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Uranus and Neptune missions: A study in advance of the next Planetary Science Decadal Survey

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ABSTRACT

The ice giant planets, Uranus and Neptune, represent an important and relatively unexplored class of planet. Most of our detailed information about them comes from fleeting looks by the Voyager 2 spacecraft in the 1980s. Voyager, and ground-based work since then, found that these planets, their satellites, rings, and magnetospheres, challenge our understanding of the formation and evolution of planetary systems. We also now know that Uranus-Neptune size planets are common around other stars. These are some of the reasons ice giant exploration was a high priority in NASA's most recent Planetary Science Decadal Survey. In preparation for the next Decadal Survey, NASA, with ESA participation, conducted a broad study of possible ice giant missions in the 2024–2037 timeframe. This paper summarizes the key results of the study, and addresses questions that have been raised by the science community and in a recent NASA review. Foremost amongst these are questions about the science objectives, the science payload, and the importance of an atmospheric probe. The conclusions of the NASA/ESA study remain valid. In particular, it is a high priority to send an orbiter and atmospheric probe to at least one of the ice giants, with instrumentation to study all components of an ice giant system. Uranus and Neptune are found to be equally compelling as science targets. The two planets are not equivalent, however, and each system has things to teach us the other cannot. An additional mission study is needed to refine plans for future exploration of these worlds.

1. Introduction

Uranus and Neptune are collectively known as the ice giant planets. They are fundamentally different from the better known terrestrial and gas giant planets, and formed and evolved in different ways (Guillot, 2005; Frelikh and Murray-Clay, 2017). The term “ice giants” reflects the consensus that, by mass, they are predominantly made of water and other so-called "ices," such as methane and ammonia. Those species were likely in a solid (ice) phase during the early stages of solar system formation. Today, however, virtually all of the water in an ice giant is thought to be

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in fluid phases (Fig. 1). The ice giants are the least understood of the three planetary types found in our solar system (Guillot, 2005). Terrestrial planets, such as the Earth, are almost entirely made of rocky material. The gas giants, Jupiter and Saturn, are predominantly made of hydrogen and helium.

Ice giants are important because they challenge our models of planet formation and evolution, and because they, along with their rings, moons, and magnetospheres, exhibit structures not yet understood. This is discussed more fully in Hofstadter et al. (2017) (hereafter referred to as the IG Study). An example of the challenge they present is that solar system formation models do not create ice giants unless restrictive timing, location, or nebular conditions are invoked (e.g. Frelikh and Murray-Clay, 2017). The venerable Voyager 2 spacecraft gave us our only close-in look at these objects during its brief dash through the Uranus system in 1986 and through Neptune's in 1989. Those tantalizing glimpses answered some basic questions, but also revealed that each is a unique planetary system containing unexpected phenomena.

Understanding the mysteries of the ice giants has implications beyond our solar system. The flood of exoplanets discovered around other stars has revealed that ice giants are common in our galaxy. Among all planets known today (see https://exoplanets.nasa.gov/for an up-to-date list), there are more ice giant sized planets as opposed to gas-giant or even terrestrial planets. (As of early May 2019, of the 3940 confirmed and categorized exoplanets listed on the referenced website, 34% are “Neptune-like” and 31% are intermediate in size between Earth and Neptune; most of these so-called Super-Earth's are thought to be more Neptune-like than Earth-like. Those numbers are to be compared to the 31% categorized as Gas-Giants, and 4% as Terrestrial. Given selection effects in exoplanet surveys, however, we cannot say with confidence whether or not ice giants are more abundant than gas giants.) Untangling the mysteries surrounding the ice giants in our solar system will lead to fundamental insights into the formation and evolution of planetary systems in general.

1.1. *The purpose of the mission study and this paper*

The above discussion explains why the 2011 Planetary Science Decadal Survey, titled *Vision and Voyages* (National Research Council, 2011, hereafter V&V) ranked a Flagship mission to an ice giant as a high priority, to be flown after a Mars sample cache and Europa mission. Now that work on those first two missions is underway, it is consistent with NASA's strategic plans to reconsider what an ice giant mission might look like. Recognizing that such a mission is likely to slip into the period governed by the next Decadal Survey, in August 2015 the Director of NASA's Planetary Science Directorate announced a "Pre-Decadal Survey" study of missions likely to be considered by the next Survey, starting with the ice giants. The ice giant study goal was to "Assess science priorities and affordable mission concepts and options in preparation for the next Decadal Survey" (Green, 2015). In regards to mission science objectives, NASA directed that they be based on V&V but “revised with recent developments in science and technology.” The full report of that study is available (the IG Study).

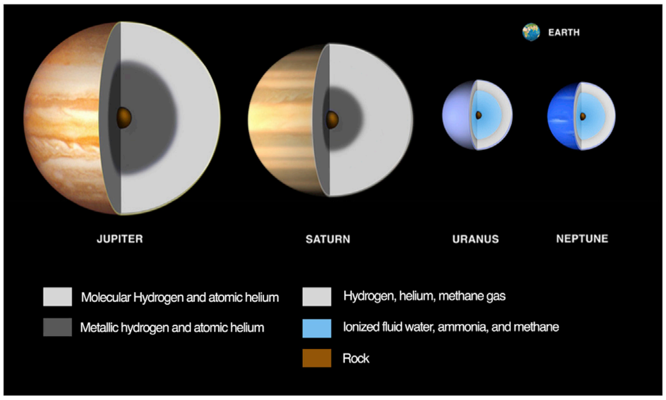

Fig. 1. Illustration of compositional and structural differences among the giant planets and their relative sizes. Earth is shown for comparison. Jupiter and Saturn are primarily made of hydrogen and helium, the terrestrial planets are almost pure rock, while Uranus and Neptune are thought to be largely supercritical water.

This paper, authored by all members of the IG Study Science Definition Team (SDT) and key members of the engineering teams, summarizes the report to make it as accessible as possible to the science community. We also clarify the discussion of science goals and potential science payloads to correct common misunderstandings that became evident since the IG Study's release in community discussions and in the recently completed National Academies mid-term review of progress implementing the V&V Decadal Survey (National Academies, 2018, hereafter referred to as the Mid-Term Review). Section 2 highlights some of the study methodology relevant for later discussions. Section 3 describes the priority science goals identified by the SDT. At the end of that section we discuss how the science to be done at Uranus is equally important to (but different from) the science to be done at Neptune, and the value of being able to compare the two planets. Section 4 discusses possible instruments to address the science goals, and presents the model payloads that were used for designing potential missions. Section 5 presents high-level conclusions regarding trajectories to the ice giants, and Section 6 summarizes the team's prioritization of possible mission architectures. Section 7 highlights relevant recent discoveries and their relation to differences among V&V, the IG Study, and the Mid-Term Review. Section 8 discusses the study's conclusions and recommendations in light of those advances.

2. Study approach

For details of how the IG Study was formulated and carried out, see the full report. There are a few aspects worth highlighting, however, as they will impact later discussions. First it should be noted that the IG Study is intended to be a broad survey sampling a wide range of missions and mission types. This allows it to guide high-level decision making, but also prevents it from extensively exploring what ultimately is the recommended mission architecture (an orbiter with probe).

The IG Study operated under a specific set of ground rules. For example, we were directed to reassess the science priorities of V&V in light of discoveries since V&V's publication. Therefore, the prioritization in the IG Study is different from that in V&V. This also allowed for a more detailed look at broad system science than was possible during the rapid V&V study. Similarly, we were tasked with identifying new technologies that could have a significant impact on an ice giant mission. In line with this directive, our study identifies items such as a Doppler Imager instrument which—while not necessary for a mission—are worthy of further study. There were also two important cost-related ground rules. First, launch vehicle costs were not included in our mission cost estimates. Second, there was some evolution of how to treat the cost target for the missions. While asked to study a range of mission costs, the initial cost target was identified as $2B (in FY15 dollars). Our preliminary reports therefore referred to our recommended mission as one with a relatively small (50 kg) payload which meets the $2B target. It was recognized, however, that a larger payload is needed to address all priority ice giant system science goals. In subsequent discussions with NASA and ESA, it was clarified that our recommended mission should be the one the science team believes should be flown, even if it exceeds the cost target by a moderate amount. We therefore ultimately recommend a 150 kg science payload for an ice-giant Flagship orbiter.

It should also be noted that, while this was a NASA study performed at the Jet Propulsion Laboratory/California Institute of Technology, many organizations were involved. The science team reflects a mix of NASA, academic, and private institutions. ESA is a full partner, having helped plan the study and contributing personnel and expertise. Purdue

University, Ames Research Center, Langley Research Center, and the Aerospace Corporation all made significant technical contributions, described in the full report.

3. Science objectives

3.1. Science objectives and priorities

The ice giants and their systems are a natural laboratory to challenge our understanding of fundamental processes in planetary formation, evolution, and structure. Following a process described in the full IG Study report, and starting with the comprehensive science output of a community workshop held in 2014 in Maryland, USA, the SDT identified 12 high-priority science objectives for an ice giant flagship mission. The list is very similar to what is in V&V, though the final prioritization changed somewhat to reflect knowledge gained in the few years between V&V and the IG Study.

We find that the two highest-priority objectives for the next ice giant mission are to

- Constrain the structure and characteristics of the planet's interior, including layering, locations of convective and stable regions, and internal dynamics
- Determine the planet's bulk composition, including abundances and isotopes of heavy elements, He, and heavier noble gases

These two objectives are ranked most highly because they define what it means to be an ice giant planet and they provide the best evidence for how and where these planets formed. These objectives must be addressed in order to understand ice giants as a type of planet, and they cannot be addressed by studying any of the other planets in our solar system. Furthermore, a space mission with both remote sensing instruments and an in situ atmospheric probe is needed to fully address these items. Earth- or near-Earth-based instruments cannot do the job (See the IG Study and Atreya et al., 2019 for a detailed discussion of the need for a probe, and the importance of measuring heavy noble gases and key isotopic ratios. Those abundances are not modified by atmospheric meteorology, dynamics, or chemistry, allowing a single entry probe to make definitive measurements diagnostic of planetary formation models [Fig. 2].).

The V&V Decadal Survey includes the above objectives (e.g. for interior structure see V&V Table ES.3; for references to noble gases and isotopic ratios, see the first paragraph on page 7–11), but does not rank them as top priority due to concerns about our ability to make the necessary measurements (V&V was limited to what could be accomplished based on current understanding and technology at the time, for a mission to launch before 2023). Our study makes use of recent technological advances and additional mission design work to mitigate those concerns (see Sections 5.2 and 7).

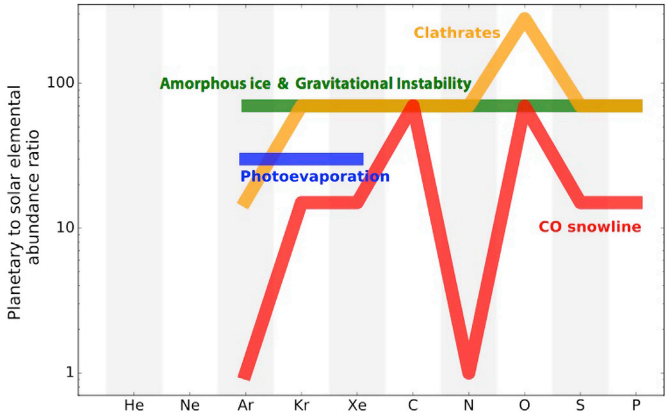

Fig. 2. Qualitative differences among the enrichment of noble gases and volatile species predicted by different Uranus and Neptune formation scenarios. Abundances are normalized to the carbon abundance. Figure is updated from Mousis et al. (2018) (Olivier Mousis, personal communication).

The remaining priority science objectives identified in the IG Study are all ranked of equal importance, and cover all aspects of the ice giant systems, from the interiors and atmospheres, rings and satellites (Fig. 3), and out to the magnetospheres and their interactions with the solar wind. They are (listed in order of distance from the planet's center):

- Characterize the planetary dynamo
- Determine the planet's atmospheric heat balance
- Measure the planet's tropospheric 3-D flow (zonal, meridional, vertical) including winds, waves, storms and their lifecycles, and deep convective activity
- Characterize the structures and temporal changes in the rings
- Obtain a complete inventory of small moons, including embedded source bodies in dusty rings and moons that could sculpt and shepherd dense rings
- Determine the surface composition of rings and moons, including organics; search for variations among moons, past and current modification, and evidence of long-term mass exchange/volatile transport
- Map the shape and surface geology of major and minor satellites
- Determine the density, mass distribution, and internal structure of major satellites and, where possible, small inner satellites and irregular satellites
- Determine the composition, density, structure, source, spatial and temporal variability, and dynamics of Triton's atmosphere
- Investigate solar wind-magnetosphere-ionosphere interactions and constrain plasma transport in the magnetosphere

It should be noted that all the objectives, with the exception of the one regarding Triton, apply to both Uranus and Neptune.

A detailed discussion of these science objectives, the associated measurements, and mission requirements can be found in the IG Study. Given our charter to utilize scientific and technological advances since V&V to reassess science goals (see Section 7), and our directive to explore a broader range of options than were presented in V&V, the prioritization and emphasis of science objectives in the IG Study is different than in V&V. The two studies are overall quite consistent, however, and no science objective in one is entirely missing from the other.

3.2. Uranus-Neptune comparative planetology

While Uranus and Neptune are equally compelling, the two planets are not equivalent. Each system has things to teach us the other cannot, and we cannot hope to truly understand “ice giants” as a class of planet without studying both examples in our solar system.

At the highest level, each planet is similar in size and gross composition, and is a potential archetype for the ice giant class of planets. Each planet has a system of rings and satellites with unusual features, evolving dynamically on decadal time scales. Each has a magnetic field with complexity unseen in the terrestrial and gas-giant planets (Fig. 4), and a magnetosphere that has unique diurnally and seasonally varying coupling to the solar wind.

In spite of these similarities, the brief Voyager flyby of each, along with Earth-based observations and modeling, have allowed us to see some fundamental ways in which the Uranus and Neptune systems differ. As an example, consider the satellites (Fig. 5). An orbiter at Neptune offers the opportunity for detailed exploration of Triton, a captured KBO which Voyager found to be active, with several “geysers” erupting (Soderblom et al. 1990). Triton is also a potential ocean world (Hendrix et al. 2018), and its exploration leverages the knowledge we are gaining from the recent New Horizons flyby of Pluto to better understand KBOs. But in the process of capturing Triton, Neptune appears to have lost its

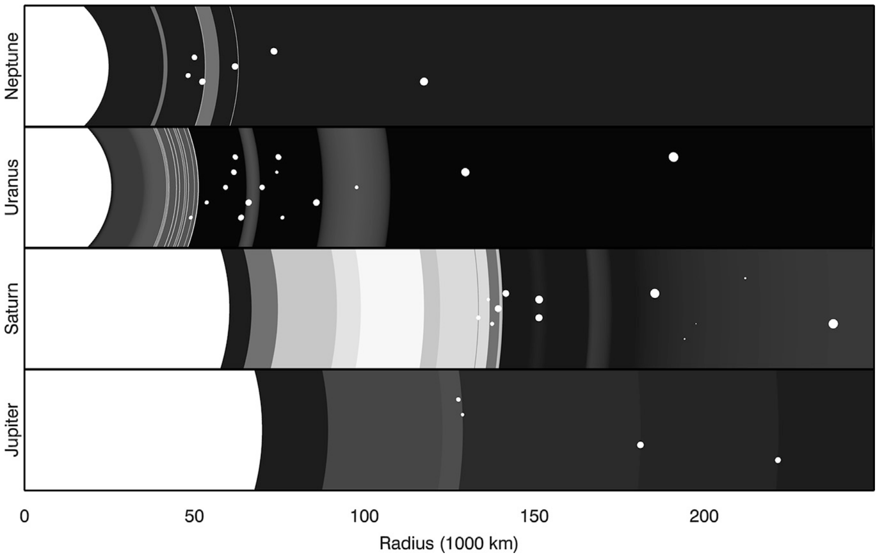

Fig. 3. Diagram comparing the ring-inner moon systems of the giant planets. The extents of the various rings are shown to scale, with greyscale levels indicating their relative optical depths. The locations of inner moons are indicated by dots. At Neptune, the outermost satellite shown is Proteus, while at Uranus the two outermost are (from right to left) Ariel and Miranda. The outermost Saturn and Jupiter satellites shown are Enceladus and Thebe, respectively. These dots do not indicate the size of the moons relative to the rings, though the relative sizes of the satellites are approximately correct. Credit: Matthew Hedman.

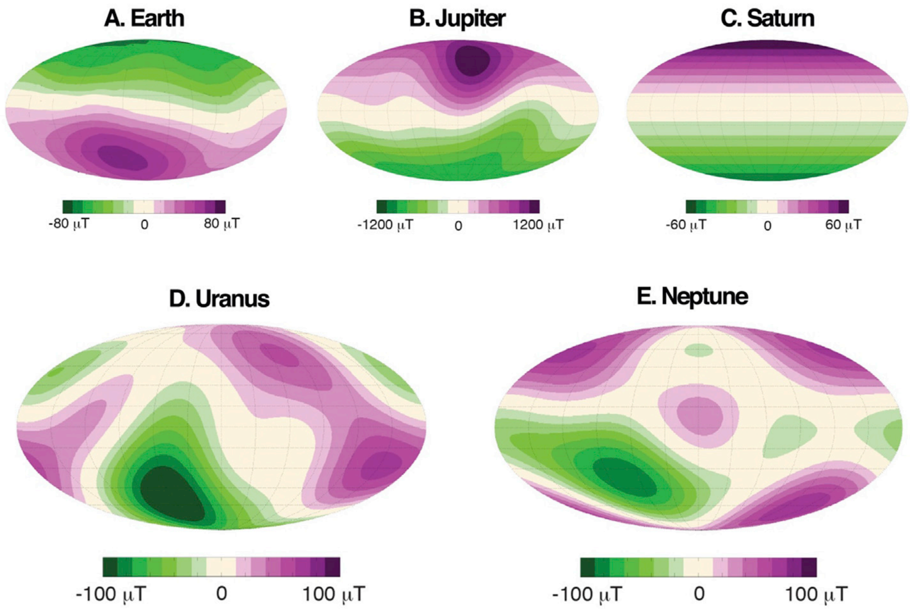

Fig. 4. Radial magnetic fields measured on (A) Earth, (B) Jupiter, and (C) Saturn are contrasted against those measured on (D) Uranus and (E) Neptune. The colors represent field intensity where purple (green) indicates outward (inward) directed fields. The measurements on Uranus and Neptune have the lowest spatial resolution (to spherical harmonic degree 3), so all planets are shown with that resolution. This comparison illustrates the ice giants' unique magnetic field morphologies. Adapted from Schubert and Soderlund (2011).

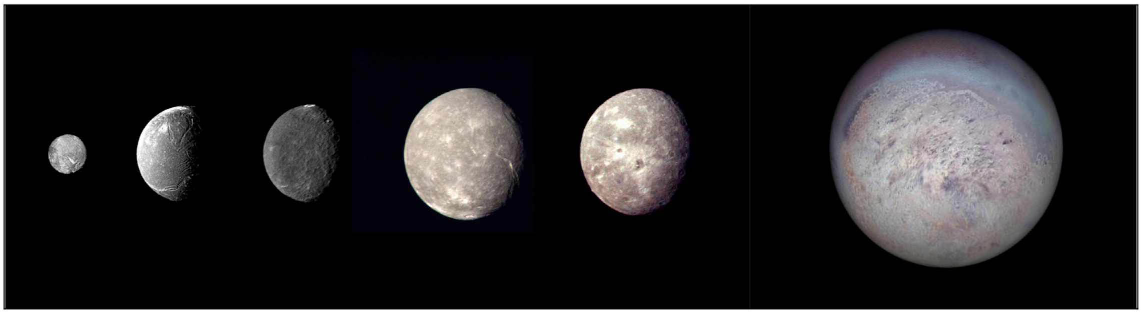

Fig. 5. Voyager 2 images of the 5 major satellites of Uranus (from the left, Miranda, Ariel, Umbriel, Titania, and Oberon) and Neptune's Triton (far right). Satellites are shown with their approximate relative sizes. Credit: NASA/JPL.

larger, native satellites, and perhaps fundamentally disrupted what a "normal" ice giant ring/moon system looks like (see Coradini et al., 2010; Mosqueira et al., 2010; Turrini et al., 2014 and references therein). To explore a regular system of large ice giant satellites, one must go to Uranus (while its satellites may also have been influenced by the giant impact thought to have given Uranus its large inclination, Morbidelli et al., 2012 suggest such impacts and their aftermath may be the norm for ice giants). The Uranian moons Miranda and Ariel are particularly interesting given the evidence of geologic activity found in Voyager images. There is also a tremendous difference in the amount of internal heat being released by the two planets (a factor of 10!) and—presumably related to this—significant differences in their internal structures (Nettelmann et al., 2013, 2016).

The SDT concludes that a mission to either ice giant system can fundamentally advance our understanding of ice giants and processes at work in planetary systems, but the highest science return will come from an exploration of both systems. Not only does each planet provide information the other cannot, but by comparing the two we see how planets react to differing physical inputs (e.g., sunlight vs. internal heat), and we get a better idea of what properties might be common among ice giant exoplanets. Therefore, while the cost ground rules of the IG Study lead us to recommend a mission to one planet, we also recommend exploring ways to send missions to both. Since completion of V&V, we note several ideas have been discussed to enable two-planet missions (e.g. Turrini et al., 2014; Simon et al., 2018).

4. Instruments and model payload

4.1. Introduction

An important area in which the original IG Study has been misunderstood is in its discussion of instruments and payloads. It does not propose a specific payload for flight, nor does it prioritize instruments, with the exception of a probe as a high priority payload element. The IG Study, being a survey of alternative architectures and mission sizes, could not reliably select instruments at this early stage. Instead, the model payload is intended to be useful in assessing alternative architectures and in providing considerations to a future science team who will take into account the latest advances and be constrained by the resources (cost, mass, power, data volume) of their specific mission. Instead of recommending a set of instruments, the IG Study recommends a payload size of 150 kg to achieve all priority objectives based on current state-of-the-art instrumentation. It is possible to address a diverse set of science objectives even with only a 50-kg payload. Criticisms of the instruments used in the IG Study model payloads as being too narrowly focused (like those found in the Mid-Term Review page S-4 and 3–20) therefore reflect misunderstandings of the IG study in this regard.

Though the IG Study does not propose a specific set of instruments for flight, it is necessary to identify representative mass, volume, power, and data volumes needed by the science payload, so that alternative mission point designs (Section 6) can be tested for their ability to accommodate a reasonable payload, trajectories can be assessed for compatibility with representative needs of instruments, and to estimate mission costs. Therefore, the IG Study science team chose to consider three “model payloads” distinguished primarily by their total mass. Masses of 50, 90, and 150 kg were selected, as being likely to span what would be available to a future Flagship mission.

Section 4.2 gives a brief overview of instruments discussed during the course of the IG Study, and Section 4.3 presents the model payloads used in later mission point designs.

4.2. Instruments

Before converging on the 12 priority science questions presented in Section 3, the SDT began with an extensive, community-defined list of >90 questions and considered the instruments needed to address them (listed in Appendix F of the IG Study). The instruments discussed by the SDT are summarized in Table 1.

In Table 1, when two powers are listed, the first is a peak value and the second represents an average. The Flight Analog column is an instrument that has flown or is under construction for flight, which the science team selected as most similar to what is desired. Mass and power estimates reflect that analog, except as noted in the comments.

The full IG Study should be consulted for additional discussion of each instrument and the measurement requirements they would satisfy. In the remainder of this section we highlight a few items that seem most relevant to discussions in the community since release of the report. We start with the Doppler Imager which is likely the least familiar instrument and one that has never flown. It represents a family of instruments that could be used to detect planetary-scale oscillations of an ice giant. Detection and characterization of these motions would revolutionize our understanding of interior structure. To date, there is a reported ground-based detection of Jupiter oscillations (Gaulme et al., 2011, 2015), and Saturn's rings display density waves that are driven by similar planetary oscillations (Hedman and Nicholson, 2013, 2014). The Saturn data, collected by the Cassini spacecraft, has led to new insights on Saturn's deep interior structure (Fuller, 2014) and rotation rate (Mankovich et al., 2019). There is to date, however, no theoretical or observational evidence indicating that such oscillations have a detectable amplitude at Uranus or Neptune (e.g. Rowe et al., 2017). The reason the Doppler Imager appears on the list of potential instruments alongside proven technologies and techniques is three-fold: 1) Part of the IG Study's charter was to assess important new technologies, and we wished to highlight the value of developing this technique; 2) A Doppler Imager or similar instrument is the best way to dramatically advance our understanding of the interior structure of ice giants; and 3) The Doppler Imager is a relatively massive, power-hungry device which generates a tremendous data volume (making full disk images on the order of every second for several weeks), so it can serve as a good stress-test of mission architectures. *Any mission capable of accommodating a Doppler Imager can easily accommodate two or more replacement instruments*.

The items on the “Additional Flight Elements” part of Table 1 deserve mention here. While not technically instruments, the SDT felt that the choice of whether or not to add them to the mission would ultimately come down to a trade-off between the science return of the new flight element against the total mass of instruments that could be carried on the main spacecraft. Hence, it made sense to place them on this list. The mass of the probe represents the total mass of the payload and entry system for a single probe (but does not include any special communication or mounting structures required on the carrier spacecraft). Details of probe design and architectures that accommodate probes are discussed in the IG Study. For SmallSats/CubeSats and Landers, the 10 kg/10 W designation was a placeholder to use while discussing payloads. The SDT considered one or more small elements (e.g. releasing a dozen CubeSats with magnetometers) as well as larger options (such as a soft lander for an icy moon). During early science trade-off discussions, the SDT decided that instruments on-board the carrier spacecraft were a better investment than very small flight elements, and that an atmospheric probe was higher priority than a larger lander or free-flyer, so detailed designs of SmallSats, CubeSats, and Landers were not developed.

4.3. Model payloads

As discussed earlier, model payloads allow mission designs to be costed and tested for their ability to accommodate science instruments, including mass, power, data rates, and pointing requirements. The SDT chose to model three payload sizes: 50, 90, and 150 kg. An atmospheric probe was considered an option to add to each of those payload sizes. The smallest mass limit was judged to be the minimum one would expect a Flagship-class mission to carry (for comparison, the New Horizons spacecraft carries about 30 kg of instruments). The 150 kg limit was picked because it is large enough to let us carry all instruments which were identified as “primary” for achieving each of our 12 priority science goals, because it is large enough to allow a diverse payload able to make and follow-up on unplanned discoveries, and also because 150 kg is small enough to force some instruments to not be carried (responding to the cost targets assigned to our study). For comparison, the Cassini orbiter carried about 270 kg of science instruments. The 90 kg limit was selected

Table 1
Instruments considered for model payloads.

Instrument	Mass (kg)	Power (W)	Flight-Qualified Analog	Comments
In Situ Instruments on Main Spacecraft (flyby or orbiter)				
Mass spectrometer	16	19	DFMS/Rosetta	Triton's atmosphere is a primary target.
Magnetometer w/10 m boom	14	10	MAG/Cassini	Team-X used 10 kg and 8 W based on Galileo.
Radio and plasma waves	5.6	2.7	LPW/MAVEN	Combines an in-situ Langmuir probe with remote sensing of low-frequency plasma and radio waves.
Plasma low-energy particles	3.3	2.3	SWAP/NH	
Plasma high-energy particles	1.5	2.5	PEPPSI/NH	
Langmuir probe	1	0.1	RPWS-LP/ Cassini	If LPW/MAVEN is used, this instrument is redundant.
Energetic neutral atoms	6.9	3	INCA/Cassini	
Dust detector	5	6.5	SDC/NH	
In Situ Probe Instruments				
Mass spectrometer	17.4	66/50	None	Specifications based on a proprietary proposal.
Atmospheric pressure, temperature package (ASI)	2.5	3.5	Galileo Probe	Team-X used 2.5 kg, 10 W power, which included accelerometer, other instruments, and a pitot tube extending 8 cm to reach beyond boundary layer.
Nephelometer	2.3	4.6	Galileo Probe	Team-X used 4.4 kg, 11 W avg which includes a boom extending beyond the boundary layer.
H_2 ortho-para instrument	1	3.5/1	None	If required to be outside boundary layer, mount on nephelometer boom. Based on Banfield et al., (2005).
Net-flux radiometer	2.3	4.6	Galileo Probe	
Helium abundance	1.4	0.9	Galileo Probe	
Imaging Spectrometers				
Vis/NIR	16.5	8.8	OVIRS/O-Rex	Assumed imaging capability and longer IR wavelengths can be added to OVIRS.
UV	7	10	UVS/Europa Clip	Specs intermediate to Alice/NH and UVS/Juno.
Mid-IR	6.3	10.8	OTES/O-Rex	Used OTES for its longer wavelength coverage than the Ralph instrument on New Horizons.
Doppler Imager	20	20	None	Based on ECHOES proposal for JUICE mission to Jupiter, with mass increased by 6 kg to account for lower illumination levels and instrument maturity.
Cameras/Bolometers				
Thermal-IR bolometer/Visible photometer	12	25	DIVINER/LRO	The mass and power levels chosen are well above what a minimal bolometer/photometer instrument would need. DIVINER is an analog: eliminate its scan capability, add imaging. Desire longer wavelengths than ETHEMIS/Europa Clipper.
Narrow-angle camera	12	16	EIS/Europa	LORRI/NH was considered as the analog, but the desire for filters and pushbroom capability drove us to use EIS (Turtle et al., 2016, LPSC).
Wide-angle camera	4	10	MDIS-Messenger	Overestimates mass and power because MDIS includes extra components.
Other				
Radar	21	50	MARSIS/Mars Express	
Ultra-Stable Oscillator (USO)	2	2	Many	Proposed JUICE USO is 2 kg and 6 W.
Microwave sounder	42	33	MWR/Juno	
Additional Flight Elements				
Atmospheric Probe	~220	Variable	Galileo	See discussion.
Smallsats/CubeSats	10+	10	None	See discussion in the IG Study.
Lander(s)	10+	10	None	See discussion in the IG Study.

as an intermediate option.

We find that a 50 kg payload could achieve significant science and (depending on the instrument set chosen) could address a broad range of objectives. It could not, however, address all 12 of our priority science goals. For modeling purposes we chose the 50 kg payload to consist of:

- Doppler Imager
- Narrow Angle Camera
- Magnetometer

This model payload demonstrates the ability of our smallest mission to achieve significant science, to accommodate our highest data volume instrument (the Doppler Imager) as well as accommodate the strict pointing requirements of the camera and magnetic cleanliness requirements of the magnetometer. It also serves to highlight our recommendation that NASA explore instruments and techniques for studying planetary oscillations. As emphasized above, however, this is not intended to be interpreted as the selected payload.

We believe a 90 kg model payload would be capable of touching upon (but not fully addressing) all 12 of our priority science goals. For modeling purposes, we added to the 50-kg case the following instruments:

- Vis/NIR imaging spectrometer
- Thermal IR/visible instrument
- Plasma suite (Radio, low-energy, and high-energy plasma instruments)
- Mid-IR spectrometer for Uranus, UV spectrometer for Neptune

The mid-IR and UV spectrometers are good candidate instruments for either planet, but to explore any differences in accommodation needs the SDT chose to specify one for Uranus and the other for Neptune. The atmosphere of Triton is a good target for UV studies, so the UV instrument was assigned to Neptune.

The large, 150 kg model payload would allow significant progress to be made in all 12 of our priority science objectives, and is diverse enough to make the type of unplanned discoveries and follow-up observations that made the Cassini mission at Saturn so productive. The SDT recommends a payload of this size for a future ice giant Flagship mission. The model 150 kg payload adds the following instruments to the 90 kg case:

- Wide-angle camera
- Ultra-Stable Oscillator (USO)
- Energetic Neutral Atoms (ENA)
- Dust detector
- Langmuir probe
- Microwave sounder (Uranus), mass spectrometer (Neptune)

The microwave sounder appears on this payload list both because of its unique ability to explore composition, dynamics, and cloud formation in the deep atmospheres of giant planets (as demonstrated by the Juno mission, see Bolton et al. 2017), and because its long-wavelength antenna is relatively large and we wanted to explore the spacecraft's ability to accommodate it. It would certainly be a valuable instrument to fly to Neptune as well, but the SDT also wished to explore accommodating a mass spectrometer on the main spacecraft which could—among other things—be used to sample the atmosphere of Triton. So, as with the medium-sized payload, we chose to model different payloads for the two planets.

For architectures with an atmospheric probe, the following probe payload was modeled:

- Mass spectrometer
- Atmospheric Structure Instrument (ASI) for temperature, pressure, density
- Nephelometer
- H_2 ortho-para sensor

Only the mass spectrometer and ASI are considered "must have" instruments (see the IG Study for a discussion). If a probe is flown which can accommodate more than those two instruments, any or all of the remaining 4 listed in Table 1 is a viable candidate. There is no special reason the SDT chose to carry a total of 4 instruments on the probe as opposed to 3 or 5. Four seems like an intermediate number, which is more than a minimal probe but still small enough to require some science prioritization and compromises.

We wish to emphasize again that these model payloads are meant to be representative examples for the purpose of estimating cost and requirements placed on the carrier spacecraft. When the mission ultimately flies, its payload will be based on the latest available technology and science information, results from the Juno and Cassini missions, as well as programmatic considerations not available to the IG Study.

5. Trajectory considerations

5.1. Getting to the ice giants

During the study, over 10,000 trajectories were explored to bring a spacecraft from Earth to either Uranus or Neptune in the 2024 to 2037 time frame. Three launch vehicles were considered (an Atlas 551, a Delta-IV Heavy, and current performance estimates for the Space Launch System, or SLS, under development), up to four gravity-assist flybys were allowed in each trajectory, and both chemical and solar-electric propulsion (SEP) options were modeled. Both flyby and orbiter spacecraft were considered. Details are in the IG Study report, particularly Appendix A. The main conclusions are:

- Launch options exist any year, but the most favorable trajectories are in the 2029 to 2032 time frame, utilizing a Jupiter gravity assist
  - Mass delivered to Uranus is maximized in launches between 2030 and 2032.
  - Mass delivered to Neptune is maximized in launches between 2029 and 2030.
  - Uranus missions launched prior to 2029 utilize a Saturn gravity assist.
  - There are no desirable Saturn flyby trajectories to Neptune.
- Uranus and Neptune do not align, so a single spacecraft cannot visit both planets
- Weighing flight time, cost, and other considerations, chemical trajectories to Uranus are preferred while a Neptune mission would likely use SEP
  - Chemical propulsion trajectories allow Flagship-class orbiters (>1500 kg dry mass) to be inserted into Uranus orbit, with flight times of 8–12 years using Atlas or Delta IV launch vehicles. Flight times can be 6 years with SLS
  - A Flagship-class orbiter on a chemical trajectory to Neptune requires an SLS launch vehicle if it is to arrive within 13 years of launch. (The 13-year travel time requirement is based on lifetime and reliability issues, primarily with radioisotope power systems, assuming a 2-year prime mission after arrival.)
  - A Flagship-class orbiter to Neptune can be flown on the Atlas V or Delta-IV Heavy utilizing SEP with flight times of 12–13 years. SLS enables flight times down to 8 years
- Flight times for flyby spacecraft can be less than indicated above, due to there being no need to slow down for capture into orbit
- To propulsively capture into orbit (as opposed to aerocapture, for example), relatively large orbit-insertion burns are needed
  - 1.5–2.5 km/s at Uranus
  - 2.3–3.5 km/s at Neptune
- In general, use of an SLS launch vehicle can increase delivered mass and/or reduce flight times in any launch year, compared to the Atlas or Delta-IV Heavy
- If it is desired to launch two spacecraft on a single launch vehicle, one going to Uranus and the other to Neptune, an SLS may be required. (Note that, scientifically, there is no need to launch both spacecraft simultaneously, but our study ground rules specified using only a single launch vehicle.)

5.2. Periapse altitude: orbit insertion and field measurements

It is desirable to fly as close to the ice giant as possible. This is because high spatial resolution in situ measurements of the gravity and magnetic fields (key for understanding the interior) require proximity, and because the fuel needed for orbit insertion (referred to as the "delta-V") is minimized by performing the burn close to the planet. During the earlier V&V mission study, concerns were raised that the region between the upper atmosphere and the known rings of both Uranus and Neptune could contain a population of infalling ring particles dangerous to a spacecraft. This concern deserves further study, and it is incorporated into our final recommendations (Section 8). In Section A.4.5 of the IG Study we discuss several risk mitigation strategies, but for our mission designs we chose to target ring-plane crossing during orbit insertion to be in a region where the atmosphere is dense enough that there could not be a population of orbiting ring particles, but still thin enough to present no risk to the spacecraft and to allow us to maintain precise pointing control. We estimate this region to be about 1.08–1.1 planetary radii from Uranus, and slightly closer in at Neptune. Additional work is needed to confirm that our uncertain knowledge of upper atmospheric structure does not significantly change the target altitude range. Other approaches for mitigating the ring-crossing hazard include targeting periapse at a higher altitude (with a corresponding increase in fuel needed for orbit insertion and a degradation in some science measurements), or releasing a small "pathfinder" spacecraft on approach that tests the safety of the desired periapse altitude (it is possible for the pathfinder to arrive early enough to allow the main spacecraft to re-target its periapse). We find it encouraging that the Juno and Cassini spacecraft, flying close to Jupiter and Saturn, respectively, encountered far fewer ring particles than expected and found the targeted region safe to fly through (e.g. Ye et al., 2018). More work is needed to understand the implications of these findings for the Ice Giants.

5.3. Radiation considerations

The radiation environment at Uranus and Neptune is relatively benign, as the ice giants do not have intense radiation fields. For the point designs studied to either planet, we estimate the total radiation dose to be under 30 krad (including a factor of 2 margin) behind 100 mil of Aluminum (0.254 mm). This dosage is not unusual for long-duration outer planet missions, with most of the exposure occurring in the inner solar system during gravity assists using Venus and the Earth. While our chosen trajectories have Jupiter flybys, the flyby distance is large enough (over 1 million km) that the Jupiter environment does not add a significant dose.

5.4. Seasonal considerations at Uranus

Because of Uranus' extreme obliquity, when the Voyager spacecraft encountered the system in 1986, near southern solstice, only the southern halves of its satellites were illuminated for imaging, and only one satellite, innermost Miranda, was imaged in detail. A goal of the next mission to Uranus is to image the unseen hemispheres, get higher spatial resolution on all satellites, and explore the weather and magnetosphere of Uranus at a different season. This calls for an encounter at or before the next equinox in 2049 (each season lasting 21 years). We note that, given the approximately 10-year flight time required (Section 5.1), launching a mission near 2030 will satisfy these requirements, while delaying another decade will not. Each Neptune season lasts 41 years, so any mission launched in the next few decades will sample a different season than seen by Voyager, and will observe previously unilluminated regions of its major moon, Triton.

5.5. Probe entry and relay

There are several conflicting requirements which make delivering an atmospheric probe while placing a spacecraft into orbit challenging. From the point-of-view of the main spacecraft, it is desired to drop the probe off before the orbit insertion burn because (assuming you are using chemical propulsion for orbit insertion) the probe's mass requires burning a significant extra amount of fuel to carry it into orbit. From a probe design and science point-of-view, however, it is desirable to release it after entering orbit because this significantly reduces the demands on the probe's thermal protection system (due to much lower entry velocities), dropping it off from orbit increases the range of latitudes which can be targeted, and because it allows time for extensive orbiter remote sensing observations before targeting the entry point. There are also trade-offs related to getting the probe's data to Earth. At the distance of the ice giants, direct to Earth transmission of probe data is impractical, as this imposes antenna pointing requirements and transmitter power levels which a probe would find extremely difficult to maintain. An orbiter must therefore play the role of relay station. To maximize data volumes returned from the probe, and for the probe to send data back from a wide range of altitudes, it is desired that the orbiter point its antenna at the probe for as long as possible, and for the probe relay to occur close to the planet. This can conflict with the spacecraft orientation needed for the orbit insertion burn, which is also desired to occur as close to the planet as possible. There are many similar trade-offs to be made which are discussed more fully in the full IG Study report (see IG Study sections 4.3, 4.5, 4.6, 4.7, and Appendix A, Section A.5). For flyby missions which drop a probe the situation is somewhat simpler because the relay spacecraft does not need to enter orbit. There are still significant science trade-offs to be made, however, such as the time devoted to probe relay vs. time spent observing the rings and satellites.

For the mission point-designs discussed in Section 6, we made the following choices for orbiter missions incorporating a probe:

- Probe release and entry occur prior to orbit insertion
- The probe enters near-equatorial latitudes
- The orbiter relays probe data for approximately 1 h
- The orbiter terminates probe relay approximately 1 h prior to the orbit insertion burn, with the probe at a depth of approximately 10 bars

Note that the maximum depth from which probe data is returned is limited by the amount of time the main spacecraft allocates for data relay. The science team identified 10 bars as a good target depth because it is well below the altitudes needed for the highest-priority measurements of noble gases and isotopic ratios (for which pressures of 1 bar are more than sufficient), and it is deep enough to possibly provide useful information on some upper cloud layers and some condensable species (such as CH_4, whose cloud is expected near 1 bar, and the H_2S/NH_3 ratio above the water cloud, which is significant for models of the deep troposphere's chemistry).

5.6. Satellite encounters/Tours

Our study mapped out a sample satellite tour for Uranus orbiter missions to confirm that spacecraft design, instrument capabilities, fuel, and trajectories were consistent with having at least two flybys of each of the major uranian satellites (Miranda, Ariel, Umbriel, Titania, Oberon) at relative velocities less than 6 km/s. For a Neptune orbiter, we developed a sample Triton tour (Section 4.5.4.3 of the IG Study) that includes 32 flybys over a two-year period, typically at an altitude of 100 km, sampling all latitudes and a wide range of longitudes, with relative velocities under 4 km/s.

For flyby missions to the ice giants, we confirmed that data volume and observing time are available for at least one satellite flyby (presumably Triton at Neptune, with Miranda or Ariel being favored by the SDT at Uranus), and that trajectories exist which cross the orbit of satellite targets. We did not identify specific times and trajectories that place the spacecraft and satellite in proximity, nor look at relative velocities for flyby missions.

5.7. Other flyby targets and science during cruise

The science team noted that on the cruise to an ice giant and—for flyby missions—after the ice giant encounter, there is a wide range of valuable science that can be done. In addition to potential observations of astronomical, heliophysics, and inner solar system targets, flybys of asteroids, comets, Centaurs, and Kuiper-Belt Objects are possible. The SDT expects and encourages resources to be devoted to such opportunities. Our Study's charter, however, was to try and optimize the ice giant science to be done for a given cost, so we did not want to give any weight to these potential observations. For that reason, we did not explore any of these other opportunities, nor consider them when ranking the science value of mission architectures (discussed in the next section).

6. Prioritized mission architectures and cost

6.1. Architectures considered and prioritization

Early in the mission study, the science team (SDT) and mission designers were brought together for a 3-day face-to-face meeting to brainstorm a wide range of feasible mission architectures. These include flyby missions, orbiters, multi-spacecraft options, multi-target options, probes, and landers. The SDT then considered its priority science goals (Section 3), and its model payloads (Section 4.3), and ranked each architecture/payload combination in terms of its science return. The process and results are discussed in detail in the full IG Study, but here and in Fig. 6 we summarize the conclusions.

- For a given payload size, a flyby of a single ice giant has the lowest science return. Adding an atmospheric probe to the flyby provides a significant increase in science
- There is a larger jump in science value, however, in going from a flyby mission to an orbiter, even without a probe
- For an orbiter mission, there is a larger science return in adding a probe than in adding additional SmallSats or a second orbiter at the same planet
- The SDT finds that there is a large increase in science return when one moves from an orbiter at one planet to two-spacecraft, two-planet options which include at least one orbiter and one probe. (There are no trajectories in the next few decades that allow a single spacecraft to visit both Uranus and Neptune.)

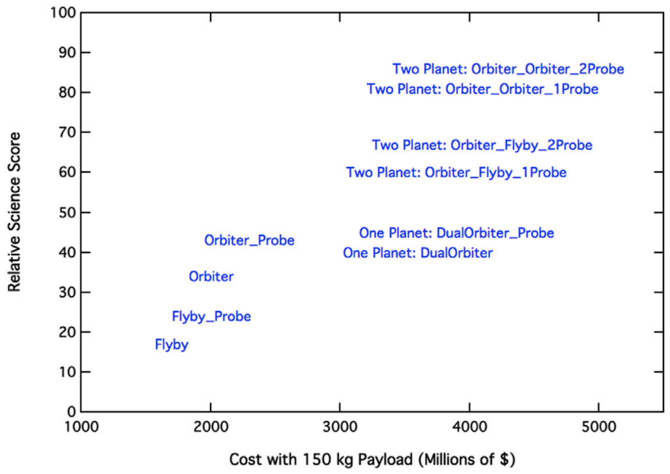

Fig. 6. Relative science value versus approximate cost for a subset of missions considered. Costs should be read from the center of the mission label (e.g. the “i” in Orbiter), but note the factors discussed in the text that can alter these numbers. For comparison purposes, all spacecraft plotted have a 150 kg science payload. Smaller payloads will reduce the science ranking, but will also reduce single-spacecraft costs by up to $600M and dual-spacecraft costs by up to $1100M. Single-planet missions are costed for Uranus; Neptune costs will be about $300M higher. Architectures are divided into three groups by their science value: flybys, single-planet orbiters, and dual-planet missions. Note that the recommended mission, an orbiter with probe, occupies a “plateau” in science value vs. cost, and is the least expensive option that achieves that level of science. See the IG Study for additional discussion. This figure is an updated version of Fig. 3–17 of the IG Study.

- In general, moving to a higher-value architecture (flyby to orbiter to dual-planet mission) increases the science return more than moving to a larger science payload (50–90–150 kg)
- The SDT did not reach consensus on the relative value of two-spacecraft, two-planet missions that do not include at least one probe and one orbiter

The lack of consensus identified in the last bullet above hinged on differing opinions on the value of trading one of our highest priority goals (measuring noble gas abundances and isotopic ratios with a probe) for the opportunity to address secondary goals and do comparative planetology by visiting both ice giants. For example, we did not all agree on whether an orbiter with probe at one ice giant was scientifically more valuable than an orbiter at one ice giant with a flyby of the other, but neither having a probe. The team did agree, however, that a single orbiter is preferable to a two-flyby architecture. Recognizing that when an ice giant mission is ultimately chosen as a new start there will be more information on its science goals and the resources available, we felt it was not meaningful to fully explore two-planet, two-spacecraft architectures at this time. But an important conclusion for future missions is that, if one flies an orbiter and probe to one ice giant, there is significant science still to be done by sending any type of spacecraft to the other ice giant.

Overall, the SDT determined that an ice giant orbiter with probe is the right baseline mission to target for the next ice giant flagship mission. The science payload on the orbiter should be 150 kg to address all 12 priority science goals (Section 3). We find a 50 kg payload is the lower limit to warrant a Flagship-level investment. Such a mission has the highest science return for an approximately $2B cost (costs are discussed in the next section). It also lies on the left (least expensive side) of a “plateau” in Fig. 6. This means there are more expensive architectures that do not do significantly more science. To significantly increase the science return above that achieved by an orbiter and probe, one must go to two-planet, two-spacecraft architectures, with correspondingly higher costs.

6.2. Mission costs

The full IG Study report should be consulted for a detailed discussion of costs. The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

During the study, we first developed rough cost estimates for a wide range of alternative mission architectures. We then selected 6 mission architectures for detailed point designs. The 6 selected were chosen to allow us to interpolate these refined cost estimates to the maximum number of architectures. It is important to recognize that the point designs do not include the mission we ultimately recommend (a Uranus orbiter with probe carrying a 150 kg orbiter science payload). A subset of the 6 point designs costed at JPL were independently assessed by the Aerospace Corporation with close agreement.

The IG Study had these ground-rules related to cost:

- Cost is in FY2015 dollars
- The cost target for the Ice Giant Flagship is $2B, but missions should be considered across a range of price points
- Assume a Class B mission (per NASA Procedural Requirements [NPR] 8705.4) [NASA has 4 categories of space missions, A through D, which are used to characterize the national importance, the cost, and the complexity of missions. Class-A missions are similar to the James Webb Space Telescope, and have stringent redundancy and risk-mitigation requirements which impose additional costs. Class-B missions are still high-priority, but have less stringent requirements. For comparison, the Mars Exploration Rovers were Class-B. Mission Class is formally selected near the time a mission is confirmed]
- Exclude launch vehicle from cost
- Include cost of Radioisotope Power System (RPS) (cost according to New Frontiers 4 guidelines as stated in the draft Announcement of Opportunity)
- Include cost of National Environmental Policy Act/launch approval process
- Include operations (full life cycle mission cost)
- Include Deep Space Network (DSN) costs as separate line item
- Include minimum 30% reserves (A–D), 15% (E–F)
  - Reserves excluded on RPS and the launch vehicle
  - Provide risk-based rationale for reserves
- Exclude cost of technology development from the mission cost estimate
- Assume no foreign contributions to reduce costs but identify areas where such contributions would be beneficial to NASA in terms of cost and interfaces

Some key cost trade-offs to consider are:

- A Neptune mission costs about $300M more than a similar Uranus mission, driven primarily by the cost of the SEP stage needed for Neptune
- The cost of adding an atmospheric probe to a mission is also about $300 M
- The total mission cost of increasing an orbiter's payload from 50 to 150 kg is approximately $600M
- A Uranus orbiter with a 50 kg science payload and an atmospheric probe fits within the $2B cost target by both JPL's and Aerospace's costing methods. A similar Neptune mission fits the cost target by JPL's estimate, but not by Aerospace's. The SDT considers such a mission a science floor, but recommends a larger orbiter payload
- A Uranus orbiter with a 150 kg science payload and an atmospheric probe is the SDT's preferred mission, and it is estimated to cost between $2.3B (JPL) and $2.6B (Aerospace). A similar Neptune mission would cost between $2.6 and $2.9B

The IG Study finds the following broad cost categories for the primary architectures considered (quoted ranges account for varying the payload size from 50 to 150 kg, and utilize JPL cost estimates. Aerospace cost estimates are 10–15% higher).

- A Uranus flyby mission with a probe would cost $1.5 to $2B
- A Uranus orbiter with a probe would cost between $1.7B and $2.3B
- A two-spacecraft, two-planet mission incorporating orbiters at both planets and a probe at one would cost $2.5 – $3.6B (assuming almost identical spacecraft built approximately the same time to realize savings in non-recurring engineering costs)

These results are reflected in Fig. 6, allowing a broad comparison of science value as a function of total mission cost.

Combining the science value, mission architectures, and cost estimates presented in Sections 3 through 6, the SDT developed a set of recommendations which are presented in Section 8 of this paper.

7. Recent scientific, technological, and programmatic advances

Before presenting the IG Study recommendations, we review some scientific and technological advances, as well as programmatic factors, that arose since the 2011 release of V&V and the 2017 release of the IG Study. These developments reaffirm the importance of an ice giant mission and have sharpened, but not fundamentally altered, the recommendations of both documents.

Four advances drive the IG Study to raise the priority of studying the internal structure of Uranus and Neptune above what was given in V&V. V&V listed this as a secondary objective (and therefore a descope option) due to concerns about the safety of the close-in orbits needed for high resolution gravity measurements. The first advance is mission design work performed as part of the IG Study which identified trajectories and mission architectures allowing safe, close orbits (Section 5.2). A second *potentially* mitigating advance is to use planetary oscillations to study internal structure, which does not require close orbits (Section 4.2). This technique does require development and validation, however. The third relevant advance, which occurred after the IG Study, is the knowledge gained by the Juno and Cassini missions during their close-in orbits of Jupiter and Saturn, respectively. Both orbiters found the region interior to the known rings to be relatively clear. In Saturn's case, surprisingly so (Ye et al., 2018). These factors together support the idea that interior structure is an achievable goal and should not be downgraded out of feasibility concerns at these early stages of mission planning. The fourth and final factor raising the priority of studying interior structure is continued modeling work showing the available data require unexpected interior structures, and suggesting Uranus and Neptune's interiors might be quite different (e.g. Nettelmann et al., 2013, 2016).

Several advances also call for the bulk abundance of the planet, particularly noble gases and isotopic ratios in the atmosphere, to be made high priority. As with interior structure, V&V felt this objective needed to be a descope option because it requires a probe and—in the limited time available to them—they did not find a fully consistent probe design and mission architecture. The IG Study, however, found architectures capable of carrying a scientifically capable probe and providing data relay during descent. We also note new predictions for the formation of ice giants (e.g. Lee and Chiang, 2016; Frelikh and Murray-Clay, 2017) and how they might be reflected in atmospheric composition (Mousis et al., 2018 and reference therein), reinforcing the importance of noble gas and isotopic measurements (Fig. 2).

The Juno mission at Jupiter also alters our thinking of how to study giant planet atmospheres. In particular, its microwave sounding instrument demonstrates both the technique's ability to study the deep troposphere and how little we understand the circulation, cloud structure, and composition at depth (Bolton et al. 2017). It is likely that any future ice giant mission will identify a microwave sounder as a key instrument for probing the atmosphere.

Finally, we note that while V&V and the IG Study call for international participation, the details are left to future programmatic decisions and inter-agency discussions. In late 2018, ESA performed its own study of how it could best contribute to a NASA-led ice giant mission. That report has recently been made public (available at http://sci.esa.int/future-missions-department/61306-cdf-study-report-ice-giants/). It is therefore timely to execute a follow-on mission study as called for by both the IG Study and the V&V Mid-Term Review. Such a study could take advantage of improved knowledge of the resources and objectives NASA and ESA intend to assign to this mission, and explore in more detail technologies that, while not needed to enable an ice giant mission, are enhancing of such a mission. These include advanced radioisotope power systems, deep-space liquid propulsion, aerocapture, and multi-spacecraft options utilizing the SLS launch vehicle. For maximum effect, this follow-on study should be completed early enough to serve as guidance both for the last half of the V&V period, should funds allow NASA's initiation of an ice giant mission, and as input to the next Planetary Science Decadal Survey, scheduled to initiate in late 2019.

8. Summary and recommendations

We reaffirm the scientific importance and high priority of implementing an ice giant mission, as recommended in the *Vision and Voyages* report of NASA's most recent Planetary Science Decadal Survey (National Research Council, 2011). Advances since the completion of that report have driven a re-prioritization of science objectives, but the need for and basic architecture of a mission remains unchanged. Launching an ice giant mission near 2030 maximizes the possible payload to Uranus or Neptune by utilizing a Jupiter gravity assist. Uranus launches prior to 2029 may utilize a Saturn gravity assist should that be deemed programmatically preferable. We note that launches to Uranus after the late-2030's will not be able to image the never-before seen Northern Hemispheres of the satellites, due to their being in winter darkness (as was the case during the 1986 Voyager 2 flyby).

To ensure the most productive mission is flown, we recommend the following:

- An orbiter with probe be flown to one of the ice giants. Based on its cost-conscious ground rules, the IG Study specified Uranus as the target. Given that the Uranus and Neptune Systems are equally valuable as science targets, evolving programmatic considerations can favor Neptune
- The orbiter carry a payload of at least 50 kg, with 150 kg being preferred
- The probe carry, at minimum, a mass spectrometer and atmospheric pressure, temperature, and density sensors
- The development of eMMRTGs (an improved radioisotope power source) and HEEET (thermal protection material for an atmospheric probe) be completed as planned
- Two-planet, two-spacecraft mission options be explored further
- Investment in ground-based research, both theoretical and observational, to better constrain the ring-crossing hazard and conditions in the upper atmosphere (both of which are important for optimizing the orbit insertion trajectory)
- Mature the theory and techniques for studying giant planet oscillations
- International collaborations be leveraged to maximize the science return while minimizing the cost to each partner
- A joint NASA/ESA study be executed that uses refined ground-rules to better match the programmatic requirements each agency expects for a collaborative mission

The IG study validated that NASA could implement a mission to the ice giants for under $2B (FY15) that would achieve a worthy set of science objectives. Mission architectures and payloads exist to achieve all priority science objectives for ~$2.5B. A partnership with another space agency has the potential to significantly increase the science return while limiting the cost to each partner. Given the development time scale of outer solar system missions, the time of the best launch opportunities, and the desire to arrive at the optimal season, now is the time to begin formulating the next mission to the ice giants.

Declaration of interest

The authors declare that they have no conflict of interest beyond the funding relationships in the acknowledgements.

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