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

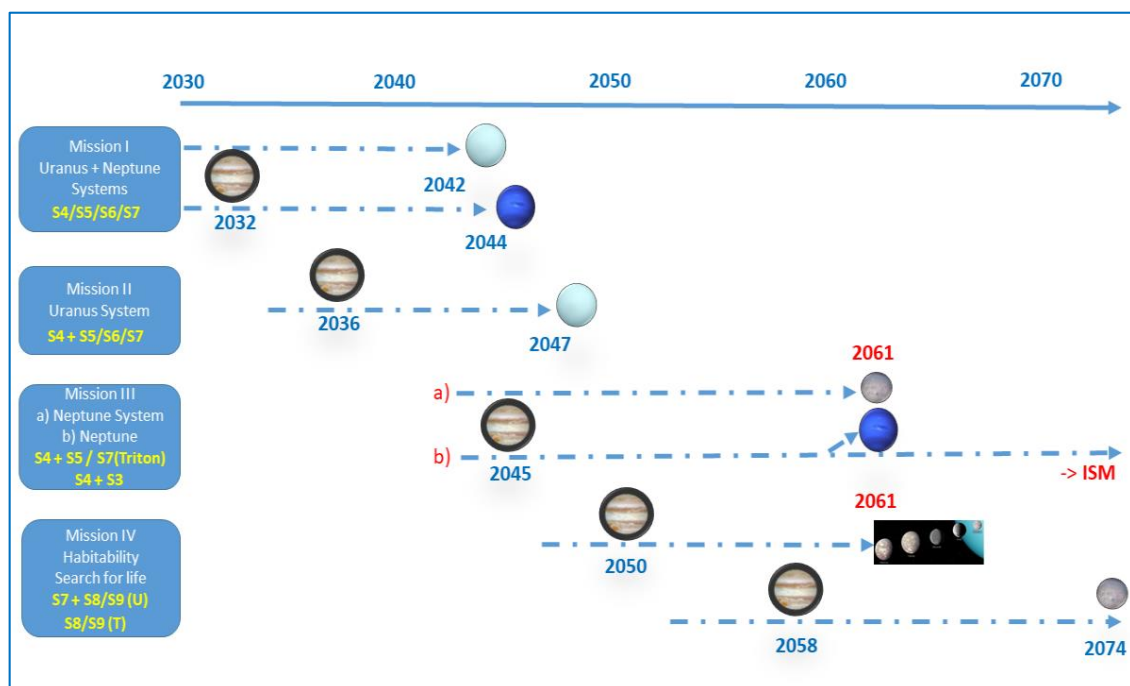
## Part II: From Measurement Requirements to Mission Scenarios

A White Paper prepared for the  
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ICE GIANTS MISSIONS NOTIONAL ROADMAP

## 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 part I of this White Paper, based on a comprehensive article in which more details can be found [1], we showed how the six “key questions” can be addressed in depth at ice giant systems and identified measurement requirements for missions to these systems.

In part II, this current White Paper, we now describe a sequence of missions to the Ice Giants that can perform the key measurement requirements identified in part I.

### 1. Reference flight science sequences

We suggest that the measurements required to address the six key science objectives of Horizon 2061 will be performed by ice giants missions using a succession of typical flight science sequences which are currently used in the design of missions to giant planet systems. These configurations can be classified in terms of eleven notional flight science sequences, S1 to S11. For each sequence, table I gives its main science applications and examples of space missions using it. Let us briefly comment it.

**S1** “Earth-based Observations” corresponds to the observations of planetary objects performed from the ground or from Earth-Moon system orbits. Building on the HST legacy, the role of these remote observations should remain very important in the coming decades with the advent of JWST and giant space telescopes in space and with Extremely Large Telescopes on the ground, which will offer unprecedented spatial and spectral resolution.

**S2** “Interplanetary cruise”: in addition to the opportunities this mandatory phase of a planetary mission offers for heliospheric science, its approach phase to a planet can be used to study the coupling of the planet to the interplanetary medium, for instance by monitoring at the same time the variations in the planet’s radio and auroral emissions. The long and continuous observation time offered by an orbiter en route to a giant planet could also be used for planetary seismology studies that would complement other approaches to the determination of the internal structure, given an instrument adapted to such a study is available on board [2] [3].

**S3** “Planetary fly-by”: a “simple” fly-by of an ice giant with state-of-the art instruments can nowadays provide an enormous science return compared to Voyager. Close (low altitude) fly-bys allowing measurements of the gravity and magnetic field along the arc of the fly-by, combined with imaging and passive microwave radiometry, can provide unique information on ice giants internal structure and atmospheric composition.

<b>FSS #</b>	<b>Flight sequence name</b>	<b>Main science addressed</b>	<b>Example(s)</b>
<b>S1</b>	Earth-based Observations	All disciplines but mainly atmosphere, rings and satellites. Access to multi-decadal temporal variations	HST, JWST, EELT...
<b>S2</b>	Interplanetary cruise	2.e/4.c - Heliosphere, Interplanetary medium effects on magnetosphere	Cassini@Jupiter&Saturn, Juno@Jupiter
<b>S3</b>	Planetary fly-by	All disciplines	Voyager
<b>S4</b>	Atmospheric entry probe	1 – Origins; 3.b – Early dynamics of the Solar System; 2.b – interiors and atmospheres	Galileo, Huygens
<b>S5</b>	Synoptic orbital survey of the system	2&3 – Diversity of systems and objects; 4 - How do these systems work?	Galileo, Cassini, JUICE
<b>S6</b>	Quasi-polar, low periape multiple-orbit survey	1 – origins; 2.b – interiors and atmospheres; 3.e – diversity of magnetospheres	Juno, Cassini proximal orbits
<b>S7</b>	Multiple satellite(s) fly-bys	1- Origins; 2.c – diversity of moons 3.d – diversity of moon systems;	Cassini, Europa Clipper, JUICE
<b>S8</b>	Planetary moon orbital survey	2.c – diversity of moons; 5 – moons activity and habitability	JUICE
<b>S9</b>	Planetary Moon Lander	5 – moons activity and habitability; 6 – search for life	Huygens, Europa lander
<b>S10</b>	Planetary Moon mobile element		Dragonfly
<b>S11</b>	Planetary Moon sample return	5, 6 - Search for life; 1 Origins; 2, 3 - diversity	Apollo, MSR, MMX-Phobos, Caesar, future ice-drilling missions

*Table 1 - Flight science sequences (S1 to S11) used in the mission plans of missions to giant planets systems to design comprehensive tours of these systems.*

**S4** “Atmospheric entry probe” will provide unique information on a broad spectrum of science questions, mainly the origins of ice giants and their atmospheric composition, and help constrain the determination of their internal structure and heat flow, as has been described extensively in [4] [5].

**S5** “Synoptic orbital survey of the system” is a series of orbits at low-to-medium inclinations, out of the equatorial plane, needed to provide a fair coverage of latitudes (for atmospheric studies), phase angles (for rings studies) and of the different magnetospheric regions.

**S6** “Quasi-polar, low periaapse multiple-orbit survey”, in contrast to S5, uses a very high inclination and a low periaapse to fly very close to the planet and, over a series of successive orbits, provide a good coverage of longitudes to describe the main planetary fields (magnetic, gravity, plasma) and perform passive far IR and/or microwave sounding of its atmosphere, an approach used by the Juno mission [6].

**S7** “Multiple moon fly-bys” allows one to characterize moons shapes, surface characteristics, exosphere, gravity and magnetic fields. This approach, extensively used by Cassini, Europa Clipper and JUICE, will be well suited for the study of the Uranian moons and can also prove effective for Triton [7].

**S8, S9** and **S10** correspond to sequences of increasing complexities and science returns for the study of a single planetary moon: first a series of polar orbits (**S8**) similar to the JUICE final sequence in orbit around Ganymede; then landing on the moon’s surface to characterize a specific site, its surface and its coupling to the sub-surface and atmosphere/exosphere (**S9**); and finally a mobile element (**S10**).

**S11**: Finally, the ultimate way of studying the origin of a planetary moon and the astrobiological information it can contain is a sample return. We list it here for the sake of completeness but do not believe it can be implemented at the ice giants by 2061.

## **2. Tentative science traceability matrix for the six key science questions.**

Based on the analysis of the six science questions presented in part I of this WP, we designed a synthesis table for the exploration of ice giants systems (Table 2). The light-blue boxes display the main measurements corresponding to each science question for the atmosphere and interior of the planet, its rings, moons and magnetosphere.

Then the four right-hand columns show how well the different possible destinations of missions to ice giant systems potentially address the six science questions. We have introduced in the “destination” columns one for combined missions to both giants and one for Triton, given its outstanding place in the family of ice giant moons.

Inspection of each horizontal line in Table 2 allows one to determine a preferred strategy to address each of the six science questions.

**Q1- Diversity of objects:** Uranus and Neptune are sufficiently different (see Table 1 in [1]) to require that both planets be visited with two suites of properly intercalibrated scientific instruments. As much as possible, one probe at each planet (S4) is needed, complemented preferentially by an S6 orbital mission or, minimally, by a fly-by (S3) providing measurements of internal planetary fields and passive microwave sounding of the atmosphere. It would be very relevant in terms of scientific added value to take advantage of another mission on its way to a farther destination, like TNO’s, heliopause boundaries or the interstellar medium.

**Q2- Diversity of systems architectures:** characterizing in depth the different elements of the architecture of at least one of the ice giants systems is required. Uranus has the additional advantage that it hosts a system of endogenic regular moons. The Uranian and Neptunian rings systems and magnetosphere are qualitatively just as interesting and sufficiently different from their gas giant counterparts to deserve an in-depth exploration using an S5 flight sequence. Between the two systems, the larger coverage of the rings and magnetospheres parameter space at Uranus points to a slight preference for this destination.

**Q3- Origin of Ice Giants systems:** In-situ measurements of key elemental and isotopic abundances in at least one the ice giants, complemented by a low-periaapse, high inclination orbiter (S6) “à la Juno” performing microwave remote sensing of the atmosphere [17] and constraining the internal structure from gravity and magnetic field measurements will revolutionize our understanding of the origins and evolution of ice giants.

Horizon 2061 science question	Measurement requirements / object type				Destination(s)			
	Atmosphere and interior	Rings	Moons	Magnetosphere	Uranus	U and N	Neptune	Triton
<b>Q1- Diversity of objects</b>	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					
<b>Q2- Diversity of architectures and relation to formation/early evolution</b>	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				
<b>Q3- Origin of ice giant systems</b>	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					
<b>Q4- How do ice giant systems work?</b>	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	Multi-wavelength observations of the changing configurations of the different ring components and of nearby or imbedded small moons at a variety of phase angles to characterize their different dynamical regimes and modes of interaction		Magnetospheric configuration, plasma domains, charged particle distributions and sources, satellite interactions, auroral acceleration processes, MIT coupling				
<b>Q5- Search for potential habitats</b>			Characterization of the habitability of active moons (Triton, Ariel, Miranda,...), presence of an ocean?					
<b>Q6- Search for Life</b>			For identified ocean moons: characterization of ocean, priority terrains for search of life, biosignatures expected					
<b>Preferred mission scenario(s)</b>	<b>S4 + S6</b> or <b>S4 + S3</b>	<b>S5</b>	<b>S7 + S8 (Triton)</b> Later <b>S9/S10</b>	<b>S5 and/or S6</b>	<b>S4 + S6/S5/S7</b> Later <b>S8/S9 ?</b>	<b>S4 + S5/S7T</b> or <b>S4 + S3</b>	<b>S7 + S8</b> Later <b>S9/S10 ?</b>	

Table 2 – Science Traceability Matrix for missions to giant planets systems based on the six science objectives of Horizon 2061. A green box indicates first priority destinations for each science question, and dark green indicates priorities of special importance. Yellow boxes in the bottom line indicates the preferred flight science sequence(s) to study each component of the system (left-hand side columns) and the preferred combination of sequences for each destination (four right-hand side columns).

Complementary measurements of the bulk and surface composition of the most primitive moons and of their internal structure, surface geology and cratering history, preferentially at Uranus where the regular moons may have been co-generated with their host planet, will provide a similar progress in our understanding of the origin of these moons and of the system as a whole. On the other hand, Triton in itself bears a strong interest, as a captured TNO, to study the origin and formation scenario of the solar system as a whole.

**Q4- How do Ice Giants systems work?** We suggest to focus the study of the “workings” of ice giants systems on a few science themes: internal dynamics and their implications for heat transfer and the dynamo; atmospheric circulation; magnetospheric dynamics and its coupling to the upper atmosphere. Performing this study at both planets would be invaluable, particularly to understand the mystery of their very different external radiation flux and for a better characterization of solar system ice giants in view of their comparison to exoplanets of a similar class (see section 2.1 in [1] and [14]).

**Q5- Search for potential habitats:** based on our current knowledge, Triton is the best candidate for a habitable moon in the two systems. Characterizing its habitability should be one of the highlights of the first dedicated mission to the Neptune system. Following a scenario similar to JUICE at Ganymede, a mission to the Neptunian system should end up with multiple Triton flybys (S7) or even better a Triton orbiter after a first phase in Neptune orbit (preferably S6, then possibly S5).

**Q6- Search for life:** once the prerequisites for the search for life have been established and the best candidate habitable moon has been identified (likely Triton, or one of the active Uranian moons), a second mission dedicated to the search for life at the best candidate planet could be designed and launched before 2061.

When read across all questions, Table 2 tells us that, in order to properly address all six questions at the ice giants, one dedicated mission to each of the systems will be needed. However, visiting only one of the two systems first will address many of these questions, and will be a huge step forward. Between the two systems, visiting Uranus first makes sense to address our first four questions: characterize ice giants in the family of planets, their systems in the family of planetary systems, understand their origin and formation scenarios, and study how they work. The corresponding preferred mission scenario is the combination of an atmospheric probe (S4) with an orbiter mission using flight sequences S6/S5/S7 in a t.b.d. order: a high-inclination sequence to probe the interior and atmosphere, a mid-inclination sequence to observe atmosphere, rings and magnetosphere, and multiple flybys of the regular moons.

On the other hand, the Neptune system is potentially a better choice to address the last two science questions, e.g. the habitability of ocean moons and the search for life there. Triton will naturally focus much attention in such a mission, whose preferred profile, after delivery of a probe (S4) could be a sequence S5/ S7@Triton, ending in orbit around Triton in a scenario similar to JUICE@Ganymede.

### **3. From mission requirements to notional mission scenarios**

Studying the implementation of these scenarios in the Horizon 2061 time frame would require a detailed analysis of launch opportunities and enabling technologies which is far beyond the scope of this WP. We only use here the studies performed for the latest Decadal survey [7] and the ESA Ice Giants CDF study report [8].

With conventional launchers used for planetary missions (Ariane, Atlas...) any mission trajectory within the 2061 timeframe will have to include several planetary gravity assists, and a flyby of Jupiter will be mandatory. Uranus and Neptune do not align, so a single spacecraft cannot visit both planets [7], as was possible for the Voyager grand

tour. For Uranus, the next possible transfers from Jupiter occur in 2036, 2050 and 2064, with a journey to destination in 11 years minimum in order to keep an arrival velocity compatible with an orbit insertion. The launch date from Earth is 2-5 years earlier, therefore in the ranges 2031-2034, 2045-2048 and 2059-2062 respectively. For Neptune, the next possible transfers from Jupiter occur in 2032, 2045 and 2058, with a minimum 16 years journey time to destination. To keep a reasonable mission duration, Earth launch dates could be 2 years earlier, e.g. 2030, 2043 and 2056. An atmospheric probe could also be delivered to Uranus or Neptune by a mission on its way to the interstellar medium, if compatible with its resources.

Finally, let us mention the interesting opportunity of a dual spacecraft dual-planet single launch in February 2031 studied in [7] and [8]. A SLS-IB heavy lift launch vehicle could send a composite of the Uranus and the Neptune orbiters directly to Jupiter together with a solar electric propulsion stage. The orbiters could carry an atmospheric probe. The two orbiters would separate during the transfer to Jupiter and perform independent Jupiter swing-by's in December 2032: a very close swing-by at a perijove altitude of ~10,000 km for the Uranus orbiter, and a much higher one at ~857,000 km for the Neptune orbiter, after which the two spacecraft would reach their targets in April 2042 and September 2044, respectively. This scenario provides an implementation of the scenario described in the ODINUS dual ice giants mission concept [2].

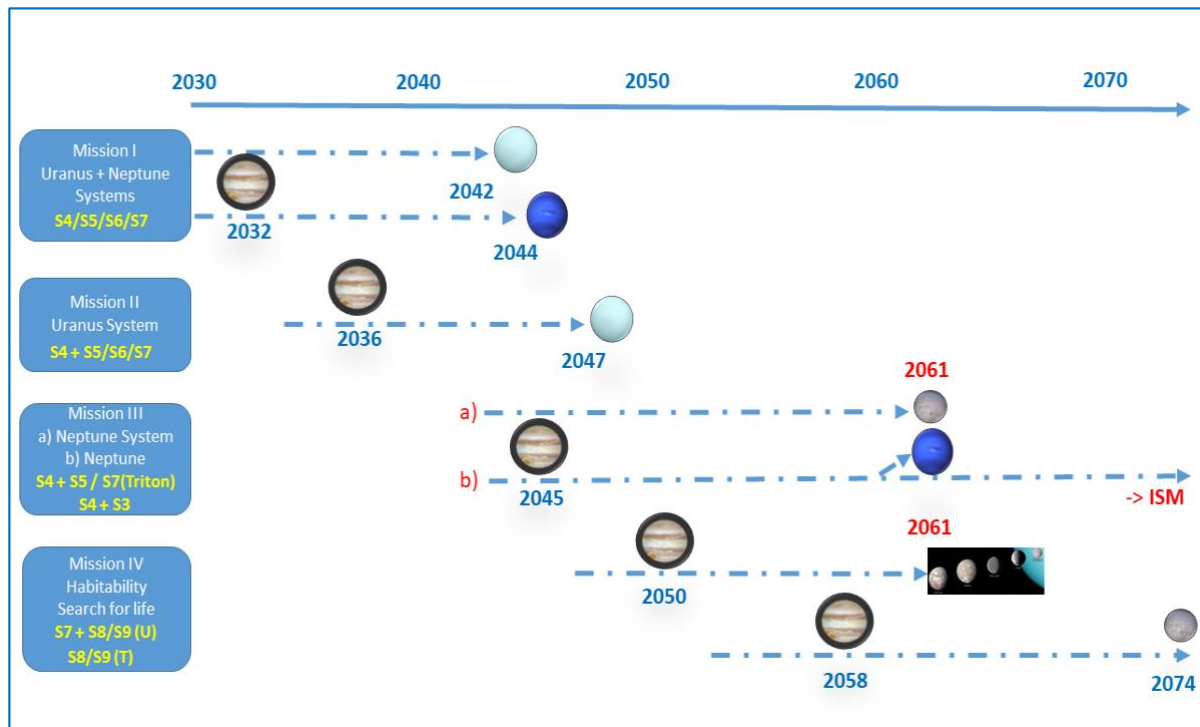
By allocating our preferred mission scenarios for each of the four possible destinations (bottom line of Table 2) to the different Jupiter fly-by windows to Uranus and Neptune just described, we built the sequence of mission opportunities, named Mission I to IV, illustrated from top to bottom in Figure 1. Mission I takes advantage of the dual Jupiter fly-by opportunity mentioned above to send two missions to the two ice giants simultaneously. If this opportunity cannot be met, one should plan to take advantage of the next two windows, one to Uranus with Jupiter fly-by in 2036 (mission II), one to Neptune with Jupiter fly-by in 2045 (mission IIIa), to fly a mission with the preferred profile to each of these planets. If only one of the two missions can be afforded, we suggest to fly mission II to Uranus and take the opportunity of a fly-by of Neptune by a different mission to the outer solar system, for instance a mission to the TNOs, the heliosphere boundaries and/or the local interstellar medium [12] [13], to deliver a probe into Neptune's atmosphere. This is what we identify as mission IIIb.

Finally, a follow-on mission dedicated to the search for life, either at one of the active moons of Uranus (mission IVa), or at Triton (mission IVb), could be designed and launched before 2061 once the best candidate for habitability has been identified by missions II and III. Mission IVa would fly by Jupiter in 2050, while mission IVb would fly by Jupiter in 2058: a very appealing window for an astrobiology mission to Triton.

#### **4. NASA-ESA collaboration opportunities**

Past studies by NASA and ESA (e.g. [7], [8]) have opened the way to international collaborations [15], showing that, from the technical point of view, a joint mission to an ice giant including an orbiter and an atmospheric probe could be developed, following a scenario similar to Cassini-Huygens. Dual spacecraft mission scenarios, with NASA and ESA flying jointly two orbiters to each of the ice giants, would also be technically feasible. Implementation of these collaboration opportunities will depend on the outcome of the current NAS Decadal Survey for Planetary Science and Astrobiology and, on the ESA side, of the Voyage 2050 planning exercise, to which three White Papers dealing with the exploration of Ice Giants systems have been submitted [9] [10] [11]. See also the follow-on publication of a science case for orbital science [16].





**Figure 1:** An illustration of the different mission opportunities offered by the fly-bys of Jupiter en route to ice giants up to 2061, together with the preferred flight sequences for each of these windows and destinations (see text).

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