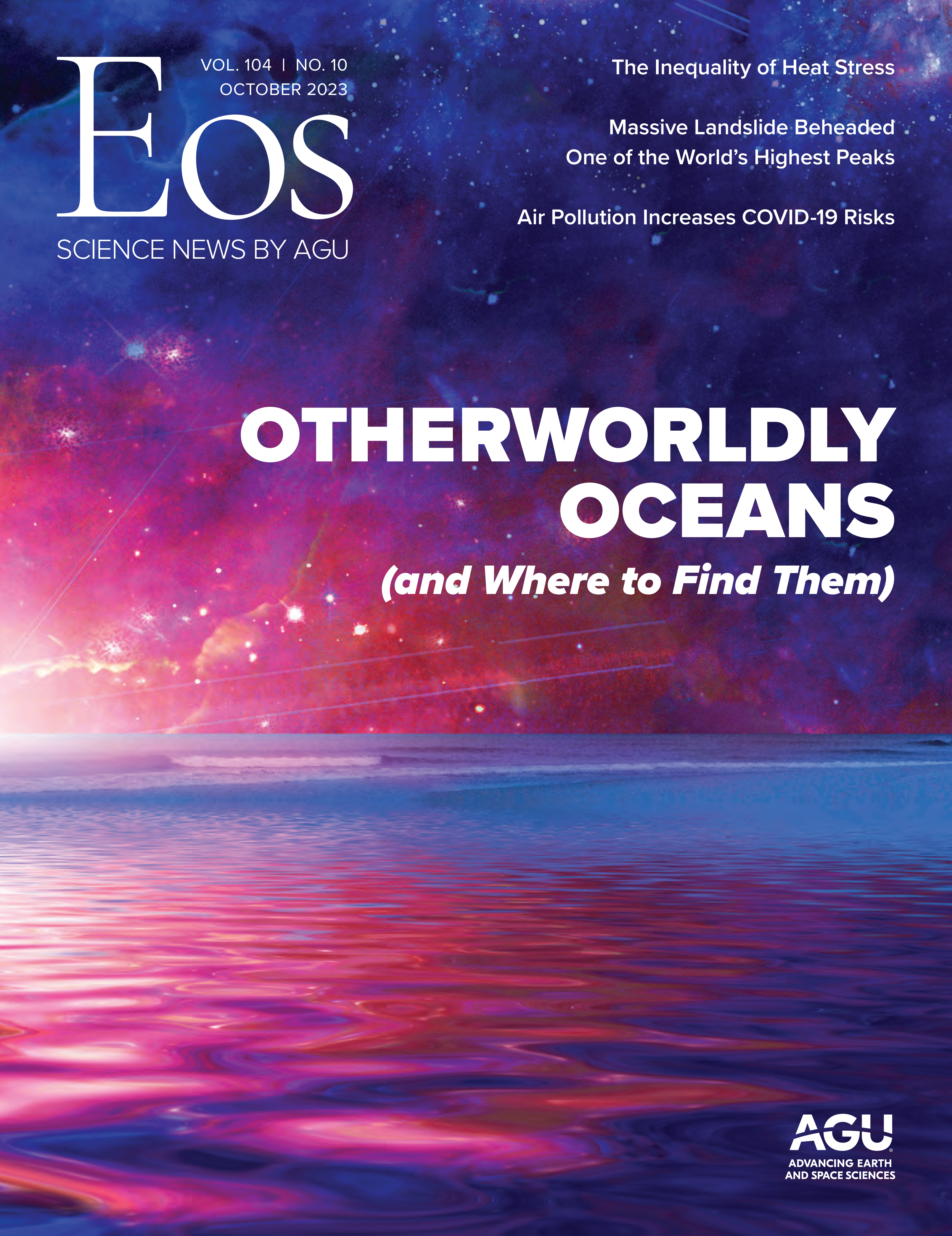

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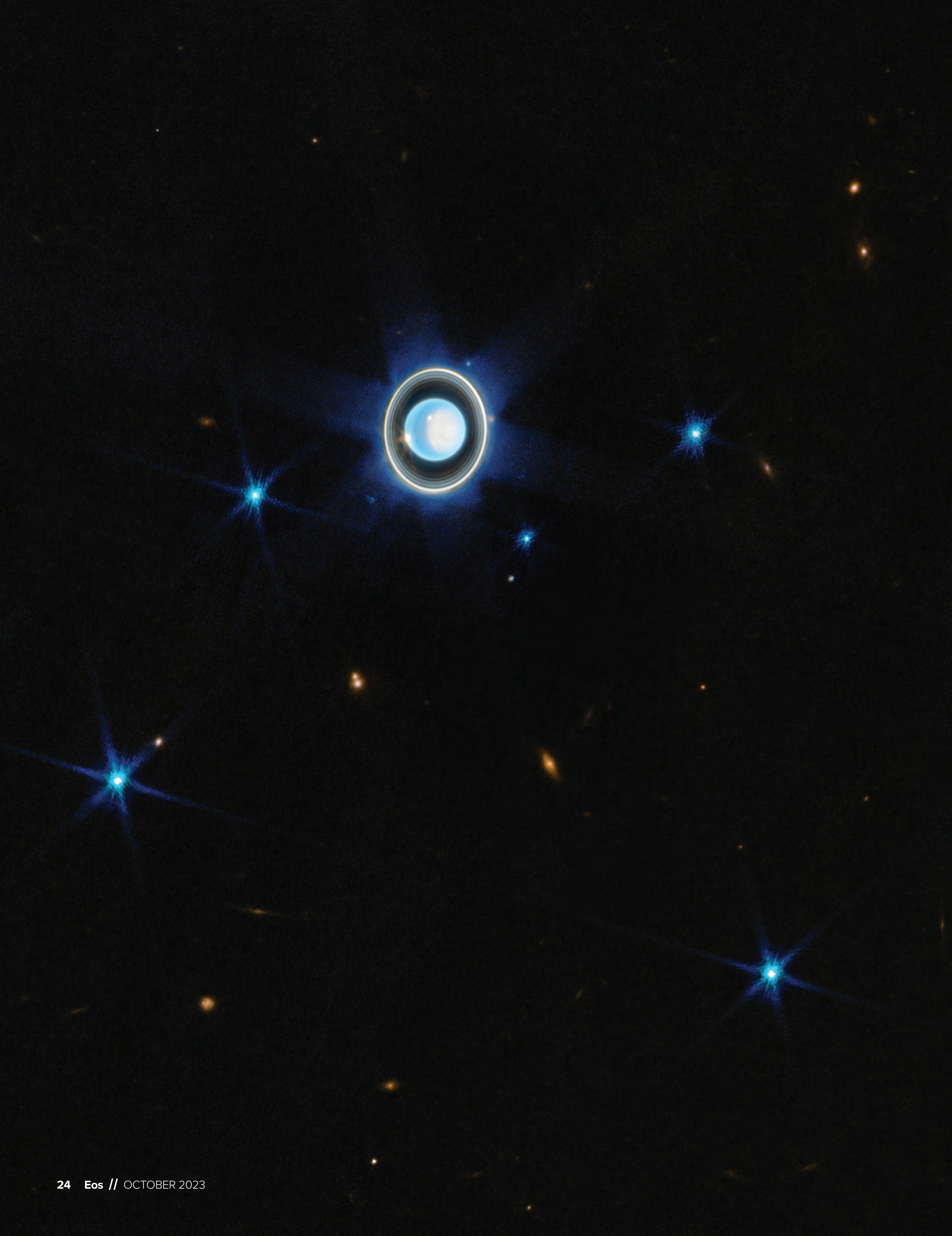
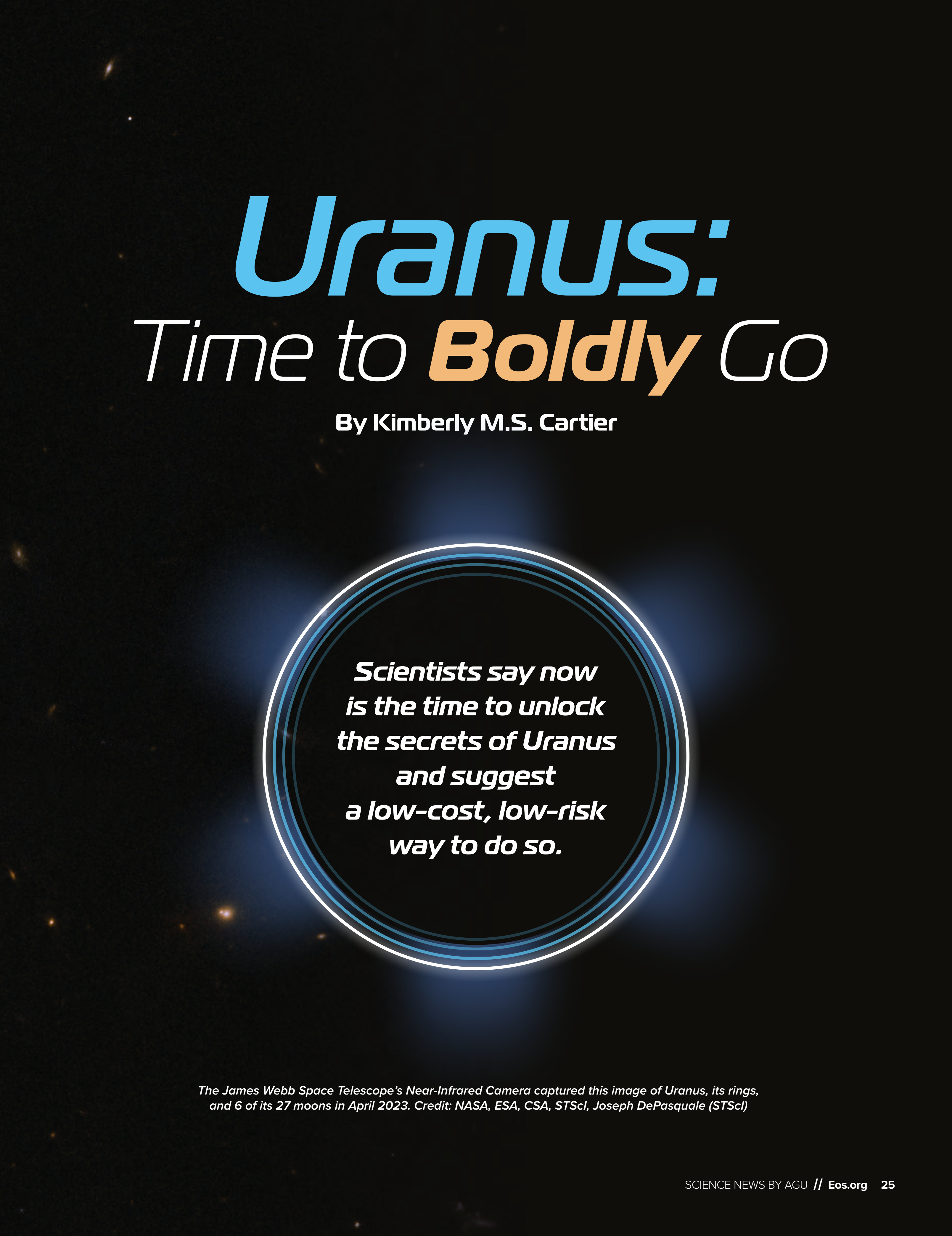


Uranus: Time to Boldly Go

By Kimberly M.S. Cartier



Scientists say now is the time to unlock the secrets of Uranus and suggest a low-cost, low-risk way to do so.

The James Webb Space Telescope's Near-Infrared Camera captured this image of Uranus, its rings, and 6 of its 27 moons in April 2023. Credit: NASA, ESA, CSA, STScI, Joseph DePasquale (STScI)

Uranus is one of the most mysterious planets in the solar system. It might not seem like much on its surface: Many photos show it to be a featureless blue-green orb with nary a cloud in sight. But its unique tilt, unusual ring system, misaligned magnetosphere, and curious variety of moons suggest that it has an interesting history that could unlock the evolutionary past of our solar system and tell us quite a bit about the planets beyond.

A brief visit to the planet decades ago by the Voyager 2 spacecraft and more recent remote observations have left scientists with more questions than answers about it.

A window of time is fast approaching during which astronomers could launch a spacecraft to Uranus. In fact, such a mission is at the top of their wish list. With abundant scientific potential and few technological hurdles, scientists argue that now is the time to return to Uranus—and this time, to stay a while.

"Every aspect of the Uranian system challenges our most basic understanding of how planets work," said Mark Hofstadter, a planetary scientist at NASA's Jet Propulsion Laboratory in Pasadena, Calif. "Voyager and Earth-based observations since then have seen things in the planet itself, in its rings, its small moons, its major satellites, and its magnetosphere that violate our expectations of how things should be," he said.

"It is therefore critically important that this once-in-a-lifetime opportunity to visit Uranus be able to explore all aspects of the system and to carry a diverse instrument suite to respond to the surprises that await us," Hofstadter said.

"Every aspect of the Uranian system challenges our most basic understanding of how planets work."

Voyager

In January 1986, the Uranian system received its first and, so far, only visitor from Earth. NASA's Voyager 2 spacecraft spent 32 days flying past the planet, capturing a small bit of gravitational energy to change its trajectory on its way out of the solar system.

While in the planet's vicinity, Voyager 2 gathered the first close-up images of Uranus's upper atmosphere, the cratered and uneven surfaces of several of its moons, and its ultrathin ring system. The craft also took measurements of Uranus's magnetic field, sampled the radiation environment near the planet, and discovered Uranian lightning.

But plenty of questions remain. Why is the planet tilted more than 90° on its side? What chemistry swirls in its interior? How does its magnetosphere interact with the solar wind throughout the Uranian year? What weather pops up as the seasons change? Could the planet's moons have recent or active cryovolcanism or subsurface oceans?

Voyager 2 flew by Uranus around the southern hemisphere's summer solstice, when the planet's northern hemisphere was completely in the dark. Uranus's moons, which orbit roughly along its tilted equator, were also only partly illuminated. "That had implications for what we could see of the satellites, the magnetosphere, and atmospheric weather patterns," Hofstadter said.

"At the time of Voyager, Uranus was famously bland looking," Hofstadter said. "It was referred to as the blue billiard ball, and so few atmospheric features were seen that the atmospheric science group of Voyager discussed giving up some of their precious observing time to other teams."

Uranus completes an orbit (and therefore a seasonal cycle) every 84 Earth years, and by 2007, it had moved into its equinox. Since Voyager, observations from the ground and from space "have found the atmosphere to be much more active and energetic at seasons other than summer," Hofstadter said. Arriving at Uranus during a different season, he said, means initiating a mission now.

The Next Generation

With several large strategic NASA missions now underway or well into development (including the James Webb Space Telescope (JWST), Perseverance rover, Parker Solar Probe, Nancy Grace Roman Space Telescope , Europa Clipper, and a Mars Sample Return mission), astronomers' next-highest priority is a mission to Uranus that includes an orbiter and an atmospheric probe. Missions this size are also known as flagship-class missions, NASA's largest and most expensive type of project that can answer multiple high-priority science questions.

"Uranus and Neptune remain the two unexplored planets in our solar system, each with its own exciting system of moons, rings, complex magnetosphere, and dynamic atmosphere," said Amy Simon, a planetary scientist at NASA Goddard Space Flight Center in Greenbelt, Md. Of the two, Uranus is closer and therefore more easily reached.

A Uranus flagship mission has appeared in past planetary science decadal surveys, which scientists proffer as a road map for NASA's budgetary priorities. The request has steadily crept up the priority list until it reached the top slot in 2022. A mission to the Uranian system has "vast potential for broad, cross-disciplinary science," Simon said.

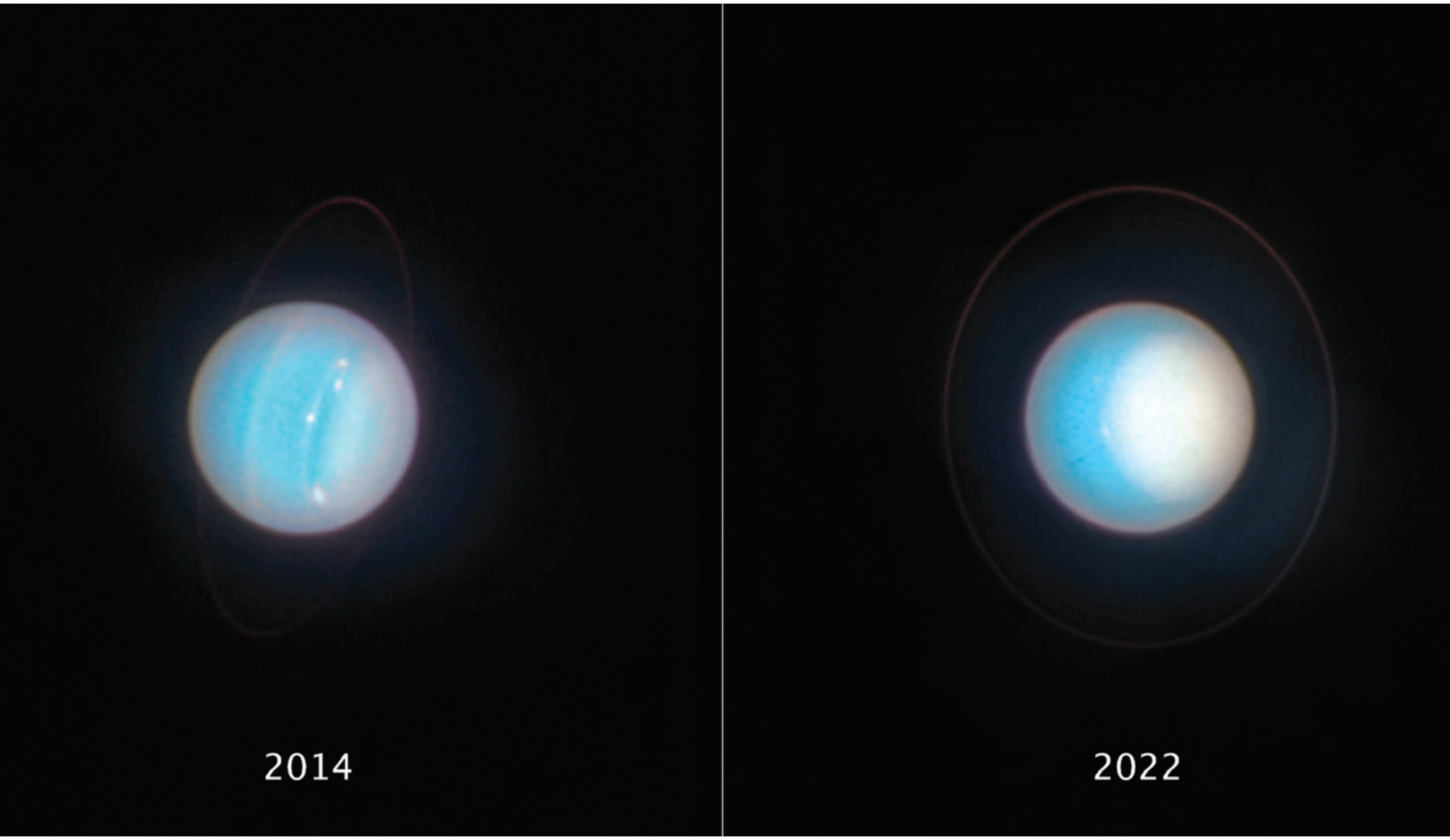
A group of planetary scientists and engineers designed a mission concept called the Uranus Orbiter and Probe (UOP) and has proposed the mission to NASA for review. The mission would deploy an atmospheric probe shortly after arrival, tour several moons, and then settle into orbit for 4.5 Earth years. The most recent planetary science and astrobiology decadal survey evaluated this mission as low risk, relatively low cost, and high reward.

It takes a lot of time and energy to travel to Uranus, said Athena Coustenis, a planetary scientist and director of research at Centre National de la Recherche Scientifique in France. An efficient flight path would take a spacecraft past Jupiter to gain some energy through a gravitational slingshot. A launch window in the early 2030s would provide the necessary planetary alignment, but there would be launch opportunities for several years following, too.

UOP's spacecraft design would rely on technologies proven to work on past missions while also offering NASA opportunities for international collaboration on instrumentation. Currently available technology is still a big step up from what was on board Voyager 2 during its flyby, Coustenis said.

"Although new technology is exciting, the community made clear in the decadal survey that waiting to explore this planet is holding up major questions in planetary science," said Kathy Mandt, a planetary scientist at NASA Goddard Space Flight Center. "Time is of the essence, so this mission needs to rely on existing technology."

The reliance on existing technology means that "the primary challenges involve cost and schedule," said Richard Anderson, a systems



With its 92° axial tilt, Uranus's seasons are vastly different from those on any other solar system planet and vary dramatically throughout its year. In 2014, 7 years after Uranus's equinox, the Hubble Space Telescope imaged the planet with several equatorial storms with clouds made of methane ice crystals. In 2022, 6 years before its northern solstice, its north pole glowed bright, and the planet displayed fewer storms. Credit: NASA, ESA, STScI, Amy Simon (NASA-GSFC), Michael H. Wong (UC Berkeley), Joseph DePasquale (STScI), Public Domain

engineer at the Johns Hopkins University Applied Physics Laboratory in Laurel, Md., and the study lead on the UOP concept. "We are actively looking into ways to reduce cost and conserve critical resources such as the plutonium needed to fuel [the spacecraft's] radioisotope thermoelectric power generators," he said.

The mission concept is smaller in size and cost than past flagships such as Galileo (which explored the Jovian system) and Cassini (which explored Saturn) but would have a similar scientific scope. "It would carry an atmospheric probe, as well as science instruments that can sense all aspects of the Uranian system," said Simon, who was a science colead for the UOP concept.

Even with no new technology, "large missions still require a long time to design, build, and test," Simon said.

Despite being similar in scale to past flagship missions, Mandt said, "what is really important about UOP is that if we focus the design to use current technology and carefully manage the scope, we have the opportunity to set a new precedent for cost-effective large-scale missions."

"A mission to the Uranus system can be completed more cost-effectively than one to Europa, for example," Anderson said.

Strange New Worlds

Many planetary scientists are particularly excited about the possibility of exploring Uranus's largest moons, Oberon, Titania, Ariel, Umbriel, and Miranda. These moons are thought to be made of rock and water ice in roughly equal amounts. (Uranus has 27 known moons, some only 15 kilometers across and blacker than asphalt.)

Given the lighting conditions at the time, Voyager 2 could map only around 40% of the surfaces of these moons. Even that much, however, was enough to demonstrate that they have wildly different surface geologies and degrees of cratering.

An arrival near equinox—which will next occur in 2049—would mean that the unseen hemispheres of the moons would be illuminated, allowing scientists to finish mapping their surfaces. "Close flybys that allow imaging or spectroscopy will tell us about surface geology and composition, as well as possibly the age of the features we observe," Simon said.

All five large satellites may have subsurface liquid water oceans at the boundary between their rocky interiors and icy surfaces. "Looking for oceans will be a very high priority and should be achievable at least for the inner moons," said Francis Nimmo, who studies planetary evolution at the University of California, Santa Cruz and was a science colead for the UOP concept.

A magnetometer on board a spacecraft could pick up on a magnetic field from a subsurface ocean. Galileo mission scientists used this method to confirm oceans on Jupiter's Europa, Callisto, and Ganymede.

Scientists are particularly interested in the oceanic possibilities of Ariel, whose smooth topography might be evidence of resurfacing from cryovolcanism. Thermal measurements and images taken at a high angle to a moon could illuminate any currently active cryovolcanoes or geysers, said Simon.

As with other watery worlds, there is the potential for life. Though many eyes turn to Enceladus and Europa as top astrobiology targets, there's no reason Uranus's ocean moons couldn't support life, too.

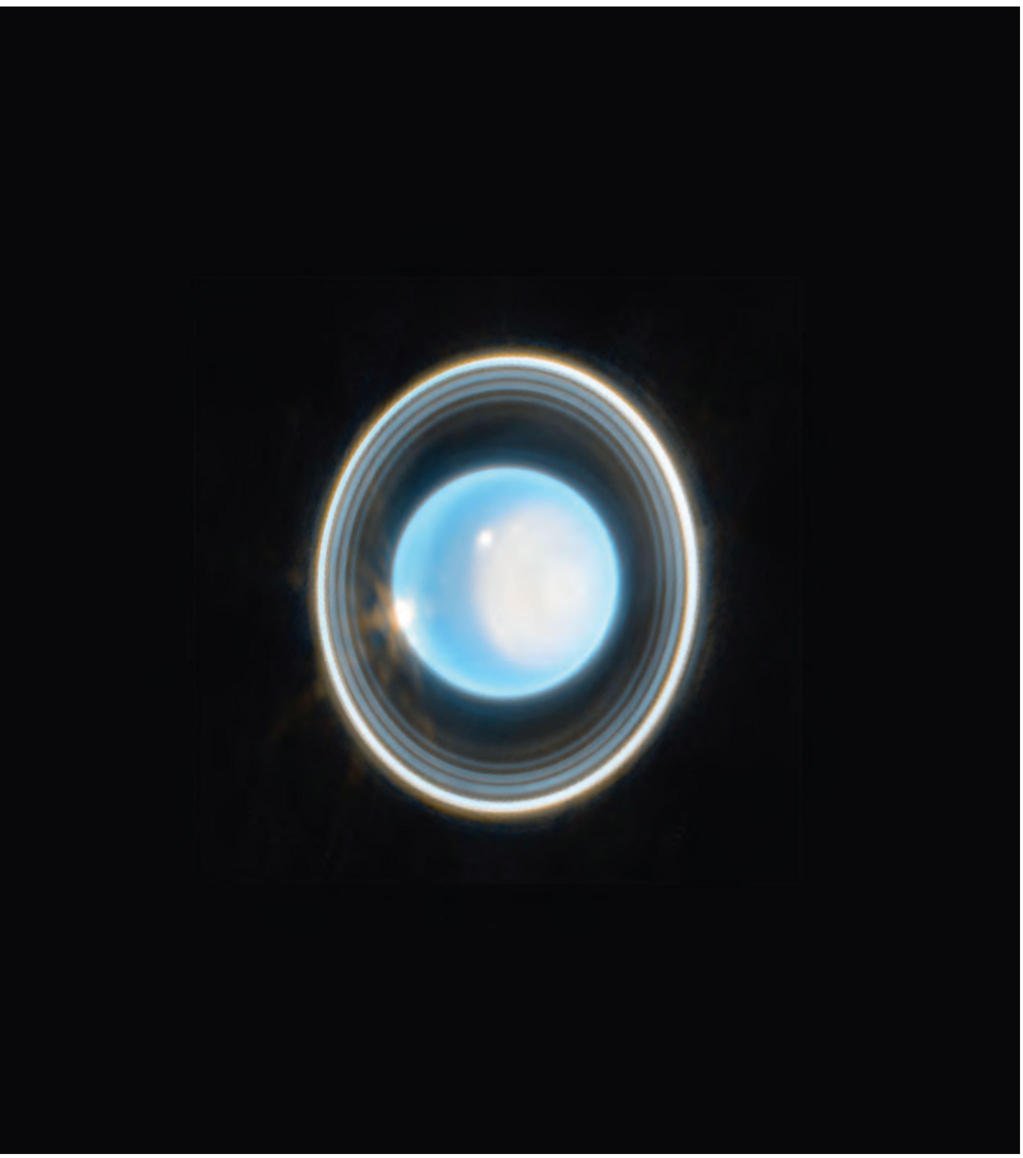
"What I'm most excited about is learning more about the habitable conditions around the ice giants and whether we can extend the possibility for life emergence in these remote regions," Coustenis said. Within Uranus's moons, scientists can look for plumes of complex organic molecules, subsurface heat, and organics at the surface, she added.

"If these worlds are indeed ocean worlds harboring deep, dark, hidden oceans of water below their icy crusts," said Leigh Fletcher, "then that might have implications for which environments in our solar system we could consider habitable and, by extension, the potential abodes for life in the universe." Fletcher is an atmospheric scientist at the University of Leicester in the United Kingdom.

Discovery

Beyond Uranus's enigmatic moons, planetary scientists are keenly interested in studying the planet itself. At the top of their scientific goals is measuring the internal structure and composition of the planet, which have been hard to model with existing data. A probe dropped into the planet's atmosphere would be key to that endeavor.

"We see ice giant planets everywhere we look in our galaxy, and it is amazing to me that we don't know what they are made of!" Hofstadter said. He's been chipping away at the question of Uranus's composition for more than 3 decades. The planet's upper cloud layers, as seen by Voyager 2, have 100 times less ammonia and far more hydrogen sulfide than expected from models.



The James Webb Space Telescope captured this image of Uranus, the "blue billiard ball," along with its narrow ring system and several of its moons, on 6 February 2023. Credit: NASA, ESA, CSA, STScI. (U. Arizona), Public Domain

Unknown atmospheric photochemistry or mixing of cloud layers might be to blame, and a probe descending into the planet's atmosphere would return data on the chemistry, temperature, pressure, and dynamics hidden beneath the clouds.

"Uranus is a world of extremes for an atmospheric scientist like me," Fletcher said. "There's really nowhere else like it, with its bizarre seasons and eerily calm atmosphere. I can't wait to see this up close, to see how its climate, circulation, and meteorology differ from the better studied Jupiter and Saturn."

Uranus's tilted spin axis means that its seasons are quite different from those on Earth: At the height of summer, one hemisphere is always illuminated, and the other is entirely dark—just as at Earth's North and South Poles, but lasting for decades. Only around the equinoxes do both hemispheres experience rapid day-night cycles and the temperature changes that come with them.

Voyager 2 passed through the system during the southern hemisphere's summer, but a mission that launches in the mid-2030s would arrive at Uranus in the early 2040s, just before the planet's equinox. The changing season might produce new weather phenomena and reveal how the planet's tilted and misaligned magnetosphere interacts with solar wind.

Detailed study of Uranus's rings could also reveal hidden details about the planet itself. "We might be able to use the rings of Uranus as a seismometer to probe the planet's internal structure, as has been done—extremely successfully—at Saturn," Nimmo said. The smoothness of planetary rings depends on the uniformity of a planet's gravity field, and shifting or swirling material inside a planet creates gravitational disturbances. Any internal changes would appear as waves, ripples, or spirals in the rings and would be visible to an orbiting spacecraft.

Really, there are a lot of Uranian oddities to explore. "I also want to give a shout-out to the tiny moon Mab," Hofstadter said. Less than 5 kilometers across, this moon is the likely source of Uranus's mu ring, which is made of micrometer-scale particles.

"The only other ring in the solar system having similar properties is Saturn's E ring, which is generated by the water plumes erupting on Saturn's moon Enceladus. Mab is far too small to have active plumes, so how is the mu ring generated and maintained?" An onboard spectrometer could help pin down the exact size and composition of the ring particles, determine whether they're a match for Mab, and, from there, narrow down how and why Mab sheds material—maybe even catch it in the act.

"Everything we learn about Uranus is relevant to understanding this class of exoplanet."

Deep Space (Planet) Nine

A long-term mission to the outer solar system could yield scientific discoveries that go far beyond Uranus and its moons, astronomers argue. First and foremost, any discoveries made about Uranus have the potential to expand our understanding of its fellow ice giant Neptune, as well as planets outside our solar system. Astronomers have found that many exoplanets are similar in size or mass to Uranus and Neptune.

"This was surprising," Hofstadter said, "because most of our planetary formation models predicted that Uranus-sized planets should be very rare. To fix our formation models and to get a better understanding of what all these ice-giant-sized exoplanetary systems are like, we need to learn more about Uranus and Neptune."

Mandt added, "Everything we learn about Uranus is relevant to understanding this class of exoplanet, such as the interior structure, how they formed, and what their atmosphere would look like in future telescopes."

There is also the potential for science while the spacecraft is in its decade-long cruise phase. Although many instruments would likely be unpowered or in a low-power state during transit, the spacecraft would still need to periodically contact Earth to report its status, location, and speed. Those ranging data provide an opportunity to locate any undiscovered massive objects in our solar system, be they asteroids, comets, or a planet.

A Uranus orbiter ideally would include onboard instruments to measure the magnetic, gravitational, and plasma environments around the planet. Data from those instruments could also provide glimpses into the solar wind and cosmic ray flux in the outer solar system that haven't been seen since the Voyager missions.

It might even be possible to detect gravitational waves while in transit, Hofstadter said. The Earth-based Laser Interferometer Gravitational-Wave Observatory (LIGO) and the future space-based Laser Interferometer Space Antenna (LISA) observatory will detect gravitational waves from many types of black hole mergers, he said, but they likely will be unable to detect them from the merger of supermassive black holes. "If properly equipped, the Uranus mission could make those observations during its 10-year cruise out to Uranus."

Enterprise

A flagship mission to Uranus—whether the Uranus Orbiter and Probe or one of several proposed to other space agencies—is still hypothetical. Here is the reality: The ideal launch window for a mission to the outer solar system is less than 10 years away and no mission has been green-lighted. Even though the leading mission concept does not require any new technologies, it could still take at least a decade to get it from the drawing board to the launchpad.

In fact, scientists are worried that NASA is already prioritizing other missions ahead of a mission to the outer solar system despite a sense of urgency from the community. The oft-delayed and over budget JWST stalled other NASA astrophysics projects for more than a decade, and astronomers have begun to worry that the NASA–European Space Agency Mars Sample Return mission will do the same to the docket of planetary science missions.

NASA's initial response to the idea of a flagship mission to Uranus was positive, but it, too, acknowledged budgetary difficulties. In a NASA Planetary Science Division (PSD) town hall following the release of the decadal survey, PSD director Lori Glaze said that the agency plans to initiate studies of an orbiter and probe mission no later than fiscal year 2024. However, Glaze also cautioned that "it's pretty challenging to start a new flagship in the very near short term due to some budget constraints."

At a later town hall at AGU's Fall Meeting 2022, she clarified that "there's significant stress on the planetary budget. It's been a bit brittle and fragile." The COVID-19 pandemic, supply chain issues, inflation, and labor costs have put pressure on the budgets of in-progress projects, which had to be absorbed by the PSD budget, Glaze explained.

"A final challenge, which money can solve, is the availability of radioisotope power systems for the mission," which agencies can purchase, Hofstadter explained. "Uranus is far enough from the Sun that we almost certainly need to rely on a plutonium-based power supply, and right now NASA doesn't have enough of it for all the missions it hopes to launch in the next decade."

The bottom line is this: If a flagship mission to Uranus is going to happen during the upcoming launch window, the whole enterprise must start moving fast.

"Excitement has been building in the planetary science community," Fletcher said. "There's no time to wait. Jupiter will continue to move on in its orbit, making the cruise trajectories to Uranus less favorable," he said. "We must get started soon to meet this opportunity."

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