The Science Case for Spacecraft Exploration of the Uranian Satellites: Candidate Ocean Worlds in an Ice Giant System

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Abstract

The 27 satellites of Uranus are enigmatic, with dark surfaces coated by material that could be rich in organics. Voyager 2 imaged the southern hemispheres of Uranus’s five largest “classical” moons—Miranda, Ariel, Umbriel, Titania, and Oberon, as well as the largest ring moon, Puck—but their northern hemispheres were largely unobservable at the time of the flyby and were not imaged. Additionally, no spatially resolved data sets exist for the other 21 known moons, and their surface properties are essentially unknown. Because Voyager 2 was not equipped with a near-infrared mapping spectrometer, our knowledge of the Uranian moons’ surface compositions, and the processes that modify them, is limited to disk-integrated data sets collected by ground- and space-based telescopes. Nevertheless, images collected by the Imaging Science System on Voyager 2 and reflectance spectra collected by telescope facilities indicate that the five classical moons are candidate ocean worlds that might currently have, or had, liquid subsurface layers beneath their icy surfaces. To determine whether these moons are ocean worlds, and to investigate Uranus’s ring moons and irregular satellites, close-up observations and measurements made by instruments on board a Uranus orbiter are needed.

Unified Astronomy Thesaurus concepts: Uranian satellites (1750); Planetary surfaces (2113); Planetary structure (1256); Surface composition (2115)

1. Introduction and Rationale for a Spacecraft Mission to Uranus

The surfaces of Uranus’s large and tidally locked “classical” moons—Miranda, Ariel, Umbriel, Titania, and Oberon—exhibit widespread photogeologic evidence for endogenic activity. The ubiquitous evidence hinting at geologic communication between the interiors and surfaces of these moons, in particular Miranda and Ariel, makes them candidate ocean worlds that may have, or once had, subsurface liquid H$_2$O layers beneath their icy exteriors (Hendrix et al. 2019; Beddingfield & Cartwright 2020b; Schenk & Moore 2020). In 1986, the Voyager 2 spacecraft flew by the Uranian system and collected tantalizing snapshots of these classical moons, measured Uranus’s offset and tilted magnetic field, and discovered ten new ring moons orbiting within Uranus’s ring system (e.g., Smith et al. 1986). Since this brief flyby, exploration of Uranus and its satellites has remained in the purview of ground- and space-based telescopes. At near-infrared (NIR) wavelengths, these telescope observations have revealed that the surfaces of the five classical moons are dominated by H$_2$O ice mixed with dark material that could be rich in organics and silicate minerals (e.g., Cruikshank et al. 1977; Cruikshank 1980; Cruikshank & Brown 1981; Soifer et al. 1981; Brown & Cruikshank 1983; Brown & Clark 1984). NIR observations have also detected carbon dioxide (CO$_2$) ice on the classical moons (Grundy et al. 2003, 2006; Cartwright et al. 2015), and nitrogen-bearing constituents like ammonia (NH$_3$) and ammonium (NH$_4^+$) could be present in surface deposits as well (Bauer et al. 2002; Cartwright et al. 2018; Cook et al. 2018; Cartwright et al. 2020c; DeColibus et al. 2020). The surfaces of the classical moons could therefore be rich in C, H, O, and N-bearing species, representing some of the key chemical requirements for life as we know it.

Although data collected by Voyager 2 and ground- and space-based telescope facilities have led to some fascinating discoveries, our understanding of Uranus’s classical moons is severely limited by the absence of data collected during close-up observations made by a Uranus orbiter. Similarly, Uranus’s small ring moons and irregular satellites remain unexplored, and their surface geologies and compositions are almost entirely unknown. New measurements made by modern instruments on board an orbiting spacecraft are critical to investigate the surfaces and interiors of the classical moons and determine whether they are ocean worlds with present day subsurface liquid H$_2$O layers. As described by multiple recent studies (e.g., Fletcher et al. 2020; Cohen et al. 2020;...
Beddingfield et al. 2020a; Leonard et al. 2021), a mission to Uranus would allow us to study interactions between Uranus’s magnetosphere and its rings and moons, improve our understanding of how geologic processes operate in cold and distant ice giant systems, and enable a more complete investigation of organics in the outer solar system. An orbiter would provide us with an unparalleled opportunity to study the origin and evolution of Uranus’s ring-moon system. Furthermore, an orbiter could provide new insight into the origins of Uranus’s irregular satellites, and whether they were sourced from the primordial Kuiper Belt or were captured from nearby heliocentric orbits (e.g., Jewitt & Haghighipour 2007).

Multiple close proximity flybys made by a Uranus orbiter would therefore address many outstanding science questions for the Uranian system (Table 1). A spacecraft mission to Uranus can be carried out with existing chemical propulsion technology by making use of a Jupiter gravity assist in the 2030–2034 time frame, leading to a flight time of only ~11 years, arriving in the early to mid 2040s (Hofstadter et al. 2019). Crucially, this arrival time frame in northern summer would allow us to observe the Uranian moons’ northern hemispheres, which were shrouded by winter darkness at the time of the Voyager 2 flyby and have never been imaged. An orbiter could then continually collect data and search for evidence of ongoing geologic activity, as well as search for evidence of volatile migration of CO2 and other species in response to seasonal changes as the Uranian system transitions into southern spring in 2050.

An orbiter equipped with several key instruments could determine whether the classical Uranian moons are ocean worlds. The highest priority instrument for identifying subsurface oceans is a magnetometer, which could detect and characterize induced magnetic fields emanating from briny liquid layers in the interiors of these moons. Visible (VIS;
0.4–0.7 μm) and mid-infrared (MIR; 5–250 μm) cameras would be vital for identifying recent geologic activity, hot spots, and possible communication between the interiors and surfaces of these moons. A VIS and NIR mapping spectrometer (0.4–5 μm) would be critical for characterizing the spectral signature and distribution of volatile species that could result from recent outgassing of material, as well as endogenic salts that may have been exposed or emplaced by geologic activity. Ideally, an orbiter would get close enough to achieve spatial resolutions of ≤100 m/pixel for large regions of each classical moon’s surface. If only a limited number of close flybys are possible, Ariel and Miranda likely represent the highest priority targets because they display the best evidence for geologic activity in the recent past.

2. Background and Science Questions

Uranus is orbited by 27 known moons (Figure 1), including its five largest moons, Miranda, Ariel, Umbriel, Titania, and Oberon, which have semimajor axes ranging between 5.1 and 23 Uranian radii (R_U) (Table 2, Figure 2). Interior to the classical moons, 13 small ring moons orbit within Uranus ring system, with semimajor axes ranging between 2 and 3.8 R_U (Table 3 and Figure 3). Far beyond the orbital zone of the classical moons, nine irregular satellites orbit Uranus on highly inclined and eccentric orbits, with semimajor axes ranging between 169 and 806 R_U (Table 3, Figure 1). In the following subsections, we briefly describe the state of knowledge and some of the outstanding science questions for these 27 moons.

2.1. Geology of the Uranian Satellites

Classical moons. The Imaging Science System (ISS) on board Voyager 2 collected fascinating images of the five classical moons (Figure 2). Because the Voyager 2 flyby occurred during southern summer, when the subsolar point was ~82°S, the northern hemispheres of these moons were mostly hidden from view and were not imaged (Smith et al. 1986). The incomplete spatial coverage, and generally low spatial resolution of the available images, limits our understanding of different terrains and geologic features, in particular for the more distant moons Umbriel, Titania, and Oberon.

The innermost moon Miranda displays abundant evidence for endogenic geologic activity, including three large polygonal shaped regions called coronae, which were likely formed by tectonic and/or cryovolcanic processes (Figures 1(a)–(c)) (e.g., Smith et al. 1986; Croft & Soderblom 1991; Greenberg et al. 1991; Schenk 1991; Kargel 1995; Pappalardo et al. 1997; Hammond & Barr 2014; Beddingfield et al. 2015; Beddingfield & Cartwright 2020b). The origin and timescale of activity on Miranda is not well understood, and it is unknown if this activity is associated with a subsurface ocean, either now or in the past. Searching for and characterizing induced magnetic fields, plumes, and surface heat anomalies, as well as analyzing geologic surface features interpreted to be cryovolcanic in origin, is paramount to determine if Miranda is an ocean world.

Tidal heating of Miranda from past orbital resonances (Tittermore & Wisdom 1990; Ćuk et al. 2020) may have been an important driver of resurfacing in the recent past. Additionally, Miranda displays ancient cratered terrain pockmarked with “subdued” craters, which have smooth floors and subtle rims that have been mantled by an unknown source of material (e.g., Smith et al. 1986; Beddingfield & Cartwright 2020b; Cartwright et al. 2020a). These subdued craters are reminiscent of lunar highlands and could be blanketed by impact-generated regolith (Croft 1987), but they are also reminiscent of the plume-mantled craters on the ocean world Enceladus (e.g., Kirchoff & Schenk 2009), hinting that a similar plume-driven mantling process may have occurred on Miranda.
Titania 4.363 788.9 ± Ariel 1.909 578.9 ± Oberon 5.835 761.4 ±

Moons Possibly contributing to a 0.28 c Possible contributors to a 2.2 a

Semimajor axis and mean radius values from the Jet Propulsion Laboratory Horizons On-Line Ephemeris System and references therein

Umbriel 2.660 584.7 ± Miranda 1.299 235.8 ±

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Table 2
Overview of the Five Classical Moons’ Geologies and Surface Compositions

| Classical Moons | Semimajor Axis (10^3 km) | Mean Radius (km) | Geologic Features and Regions of Interest | Highest Res. Images (km/pix) | Known Surface Constituents | Possible Surface Constituents |
|-----------------|--------------------------|------------------|------------------------------------------|-----------------------------|---------------------------|-------------------------------|
| Miranda         | 1.299                    | 235.8 ± 0.7      | Polygonal shaped coronae, large scale rift system, populations of subdued and fresh craters. | ~0.25 | H2O ice | |
| Ariel           | 1.909                    | 578.9 ± 0.6      | Large chasmata, flow bands, smooth plains, cratered plains, large lobate shaped features. | ~1 | H2O ice, CO2 ice | |
| Umbriel         | 2.660                    | 584.7 ± 2.8      | Heavily cratered surface with some bright-floored craters, polygonal basins. | ~5 | H2O ice, CO2 ice | |
| Titania         | 4.363                    | 788.9 ± 1.8      | Large chasmata, smooth plains, linear features, cratered terrain. | ~3 | H2O ice, CO2 ice | |
| Oberon          | 5.835                    | 761.4 ± 2.6      | Large chasmata, smooth plains, cratered terrain, ~11 km tall mountain. | ~6 | H2O ice, CO2 ice | |

Notes.

a Semimajor axis and mean radius values from the Jet Propulsion Laboratory Horizons On-Line Ephemeris System and references therein (https://ssd.jpl.nasa.gov/?sat_elem).

b Possibly contributing to the ubiquitous dark material and spectrally red material observed by Voyager 2.

c Possible contributors to a 2.2 μm absorption band detected in some ground-based spectra.

d Possibly contributing to a 0.28 μm absorption band detected in Hubble Space Telescope spectra.

Miranda’s neighbor, Ariel, also displays widespread evidence for resurfacing that could have been spurred by ocean world activity. Sections of Ariel’s imaged surface are dominated by large canyons called “chasmata” (Figure 2(d) and (e)) that were likely formed by tectonic processes (e.g., Smith et al. 1986). The smooth floors of some of these chasmata are bowed up with two parallel medial ridges that are separated by a topographic low, reminiscent of fissure style volcanism on Earth (Schenk 1991). Large fracture systems cut across other parts of Ariel’s surface, and clusters of curvilinear features referred to as “flow bands” could be cryovolcanic features (e.g., Plescia 1987; Croft & Soderblom 1991; Schenk 1991; Beddingfield & Cartwright 2021). Furthermore, Ariel’s surface geology is consistent with high heat fluxes in its interior, which could drive extrusion of material (Peterson et al. 2015). Some regions of Ariel’s surface are relatively young (~1–2 Ga) (Zahnle et al. 2003), but the fairly low resolution of the ISS images (~1 km/pixel) makes investigation of the processes that formed these younger terrains more difficult.

Although Umbriel has the darkest and oldest surface of the five classical moons (e.g., Smith et al. 1986; Zahnle et al. 2003), it has some large craters with bright floors, like Wunda crater, which has a bright annulus of material surrounding its central peak (e.g., Smith et al. 1986) (Figure 2(f)). Wunda crater is located near the center of Umbriel’s trailing hemisphere, where the abundance of CO2 ice is highest (Grundy et al. 2006; Cartwright et al. 2015). Consequently, the bright annulus of material mantling this crater may represent a large deposit of CO2 ice, possibly originating from post-impact cryovolcanic infilling (Helfenstein et al. 1989), or from the accumulation of radiolytically produced CO2 molecules that get cold trapped in Wunda (Sori et al. 2017). Furthermore, large polygonal basins are present on Umbriel, hinting at global-scale resurfacing in the past (Helfenstein et al. 1989).

However, the poor resolution of the available data (~5 km/pixel) severely limits analyses of these features and our ability to determine whether they resulted from ocean world activity.

The surfaces of the outer moons Titania and Oberon exhibit evidence for tectonism, with large chasmata and linear surface features, as well as smooth plains that may have formed from cryovolcanic processes (e.g., Smith et al. 1986; Croft & Soderblom 1991) (Figures 2(g), (h)). Additionally, Oberon has an ~11 km tall “limb mountain” that could be the central peak for a relaxed complex crater (Smith et al. 1986; McKinnon et al. 1991; Croft & Soderblom 1991; Moore et al. 2004). Similar to Umbriel, the poor resolution of the ISS images for Titania and Oberon (~3 and 6 km/pixel, respectively) limits our ability to investigate possible ocean world activity on these two moons.

Relatively less is known about the interiors of the classical moons, and measuring magnetic induction with a magnetometer is critical for determining whether they possess subsurface oceans (Cochrane et al. 2021; Weiss et al. 2021). Other measurements are needed to investigate the internal structures and bulk compositions of these moons, which is critical for improving our understanding of their formation and evolution. The densities of Ariel, Umbriel, Titania, and Oberon are 1.66 ± 0.15 g cm−3, 1.39 ± 0.16 g cm−3, 1.71 ± 0.05 g cm−3, and 1.63 ± 0.05 g cm−3, respectively, indicating that these moons are made of at least 50% silicate material by mass, whereas Miranda’s density is only 1.2 ± 0.14 g cm−3, indicating a larger H2O ice fraction (Jacobson et al. 1992). Measuring the non-spherical gravity field would shed light on the differentiation state and the nature of the endogenic activity exhibited by these moons. Measuring libration amplitudes (Steinbrügge et al. 2019) could also be used to investigate whether these moons have subsurface liquid layers. Furthermore, searching for thermal anomalies across the surfaces of these moons, using a MIR camera equipped with a suite of multiple
narrow and wide filters spanning 5–250 μm, would improve our understanding of their heat budgets and the long-term survivability of liquid water in their interiors. Thus, characterizing the surfaces and interiors of the classical moons to determine whether they are, or were, ocean worlds requires high resolution data sets, which can only be collected by a Uranus orbiter making multiple close flybys of each moon.

Ring moons and irregular satellites. Uranus possesses the most densely packed group of moons in the solar system, with nine ring moons (Bianca to Perdita) orbiting between 59,000 and 77,000 km from the planet’s center (e.g., Showalter 2020). Voyager 2 initially discovered 10 ring moons: Cordelia, Ophelia, Bianca, Cressida, Desdemona, Juliet, Portia, Rosalind, Belinda, and Puck (e.g., Smith et al. 1986). Perdita was discovered later through reanalysis of Voyager 2 images (Karkoschka 2001). Cupid and Mab were discovered using the Hubble Space Telescope (Showalter & Lissauer 2006; De Pater et al. 2006). Mab orbits within the outermost and dusty μ-ring (blue colored region in Figure 3), which might be sustained by material ejected from the surface of this tiny moon (De Pater et al. 2006; Showalter & Lissauer 2006; Sfär & Winter 2012). Furthermore, μ-ring material could spiral inward and coat the leading hemisphere of Puck (French et al. 2017), and perhaps it also spirals outward and mantles Miranda, possibly contributing to its substantial regolith cover (Cartwright et al. 2020a, 2020b). Little is known about the surface geologies of the ring moons as only Puck was spatially resolved by Voyager 2/ISS (∼4.5 km/pixel) (Figure 3). These ISS images revealed a heavily cratered surface, suggesting that Puck may have been collisionally disrupted and then reaccreted into a rubble pile (Smith et al. 1986; Croft & Soderblom 1991). Voyager 2 did not detect any of Uranus’s nine known irregular satellites, which were discovered by ground-based observers (Gladman et al. 1998, 2000; Kavelaars et al. 2004; Sheppard et al. 2005). Thus, the geologies of Uranus ring moons and irregular satellites remain unexplored, and new observations made by an orbiter would dramatically expand our knowledge of these objects.

2.2. Surface Compositions of the Uranian Satellites

Classical moons. Ground-based, NIR telescope observations (∼1–2.5 μm) determined that the classical moons have surface compositions dominated by a mixture of H₂O ice and a dark,
spectrally neutral material of unknown origin (e.g., Cruikshank et al. 1977; Brown & Cruikshank 1983; Brown & Clark 1984). Laboratory experiments indicate that the dark material has a spectral signature similar to amorphous carbon and/or silicates (Clark & Lucey 1984). More recent NIR telescope observations have determined that the Uranian moons display leading/trailing and planetocentric dust impacts (primarily with their leading hemispheres).

Table 3  
Ring Moons and Irregular Satellites of Uranus

| Satellites | Semimajor Axis (10^5 km) | Mean Radius (km) | Possible Surface Constituents |
|------------|--------------------------|------------------|------------------------------|
| **Ring Moons** |                     |                  |                              |
| Cordelia   | 0.498 0                 | 20.1 ± 3         |                              |
| Ophelia    | 0.538 0                 | 21.4 ± 4         |                              |
| Bianca     | 0.592 0                 | 27 ± 2           |                              |
| Cressida   | 0.618 0                 | 41 ± 2           |                              |
| Desdemona  | 0.627 0                 | 35 ± 4           |                              |
| Juliet     | 0.644 0                 | 53 ± 4           | H₂O ice,                     |
| Portia     | 0.661 0                 | 70 ± 4           | borganics,                   |
| Rosalind   | 0.699 0                 | 36 ± 6           | bhydrated silicates          |
| Cupid      | 0.743 9                 | 9 ± 1            |                              |
| Belinda    | 0.753 0                 | 45 ± 8           |                              |
| Perdita    | 0.764 2                 | 13 ± 1           |                              |
| Puck       | 0.860 0                 | 81 ± 2           |                              |
| Mab        | 0.977 4                 | 6–12             |                              |

| **Irregular Satellites** | | | |
| Francisco | 42.83 | 11 | |
| Caliban   | 72.31 | 36 | |
| Stephano  | 80.07 | 16 | |
| Trinculo  | 85.05 | 9  | H₂O ice, |
| Sycorax   | 121.8 | 75 | borganics, |
| Margaret  | 141.5 | 10 | bhydrated silicates |
| Prospero  | 162.8 | 25 | |
| Setebos   | 174.2 | 24 | |
| Ferdinand | 204.3 | 10 | |

Notes.

* Semimajor axis and mean radius values from the Jet Propulsion Laboratory Horizons On-Line Ephemeris System and references therein (https://ssd.jpl.nasa.gov/?sat_elem). Radius range for Mab reported in Showalter & Lissauer (2006).

b Possibly contributing to the ubiquitous dark material, as well as the spectrally red material detected on the irregular satellites.

spectrally neutral material of unknown origin (e.g., Cruikshank et al. 1977; Brown & Cruikshank 1983; Brown & Clark 1984). Laboratory experiments indicate that the dark material has a spectral signature similar to amorphous carbon and/or silicates (Clark & Lucey 1984). More recent NIR telescope observations have determined that the Uranian moons display leading/trailing and planetocentric asymmetries in their compositions (Figure 4). For example, “pure” CO₂ ice (i.e., segregated from other constituents in concentrated deposits) has been detected on the trailing hemispheres of Ariel, Umbriel, Titania, and Oberon, with larger abundances on the inner moons, Ariel and Umbriel, compared with the outer moons, Titania and Oberon (Figure 5) (Grundy et al. 2003, 2006; Cartwright et al. 2015). CO₂ ice on these moons could be generated via irradiation of native H₂O ice and C-rich material by magnetospheric charged particles (Grundy et al. 2006; Cartwright et al. 2015). Supporting this hypothesis, trapped OH has possibly been detected on these moons (Roush et al. 1997), which is a strong catalyst for radiolytic generation of CO₂ molecules from substrates composed of H₂O ice and carbon-rich species (e.g., Mennella et al. 2004; Raut et al. 2012).

H₂O ice bands are weaker on the trailing hemispheres of these moons (Figure 5), perhaps in part due to large deposits of CO₂ ice masking the NIR spectral signature (∼1–2.5 μm) of H₂O ice (Cartwright et al. 2015, 2020b). Another possibility is...
that heliocentric dust impacts promote regolith overturn and expose fresher H₂O ice, primarily on these moons’ leading hemispheres (Cartwright et al. 2018). Spectrally red material (∼0.4–1.25 μm) has also been detected, primarily on the leading hemispheres of the outer moons, Titania and Oberon (Figure 5) (Buratti & Mosher 1991; Bell & McCord 1991; Helfenstein et al. 1991; Cartwright et al. 2018). The distribution of red material could result from the accumulation of infalling planetocentric dust from retrograde irregular satellites (Buratti & Mosher 1991; Tamayo et al. 2013; Cartwright et al. 2018), which are spectrally redder than the classical moons (e.g., Grav et al. 2004; Maris et al. 2007).

Over longer wavelengths (∼3–6.5 μm), spectrophotometric data collected by the Infrared Array Camera (Fazio et al. 2004) on the Spitzer Space Telescope (Werner et al. 2004) indicate that the spectral signature of CO₂ ice is strangely absent from all of these moons (Cartwright et al. 2015, 2020b). One possible explanation is that the regoliths of the classical moons are mantled by a thin layer of small H₂O ice grains (≤2 μm diameters), which obscures the longer wavelength spectral signature of CO₂ ice retained beneath this topmost layer (Cartwright et al. 2015, 2018, 2020b). Supporting this possibility, visible wavelength polarimetry data suggest that these moons have porous regoliths, dominated by small grains (Afanasiev et al. 2014). Similarly, over longer mid-infrared wavelengths (20–50 μm), data collected by the Infrared Interferometer Spectrometer (IRIS) on Voyager 2 suggest that Miranda and Ariel have regoliths with unusual microstructures, possibly dominated by dark, isotropically scattering grains (Hanel et al. 1986). These different data sets all suggest that the regoliths of the Uranian moons are notably different from both H₂O ice-rich and dark material-rich Galilean and Saturnian moons and may be more comparable to H₂O ice-rich trans-Neptunian objects (Afanasiev et al. 2014; Cartwright et al. 2020b; Detre et al. 2020).

Although these results are intriguing, new spacecraft measurements are needed to better understand the processes modifying the surface compositions of the Uranian moons. For example, the distribution of CO₂ ice is only longitudinally constrained, limiting our ability to determine whether this volatile is generated by charged particle radiolysis, or whether it is a native constituent sourced from their interiors. Unlike the other classical moons, CO₂ ice and leading/trailing longitudinal asymmetries in composition are absent on Miranda (Bauer et al. 2002; Grundy et al. 2006; Grav et al. 2018; Cartwright et al. 2018, 2020b; DeColibus et al. 2020), adding to the mystery surrounding this moon. Because of the large obliquity of the Uranian system, and the associated seasonal effects, CO₂ ice exposed or generated at polar latitudes on these moons should sublimate, migrate in tenuous exospheres to their low latitudes, and condense in cold traps (Grundy et al. 2006; Sori et al. 2017; Cartwright et al. 2021). Spatially resolved spectra collected by an orbiter are needed to more completely understand the origin and nature of CO₂ ice. Additionally, the regolith properties of the classical moons could result from interactions with the surrounding space environment, which cannot be properly assessed without data collected by an orbiter.

Some ground-based spectra of the classical moons show a 2.2 μm absorption band (Figure 6) (e.g., Grundy et al. 2016; Cartwright et al. 2018, 2020c), which is similar to a 2.2 μm feature attributed to NH₃ and NH₄-bearings species on Pluto and its moons (e.g., Brown & Calvin 2000; Grundy et al. 2016; Cook et al. 2018; Dalle Ore et al. 2019; Cruikshank et al. 2019; Protopapa et al. 2020) and the Saturnian moon Enceladus (Emery et al. 2005; Verbiscer et al. 2006). NH₃ and NH₄ are highly efficient anti-freeze agents when mixed with liquid H₂O that could promote the retention of subsurface oceans if present within the interiors of these moons (e.g., Spohn & Schubert 2003; Hussmann et al. 2015; Nimmo & Pappalardo 2016). Because NH₃-rich planetesimals were likely incorporated into the proto-Uranian moons as they formed in the Uranian subnebula (e.g., Lewis 1972), large quantities of NH₃ could be present in their interiors. Furthermore, unlike H₂O ice and CO₂ ice, the 2.2 μm band does not display leading/trailing longitudinal asymmetries in its distribution (Figure 6), which suggests that NH₃-bearing and NH₄-bearing species are native to these moons and are exposed by impact events, tectonism, and mass wasting, and/or emplaced in cryovolcanic deposits (Cartwright et al. 2020c). Other species like carbonates (–CO₃ group), including ammonium carbonate (NH₄)₂CO₃, could be
contributing to the 2.2 \( \mu \text{m} \) band as well (Cartwright et al. 2020c). Higher spatial resolution spectra are needed to measure the spectral signature and spatial distribution of the 2.2 \( \mu \text{m} \) band to determine whether these moons are rich in \( \text{NH}_3 \) and other species that may have been sourced from liquid layers in their interiors.

The composition and origin of the widespread dark material and the spectrally red material on the Uranian moons remains poorly understood. These materials could be rich in hydrated silicates and organic constituents delivered to and/or native to these moons. Prior spacecraft missions have assessed the nature of organics in the Jupiter, Saturn, and Pluto systems, as well as on comets (e.g., McCord et al. 1997; Irvine et al. 2003; Clark et al. 2005; Waite et al. 2009; Capaccioni et al. 2015; Grundy et al. 2016; Cruikshank et al. 2020). Measuring the spectral signature of organics (e.g., C-H stretching modes between 3.2 and 3.5 \( \mu \text{m} \)) in the Uranian system represents a key heliocentric link for improving our understanding of the nature and overall distribution of organic matter in the solar system, as well as for investigating whether organics formed within the protoplanetary disk or were delivered as interstellar matter. Thus, new measurements made by an orbiter are critical for determining the spatial distribution and spectral signature of \( \text{CO}_2 \) ice and \( \text{NH}_3 \)-bearing species on the classical moons, and whether these constituents were exposed/emplaced on their surfaces by ocean world activity, as well as for investigating the origin and evolution of organic material in the Uranian System.

Ring moons and irregular satellites. Far less is known about the compositions of Uranus smaller ring moons and irregular satellites, which are too faint for spectroscopic observations using available telescopes (apparent magnitudes ranging between 19.8 and 25.8 at visible wavelengths). Photometric data sets indicate that the ring moons are dark (except possibly Mab, Showalter & Lissauer 2006), with neutral spectral slopes and slight reductions in albedo at 1.5 and 2.0 \( \mu \text{m} \), consistent with the presence of \( \text{H}_2\text{O} \) ice (e.g., Karkoschka 2001). More recent photometric measurements indicate that the ring moons may display latitudinal variations in albedo, possibly resulting from interactions with Uranus’s magnetosphere (Paradis et al. 2019). Other photometric studies determined that Uranus’s irregular satellites are dark and red (e.g., Grav et al. 2004; Maris et al. 2007), with possibly redder colors than the irregular satellites of the other giant planets (Graykowski & Jewitt 2018).

Figure 6. Left: Mercator map projection of Voyager 2/ISS images of Ariel (courtesy NASA/JPL/Caltech/USGS, reprocessed by Stryk & Stooke 2008). The cyan dots represent the mid-observation longitude and latitude for ground-based spectra that show 2.2 \( \mu \text{m} \) bands, and the black dots represent spectra that do not display 2.2 \( \mu \text{m} \) bands (modified from Cartwright et al. 2020c). These spectra are disk-integrated and average over an entire hemisphere of Ariel. Spectra for the dots labeled “1” and “2” are shown on the right. Right: example IRTF/SpecX spectra of Ariel that display 2.2 \( \mu \text{m} \) bands, offset vertically for clarity. Dotted–dashed lines highlight the wavelength range of the 2.2 \( \mu \text{m} \) band, and the dotted lines highlight the wavelength range of its band center.

Spectra of the largest Uranian irregular satellite Sycorax suggest that \( \text{H}_2\text{O} \) ice is present (Romon et al. 2001), but no spectra exist for the other, fainter irregular satellites. Therefore, the compositions of these objects are essentially unknown, and new observations made by an orbiter are needed.

3. Conclusions and Recommendations for Future Exploration

Data returned by Voyager 2 and ground- and space-based telescopes have revealed tantalizing glimpses of the Uranian moons’ geologic histories, compositions, and interactions with the surrounding space environment. However, Uranus’s 27 satellites remain poorly understood. Only six Uranian moons were spatially resolved by ISS, and the flyby nature of the Voyager 2 encounter, the lack of a VIS/NIR mapping spectrometer, and the low spatial resolution of collected data sets left many unanswered questions and limit our ability to determine whether the classical moons are, or were, ocean worlds. Future telescope facilities like the Extremely Large Telescopes (ELTs) and the proposed Large UV/Optical/IR Surveyor (LUVOIR) space telescope (e.g., Roberge et al. 2019) will be able to collect high quality images and spectra of the classical moons (Cartwright et al. 2019; Wong et al. 2020), providing new information about their surfaces (Figure 7). Although these telescope data sets will undoubtedly increase our knowledge of these moons, they will not be able to achieve sufficient spatial resolutions to identify linkages between geologic features and their surface compositions, nor probe their internal structures, or investigate moon-magnetosphere interactions (e.g., Kollmann et al. 2020). Furthermore, these telescope data sets will not be able to spatially resolve the ring moons and irregular satellites to assess their surface geologies and origins.

An orbiting spacecraft equipped with a magnetometer could search for induced magnetic fields emanating from briny oceans in the interiors of the classical moons. An orbiter could also search for plumes on the classical moons and other signs of recent endogenic geologic activity. An orbiter making multiple close flybys of Uranus’s rings would dramatically
improve our understanding of the ring moons and could investigate whether Mab is the source of the \( \mu \)-ring. An orbiter could spend time looking outward, making key observations of the distant irregular satellites, similar to Cassini’s observations of Saturn’s irregular satellites (Denk & Mottola 2019). A close pass of an irregular satellite inbound to Uranus, like Cassini’s inbound flyby of Phoebe (Porco et al. 2005), would represent an unparalleled opportunity to investigate the nature and origin of these likely captured objects. Thus, new data sets collected by an orbiter are essential for improving our understanding of the icy residents of the Uranian system and determining whether Uranus’s five classical moons are, or were, ocean worlds.

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