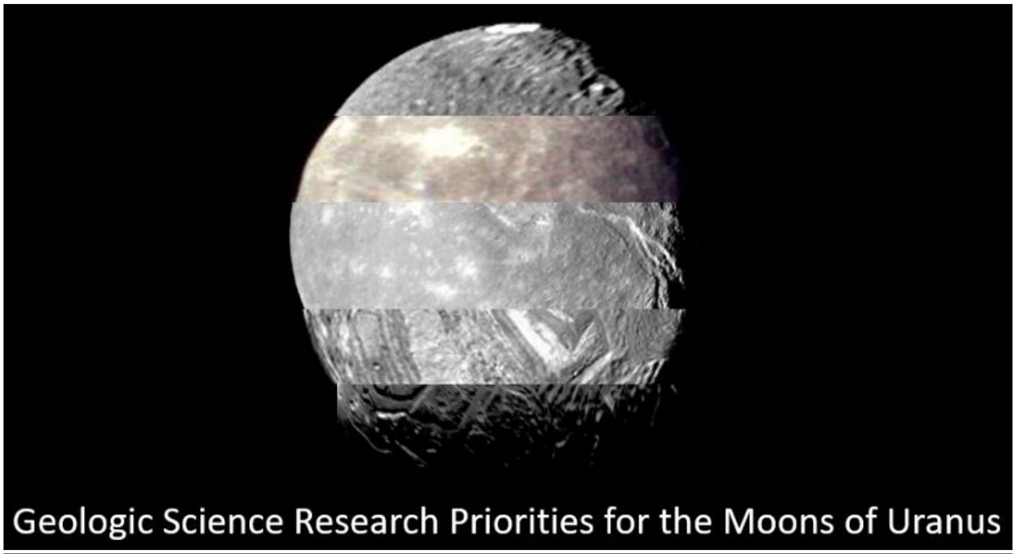

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Background

This white paper is a collective effort of the outer planets science community in outlining its scientific direction for the coming 2023 Decadal Survey to the National Research Council with references from the 2013-2022 V&V Decadal Survey. Major accomplishments from studying Uranus in the past decade using ground or space-based telescopes include: Uranus' equinox in 2007 was observed with modern instruments, revealing cloud activity, ***and the discovery of two more colored rings and several new small moon discoveries***; Uranus dynamic white polar cap; the census of known exoplanets increased using ground and space-based telescopes and created sub-categories of icy giants (mini-Neptunes, sub-Neptunes, Hot-Neptunes)**. *However, there is a lack of studies involving the rings and satellites of Uranus. This paper addresses the components and motivations to the geologic exploration of Uranian moons with orbital exploration of the Uranian system as a whole and serves as a basis for future investigative studies. Studying these moons can provide interesting insight to the evolution and dynamics of moons in our Solar System (and beyond).***

The discussion is divided into four main sections, addressing fundamental questions as they pertain to the Uranian satellite system:

-What are the key scientific questions that will be driving forward the motivation to study Uranus and the moons?

-What discoveries from the Voyager missions have led us to these key questions?

-What progress can be made in the next decade to answer these questions?

-What types of missions/instruments are necessary to obtain the answers to these questions?

What are the key scientific questions that will be driving forward the motivation to study Uranus and the moons?

Geology:

-What is the extent of differentiation (if any) on the moons?

-What is the role of water ice on the surface and subsurface processes, especially if these moons were ever or are currently ocean worlds? If they were once ocean worlds and are no longer, what was the timeline of habitability?

-What are the concentrations of various ices (H_2O, CO_2, CH_4, N_2, etc.) across the Uranian moon system?

-Is there an interaction of icy debris with the moons?

-What is the extent of tectonics regarding surficial and interior processes (i.e., tidal heating)?

-What degree has the surface been affected by mass wasting events?

Chemistry:

-What is the chemistry of the moons compared to the ring systems?

-What are the impacts of solar irradiation/tholin production on the moon surfaces?

-What are the chemical processes involved with crater impact events (i.e. relaxation, localized heating)?

-What is the extent of carbon dioxide versus carbon monoxide concentrations regarding volatile ices?

Physics:

-What is the bulk density of these moons?

-What is the extent of irradiation at the surface of these moons?

-How can the magnetic field influence the material distribution on these moons? Is there an energetic particle field to influence darkening or surface weathering of the surface? (see Kollmann et al. 2020)

-What can the geology and chemistry tell us about the internal structure?

What discoveries from the Voyager missions have led us to these key questions?

Voyager-2's fly-by of the Uranian system has given us a glance at the Ice Giant satellite system and dynamics. ***This gives us the potential to study the moons around such a bizarre planet, especially since Uranus spins on its equator, that has had no official dedicated mission.*** The Voyager-2 fly-by, although brief at Uranus, still gave us questions to ponder for an eventual mission, which we describe below. However, it should be noted that the ***resolution (~2 km/pixel) of these major moons mostly at the southern hemisphere (the only side of the moons lit at the time of fly-by) is relatively poor, giving us more reason to return and image the satellite surfaces more in detail.***

The 5 major moons of Uranus bulk densities measured by the Voyager-2 flyby suggested no clear compositional differences among them, however the debate lingers as to the nature of carbon present and whether it is dominantly organic or methane-graphite mixtures (Johnson et al., 1987; Simonelli et al., 1989; Croft and Soderblom, 1991; Rothery, 1999). Despite apparent homogeneity in composition (Cartwright et al. 2018), the satellites of Uranus display a striking range in geologic formations as observed by the Voyager-2 flyby. ***Several of these satellites have been identified in the Roadmap to Ocean Worlds goals document (Hendrix et al., 2018) as being candidates for ocean worlds in their pasts. Further exploration of the ocean worlds in the solar system is a high priority science objective and by visiting these satellites with an orbital mission, we would be able to better characterize their potential for having had an ocean.*** It is important to note that we have not observed the full surfaces of these satellites and have very limited data on them, so a definite answer of *"Does this moon have an ocean today or did it in the past?"* is not something that can currently be answered.

Miranda has probably one of the most complex surfaces of the main 5 satellites of Uranus and is the innermost satellite of the major 5. Miranda has the most densely cratered surface (Plescia, 1988), but also has some of the weirdest geologic structures across its surface. These relatively younger terrain units have not been observed elsewhere in the entire solar system. The interiors of this unit are marked by belts of differing albedo and outlined by parallel ridges- this unit is called "coronae" (Smith et al. 1986). Miranda has three specific coronae regions, each having their own unique geologic characteristic. Elsinore Corona has chaotic fault blocks. Inverness Corona has a chevron-shaped interior and an outer ridged belt, then cross-cut by younger faulting, resulting in a fault scarp, Verona Rupes, the steepest cliff in the entire solar system (Smith et al. 1986; Croft 1988). Arden Corona is similar to Elsinore in structure but has outward-facing fault scarps and has a much darker albedo outline against the cratered terrain. Current observations suggest interesting combinations of re-accretion-differentiation, localized cryovolcanism/diapirism, convection and thermal expansion (Janes and Melosh, 1988; Plescia, 1988; Jankowski and Squyres, 1988; Schenk, 1991; Pappalardo et al., 1997; Hammond and Barr, 2014). A recent study of the heat flux of Miranda by Beddingfield et al. (2015) suggest that the heat flux was quite high in the past in the Arden Corona region, consistent with a previous heating event that was as significant as Europa's current tidal heating, and supporting tidal heating from orbital activity in Miranda's past. Tidal heating has also been predicted to play a role in the surface evolution of Miranda (Pappalardo et al., 1997; Hammond and Barr, 2014; Cuk et al. 2020).

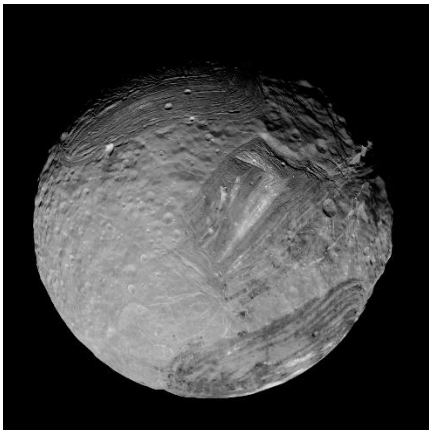

Figure 1: *Miranda imaged by Voyager 2 Inverness Corona is in center. (credit: NASA/JPL/Ted Stryk).*

Ariel has presently three distinct terrain units: cratered terrain, ridged terrain, and plains. Ariel has the lowest crater density compared to the other main Uranian satellites. Areas of the cratered units are surrounded and separated by ridged terrain, which are thought to be analogous to terrestrial sea floor spreading mechanisms (Kargel, 1988). The plains unit, which fills the graben troughs, is relatively smooth and evidence of fluid cryovolcanic flooding (Stevenson and Lunine, 1986; Jankowski and Squyres, 1988; Schenk, 1991). These linear tectonic features on Ariel could represent two different scenarios (still under debate): 1) tidal de-spinning when its rotation became synchronous or 2) collapse of a pre-existing tidal bulge if/when the orbits of Ariel and Umbriel were resonant (Rothery, 1999). Resurfacing of Ariel's surface could have also been driven by tidal dissipation within Ariel due to a resonance with Umbriel (Peale, 1988) and that flexural rift flank uplift is identified on Ariel through heat fluxes (Peterson et al. 2015).

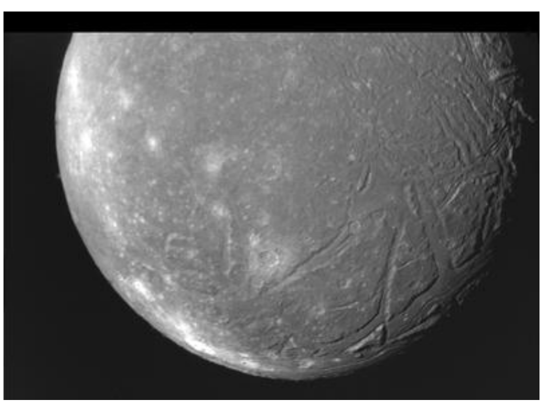

Figure 2: *Ariel as imaged by Voyager 2. Note the prominent graben terrains to the right of the hemisphere. (RING OBS ID: U_IMG_VG2_ISS_2684338_N)*

Umbriel has an albedo less than 0.2 and has similar crater frequencies as Oberon. However, unlike Oberon, there are no traces of bright ejecta rays or blankets (Rothery, 1999). It has been suggested that the relatively brighter flat floor of the 150 km diameter crater Wunda could be from cryovolcanic processes (Helfenstein and Veverka, 1988). Umbriel's dark appearance matches well with methane age-irradiation darkening, but the mystery of impact excavation not revealing any brighter material has led to questions about global resurfacing by dark cryovolcanic lavas early in Umbriel's history or the overabundance of methane tholin dust on the surface (Smith et al., 1986).

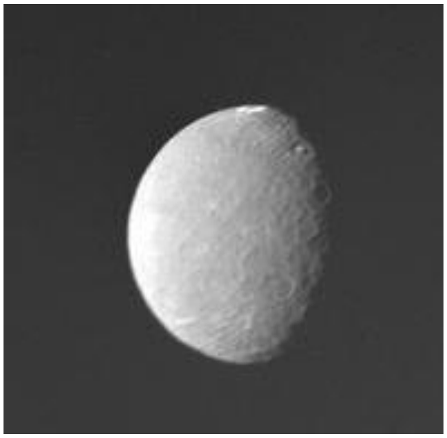

Figure 3: *Umbriel as imaged by Voyager 2. (RING OBS ID: U_IMG_VG2_ISS_2684006_N)*

Titania, although similar in size and mass to Oberon, appears like a twin to Ariel. Impact craters tend to have more viscous relaxation, suggesting resurfacing units by localized heating, not cryovolcanic (Rothery, 1999). The surface does have extensive fault scarps 2-5 km high and as long as 1500 km. Unlike Ariel, the relationship between these grabens and smooth plains remain unclear and are relatively younger as they cut through most craters. Unfortunately, Titania had the least amount of surface area imaged by the Voyager-2 fly-by, so comparisons and observations remain brief and uncertain.

Figure 4: *Titania from Voyager 2 fly-by. (RING OBS ID: U_IMG_VG2_ISS_2684315_N)*

Oberon is a heavily cratered satellite with a dark geometric albedo of 0.25. Some impact craters, however, do show bright ejecta rays and blankets, indicating a dust-rich surface overlying an icy substrate, similar to Callisto, (Smith et al., 1986; Strom, 1987; Rothery, 1999) or methane ice irradiation in the upper-millimeter surface to form tholins (Rothery, 1999). Enhanced imaging has also found hints of fault-like features, which is hypothesized to be from either impacts or localized tectonism (Croft and Soderblom, 1991).

Figure 5: *Oberon as imaged by Voyager 2. (RING OBS ID: U_IMG_VG2_ISS_2683625_N)*

Puck, the 162-km diameter moon, was discovered by Voyager 2 (Smith et al., 1986). To date, there is only one image captured of Puck (Figure 6). Although the imaging resolution for such a small moon was too poor to make any meaningful geologic interpretations, it does appear that Puck has a heavily cratered surface and dark parallel lanes, very similar to the grooves on Phobos. The extent of the low albedo nature of Puck remains unknown as either irradiation of methane, sweep-ups of co-orbiting dark particles, or carbonaceous content (Croft and Soderblom, 1991). However, the ***discovery of such a small moon made by a brief fly-by does give rise to the potential of more satellite discoveries during an orbital mission.***

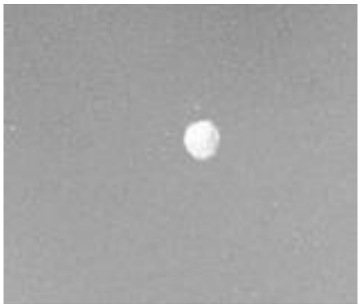

Figure 6: *The one image of Puck as imaged by Voyager 2. (RING OBS ID: U_IMG_VG2_ISS_2683716_N)*

What progress can be made in the next decade to answer these questions?

Mapping the composition and geologic state of the Uranian moons can be accomplished in the coming decade by a multi-orbit approach to observing ***1) the extent of ring interactions for material in-falling, if any; 2) compositional extent of ices and chemical boundaries, especially the amount of water ice; 3) solar irradiation interactions, especially for sublimation of ices; 4) observing and characterizing the geologic variety of icy moons in comparison with Saturnian moons or Pluto's Kuiper Belt origins; 5) finding evidence for oceans (or past oceans); 6) moon interactions with magnetic field dynamics; 7) development of orbital instrumentation for the identification of such chemical and geologic characteristics.***

To supplement these observations, advances in modeling capabilities can further assist in ice phases and interactions of such ices with ring in-falling material and solar irradiation. Magnetic field studies, both modeling and fly-by mission observations, can also complement Uranian moon research. Laboratory work for low temperature-low pressure studies have also improved to better understand the rheology of ices, which would be especially beneficial for understanding the geology of Ariel and Miranda. Within the next decade, investigations designed to identify geomorphologic regions and identify ice concentrations should be undertaken, **as these will drive our understanding of icy giant moon formation and the extent of compositions across our entire solar system.** Observing geomorphic regions will help to improve model predictions regarding icy moon surfaces, interior-surface interactions, and possibly seasonal (or tidal) interactions.

Many of these questions are not exclusive to the surface process community alone and answering them will require an interdisciplinary and collaborative approach. For example, interpreting the discovery of Verona Rupes on Miranda, the highest cliff in the solar system, is a problem of tectonics, rheology, and interior geophysics. By treating the Uranian moon system as an interconnected network can we best address these outstanding questions.

What types of missions/instruments are necessary to obtain the answers to these questions?

To maintain a global mapping of the Uranian moons, it is necessary to obtain these data by orbital encounters with capabilities at least comparable to the previous Voyager missions and should include the means to observe in the H_2O, CO_2, CH_4 absorption bands with moderate-to-high resolution. Multi-camera systems would be of benefit for IR/VIS/UV imaging for a large swath of geomorphic interpretations. Simpler, smaller payloads, even fly-bys containing portions of the instrumentation described above, should fly at every available opportunity.

The overarching goal of a future Icy Giants moon survey should be to identify a variety of geologic and rheologic formations for present temporal distribution of icy compositions and irradiated components/processes. Compositional observations should include a baseline set of ice compounds to isolate key condensation, sublimation, and geomorphic processes that control the current state of the Icy Giant moon surfaces, which will then be compared to previous Voyager images for a broader comparison. An orbit should be chosen to allow an optimum combination of global coverage and spatial resolution during the course of the mission. When planning the observations of the satellites, priority should be given to observing the northern hemispheres of the satellites if orbital geometry allows for it. If the orbital constraints are such that we must choose between hemispheres, the northern is ideal so that we can complete the view of these satellites.

The capabilities of the visual wavelength camera should be such that an image resolution across the satellite is at least 500 m/px with the ideal being closer to 200 m/px. Depending on cost and mass restrictions, a narrow angle camera (NAC) and a wide-angle camera (WAC) would be desired. Both cameras would ideally be capable of stereo imaging for the creation of digital elevation models (DEMs). Additional instrumental priorities would include technology for the purpose of induction measurements for the search and characterization of potential oceans and magnetic field studies (see white papers by Cartwright et al. 2020; Cohen et al. 2020; Leonard et al. 2020).

The Next Step in Uranus and Satellite Exploration: Recommendations to NASA

As missions to the Saturnian system (Cassini) and beyond (New Horizons at Pluto) give us insight to complex geologies, the Uranus system still have unknown origins and icy giant properties, along with complex satellite morphologies, especially those that can further our understanding of cryovolcanism.

Because none of the puzzling problems from the Voyager 2 fly-by datasets are likely to be resolved by near-Earth orbit telescopes, the case for returning to these moons as an orbiter is strong. The overarching goal of a future Uranus moon survey should be exploring the moons' timelines of habitability by identifying a variety of geologic and rheologic formations for present temporal distribution of icy compositions and irradiated components/processes. As we have described in this report, the numerous, open scientific issues surrounding the Uranus system as a whole and specifics of the main Uranian moons, and the unknown relationship of the Uranian ring system strongly motivate calls for a Uranus exploration orbiter. ***Accordingly, we recommend that in advance of the 2023 Decadal Survey, NASA fund a Uranus orbiter for icy giant and satellite interdisciplinary studies, specifically a Flagship mission to achieve the science results.***

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