Potential Ocean Worlds
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The Roadmap for Ocean Worlds (ROW) provides an overarching goal for ocean worlds exploration: **Identify ocean worlds, characterize their oceans, evaluate their habitability, search for life, and ultimately understand any life we find**. The first part of the goal—to determine which bodies have oceans and understand how to determine whether other bodies host current oceans—drives the search for and exploration of potential ocean worlds. Based on the ROW goals document (Hendrix et al., 2018), we highlight the state of knowledge for potential ocean worlds and support their exploration in the next decade to confirm if they possess oceans.

Triton: Triton is believed to be a captured Kuiper Belt Object (KBO; Agnor and Hamilton, 2006). This origin scenario leads to two unique opportunities to describe and constrain the early histories of ocean worlds. First, the capture event likely resulted in substantial tidal heating early in Triton's history (Jankowski et al., 1989; Ross and Schubert, 1990), which presents the potentially unique opportunity to study a subsurface ocean on a body for which tidal heating was relatively significant during its early thermal history. This early heating would afford an opportunity to assess the relative importance of various heat sources to create and maintain a subsurface ocean (Gaeman et al., 2012). Second, as a KBO, Triton is likely similar in bulk composition and origin to Pluto and other KBOs, which allows comparisons among these bodies and extrapolation of information learned from Triton to other bodies that are less accessible.

A variety of data hint at the possibility of an internal ocean, or at least near-surface liquid water at Triton today. The surface of Triton is young and active, which is evident from several observed surficial features. These include the observations of the young crater-retention age of Triton which gives a surface age of <100 Myr (possibly <10 Myr) (Schenk and Zahnle, 2007), possible cryovolcanic flows (Croft et al., 1995) and tectonic features (Croft et al., 1995; Prockter et al., 2005). Triton's unique surface morphology (e.g., the "cantaloupe" terrain) and young surface may indicate ongoing diapiric activity today (Schenk and Jackson, 1993). The ice shell of Triton may be capable of internally-driven resurfacing, making it potentially unique among ocean worlds (Howell and Pappalardo, 2019).

Possibly the most intriguing evidence of activity on Triton are the active geysers that have been observed (Soderblom et al., 1990); while these have been attributed to solar-powered sublimation of N_2 ice (Kirk et al., 1990), the existence of water plumes from the tiny moon, Enceladus (Dougherty et al., 2006; see also Appendix D2 of this report) provides reason to question this conclusion (Hansen and Kirk, 2015). Endogenic plumes that sample a subsurface ocean would be very exciting astrobiological targets if indeed the geysers on Triton are endogenic rather than solar-driven. Their composition can be sampled not just directly near the geysers sources, but throughout the atmosphere: they reach up to 8 km altitude and the dark material in them is observed to be carried horizontally by the ambient winds.

Pluto & KBOs: The possibility of a current ocean on Pluto and other large KBOs is partly based on theoretical modeling that computes the heat flow from the original accretion, impacts, and most importantly, radionuclides in its interior (e.g., Robuchon and Nimmo, 2011). Models for Pluto show a liquid ocean for some cases. The abundance of radioisotopes is assumed from its rock fraction. KBOs can have a substantial rock fraction (e.g., 2/3rds by mass for Pluto, and likely larger for Eris), but the types and physical distribution of radioisotopes (and other materials) will affect energy production over time. Another potential source of energy is tidal heating in the case of KBOs with moons. The Pluto–Charon system is tidally evolved (e.g., Cheng et al., 2014), but other systems may still undergo tidal heating.

There are a number of geologic features on Pluto that suggest the existence (or past existence) of a subsurface ocean, or at least a partially fluid mantle (Stern et al., 2015; Moore et al., 2016). The orientation of the informally named Sputnik Planitia nitrogen ice sheet on the anti-Charon point of Pluto may indicate reorientation and tidal wander of the shell facilitated by a subsurface ocean (Nimmo et al., 2016). Pluto has almost no equatorial flattening, indicating it remained warm enough at least through its early history to not retain or "freeze in" an equatorial bulge (Nimmo et al., 2017). Extensional tectonic deformation on both Pluto and Charon implies at least partial freezing of a subsurface ocean (Beyer et al., 2017), and Charon's Vulcan Planitia was likely emplaced by the flooding of NH_3-rich cryolavas (Beyer et al., 2019) . Some of the young terrains on Pluto may have been resurfaced by icy volcanism (Moore et al., 2016; Singer et al., 2016), indicating at least somewhat mobile material was present and perhaps some melt at depth. In addition to water ice, Pluto has other volatile ices (N_2, CH_4, CO) that might melt in the deeper subsurface or under glaciers or large ice sheets nearer the surface (McKinnon et al., 2016), causing some of the dendritic-style patterns seen on Pluto (Moore et al., 2016; Howard et al., 2017). Liquid is not currently stable on Pluto's surface, but earlier epochs of higher atmospheric pressure are possible (Stern et al., 2017).

The Kuiper Belt is relatively unexplored, so both interior modeling and rudimentary astronomical observations can provide evidence for subsurface oceans. Besides measuring the density of an object (possible only for the case of a multi-body system), the measurement of size is key, as the geometric albedo of the surface can then be known. Thermal emission measurements are an indirect way of measuring the size of KBOs, and can be done for only the largest objects. Another, more direct technique is the use of stellar occultations, which can provide accurate measurements of the occulting body's diameter with several observation sites on Earth. Highly reflective surfaces, such as those found on Enceladus and Sputnik Planitia, and to a lesser extent on Europa and Triton, are indications of active geologic processes that may closely relate to subsurface oceans.

Mimas: Mimas is the closest of the mid-sized satellites to Saturn, and of these is the smallest with a mean radius of 198.2 km. Its density of ~1150 kg/m^3 corresponds to a rock volume fraction of about 8%, which means Mimas is most likely a heat starved body. Close to its primary, this moon could be subject to intensive tidal dissipation provided that its ice could become warm in the first place. Mimas' currently high eccentricity of ~2%, however, conflicts with the idea that Mimas is dissipative at present and in the recent past (Neveu and Rhoden, 2017). Mimas' large libration amplitude (Tajeddine et al., 2014) has been attributed to the decoupling of an ice shell from the deep interior via a liquid layer, or by the presence of a highly non-hydrostatic core. The latter explanation is more likely, especially as there are increasing observations and models in favor of a formation of Saturn's mid-sized moons from irregular, porous seeds in the rings (Charnoz et al., 2010; Ćuk et al., 2016). In this context, Mimas would be the youngest moon to have emerged from the rings. The heat budget of satellites formed this way is not well-modeled (we don't know when the satellite seeds formed in the rings), but their long-lived radioisotope makeup is likely to be significantly depressed with respect to a scenario where the satellites formed in Saturn's subnebula. It is unlikely that Mimas held an ocean in recent time or even at any time in the course of its history.

Tethys: Tethys is Saturn's 5th largest satellite with a mean radius of 533 km and a mean density of 973 kg/m^3 (Thomas et al., 2007), suggesting it is mostly ice. Depending on the assumed densities of rock and ice, the rock fraction ranges from 6% by mass (Thomas et al., 2007) to 12.1% by mass (Multhaup and Spohn, 2007). If porosity is taken into account, the rock fraction may be as high as 14% (Castillo-Rogez in prep.). Nimmo et al. (2011) found that Tethys' degree 2 shape is not consistent with hydrostatic equilibrium. Due to its small size and low rock fraction, it is unlikely that heating from accretion or radiogenic decay was significant. Tethys' eccentricity is indistinguishable from zero, so it is not currently experiencing any tidal heating. Thermal evolution models (excluding tidal heating) predict that if convection ever occurred, it ceased early in Solar System history (Multhaup and Spohn, 2007).

One of Tethys' most prominent features is the large Ithaca Chasma, a rift that is about 1000 km long and 2-3 km deep. It is 100 km wide in the north and becomes two narrower branches in the south. Its flanks are raised by up to 6 km above its surroundings (Giese et al., 2007). Crater counting suggests it formed approximately 4 Gyr ago (Giese et al., 2007). Previous work has suggested that the formation of Ithaca Chasma may be related to the 400 km Odysseus impact basin or expansion due to the freezing of Tethys' interior (Smith et al., 1982). More recent work involving crater counts suggests that Ithaca Chasma pre-dates Odysseus (Giese et al., 2007). However, the formation of Ithaca Chasma is still debated. Flexural modeling of Ithaca Chasma suggests that the surface heat flux was 18-30 mW/m^2 when it formed (Giese et al., 2007). This may imply a past history of tidal heating and a higher eccentricity for Tethys, which could have occurred if Tethys passed through a 3:2 resonance with Dione (Chen and Nimmo, 2008; Neveu and Rhoden, 2019). An ocean would not be required to produce the necessary heat flux, but if the eccentricity remained high for a prolonged period of time, for example excited by a resonance, then the ice layer would start to melt which would increase tidal heat production and further thin the ice shell (Chen and Nimmo, 2008; Neveu and Rhoden, 2019). New estimates of the thermal conductivity profile which include the effects of porosity yield a heat flow an order of magnitude less than previously assumed and suggest that tidal dissipation is not required to explain the flexure observed at Ithaca Chasma. This conclusion implies that an ocean would not be required at any time in Tethys' history (Castillo-Rogez, in prep.).

Dione: Dione is one of Saturn's larger mid-sized icy satellites (radius of ~561 km) and orbits at a distance of ~377,000 km with an eccentricity of 0.0022 (bulk density: 1478 kg/m^3). The surface of Dione contains both heavily cratered and heavily tectonized regions. Young fault scarps known as the "wispy terrains" were first discovered during the *Voyager* missions (Plescia, 1983) and have been better imaged by the *Cassini* mission. Unfortunately, the ages of these features are not well constrained (Kirchoff and Schenk, 2015) but their crosscutting relationships suggest they are among the youngest features on the surface (Martin et al., 2015). The wispy terrain structures appear to be extensional in origin (Jaumann et al., 2009) but the moon also contains ridges that point to a compressional history (Collins et al., 2009). Some researchers have suggested that Dione is active and contributing particles to Saturn's E-ring and plasma to Saturn's magnetosphere (Burch et al., 2007); however, no plume activity has been observed at Dione (Buratti et al., 2011). The surface is composed mostly of water ice (Hussmann et al., 2015) and a thin coating of "dark material" similar to that found on Phoebe, Hyperion, and Iapetus (Clark et al., 2008). Dione's interior is likely differentiated into a rocky core and icy lithosphere (Thomas, 2010) where the rocky core composes about 48% of the mass, higher than most other icy satellites of Saturn, the exception being Enceladus (Hussmann et al., 2015). The ice shell likely experienced convection in the past but it is uncertain if such convection continues today (Zhang and Nimmo, 2009). Thus, little is known about the possible transport of material between the surface and deeper layers.

Similar to other icy satellites, the heating required to melt any subsurface ice into a global ocean would have to come predominantly from tidal heating. Geologic evidence for a present-day subsurface liquid layer is inconclusive; however, the large ridges (Hammond et al., 2013) and other terrains suggest at least a time in the satellite's past when it did have a subsurface liquid layer. Gravity and shape data acquired by the Cassini spacecraft have been interpreted in terms of a ~100 km thick isostatic shell overlying a ~65 km thick global ocean, thus providing a first line of evidence for a present-day ocean within Dione (Beuthe et al., 2016).

Rhea: Rhea is the largest inner satellite of Saturn, i.e., within Titan's orbit, with a mean radius of ~764 km. Its mean density of 1236 kg/m^3 corresponds to a rock volume fraction of 0.2. Tidal heating is not a major heat source in Rhea (i.e., compared against heat transfer) owing to the moon's relatively large semi-major axis. However, crater morphology reveals that Rhea benefited from enhanced heat flux with respect to long-lived radioisotope decay production (White et al., 2013). This could point to a resonance event. It is also possible that Rhea formed close to Saturn, possibly from ring material (Charnoz et al., 2010) and was subject to significant tidal dissipation in its early history. Gravity measurements obtained from multiple flybys by *Cassini-Huygens* revealed that Rhea is not in hydrostatic equilibrium, which precludes straightforward inferences on its interior structure. The departure from hydrostaticity is attributed to a large core oblateness that may be the signature of an origin in the rings (Charnoz et al., 2010), also found at Mimas (Tajeddine et al., 2014) and Enceladus (McKinnon, 2013). However, in its current location Rhea's heat budget is limited to long-lived radioisotope decay. Models suggest that the latter heat source was sufficient to promote the formation of a deep ocean in Rhea (Hussmann et al., 2006; Neveu and Rhoden, 2019). However, this ocean would have most likely been short-lived and is not expected at present.

Miranda: Miranda is the closest classical moon to Uranus (semi-major axis 129,900 km), and it is also the smallest classical moon (radius ~236 km) with a bulk density of about 1200 kg/m^3, indicating a likely silicate component in its interior. Hussmann et al. (2006) model an ice shell about 130 km thick around a 100 km radius core. The surface of Miranda is quite dramatic, showing a very disrupted and fractured nature. Most prominent are three large banded regions, called coronae, which have many similarities to banded regions on Ganymede, Enceladus, and Ariel (Pappalardo, 1994). Two main models of formation have been proposed for the coronae: the first involves massive disruption of Miranda, perhaps by an impact, and subsequent reassembly. Denser, silicate pieces that would have been moved closer to the surface through this process then sunk towards the core, causing the coronae to form above them (Janes and Melosh, 1988). This mechanism would lead to contractional surface tectonic features, however, analysis of the surface features appears more consistent with extensional surface tectonics (Beddingfield et al., 2015). Thus, the majority of works focus on formation of the coronae as a surface expression of extension above buoyant diapirs (Croft and Soderblom, 1991; Greenberg et al., 1991; Pappalardo et al., 1997). Hammond and Barr (2014) considered convection-driven resurfacing to form the extensional features of the coronae. Their global modeling reproduced the locations of the coronae.

Ariel: Ariel is the fourth largest Uranian moon (radius ~579 km) and the second farthest major satellite from Uranus (semi-major axis 190,900 km). Ariel has a bulk density of 1660 kg/m^3, similar to those of Titan, Enceladus, and Oberon and consistent with a rock:ice mass ratio of ~0.6 (Hussmann et al., 2006). Densities and rock mass fractions of the majority of the large Uranian satellites are higher than for their Saturnian counterparts. Cratering statistics show a paucity of large craters; the largest observed is ~85 km in diameter (Plescia et al., 1987; Strom, 1987). This distribution suggests complete resurfacing or modification of at least the observed area after accretion by tectonism, cryovolcanism, viscous relaxation, mantling or burial by infalling material, or some combination thereof (Croft and Soderblom, 1991; Plescia et al., 1987). Ariel's surface has undergone widespread faulting, with a system of fractures and graben 15 – 50 km wide cutting its surface and topographic relief of up to 4 km (Brown et al., 1991). The extensional tectonic regime is potentially the result of freezing of a liquid water ocean, although formation of a subsurface ocean would likely have required more than radiogenic heating alone (e.g., Plescia, et al., 1987). The tectonic activity may have been accompanied by extensive emplacement of viscous flows that appear to embay and partially bury craters, surround nunataks of cratered plains materials, and fill graben floors with convex deposits exhibiting medial grooves, bounded by troughs 1 – 2 km deep along the graben walls (Croft and Soderblom, 1991).

Umbriel: Umbriel is the third furthest mid-sized satellite of Uranus (semi-major axis 266,000 km), with a radius of 584.7 km and density 1390 kg/m^3. Geologically, Umbriel's ancient surface is dominated by impact craters (Plescia, 1987), although counts by Strom (1987) suggest that the surface is not primordial. There is no unequivocal evidence for geologic activity on Umbriel. Croft and Soderblom (1991) report numerous lineaments and troughs, including a set of horst and graben. They also interpret a large depression identified in limb profiles as tectonic, although the feature is perhaps more likely a large basin. All of the features identified by Croft and Soderblom (1991) have also been interpreted as arcuate crater rims seen at low resolution (Plescia, 1987). The extent of tectonic deformation is therefore unclear. Subtle, global albedo patterns have been suggested as evidence for endogenic (cryovolcanic) resurfacing (Helfenstein et al., 1989).

Unlike the Jupiter and Saturn systems, the Uranian satellites are not currently in resonance so no dissipation of tidal energy is likely at present (see, e.g., Peale, 1999). However, the evolution of the Uranian system, which includes chaotic behavior, is complex, and Umbriel may have participated in several resonances in its past, notably with Miranda (Tittemore and Wisdom, 1988, 1990). None of these resonances is thought to excite Umbriel's eccentricity significantly (Tittemore and Wisdom 1988, 1990), so an energy source to drive geologic activity appears to be lacking. It should be noted, however, that current studies have not included dissipation and interior evolution within the satellites themselves, and the coupled orbital-thermal evolution of the system should be reevaluated in the light of current understanding of satellite interiors (Peale, 1999). Furthermore, accretional energy alone may be sufficient to differentiate the satellite if NH_3 is present (Squyres et al., 1988).

Given the limited, low-resolution imaging data available, Umbriel is a planetary Rorschach test: the observations and inferences made regarding it appear to reflect the propensities of the investigator, rather than Umbriel itself. Umbriel is a low-albedo, heavily cratered satellite expressing limited geologic activity, and no apparent source of tidal energy, either now or in its past. As such, it seems unlikely that Umbriel has a subsurface ocean (Hussmann et al., 2006). However, some investigators have argued for extensive tectonic and cryovolcanic activity, which might imply the existence of an ocean at some point in Umbriel's past or present. Furthermore, one should always remember the lesson of *Mariner 4*: don't judge a body until you've seen its entire surface. We simply don't have enough data to assess the potential for oceans on Umbriel, or the other large Uranian satellites.

Titania: The fourth furthest classical satellite from Uranus, Titania (semi-major axis 436,300 km), is the largest Uranian moon with a radius of 789 km. Based on its relatively high bulk density (1660 kg/m^3), Hussmann et al. (2006) estimate a rock fraction of ~50 – 60%. The surface of Titania is dominated by H_2O ice mixed with low-albedo material, with CO_2 ice on its trailing hemisphere (Grundy et al., 2006). The source of CO_2 ice on the surfaces of these moons is not currently known, and possible explanations include radiolytic or photolytic production of CO_2 from H_2O and C-rich material on its surface, as well as possible outgassing of volatiles from the interior. Hussmann et al. (2006) predict a present-day liquid water ocean at the core-mantle boundary of Titania, assuming its primordial composition included a small amount of NH_3 (on the order of a percent). This ocean is predicted to underlie an ice shell with a thickness of > 100 km. However, as higher order components of the gravity fields of this moon are not known, an undifferentiated interior consisting of a homogenous rock-ice mixture cannot presently be ruled out (Hussmann et al., 2015).

Based on crater size distributions, Plescia (1987) estimated that the surface of Titania is younger than that of Oberon and Umbriel, indicating that some sort of global resurfacing process has taken place, likely sometime early in Titania's history. The surface of Titania is marked by a number of regional-scale tectonic features, including extensive faulting and parallel scarps, forming large canyon-like features, the largest of which (Messina Chasma) extends for over 1500 km. The major rift canyons include both NW-S and NE-SW components and appear to post-date almost all other structures on the surface (Croft, 1989). Several regions on the surface (notably adjacent to faults near the large Ursula impact crater) contain terrain that appears to be smooth, which might represent cryovolcanically emplaced deposits, or may be due to blanketing by impact ejecta (Plescia, 1987).

Theoretical models and the tectonically deformed surface of Titania suggest that a subsurface ocean could be present in its interior. Therefore, Titania represents a possible ocean world that should be explored further.

Oberon: The outermost classical Uranian moon, Oberon (semi-major axis 583,500 km), is slightly smaller (radius ~762 km) and less dense (1560 kg/m^3) than Titania, with a similar estimated rock fraction of ~50 – 60% (Hussmann et al., 2006). Like Titania, Hussmann et al. (2006) predict that a present-day liquid water ocean is present at the core-mantle boundary of Oberon, assuming it incorporated a small amount of NH_3 during its formation (~1% bulk composition). Oberon is predicted to have an overlying ice shell (> 100 km thick); however, it is also possible that this moon has an undifferentiated interior (Hussmann et al., 2015).

Oberon has one of the most heavily cratered and ancient surfaces of the major Uranian moons (Plescia, 1987). Like Titania, the surface of Oberon exhibits major tectonic features in the form of an extensive network of rift canyons, possibly generated by global volume expansion of ~0.5 % (Croft, 1989). The tectonic activity creating the rift canyons appears to have occurred in two phases, as both degraded and fresh canyon morphologies are observed (Croft, 1989). Smooth patches of dark material observed in the floors of several impact craters on Oberon might represent cryovolcanically emplaced deposits Analogous to Titania, theoretical models and observational evidence of global tectonism on Oberon suggest that a subsurface liquid ocean might be present. Therefore, Oberon is a possible ocean world that warrants further investigation.

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