Onwards to the ice giants

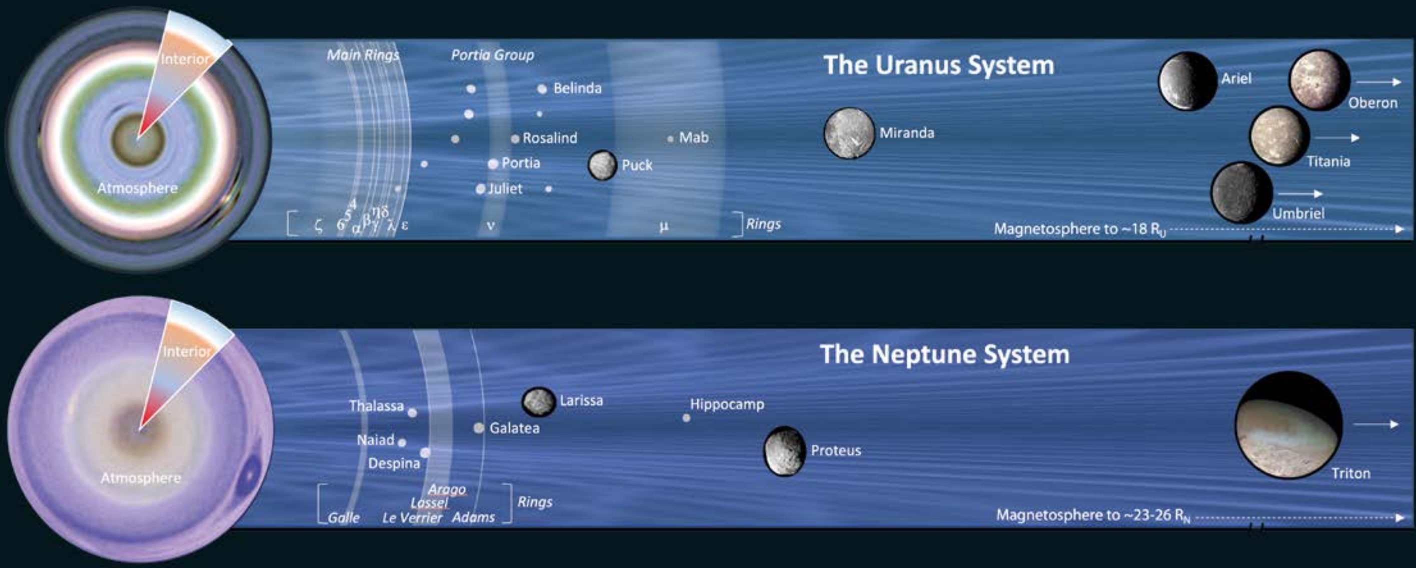
1 *Uranus and Neptune from the Hubble Space Telescope in 2018. A seasonal white cap of aerosols sits over the north pole of Uranus. A dark vortex, and associated orographic clouds, can be seen in Neptune's northern hemisphere.* (NASA/ESA/Amy Simon [GSFC] and the OPAL Team/ Joseph DePasquale [STScI])

Leigh N Fletcher describes the international effort to launch ambitious new missions to the distant ice giants Uranus and Neptune, to provide the first comprehensive exploration of these "missing links" in our solar system.

It has been a mere 239 years – about eight human generations – since Sir William Herschel's discovery of Uranus, and only 174 years (about six generations) since theoretical predictions of an eighth planet (Neptune) were proven to be spectacularly correct. But, for the vast majority of that time, these distant worlds remained unknown and mysterious, points of light wandering against the background stars. It wasn't until the late 20th century that Voyager's Grand Tour of the solar system revealed the ice giants in all their glory. To this day, Voyager 2 is the only spacecraft to have offered any sort of glimpse of these worlds, and a rather fleeting one at that, as the intrepid explorer flew quickly by Uranus (January 1986) and Neptune (August 1989) on its way out of our solar system. Voyager's myriad discoveries used technology designed in the 1960s and launched in the 1970s. Neither world has ever had an orbital mission, and even if we were to somehow launch tomorrow, more than half a century would elapse between the Voyager encounters and the next mission. Today, Uranus and Neptune sit alone on the "frozen frontier", the only major class of planet not to have a dedicated mission (figure 1).

In the early decades of the 21st century, robotic exploration of the solar system – including comprehensive orbital missions to Jupiter (Galileo, Juno) and Saturn (Cassini) – has been accompanied by a bewildering explosion in the discovery and characterization of planetary systems beyond our own. Amid the startling complexity observed in the growing census of exoplanets, one discovery has raised ice giant science to new levels of importance: it is neither the enormous gas giants like Jupiter, nor the small rocky worlds like Earth that dominate the census. Instead, worlds only slightly smaller than Uranus (4.0 Earth radii) and Neptune (3.8 Earth radii), the so-called "mini-Neptunes", appear to be the most common outcome of the planetary formation process. Uranus and Neptune, being intermediate in size between their gas-rich cousins (Jupiter and Saturn) and the terrestrial worlds, might just be our closest and best examples of a class of planets that dominates our galaxy. Of course, just because a world is Neptune-sized doesn't make it Neptune-like, but we must be able to explain how these worlds come to be before we can claim understanding of planetary origins. Uranus and Neptune provide the missing link, the missing piece in this puzzle.

It is all too easy to lump Uranus and Neptune together, as two very similar bluish-green worlds. But it is their stark differences that so intrigue planetary scientists, making them appear as two endmembers of this class of planet – the products of divergent evolution from shared origins. Uranus has an extreme axial tilt of 98°, subjecting its atmosphere and magnetosphere to unique interactions with solar flux and solar wind, whereas Neptune has a more "Earth-like" seasonal tilt of 28°. Uranus has a collection of icy "classical"



2 *The Uranus and Neptune systems, from false-colour representations of the atmosphere (southern poles) and interior, to the ring and satellite systems. The position of rings and satellites in the inner systems are to scale with the planetary radii, but the relative sizes of the satellite images are not. Arrows next to major moons indicate that they orbit at larger planetocentric distances. The magnetosphere and radiation belts would encompass the full area of the figure.* (L N Fletcher/M Hedman /E Karkoschka/Voyager 2)

natural satellites that might represent a primordial ice giant system, whereas the Neptune system is dominated by an interloper: enormous Triton captured from the Kuiper belt, and orbiting retrograde around the ice giant. Uranus has a sluggish atmosphere with episodic outbursts of convective storms, whereas Neptune's meteorology is so vigorous that the appearance of the world can change from one day to the next. Many of these differences could be explained by gargantuan collisions in their early history, with Uranus subjected to an impact so large that it completely altered the planet's evolution. A comparison of both worlds may teach us about the violent processes shaping planets across the galaxy (figure 2).

This article will explore our open questions about the ice giants, and how a future mission (supported by Earth- and space-based observatories) could provide a paradigm shift in our understanding of these worlds, just as Cassini–Huygens did for the Saturn system. We'll also explore the challenges faced by a mission of this scope and ambition, and what our community needs to do next to turn this concept into a reality.

Water worlds

It may come as a surprise, but we do not truly know whether the ice giants are icy. By mass, hydrogen and helium make up only 10–20% of the bulk, with the rest being heavier material. But the ratio of rocky material to icy (i.e. water-rich) material locked in their vast interiors is hard to constrain, as remote-sensing measurements of their atmospheres barely scratch the surface of the bulk composition. It's like trying to understand an apple's pips by studying the skin. Many of the most common elements – nitrogen, sulphur, oxygen – are locked away at depth beneath condensation clouds. At the frigid temperatures of Uranus and Neptune, dropping to a balmy –220°C at the tropopause, only methane ice condenses at an altitude high enough to be observed easily, allowing us to estimate the bulk abundance of carbon, which is substantially enriched compared to the Sun's carbon-to-hydrogen ratio. All that excess methane gas, which absorbs red light and leaves blue light to be reflected, is responsible for the blue hues of the ice giants. Moving deeper, evidence is mounting that the next cloud deck is comprised of H_2S ice (with H_2S gas above providing absorption features in the infrared, as well as a "rotten eggs" smell if you were unlucky enough to fly through the ice giant skies), overlaying deeper clouds of NH_4SH. At the bottom of what we might consider to be the atmosphere, we would find water-ice clouds atop an ammonia and water liquid solution at the several-hundred-bar level. But these deep levels are currently inaccessible to even our most capable instruments.

The high carbon-to-hydrogen ratio suggests a lot of excess "heavy material" compared to the protosolar nebula from which the planets accreted, implying that carbon (and other elements heavier than hydrogen and helium) arrived trapped in ices. Given the formation of these worlds beyond the snowline (where water condenses), a picture emerges of Uranus and Neptune forming from icy building blocks, growing larger and larger until they began to accrete the surrounding nebula gases (primarily hydrogen and helium). At this point it became a race, to build up as much atmosphere as they could before the nebula gas was lost. But here we encounter a tuning problem: the duration of the accretion phase needs to be just right to produce the right size of planet. Grow too slowly, and the planets remain as small solid objects without the hydrogen–helium envelopes. Grow too quickly, and they end up as massive gas giants. For something so finely tuned, how come Neptune-sized worlds appear to be a common outcome of the planet formation process across all planetary systems? The ice giants are the key to this puzzle.

They're "ice giants" not because they're fully made of cold ice, but because of their expected bulk composition and original building blocks. If oxygen is as enriched as carbon (current estimates of O/H range from several tens to several hundred times solar, depending on the chemical model), then we'll find water in various phases depending on the temperature. In fact, given the extreme temperatures and pressures present at great depth, water ice may be in an exotic superionic form of crystals, forming a mantle of black, hot and mushy material that can only be generated on Earth using laser-induced shockwaves in laboratories. This mantle could be below the fluid layers (possible deep-water oceans, where hydrogen and water become insoluble). These oceans could be partially dissociated, helping to explain the generation of a dynamo in the outermost ~20% of the planets, which produces the bizarre magnetic fields (see below). Given the size of Uranus and Neptune, it's possible that this superionic ice is the most common phase of water in our solar system, and yet we know very little about it. But the effect of other heavier materials on these mushy ices is unknown, and the actual ice-to-rock ratio remains poorly constrained. Indeed, when we look to other objects in the outer solar system (such as planetary satellites or Kuiper belt objects), the proportion of rock and ice in the original building blocks could be very different from "pure" ice. Measuring the bulk composition and internal structure of the ice giants, including the noble gases from an atmospheric entry probe, is an essential requirement of any future mission.

Planetary extremes

The composition and structure of their deep insides influence the circulation and chemistry of their observable atmospheres (i.e. upwards from the thick cloud decks), and the properties of ice giant magnetospheres. But these are also influenced by what's going on outside: the extreme changes in sunlight and solar wind due to Uranus's 98° tilt, as one pole can spend decades shrouded in the darkness of winter. Averaged over a planetary year, Uranus's poles receive more sunlight than the equator, whereas the opposite is true for Neptune. Both the atmospheres and magnetospheres can be thought of as planetary laboratories where we can test our theories to the extremes, far more so than we can do at any other world in our solar system.

The smaller size and slower rotation of Uranus and Neptune create a regime of atmospheric dynamics totally unlike that on Jupiter and Saturn. Rather than having lots of east and west jet streams, the ice giants have just one large westward jet at the equator, and two eastward jets near the poles. Voyager gravity measurements suggest that these jets are confined to the outermost ~1000km of the planets' radii, rather than penetrating into the depths. Rather than having a relatively uniform abundance of gases from equator to pole, the ice giants have strong gradients with more material at the equator than the poles. In fact, gases are so depleted over the poles that they glow in radio-wave observations, where we can see deeper into the hotter troposphere. Rather than having oval-shape vortices at all latitudes like Jupiter and Saturn, rolling between the jet streams, the ice giants have sporadic dark ovals that drift with latitude and have short lifetimes. The most famous of these was Neptune's Great Dark Spot, which was observed by Voyager 2 in 1989 but had vanished by the time the Hubble Space Telescope observed Neptune five years later (figure 3). That dark oval was accompanied by bright clouds that have been likened to orographic clouds on Earth, where air is pushed up and over an obstacle, leading to cooling and condensation.

Perhaps the stark differences between Uranus and Neptune are a consequence of the heat flux from below. Uranus appears to be in equilibrium, meaning that it radiates away as much energy as it receives from the Sun, implying little or no energy rising from the interior. Whether that's because the primordial energy is trapped within by layering, or because the energy was removed fast and early by the cataclysmic impact, is still a mystery. Conversely, Neptune radiates more than twice as much energy as it receives from the Sun, and that excess energy from the interior appears to drive a stormier atmosphere and stronger atmospheric mixing. Neptunian storms are so powerful that even amateur astronomers can view them from Earth, tracking the reflective cloud outbursts from night to night.

3 *A 1989 Voyager 2 image of Neptune and the Great Dark Spot, flanked by accompanying orographic clouds.* (NASA/JPL-Caltech/ISS/Justin Cowart)

Uranus, on the other hand, exhibits episodic outbursts of storm clouds, the last of which were observed in 2014–15. Stronger mixing on Neptune means that chemicals such as methane can be lofted higher into the stratosphere and into more direct UV light. The UV photons split methane apart and the resulting radicals can recombine in a rich variety of chemical pathways to create hydrocarbons, some of which can condense to form wispy haze layers. When we compare the chemistry of Uranus and Neptune, the differences produced by the strength of mixing are stark. Understanding how the circulation, meteorology and chemistry change with the seasons, from summer to winter, will be a key goal for future missions, as Earth-based observations can only ever see the sunlit hemisphere.

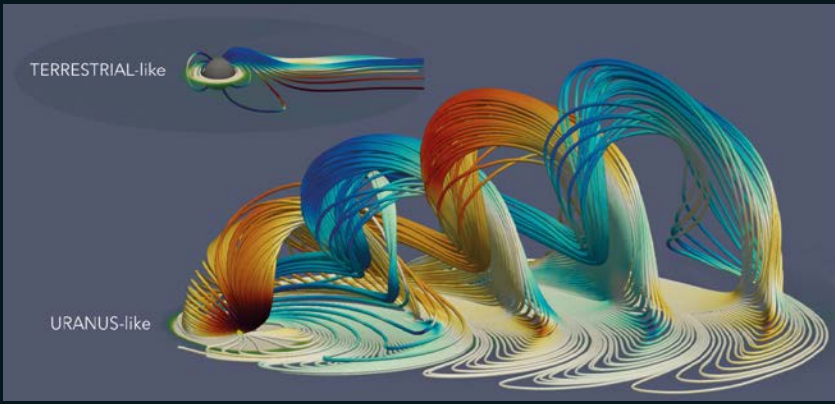
Atmospheres can be observed remotely. To study magnetospheres, we have to be there, measuring the ever-changing magnetic fields, currents and plasma properties *in situ*. Our understanding of ice giant magnetospheres comes from sophisticated modelling of the scant data acquired by the single fly-by of Voyager 2, but even that brief glimpse revealed systems of bewildering complexity that are without parallel in the rest of the solar system. Uranus's magnetic axis is tilted by 59° to the spin axis, and does not go through the geometric centre of the planet (it is offset by 31% of the planet's radius). This produces a lopsided magnetosphere that tumbles, opening and closing its magnetic field lines to the impinging solar wind and therefore reconfiguring the magnetosphere on a daily basis (figure 4). Downstream of the planet, the magnetosphere's tail is twisted into a helical structure that we cannot possibly hope to understand with a single fly-by. Neptune's magnetosphere is similarly tilted (47°) and offset (55% of the planet's radius).

These magnetospheres comprise unique plasma physics laboratories. Charged particles from within the magnetosphere impinge on the upper atmosphere to create auroral ultraviolet lightshows at a much wider variety of latitudes than on any other world. The importance of internal plasma sources, such as those from geophysical activity on satellites such as Triton, remains an open question. Understanding how these magnetospheres (and their associated dynamos) change over a variety of timescales will be a key goal of a future orbital mission. As we show below, these strange magnetospheres might provide an excellent analogue for exoplanets, or even for the Earth's magnetosphere at times of geomagnetic field reversals.

Icy systems

The rings and satellites of the ice giants are rich, diverse systems, complete with that most tantalizing of targets for exploration: terrains that no eyes, human or robotic, have ever seen. The northern hemispheres of the uranian satellites were shrouded in darkness in 1986, and the north polar regions of Neptune's satellites have not been in sunlight for the majority of the space age (Neptune's southern spring equinox was 1963, and southern autumn equinox is in 2046).

The ice giant systems are microcosms for the formation and evolution of planetary systems in general,



and their exploration may reveal the drivers of active geology and potential habitability of icy worlds. The uranian satellites may represent a primordial system of icy moons, whereas the neptunian system appears to have been substantially disrupted by the "cuckoo-like" arrival of Triton from the Kuiper belt. Triton, sometimes known as an "ocean world" due to the possible presence of an internal ocean, would be the largest known dwarf planet in the Kuiper belt if it were still only orbiting the Sun, exceeding the size of both Pluto and Eris.

The five large moons of Uranus (Miranda, Ariel, Umbriel, Titania and Oberon) exhibit extreme geologic diversity, demonstrating a complex and varied history (figure 5). Ariel and Miranda show signs of resurfacing due to tectonic stresses, potentially resulting from tidally induced melting and transient hydrothermal activity. Titania and Oberon may still harbour liquid water oceans between their outer ice shells and inner rocky cores – remnants of past melting events. Oberon and particularly Umbriel display dense populations of large impact craters, hinting at ancient terrain. Miranda's complex tectonic fractures and jumbled appearance, with rift-like canyons up to 15 km deep, suggest a complete reformation of the moon at some time in its history. The surfaces of these satellites are a mixture of water ice and a dark and bland material (maybe carbonaceous in origin). The satellites are tidally locked, so differences can be seen between the leading and trailing hemispheres due to interactions with dust and plasma within the uranian system: CO_2 ice (sometimes known as "dry ice") is concentrated on the trailing hemispheres of Ariel, Umbriel and Titania, and stronger water ice signatures are observed on the leading hemispheres. These classical satellites are joined by a collection of 13 smaller inner satellites (on regular orbits, and potentially sculpting the delicate rings), and nine outer satellites beyond Oberon (on irregular orbits, suggesting capture after Uranus formed).

The Neptune system represents what might have happened if a Triton-sized "bowling ball" was hurled at a classical system like Uranus. Triton is the only large moon in the solar system in a retrograde orbit, tilted by 157° to the equator (figure 6). It is joined by at least 13 other satellites, all more than six times smaller than Triton. Seven inner satellites (including recently discovered Hippocamp) are in regular, prograde, near-equatorial orbits; six outer satellites are in irregular and eccentric orbits (including Nereid, the most eccentric of all satellites). Many of these moons were mere unresolved points of light to even Voyager's cameras, and almost nothing is known about them. But Triton was revealed as a geological wonderland, with plumes of nitrogen gas and dust erupting many kilometres above the south polar cap, and with an atmosphere and potential internal ocean like Pluto. Curved ridges and troughs, especially in Triton's distinctive and intricate "cantaloupe terrain", hint at tidal stresses and activity that may be ongoing. Triton's surface is covered in volatile ices including N_2, H_2O, CO_2 and CH_4, and its tenuous atmosphere of molecular nitrogen (and traces of methane and CO) undergoes seasonal evolution, transporting volatiles across the surface. If Triton does possess an internal ocean, then its depth, the thickness of the overlying ice, and the degree of exchange between the ocean and the surface (e.g. where do the plumes come from?) will be essential measurements of a future mission.

4 *Comparison of the helicoidal shape of Uranus's magnetosphere to the Earth-like solar wind driven magnetosphere.* (E Roussos, from Fletcher *et al.* 2020)

"Uranus and Neptune may serve as Rosetta stones for exploring the properties of distant exoplanets"

Both ice giants possess ring systems with narrow and dense ringlets accompanied by broader dusty components. The delicate structures are shaped by gravitational interactions with satellites, which may also provide sources and sinks for some of the ring material. The rings are much darker and less massive than Saturn's, potentially indicating a parent body of water ice and dark silicate-rich material that disintegrated to form the main rings. Uranus has at least 10 identifiable rings, comprising particles of a wide range of sizes from metres to micrometres. The dust must be continuously produced by collisions to counteract the atmospheric drag that will be removing them. One of Uranus's small moons, Mab, might be the source of a tenuous, blue-toned ring, similar to the connection between Enceladus and Saturn's E-ring, but the mechanism remains unclear. Neptune has ring arcs (bright regions in the outermost Adams ring), perhaps from the breakup of a small satellite in the recent past, that were once thought to be the product of gravitational resonances with one of the small moons, Galatea, but their rapid evolution seems to discount this. The composition and gravitational relationships between ice giant rings and accompanying satellites will provide an intriguing comparison to the more extensive rings of Saturn.

Exoplanet connection

If the bulk properties of Uranus and Neptune (e.g. their heavy-element enriched fluid interiors) are truly representative of this class of intermediate-sized worlds, then they may serve as Rosetta stones for exploring the properties of distant exoplanets (and brown dwarfs) that we may never hope to visit or, indeed, resolve with a telescope. There is no doubt that any future ice giant mission will be operating during an unprecedented era of comparative planetology, alongside new exoplanet atmospheric characterization techniques in cooler and cooler temperature regimes. Measurements of exoplanet atmospheric composition, which are then used to characterize the planetary bulk, will be used as a marker for how the planet formed. *In situ* measurements of ice giant composition from an entry probe, combined with gravity-sensing of the interior structure and remote sensing of the atmosphere, will tell us whether distant exoplanet measurements of elemental abundances and isotopic ratios can ever hope to reveal the full story.

The frigid temperatures of the ice giants could reveal how atmospheres work under extreme conditions, with weak solar forcing and a climate powered by the warmth of the planetary layers below. Furthermore, the smaller size and slower rotation periods of the ice giants, compared to Jupiter and Saturn, provide access to a different dynamical regime for atmospheric circulation and weather: the way storms work, the way that jet streams are produced, and the way that energy and material are mixed throughout an atmosphere. Such a circulation regime is not available elsewhere. Exoplanet and brown dwarf observers have noted that the light from these distant worlds varies as the objects rotate,

5 *Satellites of Uranus larger than 150 km diameter captured by Voyager 2 in 1986 and mosaics processed by T Stryk.* (NASA/JPL-Caltech/T Stryk CC BY-NC-ND 3.0)

either due to shifting cloud patterns or to changing temperatures (or both). Uranus and Neptune therefore provide planetary-scale laboratories for understanding what processes are at work within the atmospheres of intermediate-sized planets.

Finally, the unique magnetic field configurations of the ice giants (especially Uranus) provide an interaction between a planet and the solar wind environment that is not seen anywhere else. For this reason, a study of Uranus is seen as a top priority by the heliophysics community, bolstering the existing enthusiasm of planetary scientists and cutting across research disciplines. How does such an extreme orientation influence magnetospheric dynamics and transport? What types of radio emissions might we expect from a world in this configuration? Such strange orientations may be commonplace beyond our solar system, such that our ice giants provide a testbed for magnetospheric theory and radio observations of magnetized exoplanets.

Time for a mission

Scientists have been dreaming, planning and preparing for a dedicated mission to an ice giant for several decades. The last US planetary science decadal survey (2009) listed a Uranus mission as its third highest priority for a flagship-class mission, after concepts that ultimately became the Mars Perseverance (2020) rover and Europa Clipper mission. Several ice giant mission concepts were proposed to ESA, as it developed a strategy for its medium-class (€0.5bn) and large-class (€1bn) missions between now and ~2035 (known as the Cosmic Vision). In 2013, ESA's Senior Survey Committee (having selected an X-ray observatory and a gravitational wave observatory for large-class launches in the 2028–34 timeframe) strongly encouraged the European community to continue to develop ice giant mission concepts through international partnerships. As a result, European and American scientists worked together as a study team in 2016–17, and ESA recently led a series of studies to understand the palette of potential contributions to any future US-led mission, including secondary orbiters, atmospheric probes, and even landers for distant satellites such as Triton. All of these studies have shown that an ice giant mission is achievable using today's technology.

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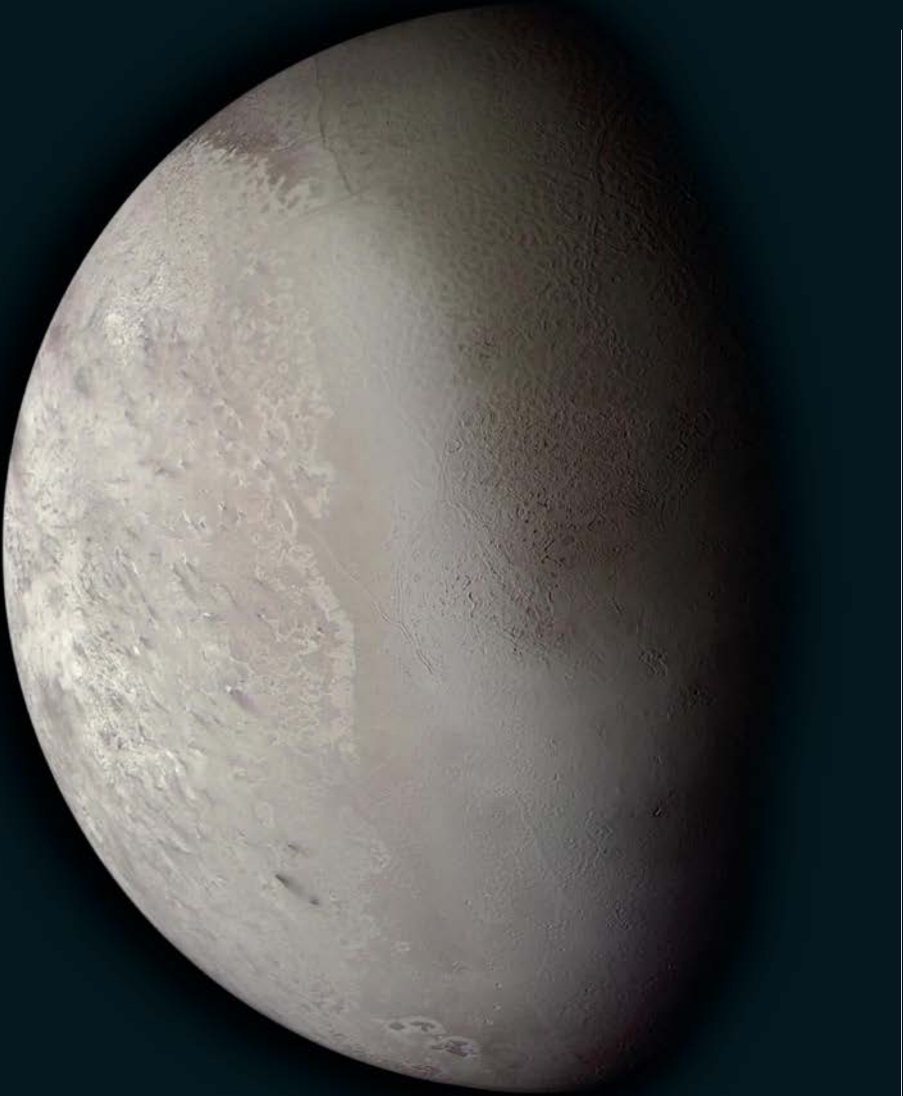
We should not, however, understate the challenges involved in mounting an ice giant mission. Although the next generation of heavy-lift launch vehicles may enable "direct" trajectories with enough fuel to deliver sufficient mass into ice giant orbit, most studies to date rely on flying past Jupiter to get a gravitational kick, propelling them onwards to Uranus or Neptune. But there's a catch: Jupiter has to be in the right place in the solar system for this to work, and this only occurs every 13–14 years. Optimal launch opportunities to Uranus exist in the early 2030s, but the window for Neptune is narrower and closer (2029–30). If we miss those, then we must wait for Jupiter to complete another lap around the Sun. Add on the 8–12-year flight time (depending on launch vehicle and trajectory), and the orbiter would likely not arrive until the 2040s. All the hardware – subsystems, instruments, computers, communications, power – has to be built to last for this long duration flight, not to mention supporting an international team through the years from mission design to completion. That long cruise phase should be seen



6 *Global colour view of Triton from Voyager 2. The south pole is at the left; several of Triton's famous south polar geysers are visible. Toward the equator at right, Triton is covered with a strange "cantaloupe terrain".* (NASA/JPL/Ted Stryk CC BY-NC-ND 3.0)

as a bonus to interdisciplinary science: the spacecraft will be able to characterize the propagation of the solar wind out beyond Saturn to the realm of the ice giants; it will be able to turn its remote-sensing instruments to the stars; and it could fly by objects such as Centaurs *en route* to their final destination.

However, the timing creates another problem. Uranus orbits the Sun every 84 years. Voyager 2 encountered the system in 1986, during southern summer when the northern regions of the planet and satellites were completely hidden from view. Uranus passed equinox in 2007 (when the north pole emerged into sunlight) and will pass northern summer solstice in 2030, but then those unexplored northern terrains will once again recede into darkness as we approach equinox in 2050. If we wait too long, then we risk missing those northern terrains for a second time. Similar arguments can be made for Neptune, where the geysers of Triton's southern hemisphere will start to disappear from view following southern autumnal equinox in 2046. There's no time to wait.

The gargantuan distances pose two further problems: power and communications. Ambitious studies with solar power at Uranus were unfeasible, such that the decay of radioisotopes such as plutonium (and maybe americium) will be required to produce the electrical power used to keep the spacecraft warm, run its instruments and send its precious data back to Earth. Suitable stockpiles of these radioisotopes are hard to come by, and the technology required to increase the efficiency of the electrical production is expensive and challenging. Improving the capabilities of nuclear power sources will significantly improve an ice giant mission, as well as enhancing capabilities across the field of long-duration spaceflight. But that still leaves the problem of communication: sending the data back to Earth requires radio communication over billions of kilometres, and the size of the transmitter is limited by the available mass and power. Compared to the flood of information that we humans are used to, the data is likely to feel like a trickle.

How do we get there, from here?

In January 2020, the Royal Society hosted an Ice Giant Systems meeting that saw the largest international gathering of scientists, engineers, mission planners, policy makers and industry to date, all united in the ambition to realize a mission to Uranus or Neptune in the coming decade. Sir William Herschel's handwritten notes on the discovery of Uranus, eight generations earlier, sat in a glass cabinet as the participants held their meeting with a sense of optimism and enthusiasm. At the time of writing, ESA is once again assessing community inputs to help shape its strategy for future missions, this time for the 2035–50 timeframe (known as Voyage 2050), and we hope that an ice giant mission can form a cornerstone of this programme. In addition, the US planetary community is gearing up for its next decadal survey, with a decade of new ice giant discoveries and mission concept development feeding into the panel's deliberations. An international partnership, continuing the legacy of the Cassini–Huygens mission, has formed and is ready to take advantage of the next funding opportunity – and hopefully the next jovian gravity assist in the early 2030s.

But how do we get there, from where we are today? All of the concepts are paper missions right now, yet to be confronted by the reality of a detailed mission design, instrument development and spacecraft fabrication schedules. Before we can even arrive at those hurdles, we have a lot of work to do in persuading our space agencies (both national and international, in the case of European nations) to support a mission. That remains a considerable funding challenge, given the ongoing commitments to missions both existing and on the schedule between now and the mid-2030s.

The potential for scientific discovery is clear, strong and compelling, encompassing the entirety of planetary science, and reaching across disciplines to heliophysics and astrophysics. However, science is a necessary, but not necessarily sufficient, condition to mount such an ambitious endeavour. We hope that national and international space agencies will rise to the challenge, enabling a mission to the frozen frontier that will shape planetary exploration for the generations to come. ●

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