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03

NEPTUNE'S CLOUDS by Heidi B. Hammel

The distant ice giant Neptune is a kaleidoscope of cloud activity.

Neptune is a lovely, lonely world. At the planet's vast distance past Uranus — Neptune lies 30 times farther from the Sun than Earth does and takes 165 years to complete a single orbit — high noon is as bright as our twilight. Yet that faint sunlight illuminates a planet surprisingly rich with activity.

Over the last several decades, Neptune has changed its appearance like an actor switching costumes between scenes. Festoons of white, puffy clouds come and go, strange and short-lived dark spots develop and dissipate — all potentially driven by the very Sun that lies so far away.

We've pieced together this view thanks to a variety of observations. Only one spacecraft has ever drawn near Neptune: NASA's Voyager 2, which zipped by in 1989. In the decades since, my colleagues and I have continued to explore Neptune's clouds using increasingly powerful telescopes here on Earth and in near-Earth space. We can even see the distant planet's weather change.

Yet although our knowledge has increased, Neptune keeps its secrets well due to its dimness and its small apparent size as seen from Earth (just 2.3 arcseconds in diameter). Our knowledge of Neptune's clouds therefore remains comparatively thin. However, every year we use new telescopes, new detectors, and new analysis techniques to grasp for more understanding. Here's some of what we know, and what is left to learn.

The Ice Giants

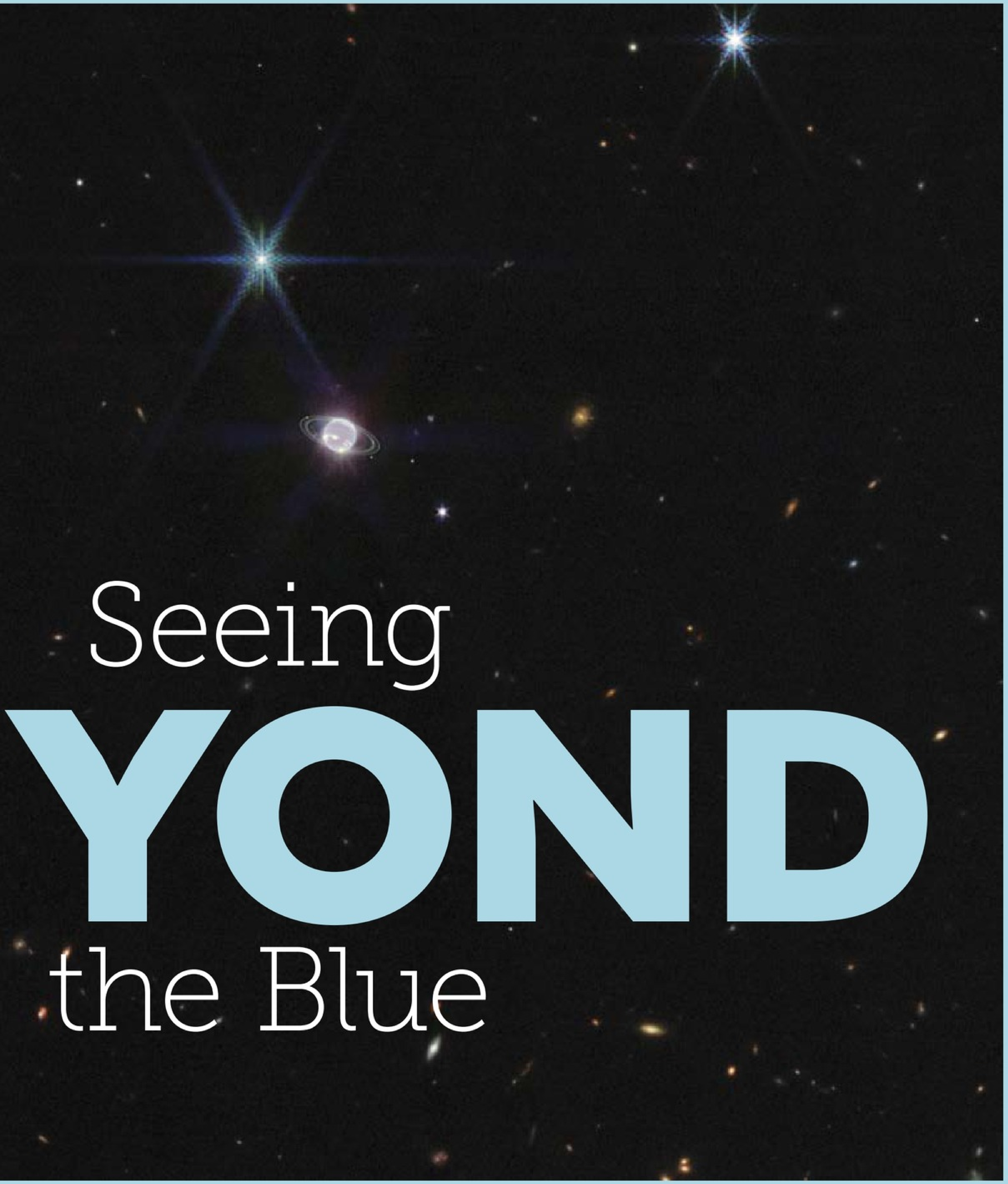
We call Neptune and its fraternal twin, Uranus, *ice giants* to differentiate them from their *gas giant* cousins, Jupiter and Saturn. We know from their shapes and gravitational fields (measured by Voyager 2) that the ice giants' atmospheres and interiors differ from those of their larger cousins (*S&T:* July 2023, p. 14).

Jupiter and Saturn are primarily composed of hydrogen, with some helium and other things mixed in. Their cores are surrounded by a thick mantle of *metallic hydrogen* — a fluid phase that hydrogen adopts under very high pressure. Above this mantle lies an envelope of molecular hydrogen.

Neptune also has a small, rocky core. But we think Neptune's thick mantle is made of a briny mixture of water, methane, and perhaps other hydrocarbons. This mantle may take up some 80% of the planet's mass. Overlying the briny layer is an atmosphere consisting primarily of hydrogen and some helium (perhaps up to 10% of the total mass), along with gases that can condense to cre-

▶ **DISTANT GIANT** This near-infrared composite image from the James Webb Space Telescope shows Neptune amid a sea of stars. The bright "star" with diffraction spikes to the planet's upper left is actually its largest moon, Triton.

Seeing YOND the Blue



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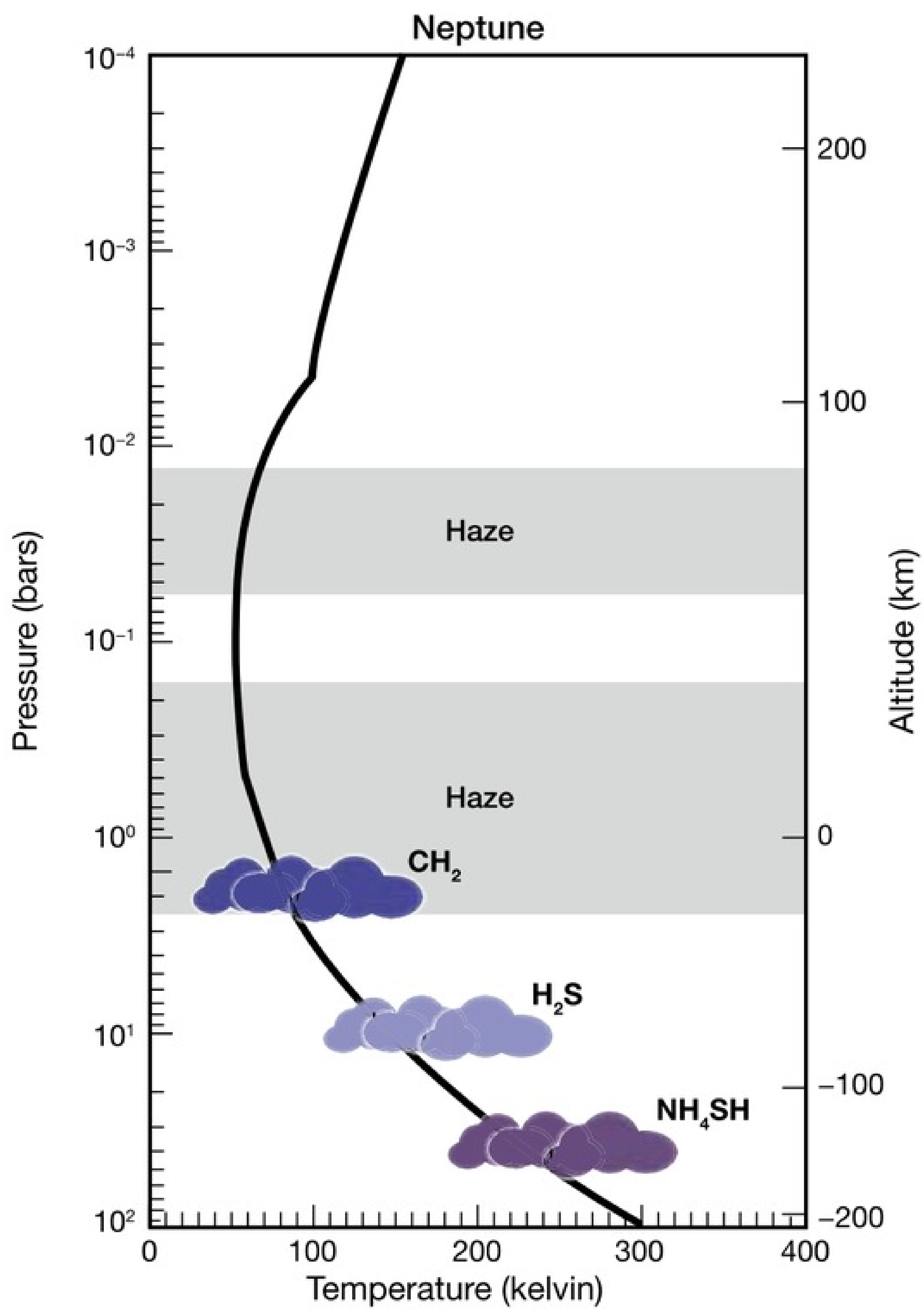


▲ **NEPTUNE'S SKY** A layer of methane clouds (CH_4) floats above a deeper layer of hydrogen sulfide (H_2S). Models suggest that farther down, ammonium hydrosulfide (NH_4HS) clouds may exist. High-altitude hazes help obscure deeper regions. Discrete white clouds appear between 0.1 and 0.6 bar. The black line traces the atmosphere's conditions.

BEATRIZ INGLESSIS / S&T, SOURCE: A. SÁNCHEZ-LAVEGA ET AL. / *THE ASTRONOMY AND ASTROPHYSICS REVIEW* 2023

ate myriad discrete clouds and banded structure. This is the atmosphere we see at wavelengths visible to the human eye.

Whether the boundaries between the atmosphere, mantle, and core are sharp — like the boundary between oil and water — or more gradual remains unknown: We don't have enough observations to accurately model Neptune's interior structure with high confidence.

Methane Clouds and Layers of Haze

Let's instead consider the atmosphere that we see: the global layer of pale blue clouds that serves as the background to bright white storms, dark spots, and banded structure.

One of the most common misconceptions about Neptune's atmosphere is that its color is a deep azure blue. This misunderstanding resulted from the Voyager 2 images, which were processed to enhance the visibility of fainter clouds and banded structure. In fact, Neptune's true color is closer to a pale aquamarine. This color results when sunlight scatters off Neptune's atmosphere: Traces of methane gas absorb the red wavelengths of light, leaving the green and blue wavelengths to be scattered back to us observers.

Neptune is slightly bluer than Uranus. Recent cloud models explain why: To match the observations, the cloud deck at a depth of about 2 bars needs to be thicker on Uranus than on Neptune. Neptune's thinner cloud deck allows sunlight to penetrate deeper into its atmosphere before being reflected back out; this leads to more absorption by the red-absorbing gaseous methane and thus makes the planet bluer.

Even prior to the 1989 Voyager 2 flyby, we knew Neptune had an active atmosphere. Throughout the 1980s, I spent many nights studying this distant world with the University of Hawai'i 2.2-meter telescope on Mauna Kea. The Hubble Space Telescope had not yet launched, and advanced methods to remove the distortion from Earth's atmosphere in images had not yet arrived on the astronomical scene. Even with the best telescopes on the planet, I could only rarely catch clear glimpses of Neptune's tiny disk, when Earth's atmosphere was still and calm.

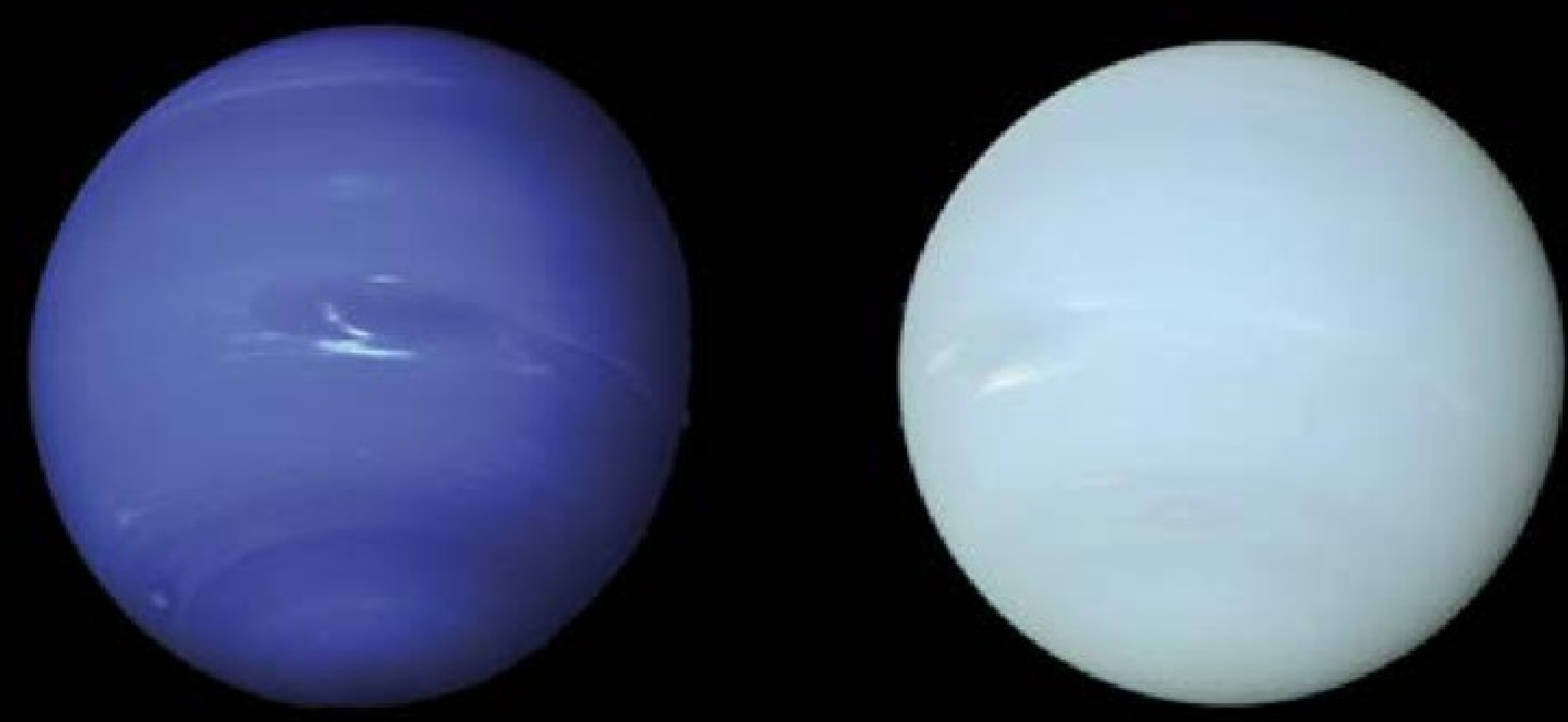
Nevertheless, I could see bright features traversing the planet's disk as it rotated rapidly. (Neptune takes 16 hours to make one rotation.) So, I expected a good show when Voyager 2 arrived.

Even so, both I and others were stunned by the panoply of clouds, bands, and raging winds that Voyager revealed.

On Earth, the atmosphere is primarily molecular nitrogen, while water is the weather wonder-worker: Water's transformation through ice, liquid, and gas phases creates our myriad clouds, rain, and hail. Similarly, although Neptune's atmosphere is primarily hydrogen, methane acts as the primary condensable gas for the visible clouds. These clouds form at extremely cold temperatures, near 60K (−213°C, or −352°F), and at a pressure level in Neptune's skies of about 1 to 2 bars, which is similar to Earth's ambient surface pressure (1 bar). In other words, the white puffy clouds are likely methane-ice crystals that have condensed out of the methane gas in Neptune's atmosphere, much like Earth's white puffy clouds condense from water vapor in our warmer atmosphere.

Newer models of the atmosphere include observations at near-infrared wavelengths, which scatter off high-altitude clouds. These models suggest that above the main visible cloud deck extends a thin aerosol haze, which reaches high up into the planet's stratosphere. This haze layer, unlike anything we see on Earth, is almost certainly due to photochemistry: Sunlight interacting with gases like methane creates other molecules composed of carbon, hydrogen, and oxygen — compounds such as ethane, acetylene, carbon monoxide, and diacetylene, all of which we've detected in trace amounts.

If we could strip away Neptune's outer layers to see what lies underneath, we would find yet another, deeper layer of clouds. This layer extends down to a pressure of about 5 bars, the same pressure experienced at the depth limit of recreational scuba diving. We think this deep layer is made of clouds of hydrogen sulfide (H_2S) as well as photochemical byproducts from the higher layers. These byproducts may rain down from above, or perhaps huge clouds in the deep layer



Early Voyager 2 image

Reprocessed image

TRUE BLUE The intensely blue image released shortly after Voyager 2's flyby is a byproduct of efforts to enhance the visibility of atmospheric features *(left)*. It bears little resemblance to a recently reprocessed version of Voyager data, calibrated to estimate Neptune's true color *(right)*.

PATRICK IRWIN

punch upwards like thunderheads and then subside, dragging the compounds downward as they do. Hydrogen sulfide clouds would be consistent with radio-wavelength measurements that probe to these depths, which suggest the presence of sulfur-bearing compounds.

Giant Dark Storms

Neptune's dim color belies its remarkably dynamic atmosphere. The Voyager view in 1989 was dominated by a huge dark storm we unimaginatively called the Great Dark Spot. Voyager also revealed that the bright white clouds I had seen in the 1980s were companion clouds skirting the edges of this giant dark storm. My very first Neptune observations with Hubble's refurbished optics in 1994 were most exciting for what was missing: There was no hint at all of the huge dark spot that dominated the Voyager images! In just five short years, it had completely vanished.

Subsequent Hubble observations over the next 30 years have revealed many more dark spots that appear and then vanish. The lifetimes range from one to six years. Small, bright white clouds often accompany the dark spots, floating at higher altitudes above the dark spots' edges. These clouds may form when atmospheric gases flow up and over the dark spot, where the methane in the gas can cool and condense into clouds.

If the white clouds are methane clouds, then what are the dark spots? Our highest-resolution data come from Voyager's observations of the Great Dark Spot. That dark vortex seemed to be created by an absence of clouds: a wobbly gap in the 2-bar cloud deck that revealed a deeper, darker layer. New models of more recent dark spots, however, link their appearance not to holes but to variations in the aerosols in that deeper 5-bar layer.

We won't solve the mystery with current equipment. Hubble and the 10-meter Keck Telescopes, along with NASA's Infrared Telescope Facility and large 8-meter telescopes such as those at Gemini Observatory's two sites and the European Southern Observatory's Paranal Observatory, have all served as key tools for studying the ever-changing atmosphere of Neptune. Yet Neptune's disk is so small as seen from Earth that we are hard-pressed to even resolve these dark vortices, let alone to truly understand their details or dynamics. Thus, we are still unsure what is driving their remarkably changeable behavior. Finding the answers will have to wait for the upcoming generation of 30-meter telescopes (*S&T:* Nov. 2018, p. 14), or a large space telescope that senses blue wavelengths, or perhaps even a future spacecraft mission to Neptune.

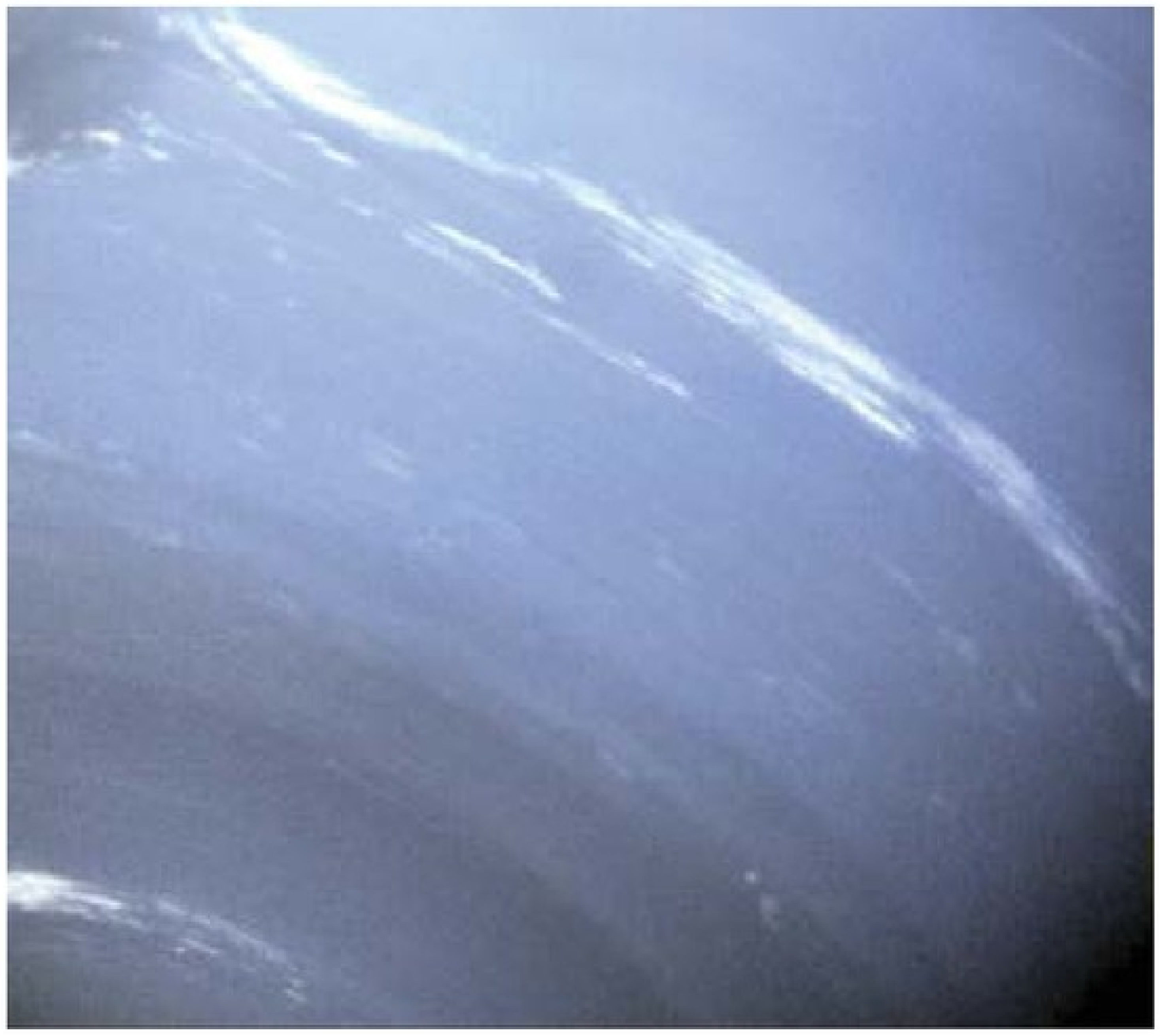
In the meantime, observations with the James Webb Space Telescope (JWST) will give us new insights into Neptune's atmosphere. JWST's first images of Neptune are spectacular and whetted our appetites, but the very best results — the spectroscopy — are yet to come.

A primary objective of our JWST studies is to untangle the complex interplay among different layers in Neptune's atmosphere. The layers interact both chemically and dynamically: Compounds move up and down, mixing and creating new molecules or being destroyed, all while wind currents shuttle gas to and fro and giant air cells rise and fall. In particular, JWST's ability to capture exquisite infrared spectra will enable us to study the composition and temperature variations of Neptune's atmosphere in unprecedented detail.

Neptune . . . and the Sun?

Until today's modern telescopes began to probe more deeply, Neptune's tiny disk as seen from Earth prevented nearly all atmospheric details from being seen. Nevertheless, beginning in the 1950s, astronomers at Lowell Observatory dutifully recorded the overall brightness of the planet, year after year, decade after decade. In recent years, amateur astronomers have also recorded these brightness changes.

The Lowell team noticed subtle changes in Neptune's brightness, which showed hints of being related to the



▲ **FESTOONS** White clouds scuttle across Neptune in this image from Voyager 2, processed to enhance the visibility of various features. The Great Dark Spot bleeds off the image's left edge.

planet's orbit around the Sun: Neptune's brightness steadily increased as it neared its solstice in 2005. But there also seemed to be a secondary signature imprinted on the data, and surprisingly it seemed to be correlated with the Sun's 11-year activity cycle.

Researchers suggested various solutions to this conundrum. The Sun emits significantly more ultraviolet radiation at the peak of its cycle than it does during solar minimum. This uptick in ultraviolet emission impacts the planets' atmospheres in various ways. Early on, some speculated that the variation in the Sun's output — even at distant Neptune — was somehow influencing the planet's upper tropospheric cloud cover.

Others speculated that high-energy particles from the surrounding galaxy might be a more important driver. The Sun's magnetic field usually shields the solar system from these particles, but that shielding effect weakens along with the field itself during the solar cycle's minimum. A fluctuating number of particles hitting Neptune's atmosphere could produce complex changes there. Yet another team of researchers suggested that solar maximum could lead to higher atmospheric temperatures, driving changes in a different way.

More recently, a new team reanalyzed all of Hubble's data on Neptune, starting with mine in the early 1990s and continuing through to the present day. They found a strong correlation between the number of methane-ice clouds and the solar cycle: As the Sun neared solar maximum, Neptune had more bright clouds.

The team hypothesized that the Sun's increased ultraviolet output triggered the formation of more photochemical products, which could in turn seed cloud formation. More clouds then increase the overall planetary brightness by reflecting more sunlight, explaining why Neptune looks brighter when the Sun is most active.

One thing that still puzzles us is how the feeble sunlight at Neptune's extreme distance could catalyze this change, since Neptune is 30 times farther from the Sun than Earth. This difference in distance would reduce what is blazing sunlight at Earth down to the light you might experience from an overhead office fixture. Perhaps all of the giant planets respond to the Sun this way, but the effect is swamped by the bright and dynamic cloud activity on Jupiter and Saturn and masked by the extreme seasonal variability of Uranus (*S&T:* July 2023, p. 14). Maybe only distant, cold Neptune is stable enough for this faint effect to be discernible.

This new study is probably not the last chapter in the story of Neptune's long-term variability. But it highlights the challenge of studying a planet whose seasons last for many decades: In my 39 years of studying Neptune, the planet still hasn't completed one full season. The first observations from Lowell Observatory were made when I was still in kindergarten, and some of the researchers doing the newest studies weren't even born yet when I was making the first Hubble observations of Neptune! The study of Neptune's atmosphere is by definition multi-generational.

Neptune in the Future

The many mysteries of Neptune's atmosphere continue to captivate me and my fellow planetary scientists. Why are its giant storms so short-lived? How can the feeble sunlight at Neptune's vast distance be driving atmospheric change? As described above, our current telescopes are chipping away at the planet's secrets, and soon JWST observations will usher in a new era in our understanding.

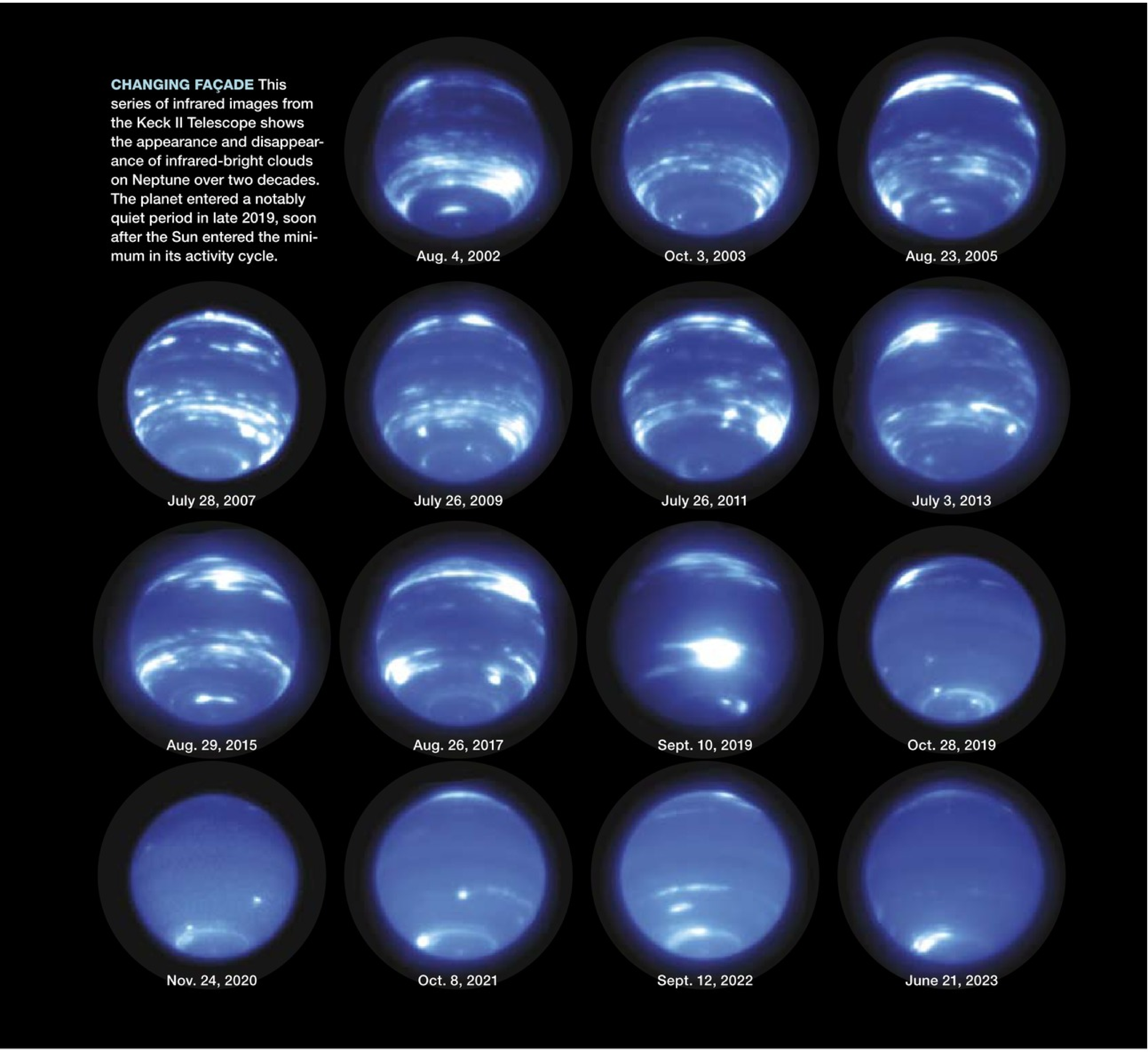
Neptune's secrets are crucial to today's burgeoning field of planetary science. With more than 5,000 exoplanets now known around nearby stars, we planetary scientists have a rich palette of planets to ponder. But to our surprise, the most populous class of planets seems to be one that is completely missing from our own solar system: worlds with sizes between those of Neptune and Earth (*S&T:* Feb. 2022, p. 20). To truly understand planets and planet formation, we need to know what these planets and their atmospheres are like.

With no planets within this size range to study in the local neighborhood, our local "ground truth" is limited to extrapolation upward from Earth or downward from Neptune.

Looking ahead, I anticipate with keen interest the development of NASA's proposed Habitable Worlds Observatory. This telescope will be a "super-Hubble" that will open a brand-new chapter in Neptune exploration. It holds the promise of being able to deliver Voyager-quality images of Neptune's atmosphere any time it looks at this blue world!

Similarly, the new class of giant ground-based telescopes in development, which have mirrors measured in dozens of meters, may also reveal breathtaking details in Neptune's atmosphere.

Someday, we will send a modern mission to the Neptu-



CHANGING FAÇADE This series of infrared images from the Keck II Telescope shows the appearance and disappearance of infrared-bright clouds on Neptune over two decades. The planet entered a notably quiet period in late 2019, soon after the Sun entered the minimum in its activity cycle.

IMKE DE PATER, ERANDI CHAVEZ, ERIN REDWING (UC BERKELEY) / W. M. KECK OBSERVATORY

nian system, to do things that are beyond the capability of even today's finest telescopes. Such a mission could track the details of Neptune's variable clouds and perhaps even send a probe into the atmosphere. We learned so much with the Voyager 2 spacecraft, even though it was launched in 1977 with technology developed even earlier. Just imagine what a modern spacecraft might reveal with today's detectors and computational abilities.

The one thing we know for sure is that, whenever we do finally send a spacecraft to Neptune, the ice giant will put on a remarkable show for us. I can't wait!

■ **HEIDI B. HAMMEL** is the vice president for science for the Association of Universities for Research in Astronomy (AURA), which operates large telescopes for NASA and the U.S. National Science Foundation.