Icy Satellite Processes in the Solar System: A plurality of worlds

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1 Introduction

Icy satellites retain a record of processes occurring over multiple scales of time and space (Fig. 1). Many are active today and are highlighted in other white papers as worthy targets of future exploration: Europa and Io are tidally flexed and heated; Ganymede is large enough to sustain its own magnetic field; the south polar plume on Enceladus remains a mystery, but compositional evidence points to a subsurface ocean (*Postberg et al.*, 2009; *Waite et al.*, 2009); Titan's atmosphere gives rise to climatic cycles strikingly similar to Earth's hydrological cycle. Other large icy satellites in the Solar System are silent today, but display diverse signs of past activity. Their stories hint at processes at work since the beginning of the Solar System. In all of these objects, compositional evolution, thermal dissipation and prospects for hosting life are regulated by common laws of physics and chemistry — and possibly biology — as illustrated in Fig. 2. Many of these objects are sufficiently dense that they could have sustained liquid water oceans (*Hussmann et al.*, 2006). Understanding the evolution and intrinsic stability of other oceans and atmospheres sheds important insight into the outcome of the experiment we are performing on our own planet. A comprehensive strategy for Solar System exploration must identify processes common to these icy worlds. Such an approach requires continued investment in discovery focused on icy satellites in the size regime 100 km and larger.

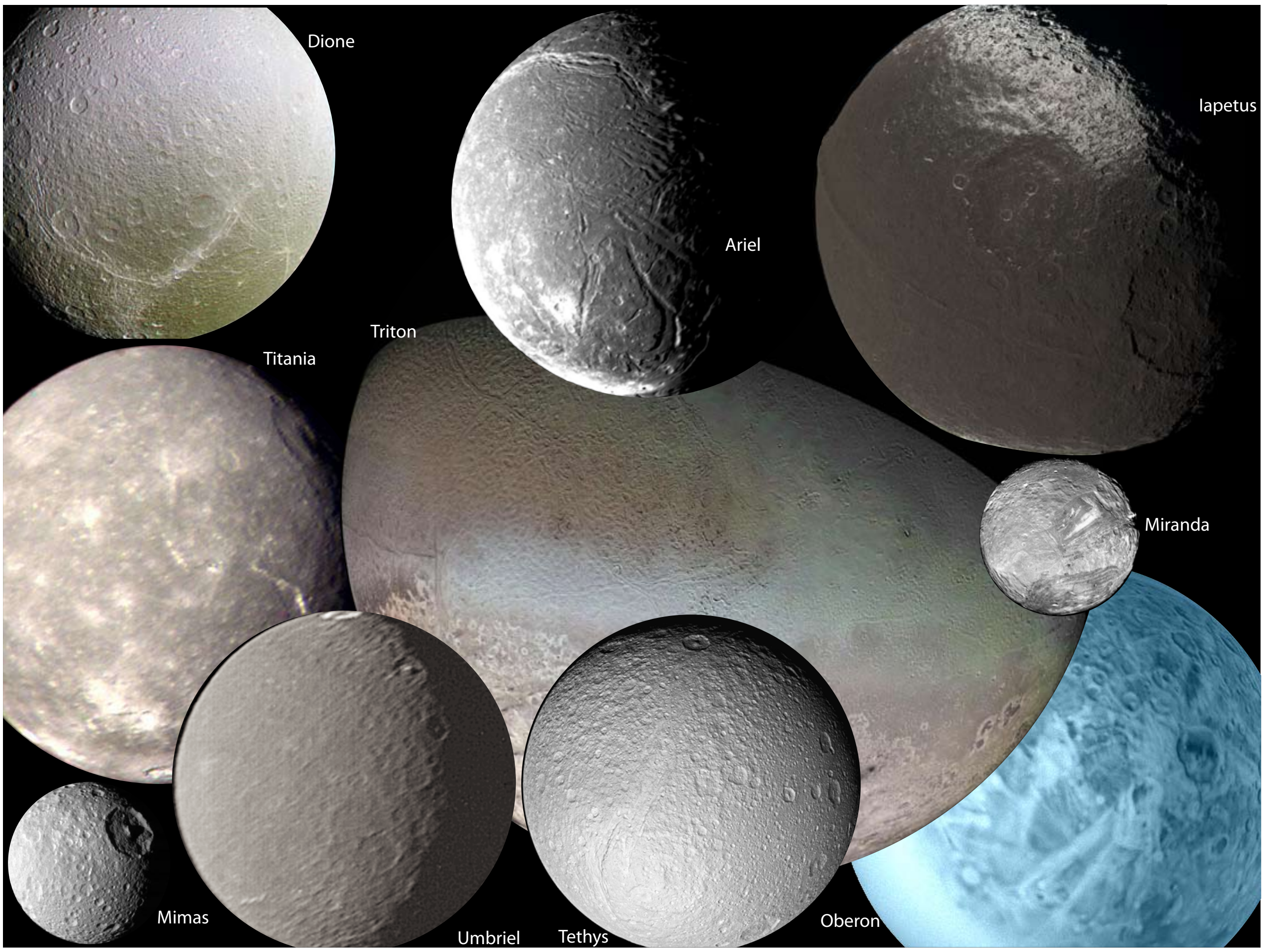

Figure 1: Larger icy satellites of Saturn, Uranus and Neptune bear unique signatures of past and present activity that challenge our understanding of planetary formation and evolution. Fractured regions are present on almost all of them, hinting at tectonic processes and the possibility of past or present liquid water. Iapetus sports an anomalous bulge on its equator that is presumed to have resulted from changes in its spin state. Triton's cold surface is marked by the results of eruptive activity observed by Voyager. All of these objects show variation in albedo and surface morphology indicative of some type of weathering or deposition.

2 Solar System Formation

The importance of studying a broad class of large icy satellites is readily apparent in the context of understanding time scales of planet formation. Currently, these are inferred from meteorite records and giant impact statistics. New information on larger icy satellites and new astrophysical observations by the Spitzer space telescope are prompting cross-disciplinary research pertaining to protoplanetary disk and icy satellite evolution (*Castillo-Rogez et al.*, 2007; *Barr and Canup*, 2008). This new insight on

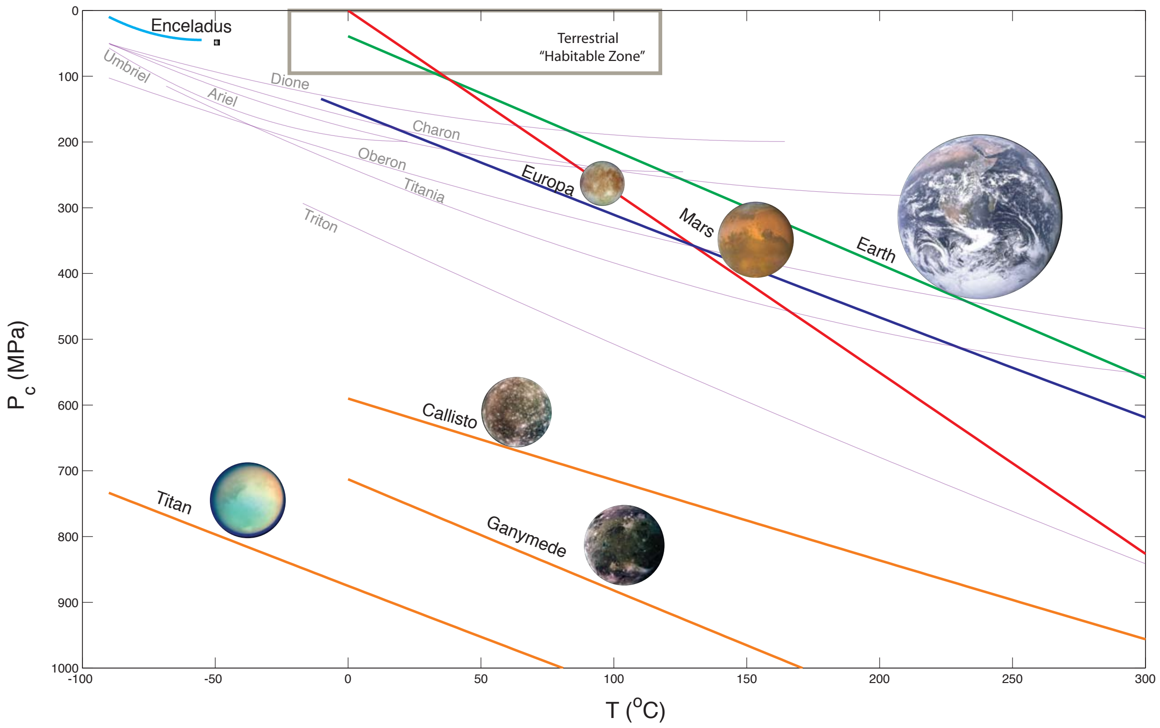

Figure 2: Larger bodies in the Solar System share common thermodynamic parameters of pressure and temperature in their interiors, albeit over different spatial scales, with implications for aqueous geochemistry and habitability of their interiors. In this figure, based on *Vance et al.* (2007), an ocean is assumed to exist at some nominal depth consistent with constraints on a body's composition of long-lived radionuclides and incorporation of ammonia (*Hussmann et al.*, 2006). Interior pressures and temperatures are shown for each object, starting at a "seafloor" depth consistent with constraints on density. Underexplored "larger" icy bodies ($R > 100$ km), the focus of this paper, are indicated by light-toned lines. The pressure and temperature limits of known life on Earth are denoted by the Terrestrial "Habitable Zone" box.

satellite formation determines input parameters to models of satellite evolution. Sampling a diverse host of objects in the Solar System is therefore key to understanding satellite formation and evolution.

In terms of their orbital dynamics, the satellite systems of Jupiter, Saturn and Uranus appear to vary greatly from one another (Fig. 3). Jupiter's satellites show a regular decrease in density with increasing orbital distance. In contrast, sizes and mean densities, i.e. rock mass fractions, of Saturn's satellites do not show any regular trend, indicating that the history of the system from accretion to the present state was completely different. Other peculiarities in the Saturn system are the large distance of Iapetus and the large eccentricity of Titan.

The composition of icy satellites offers clues to the conditions under which they formed, and to their subsequent evolution. Beyond the outer asteroid belt, the surfaces of airless bodies are dominated by water ice, and as the distances from the sun increase, more volatile materials exist as surface components. The icy satellites of Jupiter are primarily water ice, with small amounts of other components such as hydrated sulfates and salts on Europa, and CO_2 on the three outer Galilean satellites (*McCord et al.*, 1999; *Carlson et al.*, 1996). Ammonia has been detected on Enceladus (*Emery et al.*, 2005; *Verbiscer et al.*, 2006; *Waite et al.*, 2009). CO_2 has been mapped on the uranian satellites telescopically (*Grundy et al.*, 2003), and on the saturnian satellites by the Cassini Visual Infrared Mapping Spectrometer, VIMS (e.g., *Clark et al.*, 2005). Although Triton's bulk composition is dominated by water ice, its distance from the sun permits condensation of additional volatile components such as nitrogen and methane, as well as CO_2. Seasonal volatile transport of nitrogen (and concomitant waxing and waning of a tenuous atmosphere) is expected to occur on both Triton and Pluto (*Trafton*, 1984).

Compositional analyses of dark surface materials yields clues to the interrelationships among the satellites and their kindred objects such as Kuiper Belt Objects (KBOs), Centaurs, and primitive asteroids (C, P, and D-type) in the outer Main Belt. This material, found in great quantities on comets, in the uranian rings, on the dark side of Iapetus (*Cruikshank et al.*, 2008), and in smaller quantities on Triton, the uranian satellites, and the smaller satellites of the outer planets, has astrobiological importance because it is rich in prebiotic compounds and may have been transported by comets into the inner Solar System to serve as building blocks for life on Earth.

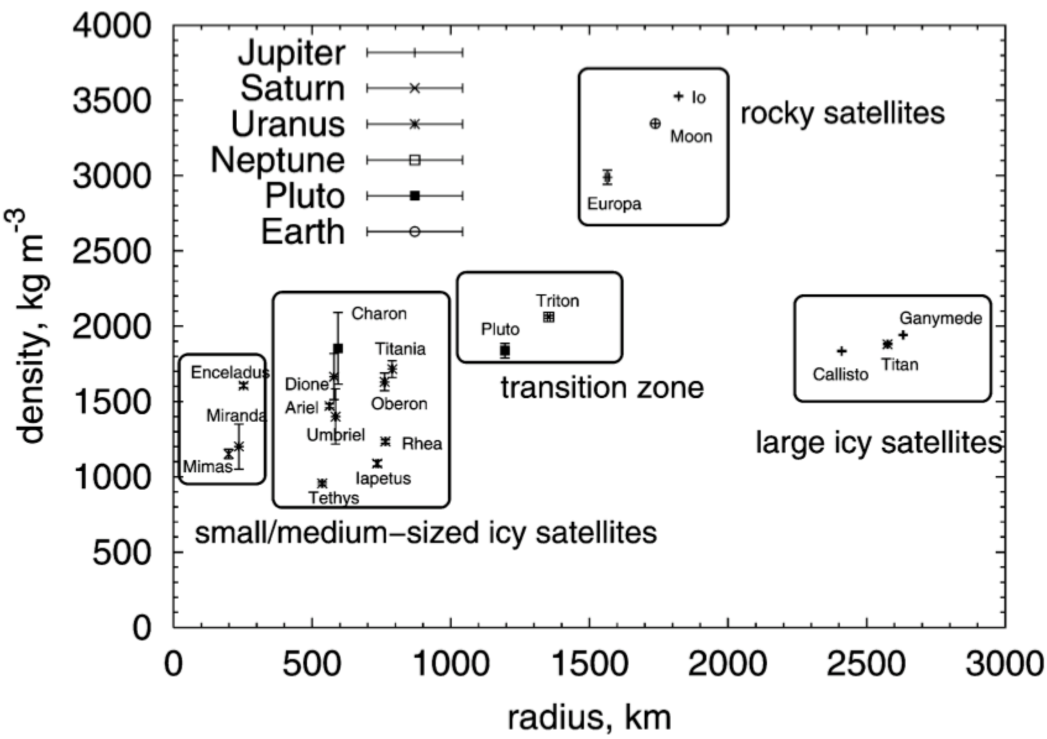

Figure 3: Densities of selected larger icy satellites ($R > 100$ km; *Hussmann et al.*, 2006).

3 Solar System Evolution

Icy satellites with older surfaces record processes from their accretion, subsequent cataclysms, and endogenic activity. Deciphering the geological evolution of these objects provides constraints on the relative occurrence of such phenomena. Internal warming and associated activity tend to erase the impact record. However, in many icy satellites, internal evolution has been limited so that these objects are the most prone to yield constraints on the bombardment history in the Solar System. Such constraints are especially important considering the disproportionate role of the lunar cratering record in setting cratering time scales (e.g., *Zahnle et al.*, 2003). Addressing the cause and extent of a Late Heavy Bombardment (*Gomes et al.*, 2005) requires comparative cratering records for multiple objects through the Solar System, with in situ constraints on surface age. Such a complementary historical record may be obtained for an older icy satellite if short-lived radionuclides provide precise constraints on the timing of the object's formation, as has been suggested for Iapetus (*Castillo-Rogez et al.*, 2007).

Interactions between the moons themselves (e.g., due to resonances) and the interactions of moons with their central planet (e.g., tides, capture processes, or interaction with the magnetosphere of the planet) can have major consequences on satellite evolution. As the moons themselves evolve, so do their orbits. Satellite orbits change due to migration in the disk during or shortly after accretion, tidal interaction with the primary, and through mutual gravitational interactions. By approaching certain ratios of orbital period, satellites can become locked in stable resonances (e.g., *Peale*, 1986).

Resonances can strongly affect satellite evolution as they force and maintain the orbital eccentricities of the satellites. Tidal heating can contribute significantly to a satellite's heat budget, especially in large satellites that orbit close to their massive primary planets. The most prominent examples are Io and Europa, and possibly Enceladus (*Vance et al.*, 2007). Tidal heating may have played a role for other satellites as well, especially early in their histories.

Although the periods of the uranian satellites Miranda, Ariel, and Umbriel are close to a Laplace-like ratio, they are not currently locked into resonance. Neptune's system is a special case because of the likely capture process of Triton (*Asphaug et al.*, 2006), which probably caused major disturbances of a previously existing satellite system. Triton's likely capture suggests an early history affected by tidal flexure and heating, though tidal processes are probably not significant in the current era (*Chyba et al.*, 1989).

Weathering processes alter satellite composition after their formation. These include sputtering, thermal cycling, UV radiation and meteorite impact. Sulfur and SO_2 frost originate on Io and are entrained in Jupiters magnetosphere and transported to the surfaces of the other Galilean satellites. Active plumes on Enceladus spread out into the vast, tenuous E-ring. This ring envelopes and coats the surfaces of Mimas, Enceladus, Dione, Tethys, and Rhea with micron-sized ice particles. Understanding the relative importance of these processes on satellite surfaces requires high-resolution geological and compositional mapping at the surfaces of such objects.

The tenuous environment surrounding a satellite provides opportunities for constraining composition and evolution through in situ measurements. Atmosphereless objects are exposed to the ambient micrometeoroid bombardment that erodes their surfaces and generates ejecta particles at a wide range of ejection speeds. Objects with radii bigger than 1000 km keep all particles with ejection speeds lower than $\approx$1000 m s^{-1}. Such objects are thereby enshrouded in clouds of dust particles. These particles move on ballistic trajectories, most of which re-collide with their parent object. In situ mass spectroscopic analysis of these particles from an orbiting spacecraft provides spatially resolved mapping of the surface composition of the object. Even trace amounts of endogenic and exogenic minerals (e.g., salts), cyanogen-, sulfur-, and organic compounds which are embedded in ejected grains can be quantified with high accuracy. In some cases (e.g., on Europa), this knowledge about surface-interior exchange processes may provide information about the internal composition of the satellite. This is also possible at moons that display active venting, as has been successfully shown with Cassini's dust detector at Enceladus (*Postberg et al.*, 2009).

4 Open Questions

The comparative studies described here are intended to answer questions about the origin and evolution of the Solar System. Intimately tied to this question is that of the origin and evolution of life. Detailed studies of objects of prime astrobiological interest — Mars, Europa and Enceladus — are necessary for seeking signs of life in the form of organic molecules, systems in chemical disequilibrium and, perhaps eventually, fossil or extant organisms. Such studies provide context for defining habitability of energy-rich icy satellites, and in the Solar System at large. The questions raised here constitute a path toward defining habitability in the Solar System.

Comparison of the four giant planet satellite systems leads to major questions that should be addressed in future exploration of the outer solar system:

- How is the variation of density of the moons as a function of distance from the planet related to accretion scenarios?
- Why is Saturn's satellite system irregular with respect to density distribution and orbital characteristics as compared to the jovian and uranian systems?
- Why is the satellite density increasing with distance in the Uranus system?
- How did the present resonances form and what were the implications for the satellite's internal energy budget and thermal evolution?
- Did resonances occur in the Uranus system in the past?
- What caused the intense past or present activity of icy satellites Europa, Ganymede, Enceladus, Tethys, Miranda, Ariel, Titania, and Triton? Why did, e.g., Callisto, Mimas, Rhea, Iapetus, Umbriel, and Oberon remain almost completely inactive for most of their histories?
- What role did tidal heating play for individual satellites?
- Which satellites are completely differentiated/partially differentiated/undifferentiated?
- Has internal melting of ice (globally, or locally) occurred within the satellites? Do some of the satellites possess intrinsic or induced magnetic fields?
- What was the effect of events, e.g., the accretion or capture of a single very large satellite — e.g. Titan in the Saturn system or Triton in the Neptune system — on the evolution of the rest of the system consisting of mid-sized icy satellites?
- What are the roles of composition and formation environment in the thermal evolution of icy satellites. What is the role of ammonia and other N and C containing volatiles?
- What is the role of short-lived radionuclides ^{60}Fe and ^{26}Al?
- Can D/H reveal anything about the presence of an early subnebula?
- What does relative impact coverage reveal about thermal evolution? About local impactor flux? About orbital migration of satellites or their host planets?

5 Mission Priorities

The Cassini Solstice Mission will address important questions related to Saturn's satellites over the next decade, with implications for reaching across disciplinary boundaries as discussed above. Smaller missions to Saturn's moons can address remaining or emergent questions. A future Flagship mission to Titan and Enceladus (e.g. TSSM) should include a targeted study of the larger saturnian satellites as part of its orbital insertion plan.

The joint NASA/ESA Europa Jupiter System Mission embraces the study of multiple larger satellites as part of a system, and is therefore a vital component of the study of larger icy satellites.

Individual missions to Uranus and Neptune would provide opportunities for studies of the formation and evolution of larger icy satellites in those systems, which might yield clues to the formation of the icy satellite systems around Jupiter and Saturn, as well as those yet to be discovered in other planetary systems.

6 Recommendations

We make the following recommendations for the panel to consider:

- Acknowledging that studies of larger icy satellites can make major contributions to answering fundamental questions about the solar system, its formation and evolution and the likelihood that other habitable environmental niches occur outside the Earth's biosphere.
- Advising that multidisciplinary laboratory and simulation studies are necessary for advances in understanding the formation, composition, evolution and habitability of larger icy worlds.
- Advising that missions to the outer Solar System should target multiple objects, particularly under-explored larger icy satellites of Saturn, Uranus and Neptune, focusing on measurements that "shed light" on composition (i.e., multispectral mapping at high resolution).

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