Part IV

Icy Satellites of the Outer Planets

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Icy Bodies of the Solar System
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Interior Models of Icy Satellites and Prospects of Investigation

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Abstract. The state of knowledge about the structure and composition of icy satellite interiors has been significantly extended by combining direct measurements from spacecraft, laboratory experiments, and theoretical modeling. Interior models of icy bodies will certainly benefit from future missions to the outer solar system, providing new and improved constraints on the surface chemistry, bulk composition and degree of internal differentiation, possible heterogeneities in radial mass distribution, the presence and extent of liquid reservoirs, and the amount of tidal heating for each target body. Here we summarize geophysical constraints on the interior structure and composition of selected Jovian and Saturnian icy satellites and investigate conditions under which potentially habitable liquid water reservoirs could be maintained. Future geophysical exploration which includes gravitational and magnetic field sounding from low-altitude orbit and close flyby, combined with altimetry data and in-situ monitoring of tidally-induced surface distortion and time-variable magnetic fields, would impose important constraints on the interiors of outer planet satellites.

Keywords. astrobiology, conduction, convection, equation of state, icy satellites, interiors, Io, Europa, Ganymede, Callisto, Enceladus, Rhea, Titan, Triton

1. Introduction

The internal structure and bulk composition of solar system bodies are key to understanding the origin and early evolution of the solar system. In general, solar system bodies are composed of rock, metal, ices, and gases. The terrestrial, i.e. Earth-like, bodies in the inner solar system are primairly composed of rock and metal since early condensation of silicate minerals and metals was initiated at relatively high temperature in the solar nebula. In turn, volatile-rich components in form of ices and gases are more abundant in the cold outer solar system because of their lower condensation temperatures. Interior structure models aim at inferring the bulk composition, masses of major chemical reservoirs, the depth to chemical discontinuities and mineral phase boundaries, variation with depth of temperature, pressure, density, and composition. In the absence of seismological data, the construction of depth-dependent models of planetary interiors must rely on high-pressure and -temperature laboratory experiments to deduce equations of state for the density, transport properties like viscosity and thermal conductivity, phase stability regions, and melting relations. Since there are usually fewer constraints than unknowns, even basic interior structure models that would involve only a few chemically homogeneous layers of constant density suffer from inherent non-uniqueness (e.g., Sohl & Schubert 2007).

2. Geophysical constraints

The state of knowledge about the structure and composition of icy satellite interiors has improved considerably in the late 70s and mid 80s, when the *Voyager* spacecraft flew by Jupiter, Saturn, Uranus, and Neptune, followed by the advent of the *Galileo* spacecraft in the Jovian system (1995-2003) and the *Cassini* spacecraft in the Saturnian system (since 2004). *Voyager* observations of the Jovian moons Io and Europa and, to a lesser extent, Ganymede suggested tidal heating to be a major heat source, possibly resulting in near-surface viscous deformation of warmed ice and cryovolcanic resurfacing (e.g., Johnson 2005).

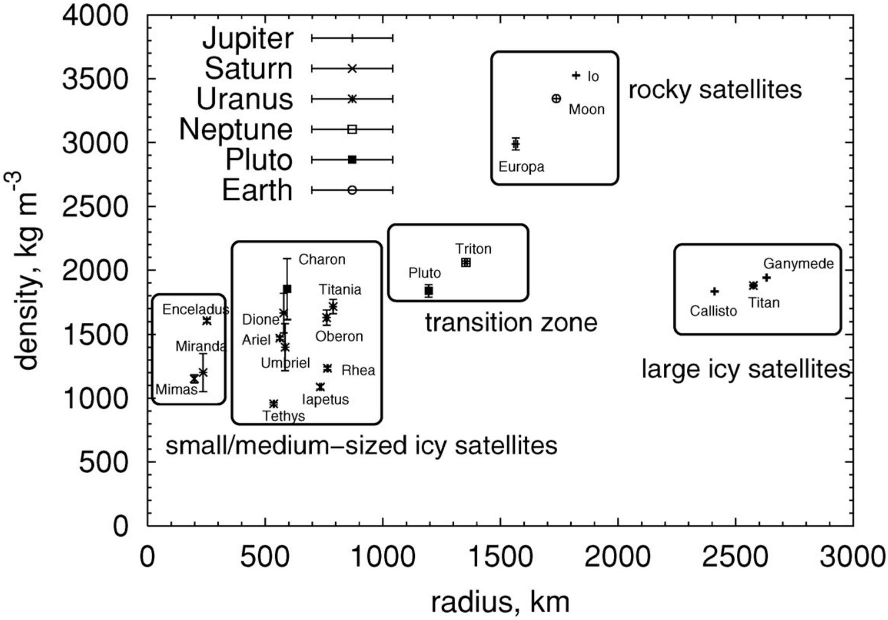

Figure 1. Radius-density relation for satellites and dwarf planets.

Models of the internal density distribution are then required to satisfy the mean density, derived from the total radius and mass, and the mean moment-of-inertia (MoI) factor, inferred from the mean radius and quadrupole moments of the gravitational field. Whereas the mean moment of inertia is a measure for the degree of internal differentiation or concentration of mass toward the center, the bulk chemical composition of a planet or satellite can be inferred from its mean *uncompressed* density. Additionally, self-sustained and/or induced magnetic fields, surface geology and composition, and the volatile inventory of a planet or satellite provide indirect information about the constitution of planetary and satellite interiors. Tectonic manifestations of endogenic activity preserved in the long-term surface record are particularly useful to infer the mode of internal heat transport (e.g., Schubert *et al.* 1986, Hussmann *et al.* 2007).

Most of the natural satellites are in synchronous rotation and subject to static and dynamic tidal forces exerted by their primaries. The non-spherical part of their gravity fields is predominated by rotational and/or tidal contributions to the quadrupolar and tesseral moments J_2 and $C_{2,2}$, measuring the polar oblateness and equatorial ellipticity of the gravity field, respectively. Superimposed are time-variable contributions which are induced by radial and librational tides along slightly eccentric orbits of a number of satellites. From the analysis of Doppler range and range rate observations acquired at around closest approach, the axial moments of inertia of only a few satellites have been inferred from gravitational perturbations on spacecraft trajectories by using the Radau-Darwin relation (e.g., Hussmann *et al.* 2007). However, the moment-of-inertia values derived in this way are almost entirely based on the assumption that the satellites are in

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hydrostatic equilibrium and the ratio $J_2/C_{2,2}$ taken constant at 10/3. Among those are the Galilean satellites Io, Europa, Ganymede, Callisto and the Saturnian moons Titan and Rhea. The shapes of most mid size Saturnian moons are consistent with hydrostatic equilibrium (Thomas *et al.* 2007), with the notable exception of Iapetus' shape that corresponds to a former rotational period of several hours (Castillo-Rogez *et al.* 2007). For Io, the volcanically most active body in the solar system, hydrostatic equilibrium was confirmed from different flyby geometries (near-polar and near-equatorial) of the *Galileo* spacecraft (Anderson *et al.* 1996a, Anderson *et al.* 2001a). Deviations from hydrostaticity are commonly attributed to uncompensated topography and/or internal dynamics.

3. Subsurface water oceans

Almost four decades have passed since extant liquid water oceans on icy moons were postulated (Lewis 1971, Consolmagno & Lewis 1978). The possible formation of liquid water layers below the outer ice shell of icy satellites is strongly dependent on their accretion history, initial thermal state, and degree of internal differentiation. The maintenance of liquid water layers at a depth of several tens of kilometres is closely related to the internal structure, chemical composition, and thermal state of icy satellite interiors subsequent to internal differentiation. Icy satellites are believed to operate in the stagnant-lid regime at present, i.e, the outer ice shell can be subdivided into an elastic conductive stagnant lid underlain by a viscoelastic convective sublayer in contact with the liquid water layer below. Controlling parameters for sub-surface water ocean formation are the competition between radiogenic heating of the silicate component, additional contributions due to, e.g., the dissipation of tidal energy, and the effectiveness of the heat transfer to the surface (Spohn & Schubert 2003). Furthermore, the melting temperature of ice I will be reduced by pressure increase with depth and the minimum melting temperature will be attained at the ice I/ice III transition. Moreover, impurities like salts and/or volatiles such as ammonia and methanol will lead to a significant melting point depression of the icy component, thereby causing even thicker and colder subsurface water oceans.

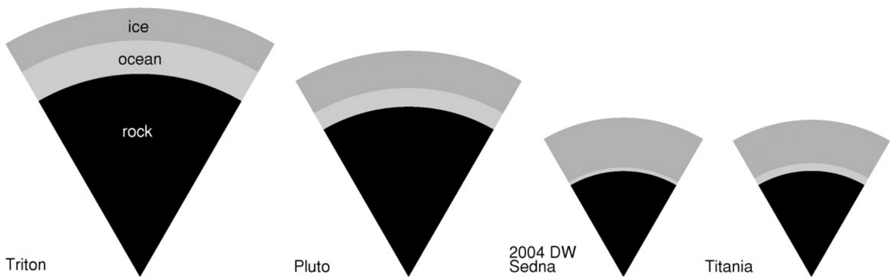

Figure 2. Interiors of ocean-bearing icy satellites and dwarf planets to scales.

In general, large icy bodies such as, e.g., the icy Galilean satellites, Titan and Triton, are more likely to harbour subsurface oceans because of slower cooling rates and more intense radiogenic heating caused by their larger rock mass fractions, as compared to smaller icy bodies. However, depending on the amount of antifreezes incorporated in the icy component during accretion, internal oceans cannot be ruled out for the largest of the medium-sized satellites of Saturn and Uranus, and the biggest trans-Neptunian objects (McKinnon *et al.* 2008), as illustrated in Fig. 2, provided those are differentiated into a rock core and a water ice/liquid shell (Hussmann *et al.* 2006). Water-rock interactions would affect oceanic composition and the mineralogy of rocks and oceanic sediments on ocean-bearing icy satellites like Europa and Triton where liquid reservoirs are likely in contact with silicate rock below. The most convincing argument for extant subsurface water oceans on icy satellites, however, results from the detection of induced magnetic fields in the *Galileo* magnetometer data collected near the icy Jovian satellites (Kivelson *et al.* 2004).

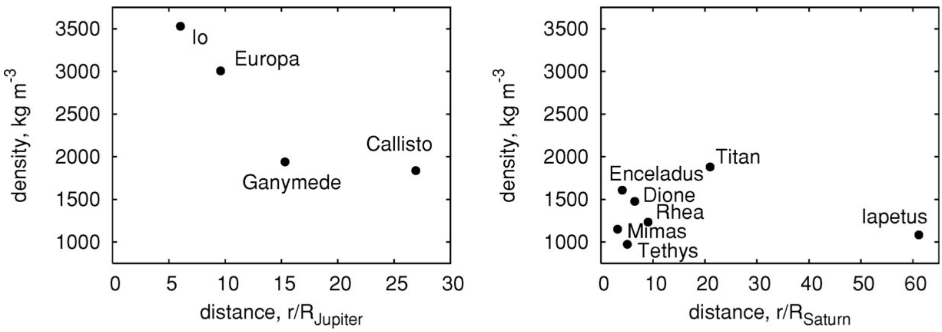

Figure 3. Mean density $\bar{\rho}$ of the (left) Galilean and (right) largest Saturnian satellites vs. distance from the primary r in units of Jupiter and Saturn radii $R_{\rm Jupiter}$ and $R_{\rm Saturn}$, respectively.

4. Jovian satellites

The prominent density gradient with increasing distance from Jupiter (see left-hand side of Fig. 3) provides important constraints on the formation of the Jovian satellites (e.g., Coradini *et al.* 1995). Whereas the mean densities of Io and Europa indicate that their interiors are mainly composed of rock and metal, and, in the case of Europa, up to 10 wt.% water ice/liquid, Ganymede and Callisto contain water ice and rock-metal components in nearly equal amounts by mass. Further indirect constraints are provided by the surface geology, spectral properties, and chemistry of each individual satellite. Active volcanism, anomalous intrinsic luminosity, and high-temperature lava flow deposits at Io's surface emphasize the importance of tidal heating in the Jupiter system, essentially maintained by gravitational interaction due to the resonant orbits of Io, Europa, and Ganymede (Laplace resonance) (e.g., Peale 1999). Additionally, magnetic induction signals were observed at Europa, Callisto, and possibly Ganymede. The observed magnetic signatures suggest the presence of *globe-encircling*, electrically conducting reservoirs of liquid water below the surface (Kivelson *et al.* 2004). Those are interpreted in terms of briny subsurface water oceans that may contain even more water than all terrestrial oceans combined.

Table 1. Physical parameters of the Galilean satellites.

satellite	R [km]	GM [km^{3}s^{-2}]	$\bar{\rho}$ [kg m^{-3}]	a [km]	b [km]	c [km]
Io	1821.46	5959.91 ± 0.02	3529	1829.4	1819.3	1815.7
Europa	1562.09	3202.72 ± 0.02	3006	1564.13	1561.23	1560.93
Ganymede	2632.345	9887.83 ± 0.03	1940	2632.4	2632.29	2632.35
Callisto	2409.3	7179.29 ± 0.01	1837	2409.4	2409.2	2409.3

Note: The mean densities are calculated from $\bar{\rho} = 3M/(4\pi R^3)$. Values of mean radius R, mass GM (G is the gravitational constant) were taken from Seidelmann *et al.* 2007 and Schubert *et al.* 2004. a, b, c denote the Jupiter-facing, orbit-facing, and polar axis, respectively.

Ganymede, the Mercury-sized, largest satellite in the solar system, possesses a self-sustained magnetic dipole field with equatorial and polar field strengths at the surface of 750 and 1200 nT, respectively (Kivelson *et al.* 1996). Since the most likely source is dynamo action in a liquid Fe-FeS core, Ganymede's interior is believed to consist of an

Table 2. Gravity field parameters of the Galilean satellites.

satellite	$R_{\rm ref}$ [km]	$J_2 \times 10^{-6}$	$C_{2,2} \times 10^{-6}$	$k_{\rm f}$	$C/(MR^2)$
Io	1821.6 ± 0.5	1859.5 ± 2.7	558.8 ± 0.8	1.3043 ± 0.0019	0.37824 ± 0.00022
Europa	1565.0 ± 8.0	435.5 ± 8.2	131.5 ± 2.5	1.048 ± 0.020	0.346 ± 0.005
Ganymede	2631.2 ± 1.7	127.53 ± 2.9	38.26 ± 0.87	0.804 ± 0.018	0.3115 ± 0.0028
Callisto	2410.3 ± 1.5	32.7 ± 0.8	10.2 ± 0.3	1.103 ± 0.035	0.3549 ± 0.0042

Note: $R_{\rm ref}$ is the reference radius associated with J_2 and $C_{2,2}$; the corresponding GM-values are given in Table 1. J_2 $(= -C_{2,0})$ and $C_{2,2}$ are degree-two gravity field coefficients, $C/M/R^2$ is the axial MoI factor, and $k_{\rm f}$ is the static fluid potential Love numbers calculated from $k_{\rm f} = 4C_{2,2}/q_r$, where $q_r = \omega^2 R_{\rm ref}^3/(GM)$ is the smallness parameter for the equilibrium figure of a synchronously rotating satellite with ω the mean angular frequency of rotation. Values were taken from Schubert *et al.* 2004.

iron-rich core surrounded by a silicate rock mantle overlain by an ice shell that may contain a subsurface water ocean sandwiched between a high-pressure water ice layer and an outermost ice I layer (Schubert *et al.* 2004). In fact, Ganymedes MoI factor of 0.3115 ± 0.0028 is the smallest measured value for any solid body in the solar system and indicates a strong concentration of mass towards the center (Anderson *et al.* 1996b, Sohl *et al.* 2002).

Callistos radius is about 200 km smaller than that of Ganymede and its mass is 70% that of Ganymede. The satellite's old, heavily cratered surface suggests that endogenic resurfacing has never happened since accretion was completed. Provided hydrostatic equilibrium is attained, the *Galileo* gravity data suggest that the satellite's axial MoI factor is equal to 0.3549 ± 0.0042. However, this value is not compatible with a fully differentiated interior and suggests partial or weak internal differentiation (Anderson *et al.* 2001b), augmented by a density increase with depth due to pressure-induced water ice phase transitions (McKinnon 1997). Furthermore, the magnetic data suggest that an ocean is present at around 150 km depth (Khurana *et al.* 1998, Zimmer *et al.* 2000). These two interpretations of geophysical data seem contradictory since the presence of an ocean would lead to internal differentiation. In order to reconcile these two observations, it was proposed that Callisto may have undergone incomplete gradual unmixing of ice and rock, proceeding from underneath the cold and immobile lithosphere, and with rock concentration increasing with depth up to the close-packing limit (Nagel *et al.* 2004).

5. Saturnian satellites

In contrast to the Jovian satellites, the lack of a prominent density gradient with increasing distance from Saturn (see right-hand side of Fig. 3) suggests an average bulk composition for the Saturnian satellites. Saturns largest moon Titan is intermediate between the Jovian satellites Ganymede and Callisto with respect to its radius and mean density. Whereas Tethys' low mean density suggests the presence of porous ice, the densities of Titan and Enceladus, Saturn's exceptionally active inner moon, indicate that both interiors are composed of ice and rock-metal in nearly equal amounts by mass. The range of interior structure models satisfying the degree-two gravity field of Rhea is attributed to the possible existence of a high-pressure ice layer and the extent of unmixing of ice and rock (Castillo-Rogez 2006). The axial MoI factor inferred from Doppler data acquired during a close *Cassini* flyby suggests that Rhea is only weakly differentiated (Iess *et al.* 2007), or even an almost homogeneous mixture of rock-metal and water ice compounds (Anderson & Schubert 2007).

From remote-sensing *Cassini* observations, it is obvious that Titan and Enceladus have been subject to intense endogenic activity in the course of their evolutions. Whether or

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Table 3. Physical parameters of the largest Saturnian satellites.

satellite	R [km]	GM [km^{3}s^{-2}]	$\bar{\rho}$ [kg m^{-3}]	a [km]	b [km]	c [km]
Mimas	198.2 ± 0.5	2.5023 ± 0.0020	1150 ± 9	207.4 ± 0.7	196.8 ± 0.6	190.6 ± 0.3
Enceladus	252.1 ± 0.2	7.2096 ± 0.0067	1608 ± 5	256.6 ± 0.6	251.4 ± 0.2	248.3 ± 0.2
Tethys	533.0 ± 1.4	41.2097 ± 0.0063	973 ± 8	540.4 ± 0.8	531.1 ± 2.6	527.5 ± 2.0
Dione	561.7 ± 0.9	73.1127 ± 0.0025	1476 ± 7	563.8 ± 0.9	561.0 ± 1.3	561.7 ± 0.9
Rhea	764.3 ± 2.2	153.9416 ± 0.0049	1233 ± 11	767.2 ± 2.2	762.5 ± 0.8	763.1 ± 1.1
Titan	2575.5 ± 2	8978.1356 ± 0.0039	1880 ± 4			
Iapetus	735.6 ± 3.0	120.5117 ± 0.0173	1083 ± 13	747.4 ± 3.1		712.4 ± 2.0

Note: The mean densities are calculated from $\bar{\rho} = 3M/(4\pi R^3)$. Values of mean radius R, mass GM (G is the gravitational constant) were taken from Thomas *et al.* 2007 and Jacobson *et al.* 2006. a, b, c denote the Saturn-facing, orbit-facing, and polar axis, respectively.

not Titan's deep interior is further differentiated like Ganymede's into an iron core and a rock mantle above is more speculative, as there is no observational clue on the possible existence of a self-sustained magnetic field (Backes *et al.* 2005). Based on gravity data collected during several *Cassini* spacecraft encounters, it cannot be safely excluded that Titan's interior is only partly differentiated, more similar to that of Callisto. Titans surface shows a number of cryovolcanic units and tectonic features that can be related to endogenic activity, as revealed by imaging during the descent of the Huygens probe (Tomasko *et al.* 2005) and Cassini remote sensing Porco *et al.* 2005, Lopes *et al.* 2007. The detection of ^{40}Ar by the Huygens probe (Niemann *et al.* 2005) suggests methane replenishment of Titan's atmosphere by degassing of the interior (Atreya *et al.* 2006). The latter may involve episodes of methane clathrate dissociation and cryovolcanic activity coupled to the satellite's thermal-orbital evolution (Tobie *et al.* 2006). Titan's orbital eccentricity is remarkably high, suggesting a relatively recent origin and/or moderate tidal heating over time (Sohl *et al.* 1995, Tobie *et al.* 2005). Finally, Titan is likely to harbour a cold, extended internal liquid reservoir, similar to those first proposed for the large icy satellites of Jupiter, but more enriched in ammonia (Grasset *et al.* 2000, Sohl *et al.* 2003, Tobie *et al.* 2005, Grindrod *et al.* 2008).

The detection of plumes of water-vapour and ice grains (Dougherty *et al.* 2006) populating Saturn's E-ring and lineated thermal anomalies (Spencer *et al.* 2006) shows that the heavily tectonized south polar region of Enceladus is cryovolcanically active (Porco *et al.* 2006). In particular, the presence of non-condensable volatile species in the jet-like plumes, like molecular nitrogen, carbon dioxide, and methane, suggests an aqueous internal environment at elevated temperatures, facilitating aqueous, catalytic chemical reactions (Matson *et al.* 2007). Possible venting mechanisms are sudden decompression of near-surface reservoirs of liquid water (Porco *et al.* 2006), chlathrate decomposition (Kieffer *et al.* 2006), and cryovolcanic processes. The recent detection of a salt-rich and basic-pH population of E-ring ice grains from in-situ compositional analysis suggests that the plumes originate from a liquid reservoir in contact with silicate rock below (Postberg *et al.* 2009). Taken together, this strongly suggests that Enceladuss interior is differentiated into a rock-metal core overlain by a water-ice liquid shell (Schubert *et al.* 2007). However, the concentration of geologic and thermal activity toward the south-polar region and the energy source required to initiate and maintain the activity are not well understood. It is possible that those are associated with a low-degree mode of internal convection (Grott *et al.* 2007) and diapir-induced reorientation (Nimmo & Pappalardo 2006) early in Enceladus' history. Tidal heating above a liquid water reservoir confined to beneath the south-polar region (Tobie *et al.* 2008) would help explain Enceladus' south pole hot spot and associated circular topographic depression (Collins & Goodman 2007).

6. Summary and outlook

The existence of potentially habitable liquid water reservoirs on icy satellites is dependent on the radiogenic heating of the rock component, additional contributions such as the dissipation of tidal energy, the efficiency of heat transfer to the surface, and the presence of substances that depress the freezing point of liquid water. Gravitational and magnetic field sounding from low-altitude orbit and close flyby, combined with altimetry data and in-situ monitoring of tidally-induced surface distortion and time-variable magnetic field, would impose important constraints on the interiors of outer planet satellites. In particular, the hydrostatic assumption – central to the construction of interior structure models – needs to be carefully evaluated by separate determination of the static components of the low-degree gravity field coefficients from independent orbits (polar) and flybys (inclined and equatorial). These coefficients are required to be determined at a sufficiently high accuracy to distinguish between tidally-induced contributions and high-order static gravity anomalies. Future recovery of static *and* time-variable parts of satellite gravity fields would provide entirely new information on the gravitational signature of intrinsic density anomalies and regional topographic features as well as on the existence and radial extent of liquid subsurface water reservoirs on icy satellites. Global shapes and rotational states and orientations in space hint at the thickness and rigidity of the overlying ice crust and would be obtained from combinations of global altimetry, imaging, and limb profiling. In particular, the correction of non-hydrostatic effects requires combined collection of gravity and altimetry data. Magnetometer measurements conducted from orbiting spacecraft and surface probes would help distinguish between intrinsic and induced contributions to the observed magnetic field, thereby providing complementary information on the depth to liquid water reservoirs and their electrical conductivities. This taken together would improve our general understanding of the origin and early evolution of outer planet satellites.

Future exploration of the outer solar system should benefit from truly international cooperation. Current spacecraft mission proposals, jointly put forward by ESA and NASA, would facilitate synergistic observations shared between several platforms and mainly targeted at discovering potentially habitable, liquid reservoirs in the outer solar system. These missions would involve orbiting spacecraft around Europa and Ganymede (Blanc *et al.* 2009), to be launched around 2020, and possibly followed by a Titan-orbiting mission, including a long-lived aerial platform and a short-lived lake lander (Coustenis *et al.* 2009). Albeit more challenging in terms of mission duration and distance, outstanding scientific gain at long sight must be expected from focused missions to the Uranian system, Neptune and Triton, and beyond.

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