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THE ESSENTIAL GUIDE TO ASTRONOMY

JULY 2023

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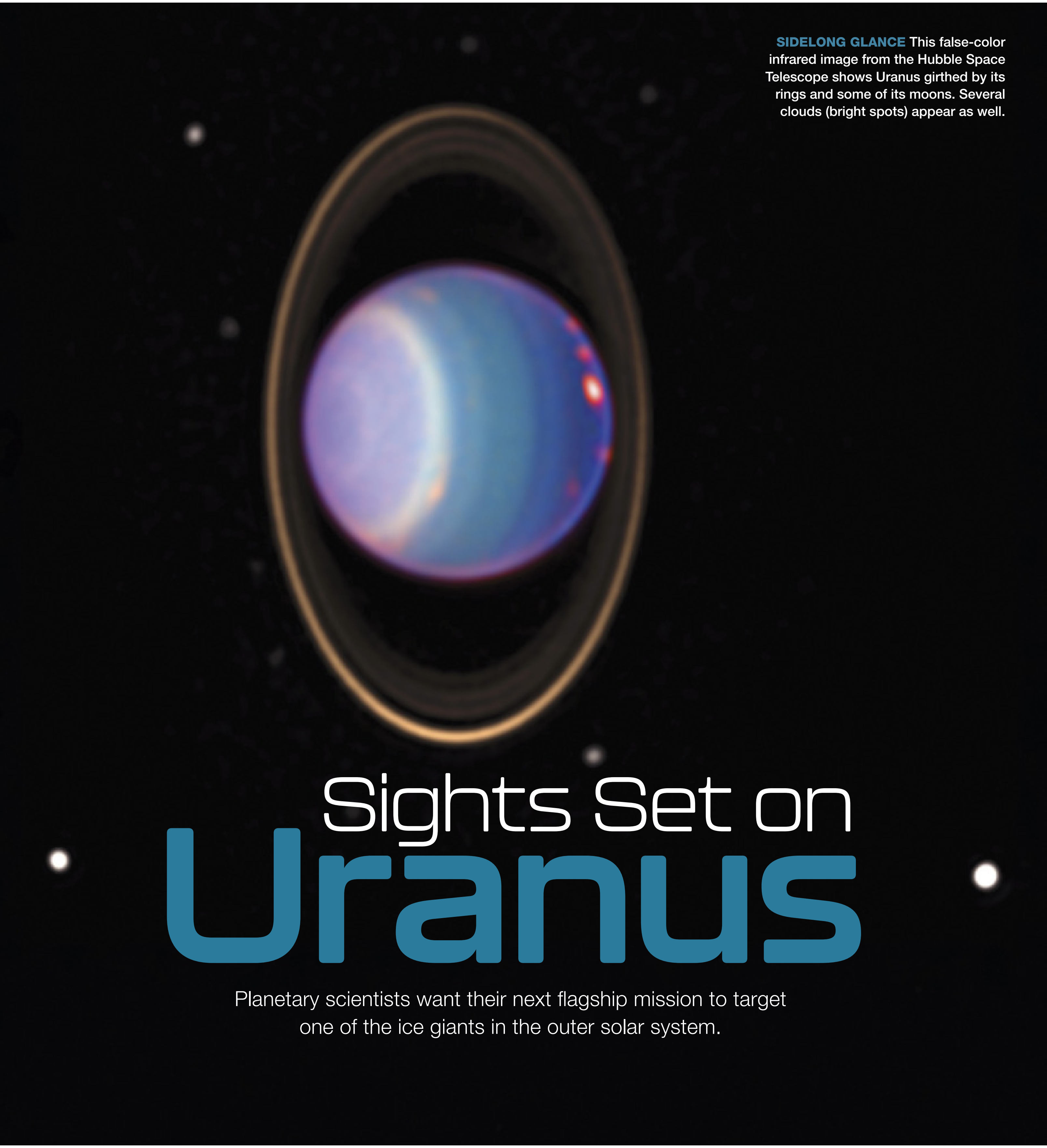


SIDELONG GLANCE This false-color infrared image from the Hubble Space Telescope shows Uranus girthed by its rings and some of its moons. Several clouds (bright spots) appear as well.

Sights Set on Uranus

Planetary scientists want their next flagship mission to target one of the ice giants in the outer solar system.

Uranus gets no respect. It is the butt of puerile jokes. Its smooth globe has been called bland and boring. So it surprises people when I tell them that of all the places in the solar system where we could send a spacecraft, I want us to go to Uranus most.

In January 1986, when I was 11-going-on-12, photos from the Voyager 2 flyby of Uranus and its moons reached Earth. I was mesmerized. Uranus was featureless, but it was a gorgeous aquamarine blue (my favorite color). Its moons were unlike anything I'd seen before: dark worlds seamed with mountains and chasms, strikingly different to the similar-size moons of Saturn.

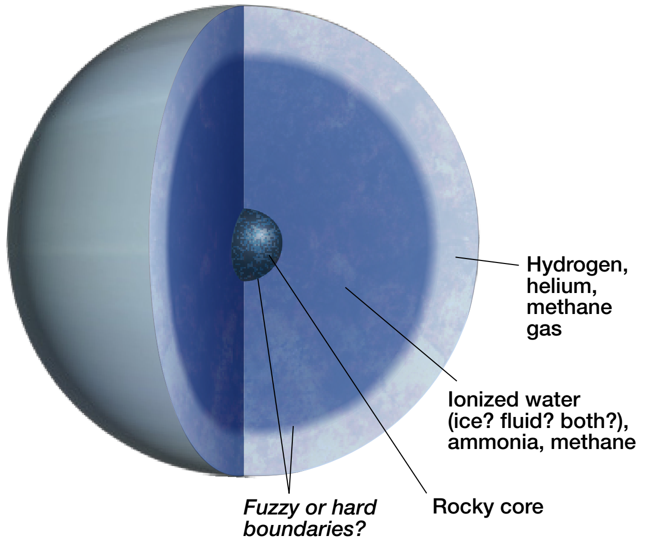
Inspired by this alluring world, I went on to become a planetary scientist. Since then, we've sent spacecraft to every other planet except Uranus and its fraternal twin, Neptune. We've studied the geology of the moons of Jupiter and Saturn, and even of comets and Pluto, but we haven't returned to those distant blue planets or their moons.

In the next decade, Uranus might finally get its turn. As part of the once-a-decade survey conducted by the National Academy of Sciences — the report that usually sets the to-do list for NASA's next planetary missions — scientists have declared that the development and launch of a Uranus Orbiter and Probe (UOP) is their highest priority for the next flagship mission. If NASA launches it in the early 2030s, as proposed, this mission could "deliver an in situ atmospheric probe and conduct a multi-year orbital tour that will transform our knowledge of ice giants in general and the Uranian system in particular," the committee wrote. Given that NASA usually follows decadal recommendations (with missions like Perseverance, currently roving Mars, and Europa Clipper, now under construction), we'll likely put a spacecraft in orbit around Uranus by the 2040s.

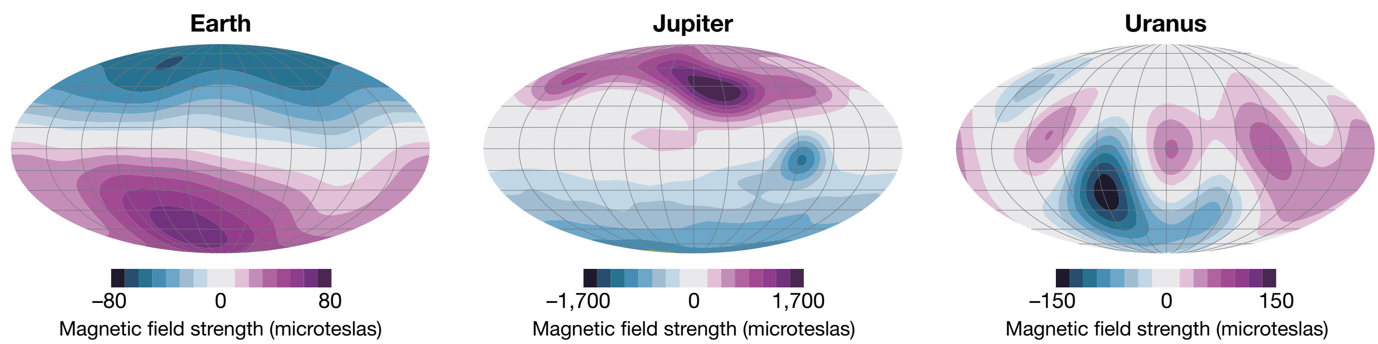
What's Inside Uranus?

Since the 1930s, we've suspected that Uranus and Neptune are made mostly of ice. ("Ice" refers to materials that are typically liquids or gases on Earth but are frozen in the outer solar system, including water and other lightweight molecular compounds like methane and ammonia.) By that time, astronomers had measured each planet's mass, volume, and *moment of inertia*, a measure of how concentrated the mass is toward the planet's center. Meanwhile, spectroscopy had shown that objects in the solar system appeared to have one of three main compositions: solar material (mostly hydrogen and helium), rock, and ice.

At that time, German astronomer Rupert Wildt asked: What if solar stuff, rock, and ice were the main ingredients for everything in the solar system, including the giant planets' interiors? Wildt calculated how much of each material would be needed in concentric layers to balance each world's mass, volume, and moment of inertia. He predicted that all four planets had rocky cores, surrounded by a layer of ice, but that Saturn and Jupiter had thick hydrogen-helium atmospheres that made up most of their mass, while Uranus and Neptune were mostly ice with only thin hydrogen-helium envelopes.

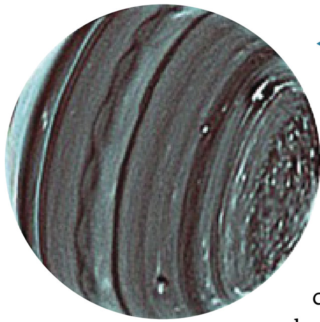


▲ **MYSTERIOUS INTERIOR** Hypotheses for the structure and composition of Uranus's interior vary, but they generally favor a rocky core overlaid by a water-rich mantle (at least partially in the form of superionic ice, although perhaps there's an "ocean" layer, too), with a gaseous envelope dominated by hydrogen, helium, and methane.



▲ **STRANGE FIELDS** The global magnetic fields of the solar system's terrestrial and gas-giant planets are predominantly *dipolar*, with a north (pink) and south (blue) pole that largely align with the planets' rotation axes. (Yes, Earth's north magnetic pole is currently at the geographic south pole.) Jupiter's field has more complexity than Earth's. But Uranus's field differs dramatically, with multiple poles grossly misaligned with the rotation axis. Neptune's field is similarly convoluted.

URANUS (FACING PAGE): NASA / JPL / STSCI; URANUS CUTAWAY: LEAH TISCIONE / S&T; MAGNETIC FIELDS: K. M. SODERLUND AND S. STANLEY / *PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A* 2020



◀ **NOT A BLAND BALL** These near-infrared composites each combine more than 100 images from the Keck II telescope to reveal subtle patterns on Uranus. White features are thick, high-altitude clouds whereas bright blue-green ones are more transparent, akin to Earth's cirrus clouds. Reddish tints mark deeper cloud layers.

ADAPTED FROM L. A. SROMOVSKY ET AL. / *ICARUS* 2015

We haven't learned much else about the interiors of the two ice giants since then. All the cutaway drawings you've ever seen that show the layered interiors of Uranus and Neptune (including the one on the previous page) are based on almost as many assumptions as Wildt made, nearly a century ago. State-of-the-art models for ice-giant interiors produce implausible compositions having anywhere from 3 to 20 times as much ice as rock, even though bodies that formed even farther from the Sun, like Pluto and Eris, have far more rock than ice.

We do know, however, that something strange is happening inside the ice giants. Voyager 2 discovered that the planets' magnetic fields look nothing like what we'd expect. Other worlds we've explored have *dipolar fields*, like a bar magnet, with a north pole and a south pole. But Uranus and Neptune's fields are multipolar, snarled things that aren't even remotely symmetrical, with north and south "poles" popping out of the planet in several locations. Furthermore, the fields emanate not from the core but from the mantle above it.

The current best hypothesis to explain the weird magnetic fields is that the dynamo that generates them originates within *superionic ice*, an odd form of water that might exist at the high temperatures and pressures within the ice giants' mantles. In superionic ice, hydrogen nuclei (that is, protons) can move freely within a solid lattice of oxygen nuclei, much as electrons move freely within a conductive metal. But we know neither the magnetic fields' shapes nor the planets' internal structures and temperatures well enough to connect magnetic-dynamo theory with our scant observations. To make matters worse, Neptune radiates 10 times more internal heat than Uranus, and we don't know why or how to explain their different heat flows with the same theory.

It's all a giant mystery.

Exoplanetary Ice Giants

Scientists have new reason to care about the ice giants, thanks to the planetary systems they've found around other stars. More than half of all known exoplanets have diameters between one and four times that of Earth, putting them between Earth and Uranus (*S&T:* Feb. 2022, p. 20). Mass and density estimates make these worlds look even stranger. Instead of being clearly rocky (like Earth) or hydrogen-helium dominated (like Saturn), exoplanets with diameters in between have densities all over the map, from rock-like to ice-like to gas-like. Without knowing their moments of inertia — the crucial piece of information that Wildt used to estimate the compositions of our solar system's giants — scientists can only guess what any given exoplanet is made of. And if we don't know their compositions, we can't figure out how this most common size of planet formed, nor can we understand why they're so diverse.

The exoplanet revolution has fundamentally changed the way space agencies view the goals of planetary exploration. Previously, exploration goals were driven by destination: We go to Venus, or Jupiter, or Pluto primarily to study those worlds — although, of course, the science we achieve at one world is applicable to others. The new idea is grander: We don't travel the solar system just to tour those destinations. We go to other worlds to answer open questions about planetary systems generally, and we select destinations based on their potential to answer those questions.

Just as this perspective shift has turned the international scientific community's gaze back to Venus (*S&T:* May 2022, p. 12), it has also fueled support for a mission to one of our neighborhood ice giants.

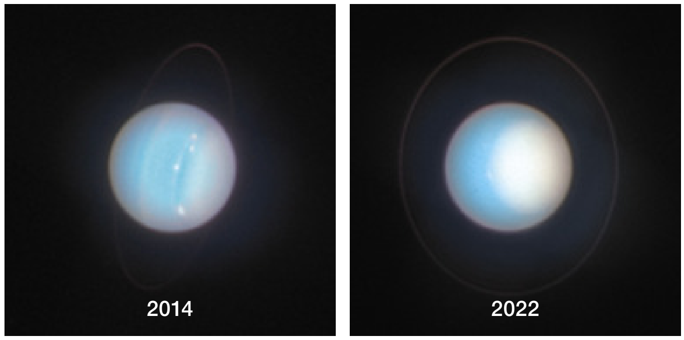
Why Uranus, Why Now?

Scientifically, Uranus and Neptune are equally interesting, but they are not the same. Although similar in mass and color, one (Neptune) releases more heat from its interior, compared to the sunshine it receives, than any planet in the solar system; the other (Uranus) emits the least. Their ring systems are very different: Uranus has thin, dense rings, studded with a dozen closely packed satellites, while Neptune's rings are sparse and clumpy. Uranus also has a set of spherical, mid-size icy moons to explore; only one of Neptune's moons is round, but it's big and likely captured from the Kuiper Belt. A compelling case could be made for the scientific value of sending the first ice-giant orbiter to either one.

But Uranus is a lot closer to us than Neptune is, orbiting some 19 astronomical units from the Sun instead of Neptune's 30 a.u. That alone tips the decision in Uranus's favor: Less distance to travel means a shorter cruise and therefore less fuel and money spent en route. Closer to the Sun also means less of a climb out of the solar gravity well; the same launch vehicle can deliver a heavier spacecraft to Uranus than to Neptune.

Choosing Uranus has other practical advantages, particularly the possibility of a Jupiter gravity assist. Through 2033, Earth, Jupiter, and Uranus will periodically align in such a way that a spacecraft could use the giant planet's gravity as a boost toward Uranus, shortening the flight of a lightweight craft to as few as eight years, although a heavier orbiter capable of addressing the full list of scientists' questions would take at least 12 years to arrive.

There's one more reason to go to Uranus first: seasons.



▲ **CHANGING SEASONS** *Left:* In November 2014, seven years after the northern hemisphere's spring equinox, storm clouds of methane ice crystals appear at mid-northern latitudes. *Right:* Eight years later, with the Sun beating down on high northern latitudes, a thick, smog-like haze has built up over the north pole.

Uranus orbits the Sun while lying on its side (why? we don't know), and it experiences extreme illumination changes as a result. In January 1986, Uranus was close to its southern summer solstice, with the Sun overhead at a latitude of 82° south. Uranus's southern hemisphere baked in continuous sunlight. The continuous radiation built a thick haze that obscured atmospheric activity beneath it. At the same time, the north poles of both planet and moons stayed in perpetual darkness, hiding them from Voyager 2's view.

Nearly 22 years later, in December 2007, Uranus passed through an equinox. The shift of seasons brought dramatic changes to Uranus' atmosphere, which lit up with storms and belts visible from Earth. Now, in 2023, atmospheric activity is shutting down again as the planet approaches its 2030 solstice, plunging the southern hemisphere into darkness.

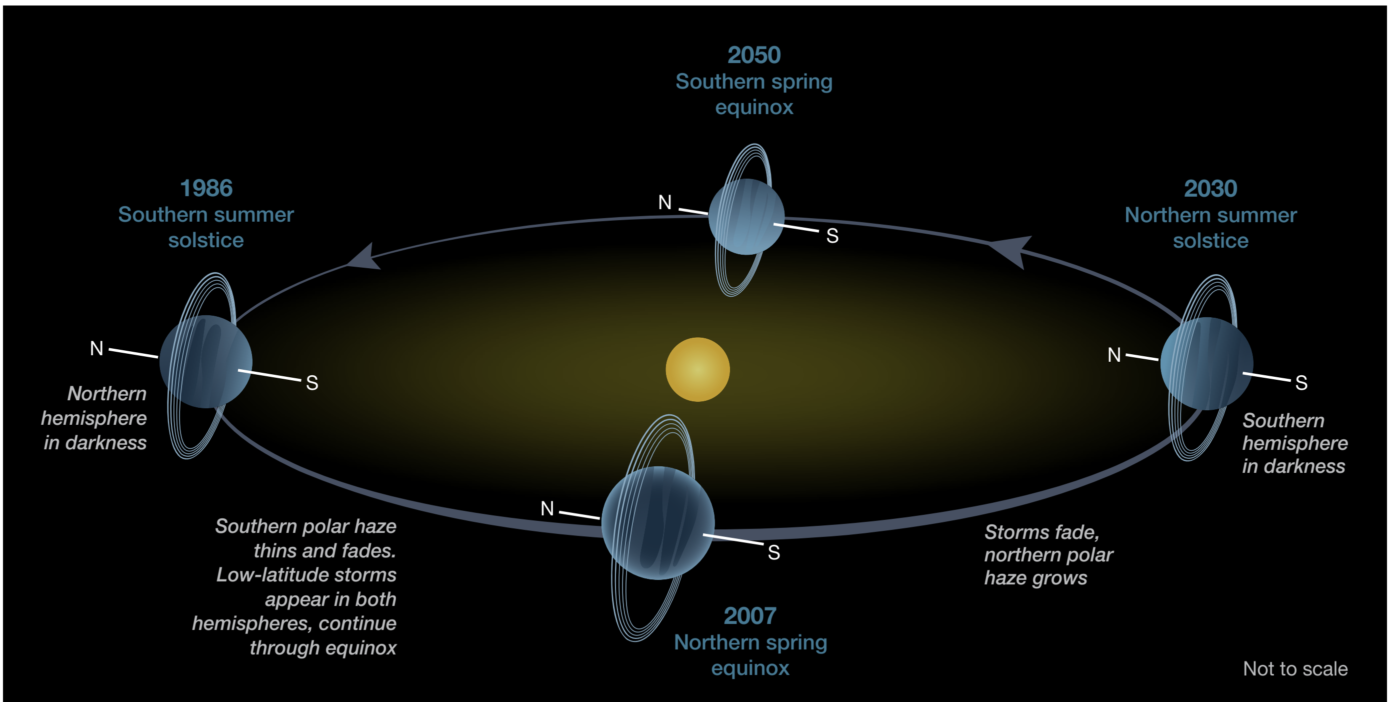
The next equinox comes in February 2050. So the best chance to see the most dynamic state of Uranus's atmosphere, to study the rings at a full range of solar illumination angles, and to see all of the satellites lit pole-to-pole with sunlight comes in the 2040s, as Uranus approaches equinox. Each year after 2050 will hide more and more of the north poles of both the planet and its moons in winter darkness and will produce more atmospheric haze, making Uranus harder to interpret.

Neptune poses no such time crunch. Its less extreme axial tilt makes arrival at a specific time of year less urgent, and although its weather changes as seasons shift, it produces dark storms and bright "scooters" year-round. Neptune's year is so long, with each season lasting 40 years, that any mission we launch in the next half-century will see the planet at a different season than Voyager 2 did.

What Would a Mission to Uranus Look Like?

At the moment, the proposed Uranus mission is mostly a list of questions, both about the science and the spacecraft design. NASA hasn't yet committed to sending it, either. Nevertheless, planetary scientists are throwing themselves into the discussion, advocating for which mysteries they most want to solve and how they would learn the answers.

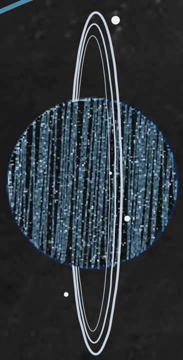
We can speculate on what the mission might look like,



URANIAN SEASONS Because of its rotation axis's extreme tilt — 98° from the orbital plane — Uranus experiences dramatic seasonal changes over the course of its year. When Voyager 2 flew by in 1986, the northern hemisphere was in complete winter darkness. By sending a spacecraft to rendezvous with the ice giant in the 2040s, scientists hope to catch the storms and weather systems that pop up around equinoxes.

URANUS IMAGES: SCIENCE: NASA, ESA, STSCI, AMY SIMON (NASA-GSFC), MICHAEL H. WONG (UC BERKELEY), IMAGE PROCESSING: JOSEPH DEPASQUALE (STSCI); ORBIT DIAGRAM: BEATRIZ INGLESSIS / S&T, SOURCE: M. SHOWALTER AND M. GORDON / SETI INSTITUTE

VOYAGE TO URANUS Scientists' favored mission scenario has the orbiter and probe launching from Earth in 2031 or 2032, making a loop around the Sun, and then swinging by Earth for a gravity assist to shoot it toward the outer solar system. A Jupiter flyby would give it another boost, rocketing it toward Uranus for a mid-2040s arrival. Once there, orbiter and probe would investigate every aspect of the planet, rings, and moons; here are some of the questions on scientists' list. The primary mission at Uranus would last 4½ years.



ORIGINS

When, where, and how did Uranus form?

Did a catastrophic impact knock Uranus sideways?

RINGS

What are the rings made of?

How old are they?

What sculpted them into their current configuration?

How do they relate to the moons?

MAGNETOSPHERE

Why is the magnetic field so complex?

How does it interact with the solar wind?

How does it affect the upper atmosphere, moons, and rings?

Probe

MOONS

How old are the moons, and how did they form?

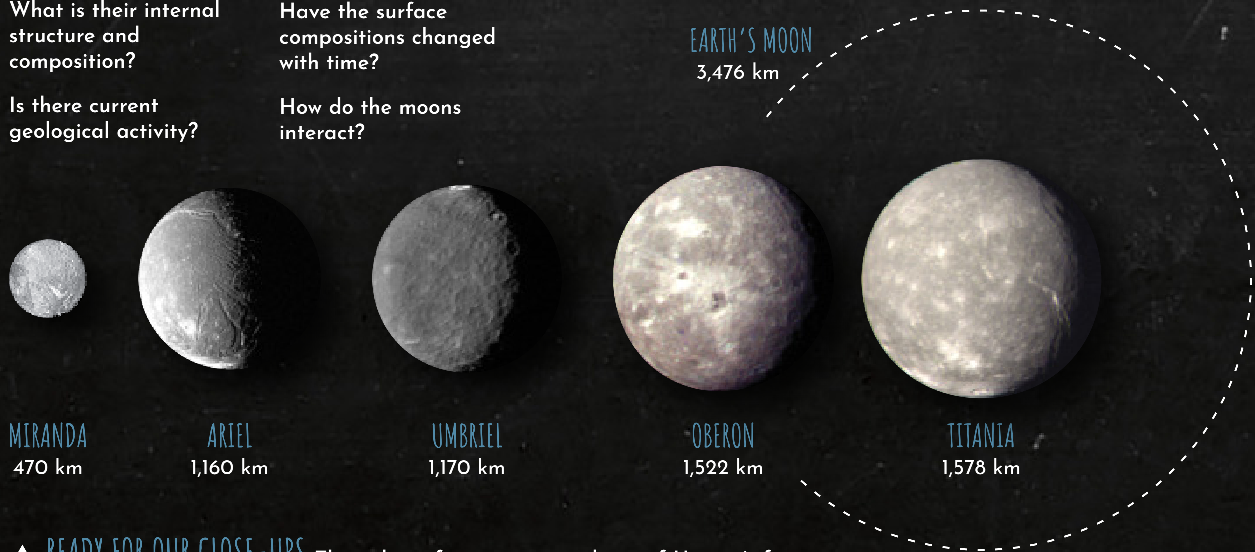
What is their internal structure and composition?

Is there current geological activity?

Do any have subsurface oceans?

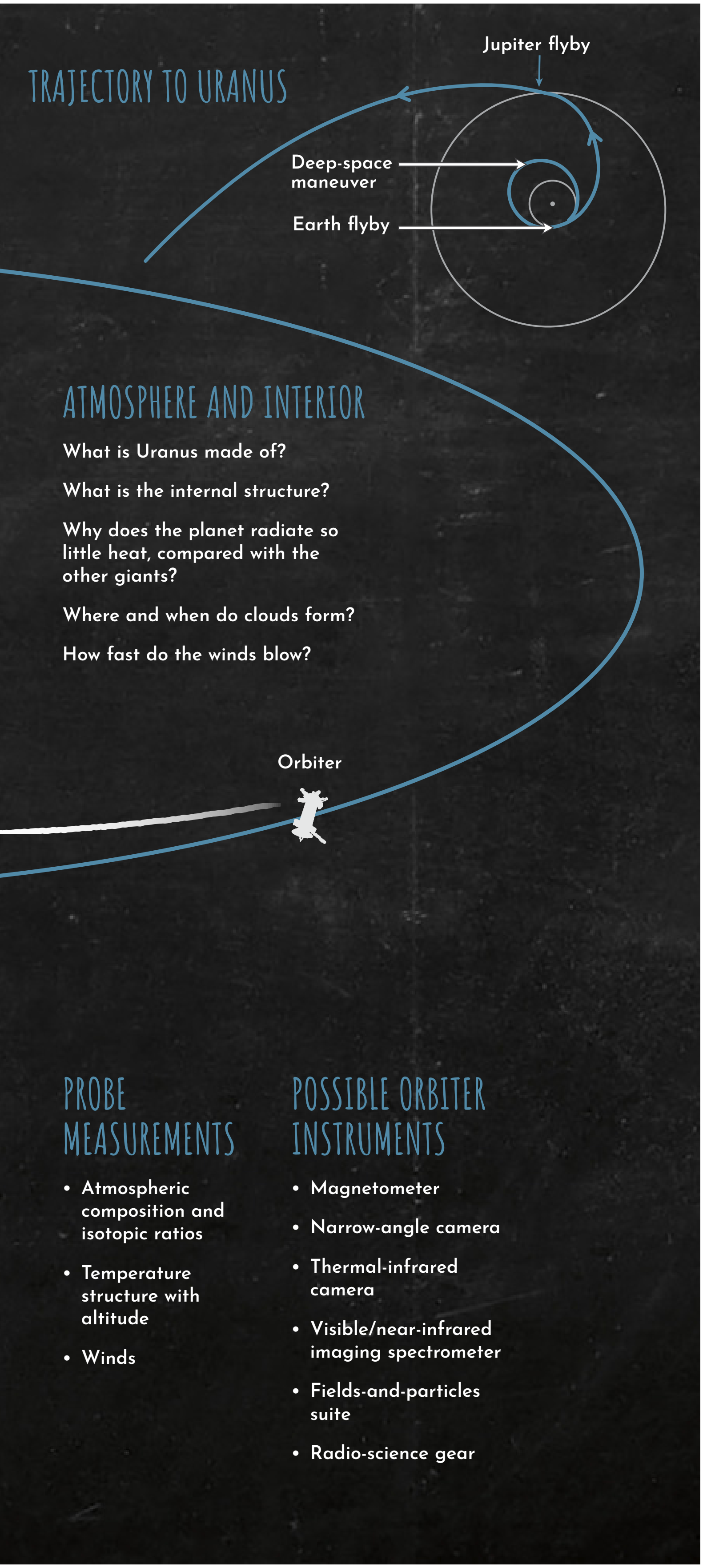
Have the surface compositions changed with time?

How do the moons interact?



▲ **READY FOR OUR CLOSE-UPS** The only surface images we have of Uranus's five largest moons come from Voyager 2, and they're small and sometimes blurry. But they show signs of resurfacing. Sizes are diameters.

INFOGRAPHIC: BEATRIZ INGLESSIS / S&T; MOONS: NASA / JPL (5)



based on the study submitted to the decadal survey. The study concluded that we know so little about ice giants that we need a flagship mission with an atmospheric probe, like Galileo was at Jupiter and Cassini at Saturn, to investigate the planet's system from interior to magnetosphere, rings, moons, and all. The recommended flagship would cost at least $2 billion. Worried about asking NASA for too much and ending up with nothing, scientists have also proposed less expensive, $1 billion scenarios that could achieve a subset of the flagship mission goals: a Juno or a New Horizons analog, rather than a Cassini.

There are literally tens of thousands of potential mission scenarios, mixing and matching rocket types, gravity assists, cruise times, payload sizes, and onboard power supplies. Because the questions about Uranus are so broad, the instrument suite must cover a wide range of capabilities. It's useful to compare the potential Uranus mission to the recent Cassini flagship and New Horizons' fast flyby: The Uranus orbiter's instruments will have similar scope to those on Cassini, but thanks to advancements in miniaturization and automation that enabled the New Horizons, Dawn, and Lucy missions, they will be much smaller and require less power and data volume.

Since the most important questions about Uranus relate to its interior structure and composition, it's almost certain that the mission would carry a magnetometer to probe the gnarly magnetic field and glean information about the planet's guts. As on every mission, radio science will reveal the distribution of mass within the planet through ultra-precise tracking of the spacecraft, and we'll study Uranus's atmospheric composition, temperature, and pressure by beaming the craft's radio signal through the atmosphere back to Earth.

The choices among other instruments depend on budget, available mass and power, and scientific focus. A fields-and-particles suite including energetic-particle detectors, plasma spectrometers, and other devices could study the charged atoms whipped up by the magnetic field and the dust knocked off the moons and rings. Spectrometers in visible and near-infrared wavelengths could investigate the composition of moons, rings, and planet, while a thermal-infrared instrument would be able to map surface temperatures and study the nightsides of planet and satellites from the heat they radiate. Narrow- and wide-angle cameras could perform distant and close-in imaging, making maps of the moons, rings, and planetary storms. If we're very lucky, we might witness the effects of an impact like that of Shoemaker-Levy 9 on Jupiter in 1994 and study the stuff dredged up from below.

A probe would be costly in terms of mass and budget; making physical room for a probe and taking on its complexity and risk would necessarily reduce the capability of the mothership that deposits it into Uranus. But a probe is essential to nail down answers to the questions surrounding how and when Uranus formed, and from what materials. For example, one model for solar system formation, *gravitational instability*, would leave Uranus and Neptune with fractions of the elements heavier than helium that are about 100 times higher than those found in the Sun. A different model suggests that Uranus and Neptune originated at an ice-giant sweet spot, the *CO snowline*, at a solar distance where carbon monoxide condensed into a solid but nitrogen was still a gas. If this is true, then Uranus will have 100 times as much carbon and oxygen as the Sun does, but a much smaller enhancement of the other elements. A probe's sensitive measurements could help differentiate among these scenarios by revealing various elements' abundances and isotopic ratios. It could also tell us the atmospheric structure, where clouds form, and how deep the winds go.

The Mission Scenario

As put forth for the decadal survey, the UOP concept study requires a sizable rocket. It assumes that the giant Space Launch System will not be available, favoring an expendable Falcon Heavy instead. (A reusable Falcon Heavy gives too small a boost.) The ideal mission scenario is a launch in 2031 or 2032, with a gravity-assist flyby of Earth two years later, then another past Jupiter, reaching Uranus 12 or 13 years after launch. That scenario gets you 5 tons of spacecraft in orbit around Uranus. An SLS launch vehicle, if available, could cut the travel time substantially, down to as little as six years.

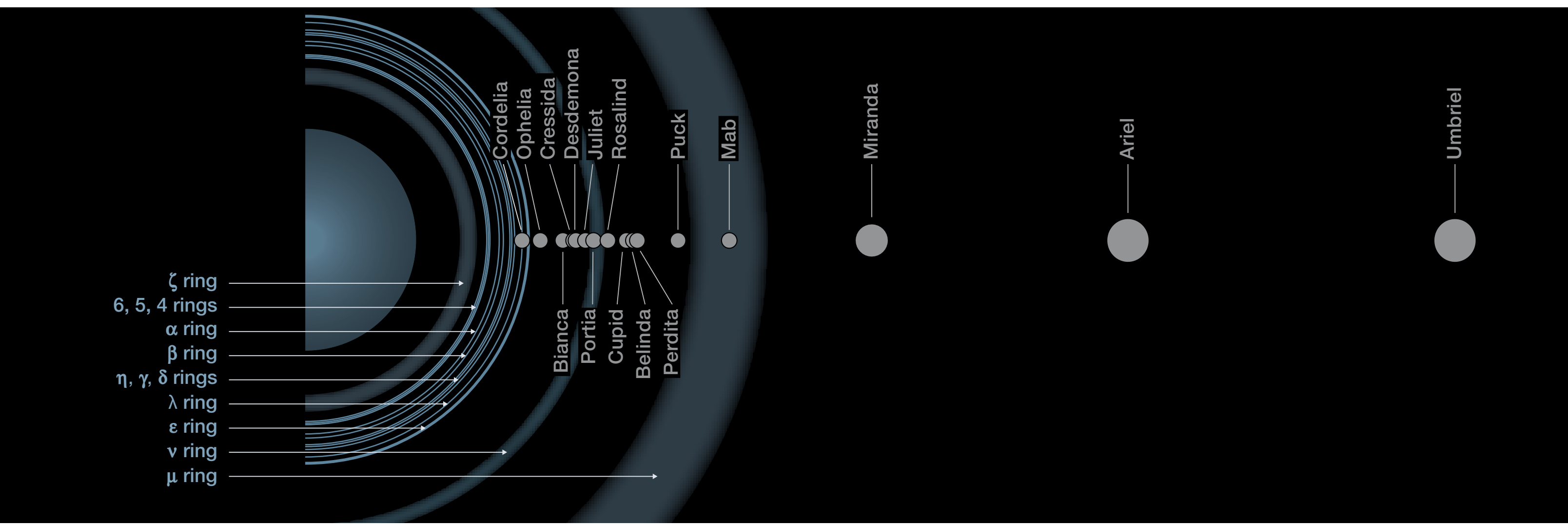
A later launch without a Jupiter flyby would require some combination of a longer cruise (up to 18 years, beyond which the decaying power supply from the radioisotope generators becomes an issue), more fuel-guzzling rocket maneuvers (increasing risk and reducing the amount available to steer the science orbits), lower spacecraft mass (limiting science instruments and maneuvering fuel), the addition of a Venus gravity assist (imposing challenging thermal requirements on the spacecraft that reduce the mass budget), and/or help from a solar-electric propulsion stage (adding cost and complexity).

Spacecraft can release their probes on approach or after entering orbit. Both options come with tradeoffs. The UOP concept has the spacecraft first enter a highly elliptical orbit and then launch the probe, like Cassini did with Huygens. This setup would enable the team to select the entry point for scientific reasons rather than trajectory ones. As soon as the probe mission was over, the orbiter would use another rocket burn to pull closer to the planet, entering an orbit optimized for planet, ring, and satellite science.

At first, the orbiter's path around Uranus would be tilted out of the ring plane. Such a tilted orbit is great for study of the magnetosphere, rings, and poles, but it doesn't enable many encounters with the icy moons — some of which appear in Voyager 2 images to have been resurfaced by geological activity; they might even have subsurface oceans. Ariel, Umbriel, Titania, and Oberon are all large enough to provide tweaks to an orbiter's path around Uranus. So the post-probe-mission rocket burn would target one of those moons — likely the most massive one, Titania — to set up a resonant orbit, meeting the moon in the same location every time the spacecraft passed through the ring plane. Over time, moon flybys would slowly change the orbit, just as Cassini did at Saturn with flybys of Titan. Eventually, the spacecraft would equatorialize its orbit, traveling within the ring plane.

A ring-plane orbit makes the rings largely invisible — because they're so thin, it'll be like looking along the edge of a razor — but allows pole-to-pole monitoring of planetary weather. Flying in the ring plane also generates far more opportunities to observe the moons, including mutual events (where one moon occults another from the craft's perspective). These events are necessary for precisely determining the moons' orbits, which in turn would reveal the satellites'

▼ **CROWDED SYSTEM** A collection of small and mid-size moons huddles around Uranus. (We've omitted the outer nine moons; they follow elongated, highly inclined orbits.) Some rings are dusty, others icy. It's unclear what sculpts the narrow ones. The many small moons just outside the main rings orbit so close together that they're in danger of collision or migrating toward the planet — in fact, the current set of moons might be fairly recent, part of a destruction-and-creation cycle that supplies ring-forming debris. Moon sizes are not to scale.



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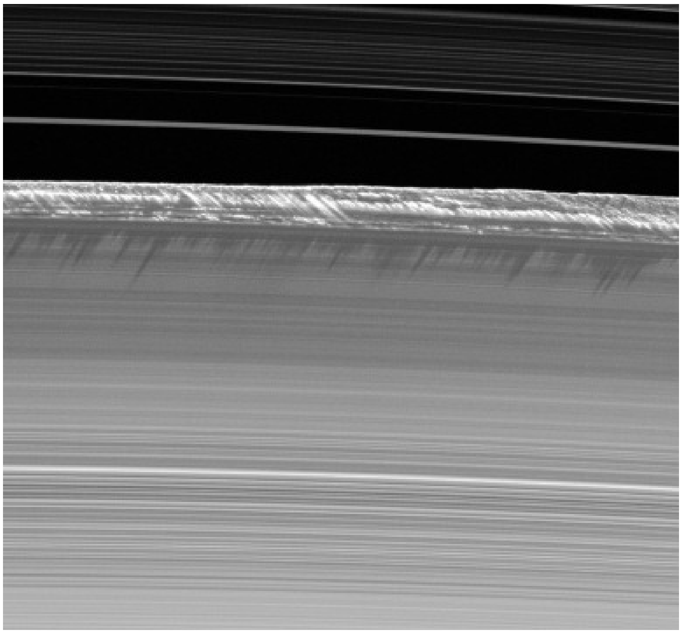

▲ **RING PEAKS** This Cassini image reveals vertical structures rising abruptly from Saturn's icy B ring. The peaks tower as high as 2.5 km (1.6 mi) above the rings and may be "splash-ups" created by passing moonlets. They appear stark thanks to the low illumination angle of equinox, when sunlight shines obliquely along the ring plane and causes structures jutting out of the plane to cast long shadows. An orbiter at Uranus might see similar structures during the planet's own equinox.

NASA / JPL / SPACE SCIENCE INSTITUTE

masses and gravitational tugs on each other. The spacecraft could spend a long time in such an orbit; the lifetime of the mission will ultimately be limited by the waning power available from its radioisotope power source.

The end would eventually come. To prepare, the orbiter would execute multiple flybys of the innermost thousand-kilometer-size moon, Ariel — which may have the geologically youngest surface of the bunch — to pull the spacecraft into a death spiral. Finally, a rocket burn at apoapsis would reduce the orbital periapsis to one that intersects Uranus's atmosphere, burning it up in the planet's icy air. This disposal method avoids harm to any potential habitable environment on the moons.

The baseline orbital mission would last less than five years. But history suggests that once an orbiter is safely at Uranus, NASA would consider mission-extension scenarios that would send the orbiter on additional tours, perhaps studying the anti-Sun side of the magnetosphere or performing dedicated gravity-tracking flybys of moons, as Cassini did at Saturn. The availability of gravity assists from four moons at different distances from Uranus make the options nearly endless.

To Infinity, and Beyond!

We still don't know exactly what the first dedicated ice-giant mission will look like, or what it will discover. The scenario I've outlined here, as detailed as it is, is just one concept. It also doesn't include how other space agencies might collaborate with NASA. The European Space Agency, for example, contributed the Huygens probe to Cassini and is also considering building an ice-giant orbiter.

One thing we do know is that the scientists and engineers developing a future mission to Uranus — or Neptune — will not be the ones operating it when it arrives. The mid- and late-career scientists who have the professional standing and the time to propose future missions will be edging toward retirement by the time a spacecraft actually enters orbit. This mission will belong to today's early-career scientists.

Studying the outer outer planets requires patience, faith, and hope — an optimistic view that, two or three decades from now, today's children will be enjoying the opportunity to be the first to study a new kind of planet from orbit. These days, such optimism is a breath of fresh air. So tell your kids: It's time to probe Uranus!

■ Contributing Editor **EMILY LAKDAWALLA** is a freelance science writer and space artist based in Los Angeles. Find her work, socials, and shop at **Lakdawalla.com/emily**.