Science Goals and Mission Objectives for the Future Exploration of Ice Giants Systems: a Horizon 2061 Perspective

Part I: From Science Questions to Measurement Requirements

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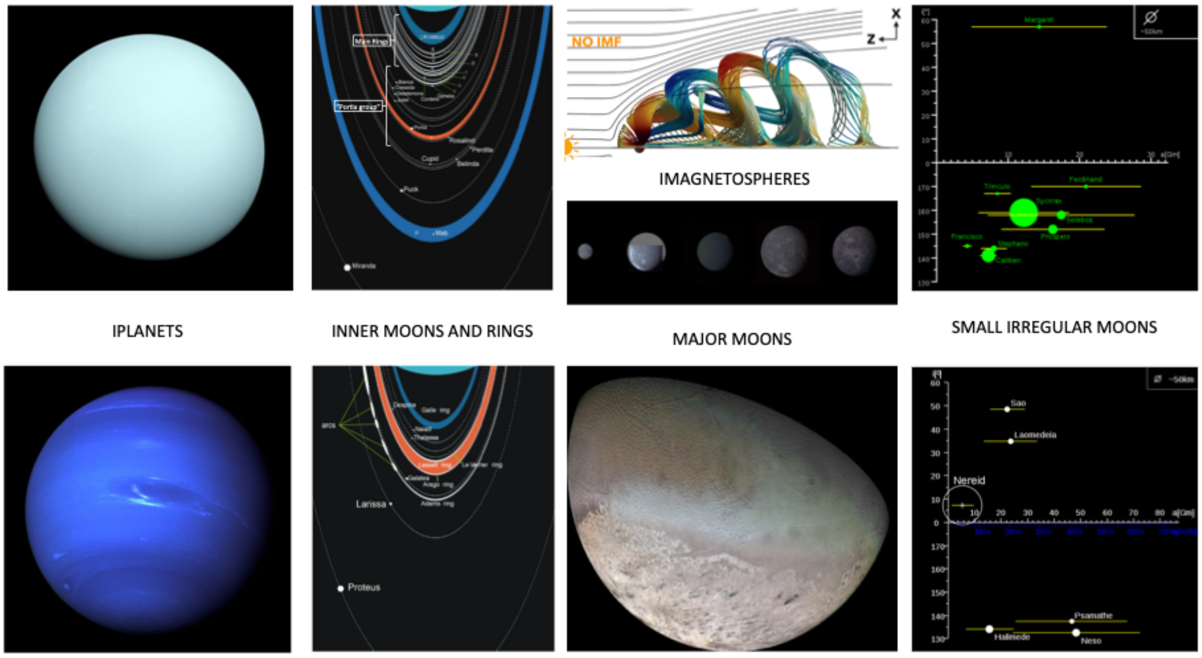

IPLANETS

INNER MOONS AND RINGS

MAJOR MOONS

SMALL IRREGULAR MOONS

ICE GIANTS SYSTEMS

Introduction

Planetary science has experienced in the last two decades the emergence of a new unifying paradigm: the concept of “planetary system”, which links together the solar system, giant planet systems and extrasolar planetary systems. Among them, *primary* planetary systems orbit a star while *secondary* planetary systems, including the four Giant Planets systems, have a planet as their central object.

The “Planetary Exploration, Horizon 2061” foresight exercise (http://horizon2061.cnrs.fr/) has proposed six key science questions, Q1 to Q6, for the comparative study of planetary systems:

Q1- How well do we understand the diversity of planetary system objects?
Q2- How well do we understand the diversity of planetary system architectures?
Q3- What are their origins and formation scenarios?
Q4- How do they work?
Q5- Do they host potential habitats?
Q6- Where and how to search for life?

The legacy of 20th century solar system exploration, despite its wealth of discoveries, leaves a huge gap in their exploration: the two ice giant systems have been visited only once by the fly-by of the same probe, Voyager 2, in 1986 and 1989. In this White Paper, based on a comprehensive article in which more detail can be found [1], we show how the six “key questions” can be addressed in depth at ice giant systems and identify measurement requirements for missions to these systems.

1. Diversity of planetary systems objects (Q1): the place of ice giants.

Twenty-five years of fruitful exoplanet detection and characterization have taught us that planets with sizes intermediate between Uranus or Neptune and Earth, the so-called “sub-Neptunes”, are very common in our Galaxy.

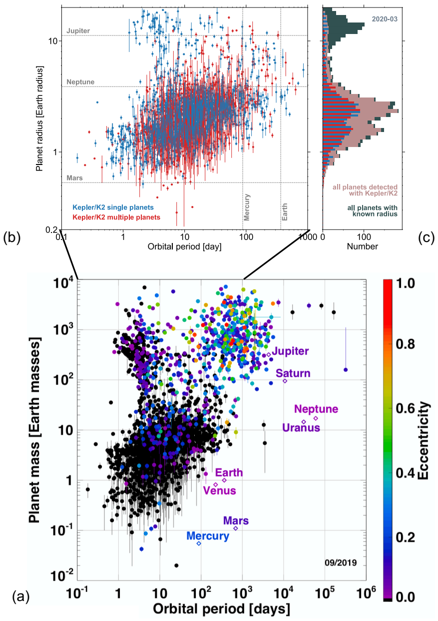

Figure 1*: (Panel a) Mass vs. orbital period distribution of all exoplanets for which these parameters have been determined so far; (panel b) Inventory of the 2404 planets whose radius has been determined by the Kepler/K2 surveys as a function of their orbital period; (panel c) histogram of their statistical distribution sorted by radius.*

This inventory shows that sub-Neptunes are not directly comparable to our ice giants, being located on orbits with significantly shorter periods, e.g. much closer to their stars. For this reason, exploring the links between solar system ice giants and sub-Neptunes via progress in observations and modelling should be a priority for Planetary Science in the coming decade. *Adapted from* [2] *based on data extracted from exoplanet.org.*

Figure 1 shows that a major quantitative step forward in our knowledge of Neptune-class planets is needed to better understand their central place among planets:

(1) for *exoplanet research*, one must take advantage of progress expected in the decades to come in exoplanet detection and characterization techniques to extend the survey of exoplanets towards the right-hand side of panels a and b, in order to ultimately cover the region of parameter space where Uranus and Neptune reside;

(2) for *solar system research*, one must accomplish orders-of-magnitude improvements in our knowledge of ice giants *interiors and atmospheres* by performing some of these key measurements on interiors and atmospheres: (1) spherical harmonic developments of gravity and magnetic fields to the highest possible degree; (2) chemical and isotopic compositions of heavy elements, noble gases and condensable atmospheric species; (3) multi-wavelength observations of the horizontal and vertical distribution of clouds and condensable species at the synoptic and regional scales; (4) the degree of internal layering and chemical differentiation of the atmospheres and interiors; (5) their global energy balances; (6) the shapes of the planetary bodies.

2. Diversity of planetary systems architectures (Q2).

Diversity that can be found in ice giants systems in their ring and moon systems (Figure 2) and magnetospheres (figure 3).

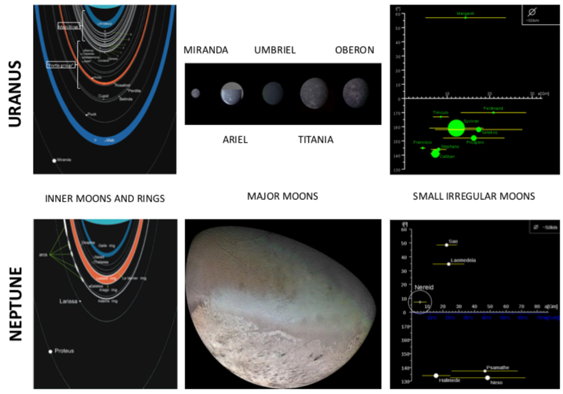

Figure 2*: A synthetic description of the ring and moon systems of the ice giants. One can distinguish three main components from left to right, located at increasing radial distances to their host planet: (1) their interspersed systems of rings and small inner moons, (2) their major moons (five for Uranus and only Triton for Neptune); (3) their populations of small irregular satellites, represented here as a function of radial distance (horizontal axis) and inclination (vertical axis).*

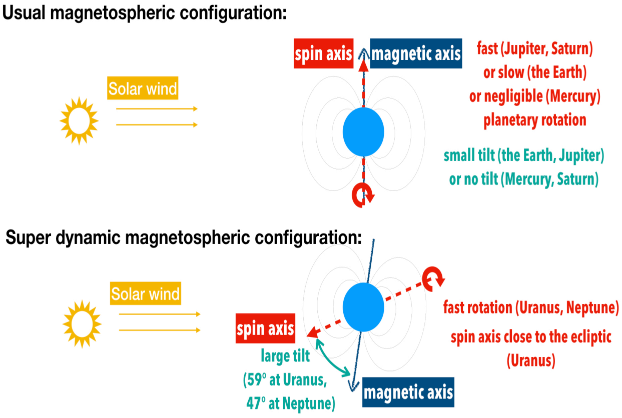

Figure 3*: an illustration of the unique configurations of ice giants magnetospheres: because of the large tilt existing between their planetary spin axis and their magnetic dipole moment, their interaction with the solar wind experiences a strong modulation at the planetary rotation period. In the case of Uranus, the low inclination of its rotation axis about its planetary orbital plane adds a strong seasonal variation to the planetary spin modulation.*

Key measurement requirements

Moon systems: Since the original moon system of Neptune seems to have been wiped out by the capture of an exogenic body, e.g. Triton, studying the regular moon system of Uranus is the priority to shed new light on the possible scenarios of in-situ generation and evolution of giant planet moons. Accurate measurements of the satellites' shapes, masses, first gravity moments (for an evaluation of their degree of differentiation), mapping of surface properties and geologic features (with emphasis on their cratering record and chemical and mineralogical composition), and estimates of bulk composition should be performed at all or most regular moons. Close flybys of a few of the irregular satellites, which are unique witnesses of the populations of small bodies that resided in the outer solar system at the times of ice giants formation and migration, will be a must. They will provide orders of magnitude increases in our poor knowledge of their mass, shape, cratering, bulk and surface composition, all invaluable to a better understanding of their nature and origins.

Magnetospheres: Ice giant magnetospheres offer unique seasonal and planetary spin modulations and equally unique time-varying configurations and characteristic Alfven Mach numbers of their interactions with the solar wind. For this sole reason, investigating their structure, dynamics, plasma and particle regimes and auroral emissions is mandatory to explore the diversity of magnetospheric configurations in the Solar System. Exploring at least one ice giant magnetosphere, preferably at Uranus which offers the largest amplitude in its seasonal and planetary spin modulations, would be a major advance for this field with broad applications. This requires an in-situ exploration by an orbiter providing a good coverage of magnetic latitudes, local times and radial distances and exploring the medium and distant magnetosphere as well as auroral and polar phenomena.

Ring systems: Future spacecraft investigations offer a unique opportunity to settle fundamental, first-order science questions concerning Ice Giants ring systems and their relation to the rings of Jupiter and Saturn, an investigation that will also shed light on models of planet formation and migration in the solar system and will address many other questions: what are the differences in ring composition? What is the origin of ring systems, and why are they so different? How do ring-moon systems evolve? What is the bombardment history of giant planets by projectiles from the Kuiper Belt or the Oort Cloud? What are the precise mechanisms of ring confinement?

Imaging at high and intermediate phase-angles will constrain the shapes and properties of known dust rings. It can potentially lead to new rings discoveries and constrain the large-scale structure of the systems. Multicolor imaging at a range of phase angles will determine the size distribution of the grains that form the dust rings. Imaging at low phase-angles will probe the structure of dense rings and allow for a comprehensive search and discovery of yet unseen moons that serve as sources for ring material, interact dynamically with the rings and determine their long-term evolution. Stellar occultations performed with a high-speed photometer, as well as radio occultations, will determine the precise radial and azimuthal optical depth profiles of the denser rings, resolve their fine sub-structure and modes induced by resonant confinement by the satellites. An IR spectrometer can determine the ring composition and constrain the thermal inertia of the dense rings through observation of the night-day cycles. In a complementary manner, a dust detector will directly determine the composition of grains forming the low optical depth dust rings [3] and of particles lifted from the dense rings [4]. It will also provide a measurement of the flux and composition of interplanetary particles in the outer solar system, a quantity of high importance to understand the origin and evolution of rings. Neutral mass spectrometry can likewise determine the volatile components of the rings.

3. Origin and formation scenarios of ice giant systems (Q3)

There are two leading theories on how giant planets formed: core accretion ([5]; [6]) and disk instability. Only in-situ and close-in observations will make it possible to discriminate between these scenarios.

The formation conditions of the building blocks of Ice Giants are of particular interest in this perspective. It was proposed ([7]; [8]) that these icy building blocks could be divided into an outer reservoir of pristine amorphous ice with protosolar composition and an inner reservoir consisting of pristine water ice that was volatilized in the Solar Nebula and then re-condensed as crystalline ice on refractory grains at 150 K [9].

However, the noble gas abundances measured by *Rosetta* in comet 67P/C-G provide evidence for a third reservoir intermediate to these two. This reservoir was heated to the transition point from amorphous to crystalline ice, which caused the release of the volatiles that had been adsorbed in the pristine ices. As the Solar Nebula cooled, formation of clathrates and condensation of the released volatiles led to the composition of the building blocks for 67P/C-G.

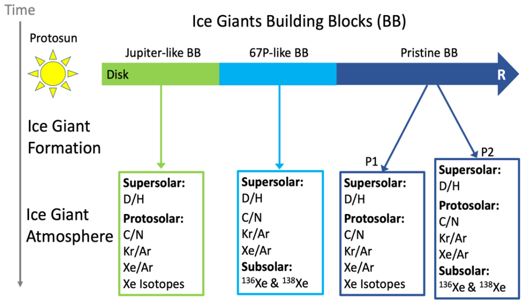

Figure 4: Four scenarios connecting the origin of Ice Giants building blocks to measurements of their noble gases abundances and isotopic compositions based on where their building blocks formed within the SN. From [10].

Figure 4 shows four different possible pathways connecting the current composition of ice giants atmospheres to their building blocks. Their composition varies with distance from the young Sun as does the composition of ice giant atmospheres resulting from formation with these building blocks [10]. The series of chaotic events that dominated the Primordial Solar System period after the initial formation of giant planets also had a profound influence on their early evolution and orbital migration, as described in the Nice model (e.g., [11]; [12]). Measuring the bulk and atmospheric elemental and isotopic compositions of Neptune and Uranus thus offers a critical test to this model.

Key measurements requirements.

Uranus and Neptune: *In situ* measurements with an entry probe are necessary to further constrain the origin of ice giant systems and their atmospheres and interiors, and to provide ground-truth for improved understanding of extrasolar planetary systems. Only *in situ* exploration by a descent probe (or probes) can provide the composition of the deep, well-mixed atmosphere where pristine materials from the epoch of solar system formation can be found. Particularly important are the noble gases, undetectable by any means other than direct sampling, that carry many of the secrets of giant planet origin and evolution. The primary goal of an ice giant entry probe mission is to measure the well-mixed abundances of the noble gases He, Ne, Ar, Kr, Xe and their isotopes, the heavier elements C, N, S, and P, key isotope ratios ^{15}N/^{14}N, ^{13}C/^{12}C, ^{17}O/^{16}O and ^{18}O/^{16}O, and D/H, and disequilibrium species CO and PH3, which act as tracers of internal processes, and can be achieved by a probe reaching 10 bars. A descent probe would sample atmospheric regions far below those accessible to remote sensing, well into the cloud forming regions of the troposphere to depths where many abundant species of cosmogenic significance are expected to be well-mixed. By extending the legacy of the Galileo probe mission, Uranus and/or Neptune probe(s) will further discriminate competing theories addressing the formation and evolution of giant planets, of the entire solar system and of other planetary systems. Probe measurements should be complimented by microwave measurements to provide a global structure of the important volatiles and an understanding of the dynamics in the deep atmosphere.

Satellite systems: Future exploration missions could help to pin down the mechanisms of formation and/or capture of the satellite systems of ice giants by providing further constraints on the composition and interior structure of the moons, their host planet and rings. In order to elucidate the relative roles of the different scenarios for the formation of moon systems at ice giants, it is urgent to raise our level of knowledge of their satellites to a level comparable to the one we have for the gas giants. Since the original system of regular moons of Neptune appears to have been disrupted by the capture of Triton, studying the Uranian moon system is the priority to shed new light on the possible scenarios of in-situ generation of giant planets moons inside a circum-planetary disk (CPD) [13]. Characterization of several of the irregular satellites will be essential to better know their mass, shape, composition, cratering records and surface weathering, all important elements to better understand their origin, their connection to the other populations of small bodies of the outer solar system, and the history of their capture. Measurements of the chemical and isotopic compositions of the satellites would reveal important clues regarding their formation conditions, as well as the origins of their building blocks. D/H measurements, as well as the determinations of isotopic ratios in the main C-, N-, and O-bearing molecules, will be of primary importance.

Rings: Constraining the age of the rings together with the one of the moons with which they interact most will be essential to make significant progress in our understanding of their formation and age. If the rings are primordial or sufficiently old this may also put constraints on the event that tilted Uranus. Measurement of the chemical and isotopic composition of the rings would enable a connection between them and the material that took part in the assembling of satellites, as shown by the Cassini spacecraft during the Grand Finale ([4]; [14]).

4. **How do ice giants and their systems work?** (Q4)

Designing and flying an in-depth exploration of the two Ice Giants will be the only way to start better understanding how ice Giants systems work.

Key measurement requirements:

Atmospheres: in situ measurements on atmospheric composition and thermal structure by a probe will be combined with orbital observations of atmospheric dynamics at high-resolution and multiple wavelengths and with ground-based surveys of the atmospheric activity of these planets as their slowly evolving seasons proceed. Accurate measurements of the gravitational fields can be used to determine the depth of the winds (e.g., [15]), and possibly also the internal rotation period [16], which are important for atmospheric dynamics and potentially the dynamo as well.

Interiors: gravity and magnetic field measurements close to the planet at a variety of latitudes and longitudes will allow characterization of the ice giants' higher degree structure. Since the internal magnetic field may have undergone temporal changes since the Voyager 2 epoch, new observations will provide constraints on secular variations and potentially identify changes in the locations of flux patches indicative of zonal and/or meridional winds in the deep interior [17]. While the ice giants were long sought to be convective throughout, with an interior dominated by a fluid water—rich C-H-O-N mixture, recent improvements in planetary and dynamo modelling as well as in the understanding of equations of state and thermodynamic properties at ice giant compositions, pressures and temperatures suggest that the internal structure may be much more complex [18].

Plasma environments: While some aspects of the Uranian magnetic field and magnetospheric physics can possibly be investigated remotely from the tracking of its auroral emissions through UV or radio Earth-based facilities, the in-depth study of the ice giant atypical magnetospheres requires in situ measurements from dedicated explorations probes with close-in passes within their polar regions ([19] ; [20]; [21]). Such a Juno-like polar exploration is accessible to equatorial orbiters at both planets owing to their large magnetic tilt, especially at Uranus. Key measurements include magnetic observations from close-in distances sampling all longitudes to accurately measure the topology of the magnetic field, its dynamics and the main electric currents coupling ionosphere, magnetosphere, solar wind, moons and/or rings. Complementary observations of high and low energy charged particles will sample the various plasma populations, their sources/sinks and their main transport and energization processes. Plasma and radio wave observations will be essential to probe auroral emissions remotely, and improve our knowledge of the planets' rotation period and magnetospheric dynamics. They will also provide an in-situ validation of their radio emission mechanism (suspected to apply to exoplanets as well), and allow one to monitor lightnings (which can be used as a diagnostics of the ionospheric peak plasma density) and local plasma waves (giving access to in situ plasma parameters). Finally, UV spectro-imaging will accurately track the locus/structure of active magnetospheric regions and their energetics.

5. Active moons and potential habitats (Q5)

Habitable worlds are celestial bodies that have environments capable of sustaining life. Within Ice Giants systems, potential habitable worlds are Triton and the subset of Uranian moons that might support interior oceans.

Key measurement requirements

Uranian moons: The questions of which of these moons have oceans can only be settled by another mission that performs close flybys in which magnetic field searches for induced or intrinsic fields, gravity data on interior mass distributions, and comprehensive imaging is obtained for each of these moons. Plume searches on Ariel and high-resolution imaging on Miranda are compelling key priorities. Any spacecraft performing these investigations will need to be in an orbit around Uranus in or close to the plane of the Uranian moons, or to cross it frequently. Voyager 2 gave us just enough data to argue that these moons are worth a detailed future visit.

Triton: Triton is the largest of the known objects in or thought to be once in the Kuiper Belt; its retrograde orbit indicates almost certain capture by Neptune. It is more massive than either Pluto or Eris, and with a density of just over 2 g/cm^3, has a significant fraction of rock in its interior. The paucity of impact craters and unusual surface geology of its water ice crust, combined with overlays of pure and mixed nitrogen, carbon dioxide, methane and carbon monoxide ices [22], speak to a complex history over geologic time. Although heating associated with capture at Neptune is likely mostly lost by now, other sources (radiogenic, obliquity tides) are each sufficient to allow for a cold ocean containing water and ammonia. Even a New Horizons payload on a close flyby of Triton would reveal much more than did Voyager 2's more limited payload. For that reason, the proposed Discovery mission Trident to do such a flyby [23] is scientifically attractive. However, a thorough understanding of Triton as an ocean world might require multiple flybys to determine the state of its crust, the density distribution in its interior and to detect an induced magnetic field. Probing beneath the nitrogen ice and into the ice crust will require techniques such as a penetrating radar.

6. Key measurements preparing for a future search for Life (Q6)

Extensive characterization of the habitability of the moons of Uranus and Neptune is required before a search for life can be engaged. Triton shows the most promising characteristics so far. However, the presence of liquid water below the ice and its communication with the surface are currently not established. A future mission to an Ice Giant system should include searching for oceans and for possible ocean material imprints on the surface at all potentially habitable moons, using an instrument payload primarily designed for a multi-disciplinary exploration of an Ice Giant system. A dedicated search for life will require accessing ocean material, likely by way of a lander.

7. Synthesis: from science objectives to measurement requirements

Based on our analysis, table I below displays the correspondence between science questions, measurement requirements and destinations for the exploration of ice giants systems. Light green boxes show which destinations (Uranus, Neptune, both planets, and Triton) address each question. Dark green suggests some priorities.
In part II of this White Paper we will describe a sequence of missions to the Ice Giants that can perform the key measurement requirements described here.

Horizon 2061 science question	**Measurement requirements / object type**				**Destination(s)**			
	Atmosphere and interior	Rings	Moons	Magnetosphere	Uranus	U and N	Neptune	Triton
Q1- Diversity of objects	Understanding the place of Ice Giants in the family of planets: bulk and atmospheric composition, internal structure, relations to atmospheric circulation	Ring particles physical, properties, composition, albedo, from multispectral imaging at varied phase angles, occultations, dust measurements	Moons shapes, surface geology and composition, exosphere composition, bulk composition, activity, internal structure		🟩	■	🟩	
Q2- Diversity of architectures and relation to formation/early evolution	Determining the orbital evolution of ice giants in the early solar system and the role of giant collisions in their formation and evolution	Rings types, radial distribution, dynamics, interactions, exchanges of material with moons, multi-decadal temporal evolution	Moons mass and size radial distribution, dynamics, resonances and tides, orbital evolution.	Plasma and magnetic field configurations, solar-wind-magnetosphere-ionosphere coupling, MIT coupling regimes, radio and auroral emissions	■	🟩	🟩	
Q3- Origin of ice giant systems	Abundances and isotopic ratios of heavy elements and noble gases in planetary atmosphere; bulk composition; degree of differentiation and internal layering	Determination(s) of the age of rings	Abundances and isotopic ratios of heavy elements and noble gases in exosphere & surface; bulk composition; surface geology incl. cratering		■	🟩	■	🟩
Q4- How do ice giant systems work?	Internal dynamics, heat transfer mechanisms and associated layering (stable vs. convective layers), measurement of spherical harmonic components of B field to the highest possible degree	?	?	Magnetospheric configuration, plasma domains, charged particle distributions and sources, satellite interactions, auroral acceleration processes, MIT coupling	■	🟩	🟩	
Q5- Search for potential habitats			Characterization of the habitability of active moons (Triton, Ariel, Miranda,…), presence of an ocean?		🟩			■
Q6- Search for Life			For identified ocean moons: characterization of ocean, priority terrains for search of life, biosignatures expected		🟩			🟩

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