arkansas, [8]Univ. of Lancaster, [9]JPL/Caltech, [10]Univ. of Leicester, [11]Paris Diderot Univ., [12]Paris Observatory at Meudon, [13]NASA/LaRC, [14]Univ. of Nebraska-Lincoln, [15]Univ. of Zurich, [16]Univ. of Liverpool, [17]Tohoku Univ., [18]American Museum of Natural History, [19]Aix Marseille Univ., [20]National Institute of Astrophysics, Italy, [21]JAXA, [22]Johns Hopkins Univ., [23]DLR, [24]Univ. of California, Berkeley, [25]Univ. of Bern

Introduction: Uranus presents a compelling scientific target and provides a unique opportunity to explore Ice Giant system science. The Ice Giants, Uranus and Neptune, represent a distinct class of planets within our solar system that has yet to be fully explored or understood. Characteristics of the Uranian system, in particular, include: 1) a dynamically full and haphazard ring-moon system; 2) five major satellites - potential ocean worlds with drastic surface features; 3) a dramatically configured magnetosphere with highly-tilted rotational and magnetic axes; 4) a bulk planetary composition dominated by heavier "ices" such as H_2O, CH_4, and NH_3; and 5) a unique wind pattern and unknown circulation structure. Detailed study of Uranus by an orbiter is crucial not only for valuable insights into the formation of our solar system but also for providing ground truths for the understanding of Ice Giant-sized exoplanets [1]. As such, the imperative and timely exploration of Uranus will not only enhance our understanding of the Ice Giant planets but also extends to planetary dynamics throughout our solar system and beyond.

The 2013 Planetary Science Decadal Survey *Vision and Voyages for Planetary Science in the Decade 2013-2022 (V&V)* 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" [2]. 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 unclear whether a mission would make the 2030-2034 launch window necessary to take advantage of a Jupiter gravity assist to reach the Uranian system before it reaches equinox in 2049; after this the northern hemispheres of the satellites not imaged by *Voyager 2* will begin to recede back into darkness. The timeliness of a mission to Uranus is thus a primary motivation for evaluating what science can be done with a lower-cost, potentially faster-turnaround mission, such as a New Frontiers (NF)-class orbiter to Uranus. This presentation summarizes one of three such proposals submitted to the 2019 Planetary Sciences Pre-Decadal Mission Concept Study (PMCS) opportunity. *V&V* recommended in-situ measurements of noble gases and elemental isotopic ratios crucial for understanding the origin and evolution of Ice Giant planets. However, this paper presents the scientific basis for a mission which omits science objectives only achievable via in-situ measurements as descoping these may become necessary to launch a mission by 2034.

Voyager 2's brief flyby encounter [3] with Uranus provided a glimpse at the complexity and uniqueness of the planet and ultimately motivated more questions than answers. Our current limited understanding of Uranus is analogous to that of other planets prior to long-lived orbital missions (e.g., after the *Pioneer* and *Voyager* missions to Jupiter and Saturn). Just as our understanding of those planets was transformed beyond expectations by dedicated orbiter missions (e.g., *Galileo*, *Juno*, *Cassini*), so too will our knowledge of Uranus expand from the necessary multi-year measurements and investigation. Flybys only provide limited snapshots of a planetary space environment at a given location and time. It is challenging, if not impossible, to characterize a system with such a limited *in situ* dataset. The only way to comprehensively understand Uranus is with an orbiting mission.

Orbital missions have flown to every planet in our solar system except for the Ice Giants. At each planet these first orbiters revealed many surprises that were missed during the initial flybys. For example, a major discovery of *Cassini* was the eruption of material from the subsurface ocean of Enceladus [4-5], which was unnoticed by previous flybys. Future missions to Uranus will undoubtedly provide similar system-science surprises.

Science Objectives: A "proto-Science Traceability Matrix" (STM) in *Fig. 1* summarizes a broad array of potential science objectives and outstanding mysteries, which covers all areas of the Uranus system (rings, satellites, magnetosphere, atmosphere, and interior). Though not explicitly defined here, a NF-class Uranus orbiter mission is expected to achieve many of the science objectives outlined.

	Outstanding Mystery	Science Objective *(Relevant V&V Science Goal)*
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)
		Determine the composition & origin of Uranus' rings & small satellites. (1)
SATELLITES	*Do any of Uranus' classical satellites sustain a subsurface ocean?*	Determine whether the classical Uranian satellites have signatures indicative of subsurface oceans. (6)
	Which processes formed the extremely dark & resurfaced terrains of the five classical Uranian satellites?	Determine the surface compositions of the classical Uranian satellites. (4)
		Understand what processes formed & modify the surfaces of the classical Uranian satellites. (4 & 5)
MAGNETOSPHERE	*How does plasma transport work in Uranus' unique magnetospheric configuration?*	Understand how internal & external drivers generate plasma structures & transport within Uranus' magnetosphere. (1 & 3)
	How does Uranus generate such an intense electron radiation belt?	Understand what processes generate Uranus' intense electron radiation belt. (1 & 3)
INTERIOR	*How is Uranus' interior structured below the clouds and how does it behave?*	Understand the configuration & evolution of Uranus' magnetic field. (1 & 3)
		Determine the bulk composition & the distribution of materials within Uranus. (1 & 2)
		Understand Uranus' global energy balance & internal heat flow. (1)
ATMOSPHERE	*What mechanisms drive Uranus' large- & small-scale atmospheric dynamics?*	Understand Uranus' atmospheric heat transport mechanisms. (1 & 3)
		Understand Uranus' zonal & meridional circulation patterns. (1 & 3)
		Determine the thermodynamics & chemistry of Uranus' clouds and hazes. (1 & 3)

Figure 1. "Proto-Science Traceability Matrix" outlining the multidisciplinary outstanding mysteries and potential science objectives that could be addressed by a New Frontiers-class Uranus orbiter mission.

NF-class Design Considerations: Whereas a NF Uranus orbiter could be undertaken with current technologies, given appropriate trades in design, implementation, and scope, the mission would be significantly enhanced by future technologies. To achieve a meaningful NF-class Uranus orbiter mission, the mission design parameters must be assessed against completion of the science objectives, cost cap, and feasibility. In particular, studies that trade science scope and instrumentation/operational capabilities against simpler and cheaper options must be fundamental to the mission design. **A high priority for a NF Uranus orbiter should be to maintain a balance across research disciplines.**

A primary driver for the mission will be a total mission duration of no more than 14 years based on the flight design life of the Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs). A typical baseline would be a two-year mission in orbit at Uranus with a system tour that enables surface mapping of the large satellites as well as spatial coverage of the planet and rings/small moons. Furthermore, the mission should be designed to complete its baseline mission by Uranus spring equinox (2049), enabling different illuminations of the satellites and seasonal orientation of the planet and magnetosphere than observed by *Voyager 2*.

A significant driver of the mission design and subsequent design parameters is determination of the total mass that can be put into Uranus orbit within the NF cost cap. As such, the cost/risk-vs.-benefit of using aerocapture for orbit insertion should be considered [6].

Because significant propellant mass is needed to put a spacecraft into orbit at Uranus (~3 kg propellant per kg dry mass), mass efficiency is also critical to a mission's feasibility. A realistic ~60-kg payload (e.g. five instruments and radio science), would provide closure to several mysteries summarized in *Fig. 1*.

Finally, 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 requires six MMRTGs. Owing to the relative inefficiency and significant cost of MMRTGs, 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. Other design considerations that place significant constraints on the feasibility of a NF Uranus orbiter include deep-space communications (specifically the power required for downlink) and radiation shielding mass.

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