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SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

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The Neglected Ice Giants

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Half a century ago, Uranus, Neptune, and Pluto marked the ultimate in planetary mystery. Even as men set foot on the Moon and spacecraft sped past Venus and Mars, the outermost worlds seemed to yield their secrets as slowly as they revolve around the Sun: Uranus, twice as remote as the Ringed Planet, completing an orbit once every 84 years; Neptune, a billion miles beyond, taking a leisurely 165 years to do the same; and Pluto, nearly a billion miles beyond that, its year 248 times longer than our own.

Today, planetary scientists marvel at exquisite images from our recent trip to Pluto, but its two giant neighbors still languish. Uranus and Neptune have entertained only one passing spacecraft, Voyager 2, back in 1986 and 1989, respectively. Since then, we've relied on the Hubble Space Telescope and adaptive optics on large ground-based telescopes, which now let astronomers scrutinize Uranus and Neptune from afar.

"We have learned an incredible amount since Voyager," says Imke de Pater (University of California, Berkeley), who tracks storms on Uranus and Neptune by using Hubble and the Keck Observatory in Hawai‘i. Other observers have spotted new rings and moons.

But David Stevenson (Caltech), who is more interested in the planets' interiors than their atmospheres, sees things differently. "We've learned remarkably little about Uranus and Neptune since the Voyager encounters," he says. We still don't know what substance constitutes the bulk of each planet, he adds, nor do we know whether the planets are layered like Earth, with a core, mantle, and envelope.

Planetary scientists do agree on one thing, though: "We're all eager to go back," says William McKinnon (Washington University).

Twin Planets

With similar colors, diameters, masses, densities, and rotation rates, Uranus and Neptune are twin worlds. Even their discoveries were intertwined. Irregularities in the motion of Uranus around the Sun stemmed from Neptune's gravitational pull, leading to the more distant planet's discovery.

Both planets owe their distinct colors — Uranus is green or aqua, Neptune blue — to methane gas. Their atmospheres consist mostly of hydrogen and helium, but 3% or 4% of the air is methane. This molecule absorbs red light but reflects green and blue.

No one knows, however, why the planets differ slightly in hue. Perhaps Neptune's air has more methane, causing a deeper blue. Perhaps haze subdues the color on Uranus. Or perhaps Neptune has tiny particles that enhance its color via *Rayleigh scattering*, the same phenomenon that causes the blue sky on Earth.

All four giant planets — Jupiter, Saturn, Uranus, and Neptune — have about the same amount of ice, rock, and metal, roughly 10 to 20 Earth masses, at their centers. A hydrogen-

▼ **FORLORN** Voyager 2 took these parting shots of the crescents of Uranus *(left)* and Neptune during its flybys in the 1980s. No spacecraft has visited since.

URANUS & NEPTUNE: NASA / JPL

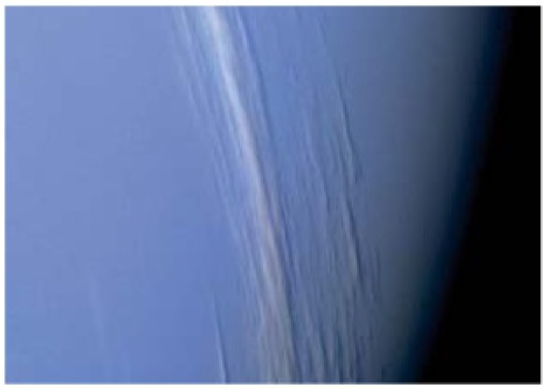
The NEGLE

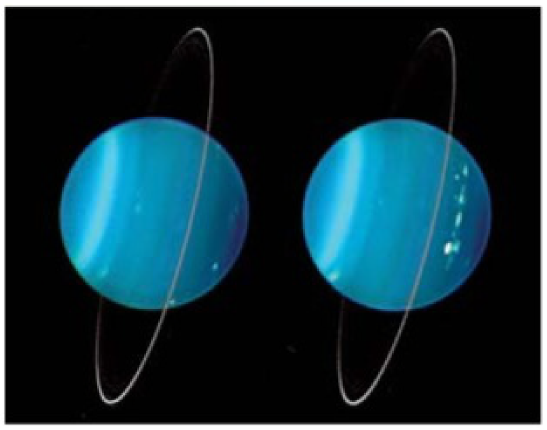
Decades after a lone spacecraft flew by, the solar system's ice giants and their many moons still guard plenty of secrets.

helium envelope surrounds these centers. Yet this similarity points to a great difference. For Uranus and Neptune, the hydrogen-helium envelope accounts for just a small fraction of each planet's mass. Jupiter and Saturn, on the other hand, are mostly hydrogen and helium.

When Jupiter and Saturn were forming, they must have grabbed lots of hydrogen and helium from the protoplanetary disk around the newborn Sun, whereas Uranus and Neptune took just a little. "You might think of Uranus and Neptune as being naked Jupiter and Saturn," Stevenson says. McKinnon adds, "They're baby giant planets that didn't get to grow up." Indeed, each of these "baby giants" is only 5% as massive as Jupiter and, at four times Earth's diameter, about a third as wide.

Because hydrogen and helium are gases on Earth, planetary scientists call Jupiter and Saturn gas giants, but their great gravity actually squeezes most of these gases into a fluid. In contrast, Uranus and Neptune are ice giants, so named because they have large quantities of three compounds that were frozen solid in the cold outer solar nebula: water (H_2O), methane (CH_4), and ammonia (NH_3), in unknown proportions. Because oxygen is more common in the cosmos than carbon and nitrogen, the main component in both planets may be water. And despite the term "ice giant," this water is mostly liquid, because the interiors are so hot.





◀ *Top:* Voyager 2 caught these linear clouds on Neptune, where they stretched approximately along lines of constant latitude. *Bottom:* Several storm systems appear in these infrared composites of Uranus taken by the Keck II telescope.

NEPTUNE CLOUDS: NASA / JPL; STORMS ON URANUS: LAWRENCE SROMOVSKY / UNIVERSITY OF WISCONSIN. MADISON / W. W. KECK OBSERVATORY

At the greatest depths, however, intense pressure may squeeze the water into *superionic ice*, which Burkhard Militzer (University of California, Berkeley) compares to a soft solid, like chalk. "It's neither completely solid nor completely liquid," he says. In superionic water, the oxygen atoms are locked into place but the smaller hydrogen nuclei move like people walking through a parking lot full of stationary cars, he explains.

Hydrogen nuclei are protons, and a current of protons through each planet's mantle may explain one of Voyager's strangest findings: Both planets have tilted magnetic fields that arise far from the planets' centers. In contrast, Earth's magnetic field comes from the flow of electrons through molten iron in our planet's outer core.

Uranus and Neptune probably have more "ice" — that is, water, methane, and ammonia — than rock and metal combined, but Stevenson says this is not known with certainty.

CTED
Planets

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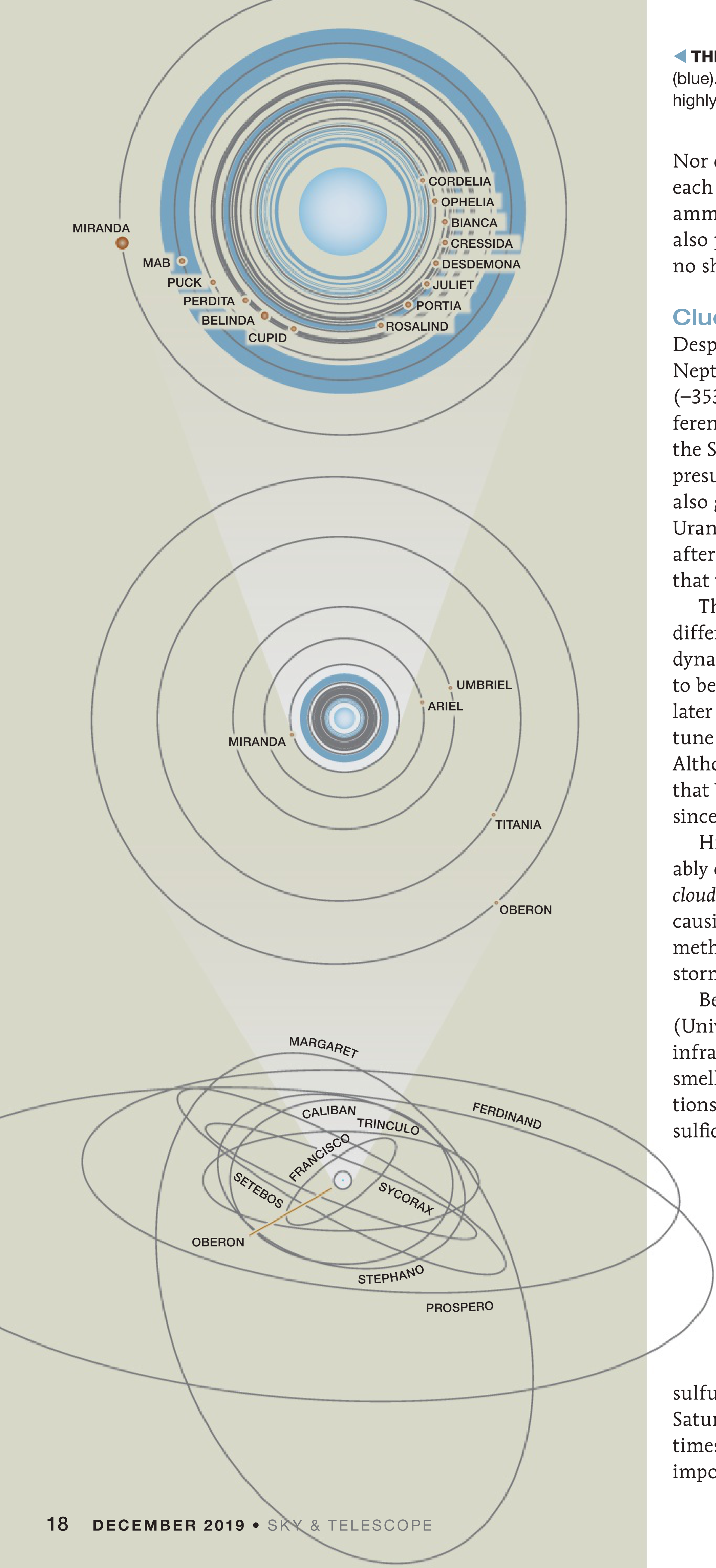


◀ **THE URANUS SYSTEM** Uranus has 27 known moons and 13 rings (blue). The inner 18 moons orbit the planet's equator; the others follow highly inclined paths, suggesting they're captured objects.

GREGG DINDERMAN / S&T

Nor do we know whether the planets are layered. If they are, each planet may have a rock-iron core, a water-methane-ammonia mantle, and a hydrogen-helium envelope. But it's also possible that the various substances mix together so that no sharp boundaries exist.

Clues from Clouds

Despite their different distances from the Sun, Uranus and Neptune have the same effective temperature of 59 Kelvin (−353° Fahrenheit). This similarity actually betrays a key difference: Uranus radiates no more heat than it receives from the Sun, whereas Neptune emits more than twice as much, presumably leftover heat from its birth. Jupiter and Saturn also give off more heat than they receive. No one knows why Uranus is unique. Perhaps it lost its heat of formation soon after birth, or, conversely, perhaps its interior is so stratified that the heat can't escape.

The unexplained contrast in heat flow does explain another difference between the two ice giants: "Neptune is a lot more dynamic than Uranus," de Pater says. Voyager showed Uranus to be so bland that the planet made news when astronomers later detected clouds and storms there. In contrast, Neptune has plenty of both, thanks to its vigorous internal heat. Although the planet's best-known storm, the Great Dark Spot that Voyager 2 saw, has vanished, similar storms have erupted since. Fast winds race across both planets.

High white clouds often fringe the dark storms and probably consist of methane ice. These clouds resemble *orographic clouds* on Earth, where air rises over mountains and cools, causing water vapor to condense and form clouds. Likewise, methane-laden air on Uranus and Neptune rises over the storms and condenses, creating the high white clouds.

Below lies the main cloud deck. In 2018 Patrick Irwin (University of Oxford, UK) and his colleagues reported the infrared signature of hydrogen sulfide, a poisonous gas that smells like rotten eggs. This work confirmed earlier suggestions indicating that the main cloud deck consists of hydrogen sulfide ice.

Why hydrogen sulfide? Beneath the hydrogen sulfide clouds, ammonia (NH_3) and hydrogen sulfide (H_2S) join to form yet another compound, ammonium hydrosulfide (NH_4SH). Because each molecule has one atom of nitrogen and one of sulfur, whichever element is less abundant gets used up, leaving the other to form a gas. An overabundance of sulfur explains the hydrogen sulfide in the air above.

The discovery means Uranus and Neptune have more sulfur than nitrogen. That makes them unlike Jupiter and Saturn and unlike the overall galaxy, which has nearly five times as much nitrogen as sulfur. "This observation is quite important," de Pater says. "It really does show that the formation of the planets isn't as simple as people initially had thought."

If instead nitrogen were more common in the atmosphere, ammonia clouds would form, as they do on Jupiter and Saturn. Perhaps, at the greater distance and colder temperatures of Uranus and Neptune, water ice in the planetesimals that built the two worlds trapped more sulfur-bearing gases than nitrogen-bearing ones.

Far below all these clouds, temperatures become warmer, and scientists expect good old-fashioned water clouds to exist. But no one has yet seen them.

URANUS STATS

AVERAGE DISTANCE FROM THE SUN
2.87 billion km (19.2 a.u.)

YEAR
84 Earth years

ESTIMATED DAY
17 hours 14 minutes

AXIAL TILT
97.8°

MASS
14.54 Earths

RADIUS
4.0 Earth radii

MEAN DENSITY (WATER = 1.00)
1.27

KNOWN MOONS
27

RINGS
13

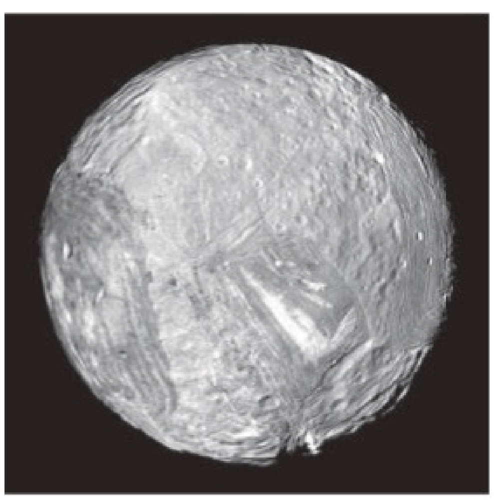
DISCOVERED
March 13, 1781

Rings and Things

Both Uranus and Neptune spin fast but have very different axial tilts. Voyager found that Uranus spins every 17 hours or so and Neptune about every 16 hours — faster than Earth but more slowly than Jupiter and Saturn. These figures constrain models of planetary interiors; however, with only one spacecraft measurement, some scientists have questioned the numbers.

Although Uranus and Neptune have similar spin periods, their rotation axes are another story. Early in Uranus's life, an object roughly twice as massive as Earth might have slammed into the planet, knocking it over. Or that object may have whizzed by the planet, twirling it around via gravity. Either way, Uranus now lies on its side as it spins, with an axial tilt of 98°. In contrast, Neptune's axis tilts only 28°, similar to Earth's.

Both Uranus and Neptune have rings, though they're much darker than those around Saturn. Astronomers first detected Uranus's rings in 1977, when the planet passed in front of a star and 5 narrow rings blocked the star's light before and after the planet did. Subsequent discoveries have boosted the total number of known rings to 13. Because of its drastic axial tilt, Uranus points one pole almost directly sunward during summer and winter solstices, giving observers on Earth a face-on view of the rings, first from the top, then decades later from the bottom.



◀ **MIRANDA** This 1986 image from Voyager 2 shows the varied terrain on Uranus's icy moon Miranda. Features that look like compressional folded ridges mix with faults, and some of the scarps are up to 5 km high — higher than the walls of the Grand Canyon. The moon itself is less than 500 km wide.

URANUS PLAYING CARD: TERRI DUBÉ / *S&T*, BACKGROUND IMAGE: ALLIES INTERACTIVE / SHUTTERSTOCK.COM, URANUS IMAGE: NASA / JPL-CALTECH; MIRANDA: NASA / JPL

Neptune has six rings. Ground-based astronomers saw hints of one in the 1980s (*S&T:* June 1989, p. 606), but Voyager definitively discovered five. A sixth ring, which may not fully wrap around the planet, also appears among the others in the Voyager data. In addition, the spacecraft saw enhancements of material in four sections of the outermost ring. How these *ring arcs* arose is unknown, but they may owe their existence to gravitational resonances with various satellites or to collisions in the ring. Since Voyager's visit, two of the four ring arcs have disappeared; perhaps new ring arcs will form in the future.

Whereas Saturn's stunning rings glisten with water ice, those of Uranus and Neptune are dark, probably due to carbon compounds. Small moons tug on the rings and actually spawn others. For example, the moons Cordelia and Ophelia orbit Uranus on either side of its brightest ring, named Epsilon, their gravity keeping that ring narrow, while Neptune's moon Galatea probably sprinkles material along its orbit and creates the diffuse ring it inhabits.

It's a Mab Mab World

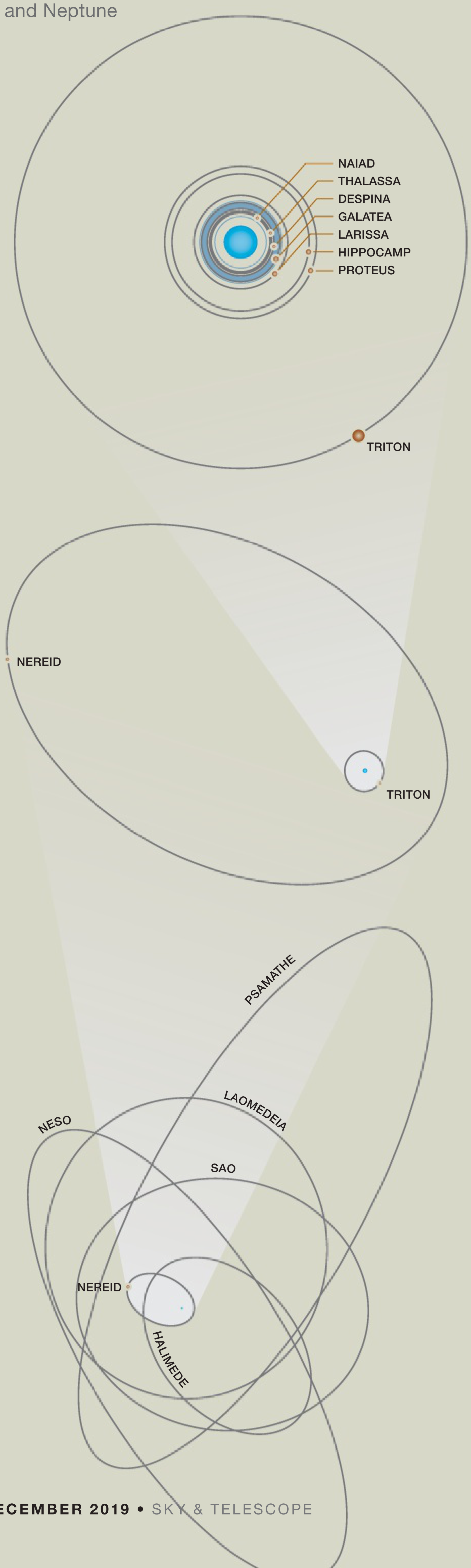
Indeed, both planets have lots of moons. When Voyager flew past, it tripled the number known at Uranus from 5 to 15 and quadrupled the number known at Neptune from 2 to 8. This created the pleasing coincidence that the eighth planet from the Sun had eight known moons.

But Hubble and ground-based telescopes have nearly doubled the numbers again. Today, Uranus has 27 known moons and Neptune 14.

On its visit to Uranus, Voyager passed closest to Miranda, the smallest and innermost of the five classical Uranian moons, and astonished scientists with pictures of radically different terrain types, some ancient, others young. "It's a kind of schizophrenic world," McKinnon says.

Thirteen additional moons, most found by Voyager, lie inside Miranda's orbit. All are smaller than Miranda. One of the most intriguing is Mab, which Mark Showalter (SETI Institute) and Jack Lissauer (NASA Ames) found in 2003. Mab lies in the outermost ring, named Mu. In like fashion, the moon Enceladus, which orbits Saturn and is about the size of Miranda, lies in that planet's E ring. The E ring comes from geysers on Enceladus that spew water along its orbit. Both rings are blue, so Mab might be doing something similar around Uranus.

But there's a problem. "Mab is tiny," Showalter says. It's much smaller than Enceladus. How can a moon that's roughly a dozen miles across be geologically active? No one



◀ **THE NEPTUNE SYSTEM** Neptune has 14 known moons and six rings (blue, four combined here due to scale). The planet likely captured Triton from the Kuiper Belt, as well as five far-out satellites that travel on wildly tilted orbits.

knows — so perhaps the ring comes instead from meteoroids that strike the moon and kick up dust. But dusty rings are reddish, not blue. The puzzle therefore remains.

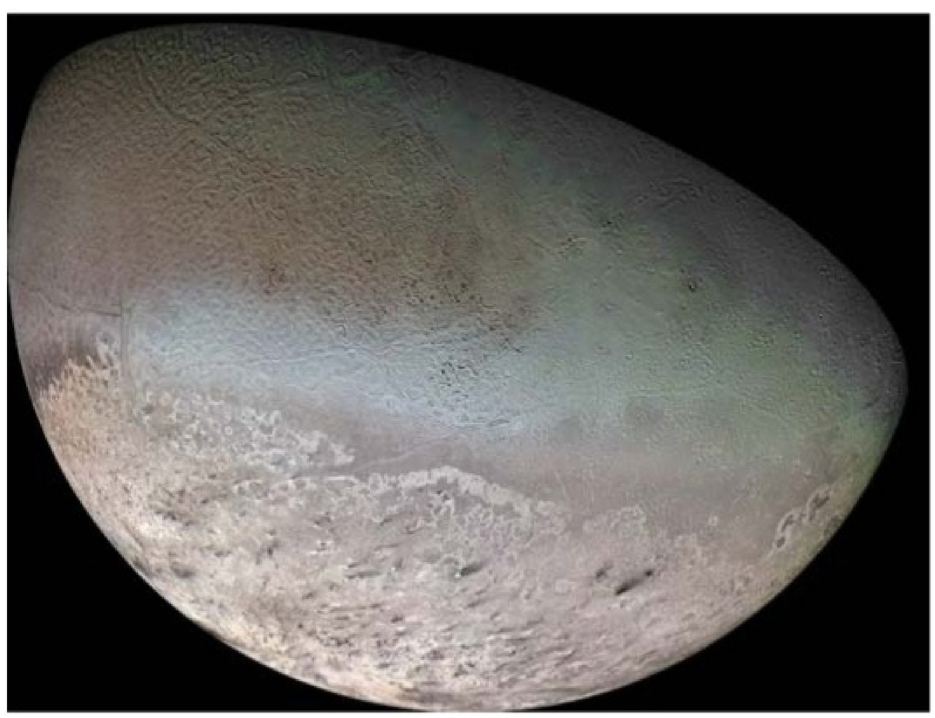
Nine of Uranus's inner moons constitute the most tightly packed satellite system ever seen. Planetary scientists have long recognized that the moons are in danger, as gravitational tugs among the moons may make them swerve into the wrong lane. In 2017, Robert Chancia (University of Idaho) and his colleagues measured the mass of a small inner moon named Cressida based on how its gravity distorts Uranus's Eta Ring. Knowing the mass, the scientists then predicted that the moon might crash into its neighbor, Desdemona, in just a million years. The debris from that collision should encircle the planet in a new ring.

All the moons near Uranus — the 13 innermost moons plus the 5 satellites known prior to Voyager — are so-called regular satellites, because they follow fairly circular orbits close to the planet's equatorial plane. In contrast, at much greater distances lie 9 additional moons, all found since Voyager, on elliptical and inclined orbits. These "irregular" satellites did not form with Uranus but instead were captured by it. All but one of the irregular satellites orbit the planet backward, opposite the direction it spins. Retrograde irregular moons outnumber prograde ones because the Sun's gravity can't as easily yank a retrograde moon away from its planet.

Far-Out Moons

At Neptune, the standout moon is Triton. It is nearly twice as large as Uranus's largest moon and slightly larger than Pluto. Yet Triton revolves backward, a sign that it, too, is a captured world, one that once roamed through space on its own as

▼ **TRITON** This color mosaic of Voyager 2 images shows the nitrogen-ice surface of Neptune's largest moon. The dark streaks overlying the south polar cap's pinkish ice may be from geyser plumes.



NEPTUNE MOONS: GREGG DINDERMAN / S&T; TRITON: NASA / JPL / USGS

Pluto still does. Triton is the largest retrograde moon in the solar system.

Its arrival doomed most of Neptune's other moons. Triton probably smacked into some, tossed others into the planet, and ejected still others altogether. One moon that managed to hang on was Nereid, but its orbit became stretched out due to the newcomer's gravity. Nereid now has the most elliptical orbit of any moon in the solar system, with an orbital eccentricity of a whopping 75%.

Triton suffered, too. Its initial orbit around Neptune was elongated, but Neptune's tides forced its path to become circular, internally scorching the moon and melting all its ice and maybe even its rock. Volcanic eruptions must have spewed out lots of gas, wrapping the moon in a thick atmosphere. Today, Triton's atmosphere resembles Pluto's, tenuous and full of nitrogen. Geysers send additional gas into the air.

Triton is about as close to Neptune as the Moon is to Earth. Inside Triton's orbit lie seven other satellites, all on circular paths, all but one found by Voyager. The largest, and the second largest orbiting Neptune, is Proteus. Voyager images revealed a battered world with a huge crater named Pharos. The crater might be a scar from an impact that created the small moon Hippocamp, which Showalter spotted in 2013 in an orbit that lies near Proteus.

Beyond the orbits of Triton and Nereid, five other irregular satellites pursue elliptical and inclined orbits around Neptune. The most distant, Neso, ventures farther from its planet than does any other moon in the solar system. At its extreme, Neso skirts 72 million kilometers from its master — nearly half the distance between the Sun and Earth. So distant is Neso that it takes 26 years to orbit Neptune once, nearly as long as Saturn takes to circle the Sun. Yet Neptune can retain this remote retrograde moon because the planet itself is so far from the Sun's gravity.

In 2003 Scott Sheppard (Carnegie Institution for Science) and his team discovered Psamathe, a retrograde moon whose orbit overlaps Neso's. He speculates that the two moons might once have been a single object that split apart when a large comet hit it.

"Almost all these moons are just points of light" through a telescope, he adds. "So we really don't know much about them."

NEPTUNE STATS

AVERAGE DISTANCE FROM THE SUN
4.5 billion km (30.1 a.u.)

YEAR
165 Earth years

ESTIMATED DAY
16 hours 7 minutes

AXIAL TILT
28.3°

MASS
17.15 Earths

RADIUS
3.9 Earth radii

MEAN DENSITY (WATER = 1.00)
1.64

KNOWN MOONS
14

RINGS
6

DISCOVERED
September 23, 1846

Return to the Ice Giants?

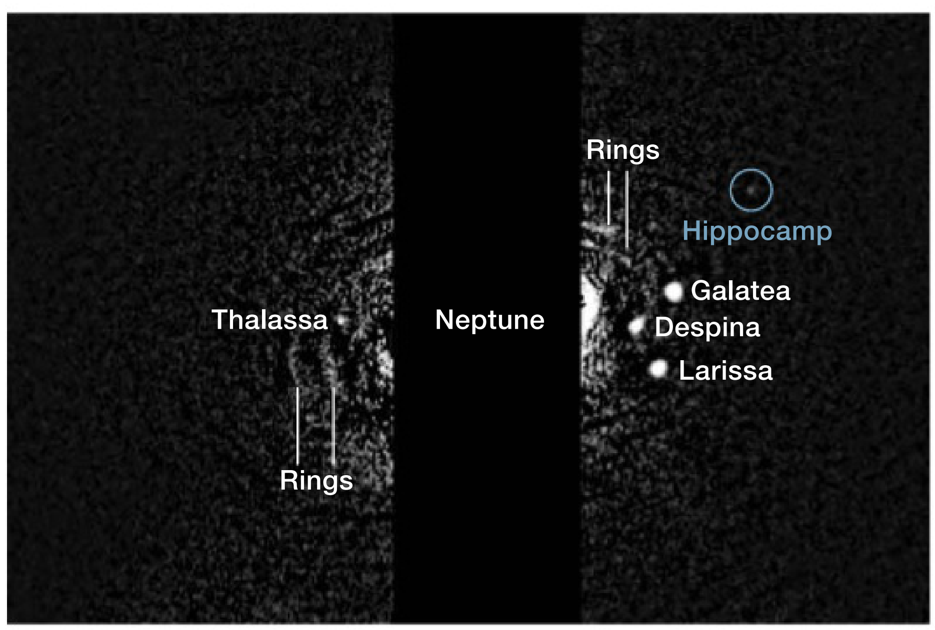
All these moons and the planets they orbit provide rich targets for future spacecraft. An orbiter like the ones Jupiter and Saturn have received would scrutinize these systems for years. To reach the planets quickly, a spacecraft must swing by Jupiter, whose gravity would fling the craft outward. The next launch opportunities to Uranus and Neptune occur around 2030, leading to encounters around 2040.

No such missions are yet funded, but planetary scientists in both the United States and Europe are drawing up plans. After all, every planet from Mercury to Saturn has received at least one orbiting spacecraft, and we now know that planets the size of Uranus and Neptune abound throughout the galaxy (*S&T:* Sept. 2019, p. 16). Orbiters to the two nearest examples would divine clues to their interiors, compositions, and atmospheres. Moreover, such spacecraft would fly past moon after fascinating moon and could discover additional satellites as well.

Uranus in particular presents a timely opportunity. By bad luck, Voyager flew past when one of the planet's poles pointed nearly sunward, which meant that, even as Uranus and its regular satellites turned, one side of each world stayed hidden in darkness. In contrast, sunlight will illuminate them in full at the next equinox, in 2050, so a spacecraft still in orbit then could see all of Uranus and its regular moons.

The challenges of reaching these distant worlds are great, but the scientific rewards are likely to be far greater.

■ Ever since childhood **KEN CROSWELL** has been especially intrigued by distant and mysterious Uranus, Neptune, and Pluto. He is the author of eight books, including *Planet Quest* and *Ten Worlds.*



▶ **MOON SHARD** Little Hippocamp (about 18 km across) appears around Neptune in this Hubble Space Telescope composite. Also visible are four other moons and a couple of rings. The black bar prevents the planet's light from swamping the image.

NEPTUNE PLAYING CARD: TERRI DUBÉ / *S&T*, BACKGROUND IMAGE: ALLIES INTERACTIVE / SHUTTERSTOCK.COM, NEPTUNE IMAGE: NASA / JPL; HIPPOCAMP: NASA / ESA / M. SHOWALTER (SETI INSTITUTE)