STORM

From Mars' tenuous carbon dioxide atmosphere to Jupiter's hydrogen-rich envelope, the solar system's worlds provide an often-bewildering array of planetary weather.

by Michael Carroll

For several years, the sky has grown darker. Brown hazes and ice-crystal sundogs give way to the purple of near-vacuum. Finally, the last vestiges of atmosphere collapse to the ground as frost. Winter has arrived on Neptune's moon Triton. Although Triton's weather seems alien, spacecraft and ground-based observations paint an ever-clearer picture of weather on this moon and other worlds.

Weather is one of many ways that the universe attempts to maintain balance. Hot air rises, cold air sinks — and weather is born. On Earth, hot air rises over the region that directly faces the Sun, near the equator. This warmed air drifts poleward, where it cools, descends, and migrates back toward the equator. This conveyor belt is called a Hadley cell, and it's a feature common to many planetary atmospheres.

Our acidic neighbor

Simplified Hadley cells dominate the overall air circulation on Venus. But while Earth's 24-hour spin twists clouds into spirals, Venus' 243-day rotation scarcely disturbs its air currents. Earth's atmosphere self-corrects: As temperatures rise, clouds condense, and the planet cools. Like a thermostat, cooling kicks in just as things start to heat up.

But on Venus, the thermostat is broken. The meteorological portrait painted by Soviet, American, and European probes shows that the planet's atmosphere, composed largely of carbon dioxide (CO_2), traps heat and leads to a runaway greenhouse effect. The study of Venus has helped scientists understand both the greenhouse effect and holes in the ozone layer on Earth.

The similarities with our planet seem to end there. Weather on Venus is ruled not by water, but by acid. Solar radiation tears apart carbon dioxide and the leftover bits combine with sulfur dioxide and water, resulting in sulfuric acid hazes.

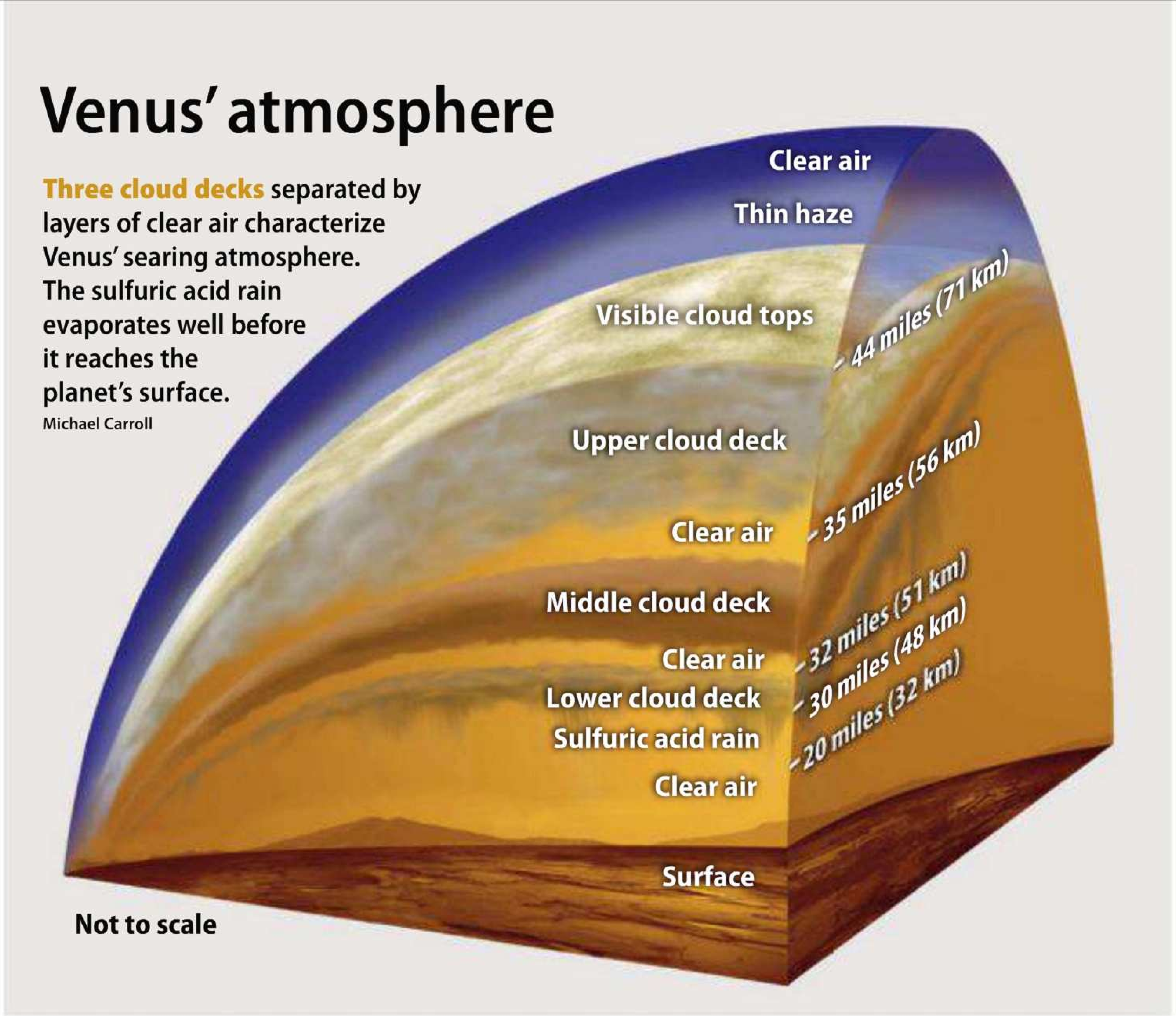
Venus' uppermost acid clouds are opaque and form the visible "surface" we see from Earth. Beneath this layer lies a zone of clear air that separates the upper and middle cloud decks, both of which consist of acidic particles ranging from smoke-sized to the size of water droplets in fog on Earth. Larger and still-mysterious particles dominate the lowest, third cloud deck.

Composition changes may cause the cloud-deck differences. The Soviet Venera 12 spacecraft, which

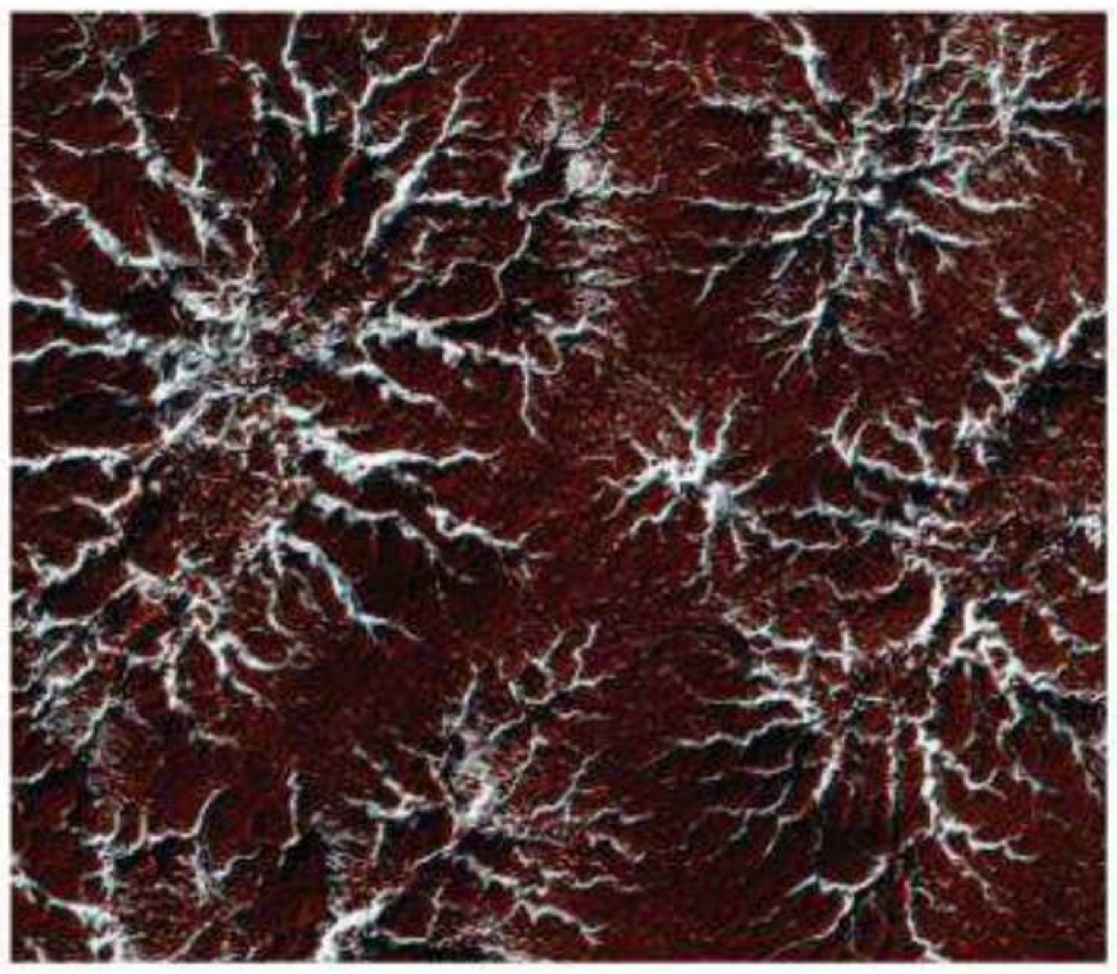
(Above) Understanding Earth's dynamic weather often stumps meteorologists and climatologists. Scientists study the atmospheres of other worlds to learn about our home planet. NASA/The Visible Earth

WARNING

Jupiter's massive atmosphere features huge storms and intense turbulence. The biggest systems can last for decades — if not centuries. The small-scale instabilities often change from one day to the next. NASA/JPL/SSI



Water-ice clouds drift past the summit of Ceraunius Tholus, a martian volcano whose base spans 80 miles (130 km) and peak rises 3.4 miles (5.5 km) above the surrounding plains. Clouds and ground fog often appear in Mars' thin air. ESA/DLR/FU Berlin (G. Neukum)



"Spiders" invade Mars' polar caps during spring, when returning sunlight vaporizes frozen carbon dioxide and leaves behind channels filled with ice. By summer, much of the polar ice will have turned to gas, replenishing the martian atmosphere. NASA/JPL/University of Arizona

directly sampled the atmosphere en route to its landing in 1978, detected 20 times more chlorine than sulfur. The droplets could be sulfur-coated chlorine, or they might be some sort of airborne crystals. At an altitude of 30 miles (48 kilometers), sulfuric acid pours into clear air, evaporating before it can make landfall.

Despite Venus' lazy rotation, its atmosphere races at breakneck speed. Viktor Kerzhanovich of NASA's Jet Propulsion Laboratory (JPL) discovered this phenomenon, called "superrotation," while at Moscow's Institute for Space Research. Kerzhanovich measured the drifts of Venera spacecraft during their descents. He remembers: "All of my teachers thought the winds were 2 to 3 meters per second [6 to 10 feet per second] in the bulk of the atmosphere. But the superrotation happens at all the heights, even below the visible clouds. Even today, the mechanism for this is unknown." From the equator to the pole, and from about 330 feet (100m) up to 60 miles (100 km), Venus generates hurricane-force winds.

Michael Carroll, *a frequent contributor to* Astronomy, *is a space artist and science writer. His latest book is* Drifting on Alien Winds: Exploring the Skies and Weather of Other Worlds *(Springer, 2011).*

Into thin air

Mars is the only other terrestrial planet with a substantial atmosphere. But while Venus' atmosphere is nearly 100 times thicker than Earth's, Mars' atmosphere is barely 1⁄100 of our planet's.

Mars' polar caps are closely linked to its weather. They contain a mix of water ice and frozen CO_2 (dry ice), which freezes out of the atmosphere. The polar CO_2 ices constitute a substantial portion of the thin martian atmosphere, says California Institute of Technology planetary scientist Andrew Ingersoll. "On Mars, there's an annual winter deposit of CO_2. When the Sun hits it, it evaporates into the atmosphere. Atmospheric pressure goes up and down on Mars by about 30 percent."

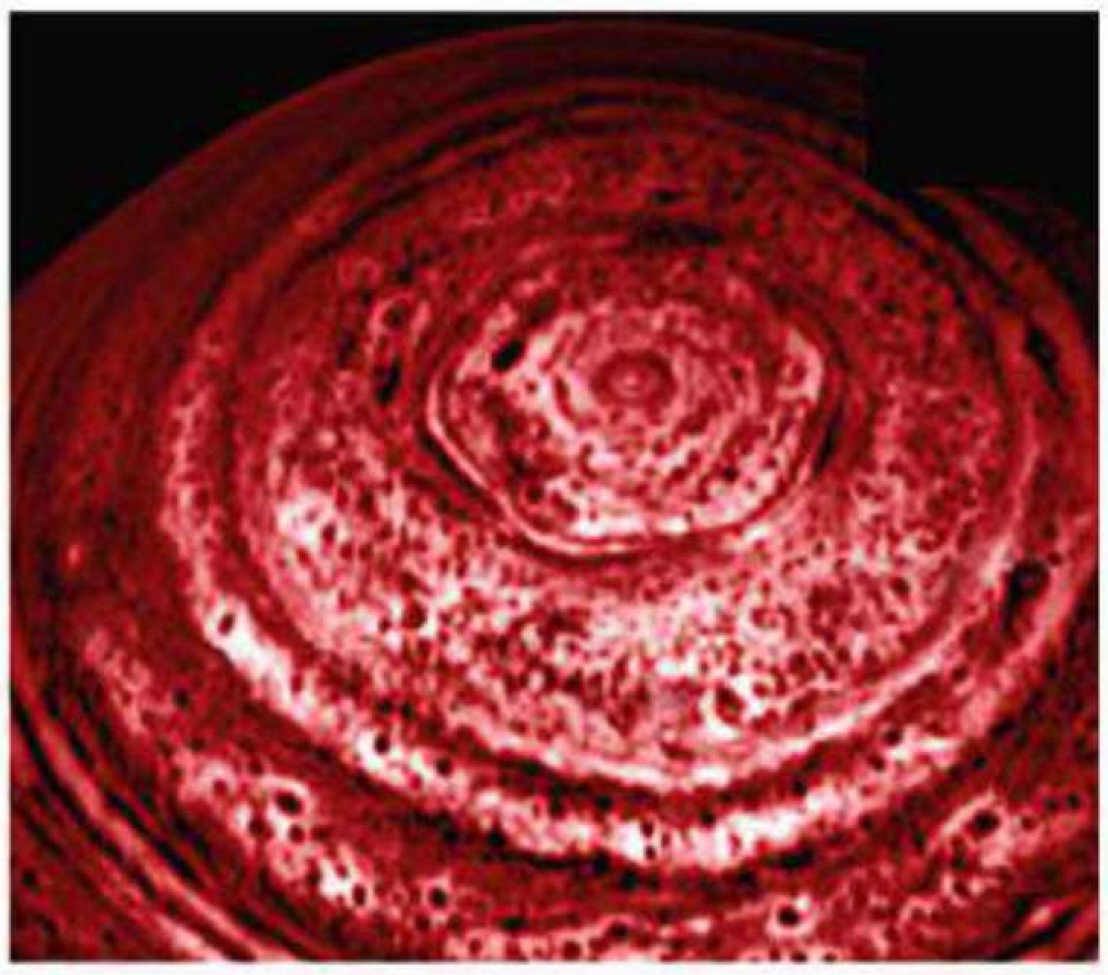
Scientists have known for decades that Mars sports a variety of clouds as well as ground fog. But researchers recently discovered another cloud system: an equatorial belt. Mars Reconnaissance Orbiter scientist Steven Lee says that orbiting spacecraft usually give views of small areas spread across the surface. "[We] didn't realize that this equatorial belt of clouds formed during aphelion [the point in the planet's orbit when it is farthest from the Sun]. Once we got Hubble observations, these cloud belts just jumped right out."

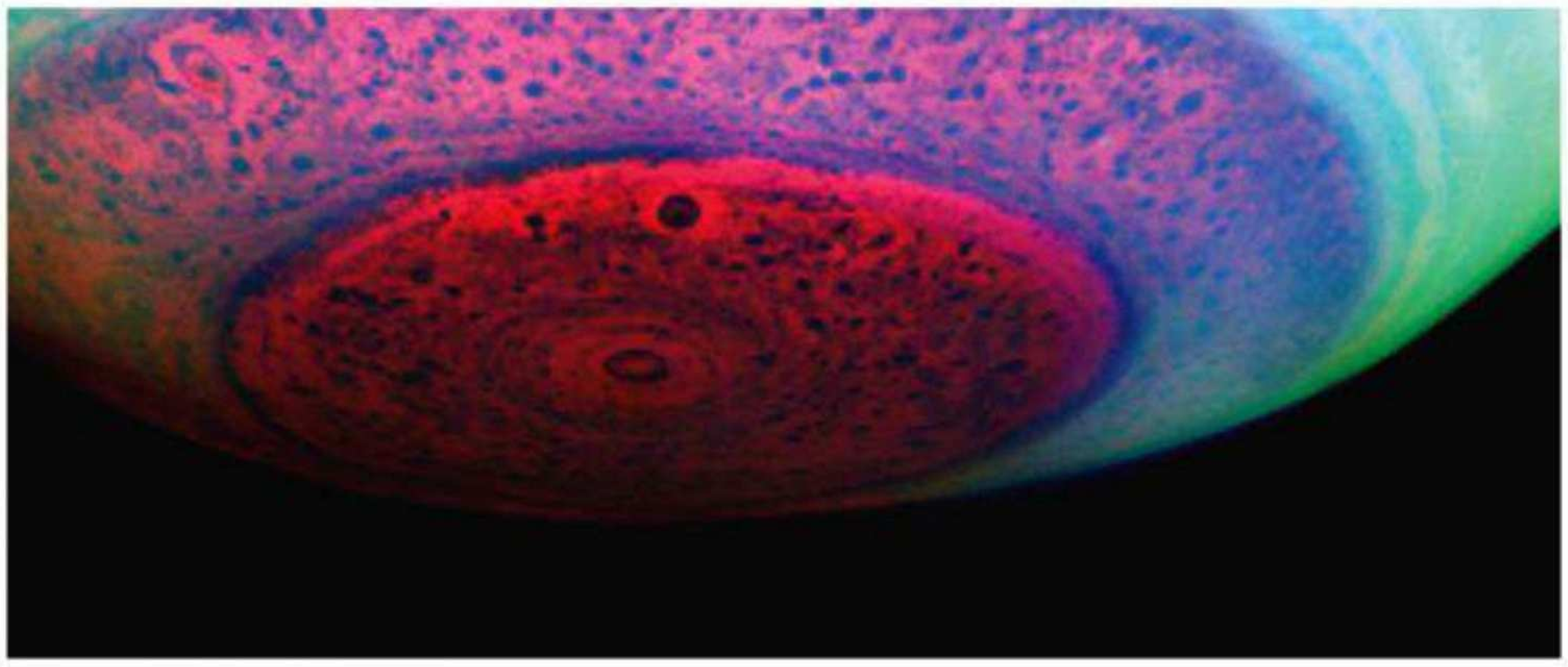
The Red Planet taught scientists an early lesson: The surface below informs us of the weather above. Martian river channels imply that a much thicker atmosphere once generated an active cycle of rainfall, evaporation, and condensation. Soil chemistry reveals telltale signs of past environments. And glaciers, which require a stable climate over long periods, leave distinctive erosional features. Says William K. Hartmann of the Planetary Science Institute, "Geology is intimately tied to climate science. You could almost say you can't understand one without the other."

The seasonal ebb and flow of Mars' atmosphere, its global dust storms, and the layered ice deposits at the poles teach scientists that evidence for climate change on a planet can lurk in surprising places.

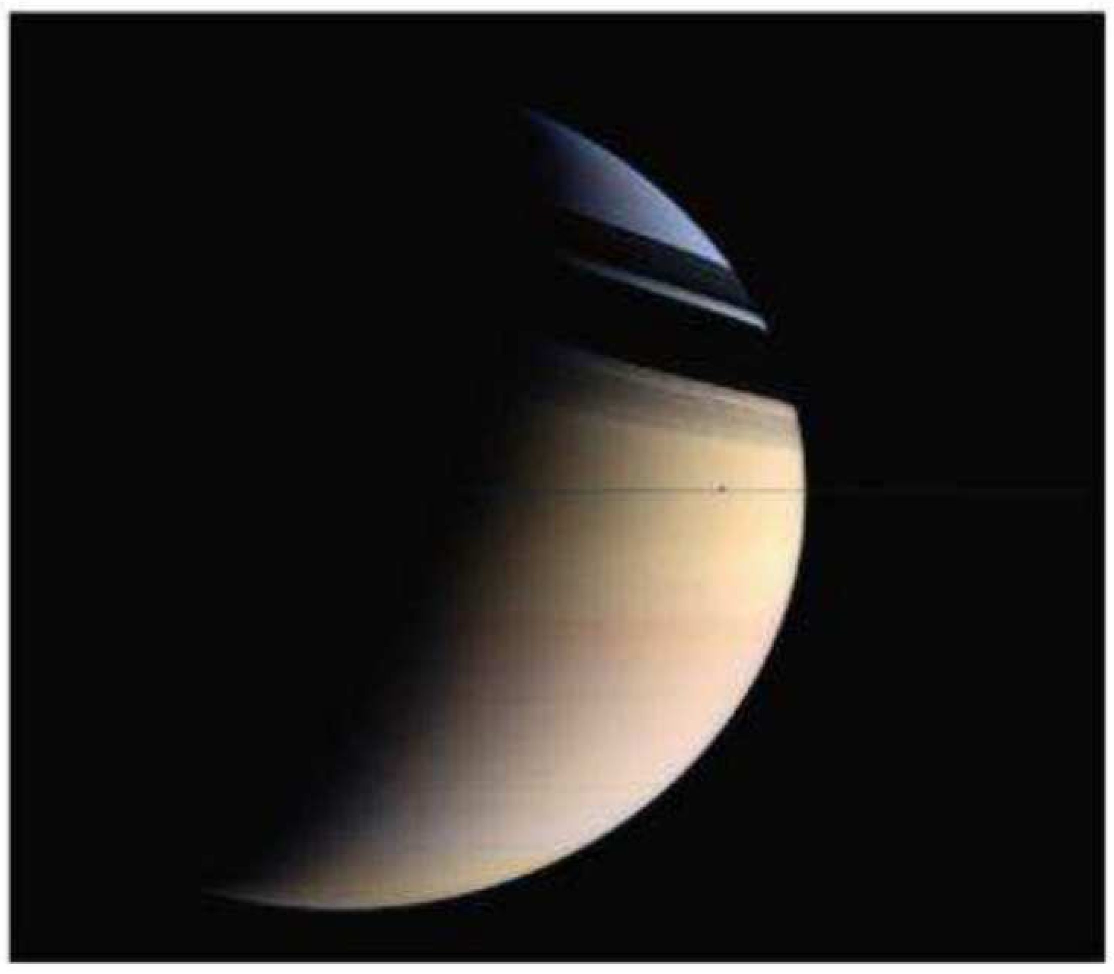
The land of giants

Unlike the terrestrial planets, the outer planets have no solid surfaces. Hydrogen and helium dominate the atmospheres of Jupiter, Saturn, Uranus, and Neptune. Both Jupiter and Saturn have a proportion





Saturn's poles show remarkable atmospheric structures. The north pole (left) features a nested set of hexagons that extends at least 47 miles (75 km) below the cloud tops. The south pole (right) shows a hurricane-like vortex surrounded by a series of concentric clouds. NASA/JPL/University of Arizona



Blue clouds cover much of Saturn's northern hemisphere, in stark contrast to the planet's overall butterscotch hue. Scientists suspect the blue tint comes from cooling caused by the rings' shadow and should disappear in the next few years as the shadow heads south. NASA/JPL/SSI

of helium and hydrogen, the fundamental building blocks of the solar system, that closely matches the Sun's. Uranus and Neptune have evolved slightly different atmospheric recipes, with more methane mixed in.

A rich brew of complex chemistry paints the clouds of Jupiter and Saturn in tans and grays. Farther from the Sun, methane tints Uranus and Neptune blue. Hydrocarbon hazes also tinge Uranus a pale shade of blue-green. Neptune's clearer air reveals a teal cloud deck.

On Jupiter and Saturn, the highest of three cloud decks consists of ammonia. Below swirl the ammonium hydrosulfide clouds that give these gas giants their reddish-brown bands. The lowest deck holds white clouds of water vapor that break through upper layers. Underneath this deepest deck, rising temperatures allow rain to fall into an eternal night of crushing pressures, as gaseous hydrogen transforms into liquid metal.

Although Neptune and Uranus appear to arrange their cloud decks similarly, the top layer on both consists of brilliant white tendrils of methane ice that form due to these worlds' colder temperatures.

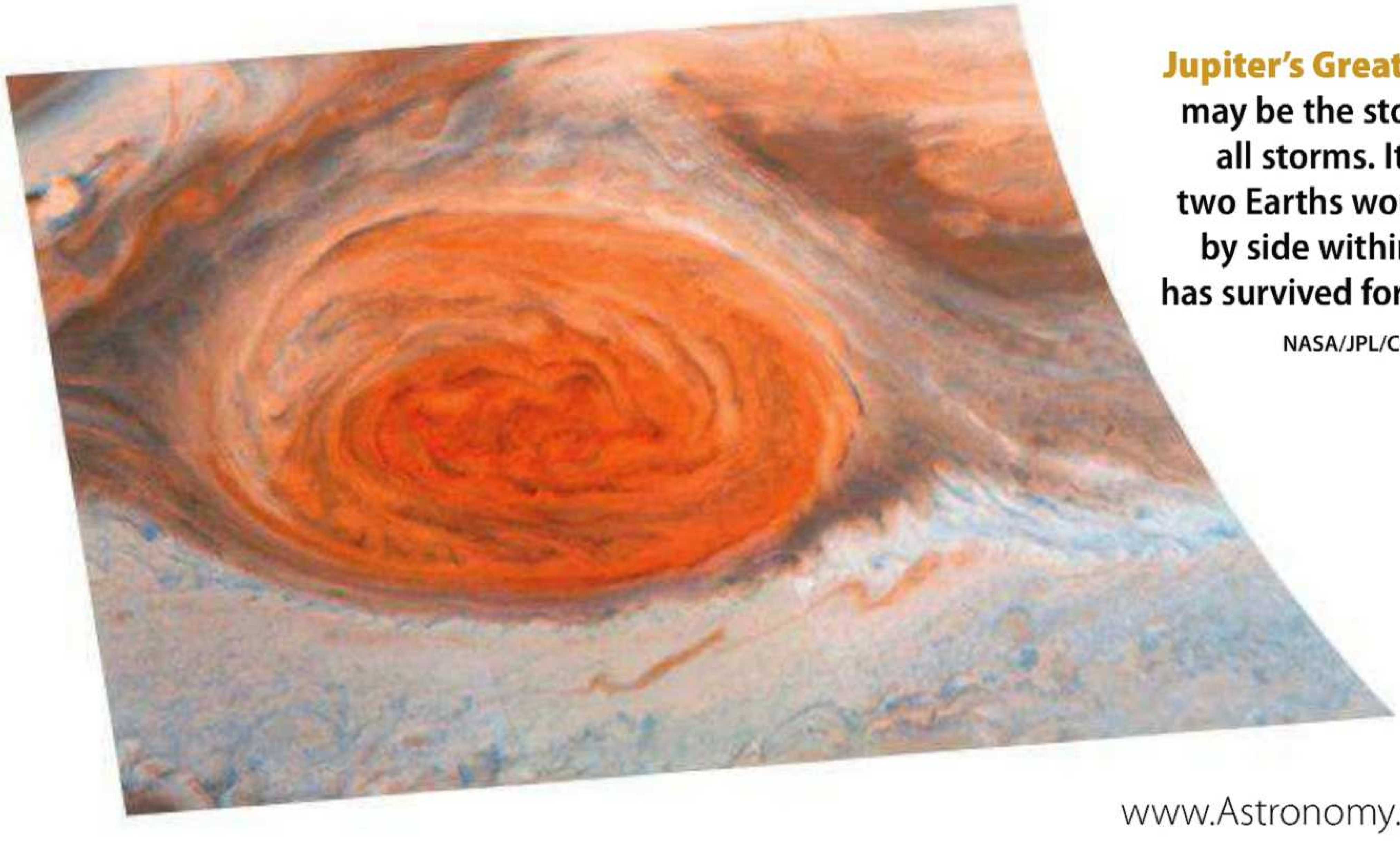
Giant-planet atmospheres have one other marked difference from terrestrial weather. On the outer worlds, polar temperatures nearly match those at the equator. Perhaps the internal heat generated by these planets comes out preferentially at the poles, balancing global temperatures. Another idea suggests that heat transfer in the massive atmospheres is more efficient than on the terrestrial worlds, reducing temperature differences to nearly zero.

While terrestrial storms come and go in days or weeks, storms on the giants can last for decades. But not all their weather is so long-lived. "A fundamental surprise [at Jupiter] was how turbulent the atmosphere is, given that the large structures are so permanent," says Ingersoll. "The small scale was just a mess, with things changing daily." The planet's turbulence was not random, but organized. Paradoxically, adds Ingersoll, "It wasn't that the jet stream was spinning off these eddies and cyclones. It was as if the eddies were maintaining the jet stream, pumping up the large motions."

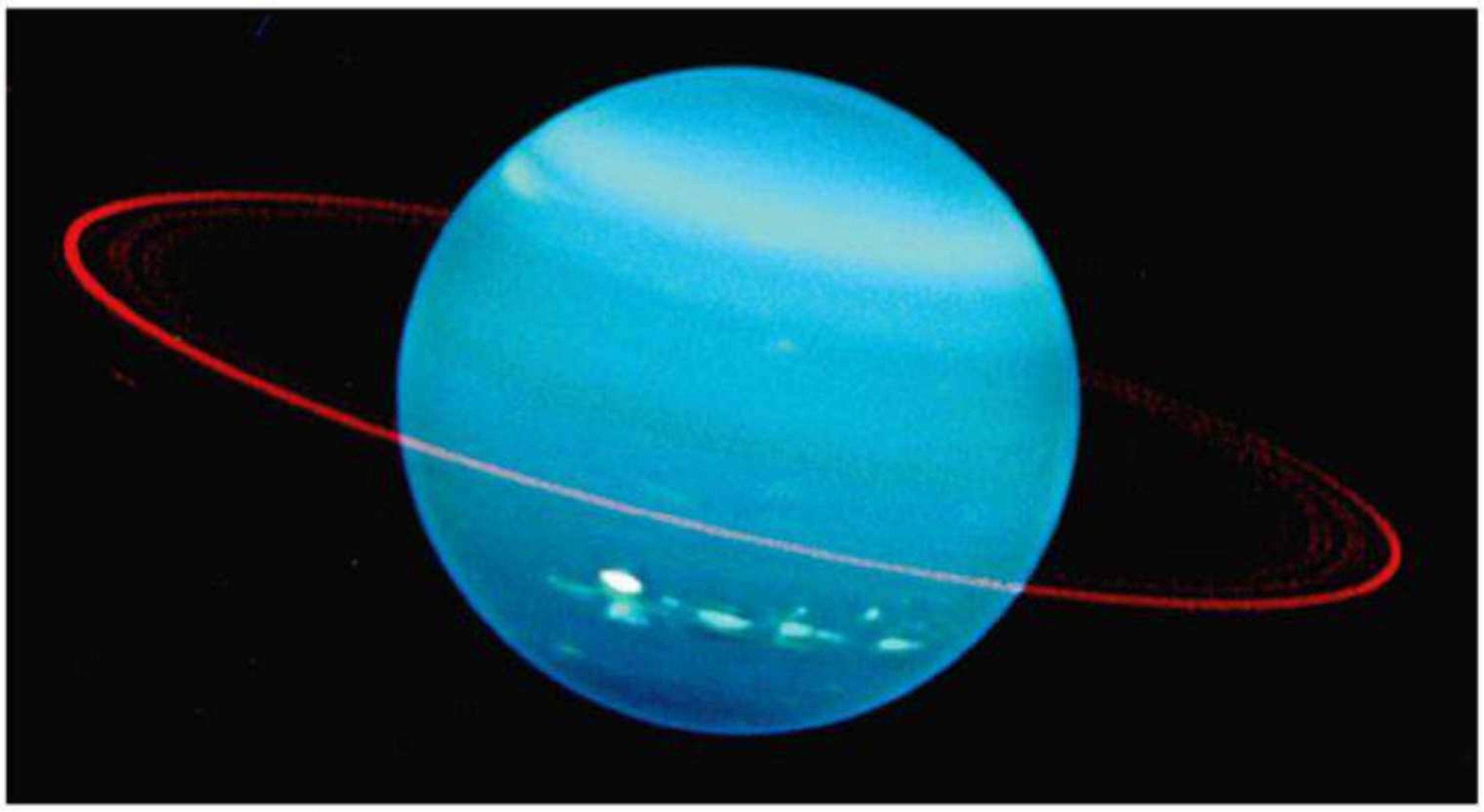
Jupiter catches far more solar energy than the more distant planets. Saturn receives about 1⁄3 the sunlight of Jupiter, while Uranus gets 1⁄14 and Neptune 1⁄33. With less heat to drive air currents, many researchers assumed that Saturn, Uranus, and Neptune would have subdued activity. But distance does not bring calm. Ingersoll thinks that as solar heating decreases, the power that drives both large-scale storms and small-scale turbulence diminishes. "At Neptune [for example], you produce an atmosphere that has so little small-scale turbulence that the winds are free to build up."

Lord of the rings

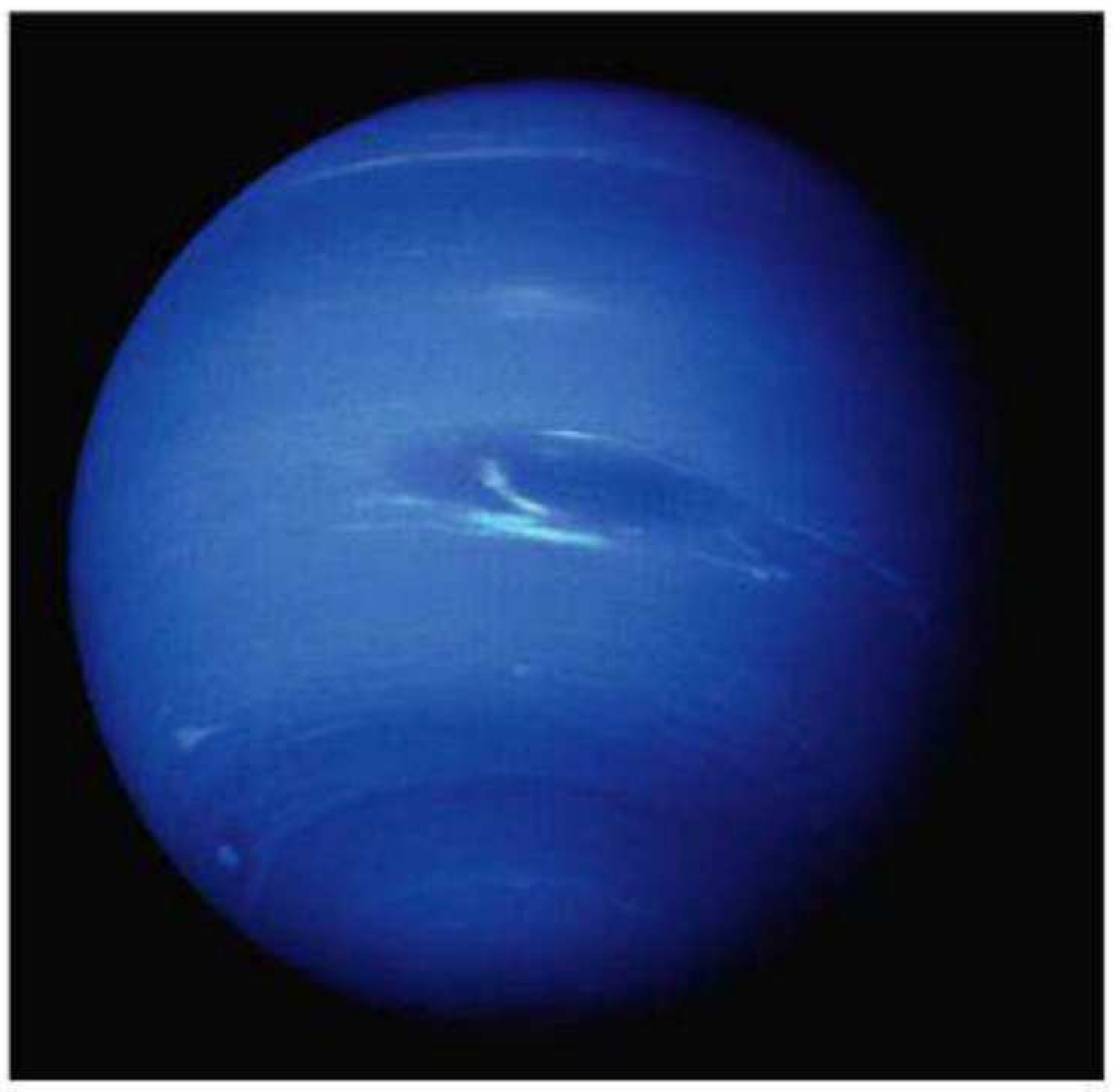
As on Venus, air races around Saturn in superrotation, generating bizarre storm systems. A "string of pearls" 37,000 miles (60,000 km) long punches holes in Saturn's upper cloud deck. Strange doughnut-shaped storms resemble smoke rings, with clear air in the center. South of the equator lies Thunderstorm Alley, where massive storms last for months.



Jupiter's Great Red Spot may be the storm to end all storms. It's huge — two Earths would fit side by side within it — and has survived for centuries. NASA/JPL/Cornell University



Uranus looked bland when Voyager 2 flew past in 1986, but the ice giant erupted with atmospheric activity as it approached its 2007 equinox. Here, a string of white clouds spreads across the planet's northern hemisphere. Lawrence Sromovsky (University of Wisconsin)/Keck Observatory



Neptune's Great Dark Spot (near center) surprised scientists when Voyager 2 spotted it in 1989. The feature, which spans about 1 Earth diameter, had disappeared by 1993. However, other similar spots have cropped up from time to time in the years since. NASA/JPL

In Saturn's northern hemisphere, clouds appear bluer than the rest of the planet. "We still don't know what causes the northern blue," says Carolyn Porco, the leader of the Cassini spacecraft's imaging team. "We think it has to do with the fact that the rings cast shadows that cool the atmosphere." The level of the cloud deck may sink as it chills and the air above clears. And, like on Earth, you get a blue sky. Saturn passed through its equinox in 2009, when both hemispheres received equal sunlight. Since then, the shadows have shifted south and the blue tint is fading. Observers are watching for the blue to appear in the southern hemisphere.

Saturn displays polar wonders as well. Locked directly over the south pole, a vast whirlpool gazes from concentric clouds like a Cyclops. The storm's clifflike rim rises 40 miles (65 km). A colossal hexagon drapes the northern pole. The Voyager spacecraft spied this baffling air stream 3 decades ago, and it remains one of the great planetary mysteries.

Big, blue, and cold

The cores of Uranus and Neptune have more water and lower temperatures than those of Jupiter and Saturn, inspiring scientists to brand the outermost planets "ice giants." Ice-giant weather appears significantly different from that of their bigger cousins. Both outer worlds show far less banding, and Uranus has a more subdued atmosphere than any of the other three giants. "It's weird that on both Uranus and Neptune, we don't see zones of clouds like we see on Jupiter and Saturn," says JPL's Kevin Baines. "We've been trying to explain it away for a couple decades."

In any atmosphere, a battle rages between upwelling air currents keeping particles afloat and gravity pulling particles down. On the ice giants, cloud-forming particles may not stay airborne long enough to become visible clouds. Baines advocates another possibility for the clear air: "Methane may condense so rapidly, and there's so much of it, that in a few seconds you go from a little droplet to something the size of a beachball. You don't see any clouds because it all rains out of the atmosphere too quickly."

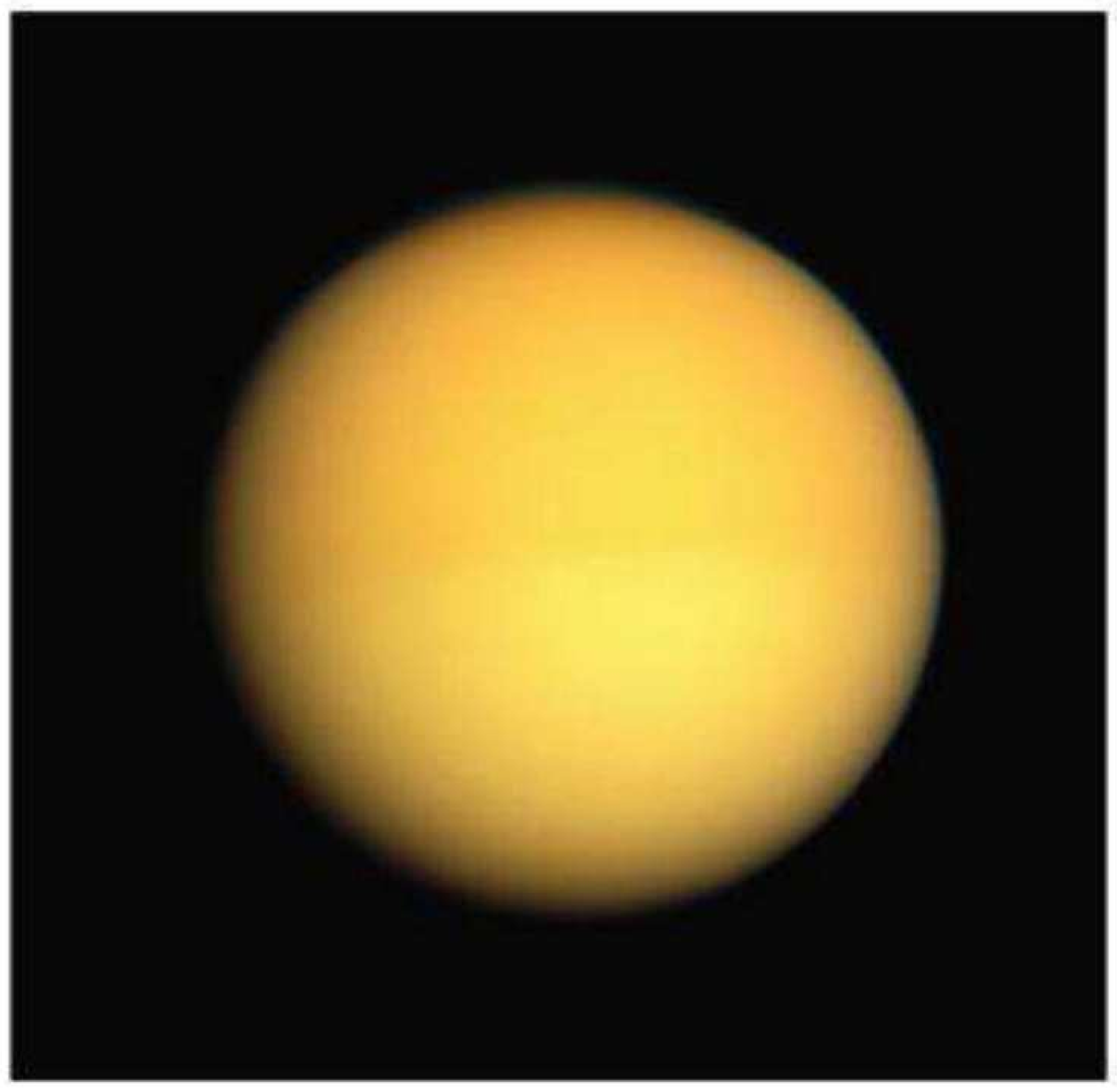
Heidi Hammel of the Massachusetts Institute of Technology studies the ice giants using the Hubble and Keck telescopes. Since Uranus' 2007 equinox, Hammel has found structures on this planet that resemble Neptune's weather. "We saw a lot of bright features poking up to high altitudes," she says. "Hubble and Keck images showed a dark feature along the lines of Neptune's Great Dark Spot," a massive storm discovered by Voyager 2 during its 1989 flyby.

The dark spot on Uranus bolstered the idea that its weather is beginning to resemble Neptune's. While dark storms last for roughly 5 years on Neptune, no one knows how long they last on Uranus. Hubble and Keck are the only telescopes with enough resolution for Hammel's work, and time on these instruments is precious. "With Hubble, we might get 6 hours a year. On Keck, it's 10 or 12 hours a year." Despite these limitations, Hammel could see the dark spot or its companion bright clouds for many months. "It wasn't as big [as a similar storm on Neptune], but it seems similar structurally."

At the solar system's edge

Neptune's remarkable blue face stands in stark contrast to the soft blue-green of Uranus. The outermost planet's clouds are intrinsically blue, says Hammel. "There is some kind of coloring agent in the atmosphere that gives it the more bluish color." Yet the agent's identity remains a mystery.

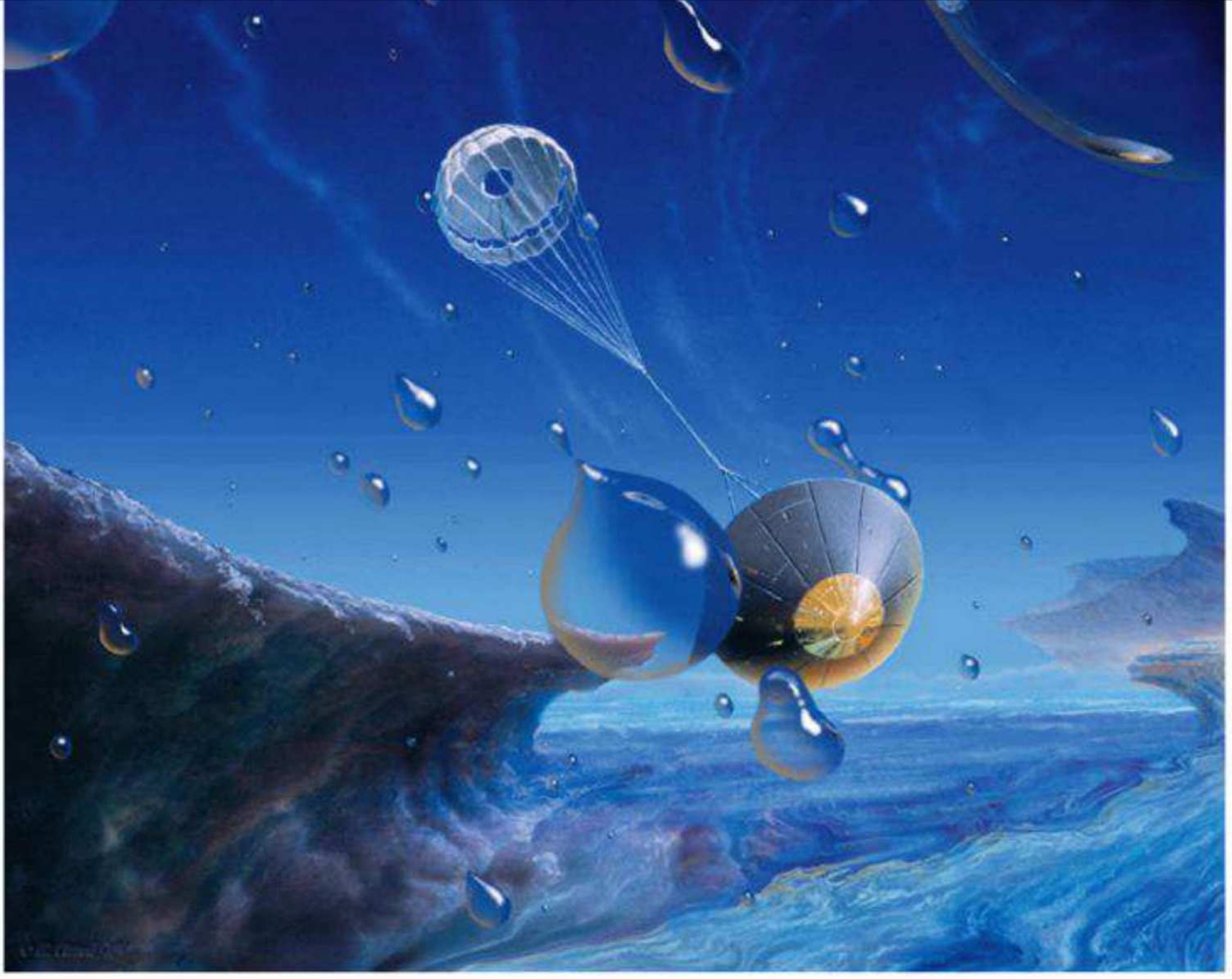
Bright methane crystals skitter across subtle belts and zones and spiral into cyclonic features. Unlike clouds on Jupiter and Saturn, Neptune's are difficult to track, says Baines. "You go to Jupiter and see the Great Red Spot and it's there



Haze-shrouded Titan, Saturn's largest moon, has a nitrogen-rich atmosphere denser than that of Earth. Methane rains from Titan's clouds and pools in vast lakes on the surface. NASA/JPL/SSI forever. You see zones and belts that, on the first order, are permanent. But on Neptune you've got wispy clouds that are very ephemeral. It's hard to measure wind speeds on Neptune because you can't tell if the cloud you're following is the same cloud that you saw an hour before."

Despite the transience of its clouds, Neptune has long-lived phenomena. The Great Dark Spot, named for its similarity to Jupiter's Great Red Spot, had a diameter equal to Earth and rotated once every 8 days during Voyager 2's 1989 passage. As the storm obstructed the planet's streaming atmosphere, air deflected upward and bright methane clouds condensed. By the time Hubble came on line with its corrected optics in 1993, the spot had vanished. But another storm soon appeared in Hammel's images. "In 1994, we saw a northern dark spot," she says. "After 5 years, that one was gone and there was another one closer to the equator. That one disappeared after about 5 years. We haven't seen one since."

Although Neptune's distance from the Sun remains nearly constant, the planet's atmosphere is warming. Hammel is mystified. "I don't think we understand atmospheres, and why they warm, as well as people think we do. There may be mechanisms that we aren't fully accounting for as we model planetary atmospheres. That includes Earth."



An atmospheric probe parachutes through Neptune's thick clouds and beachball-sized methane raindrops in this artist's impression. It likely will take such a mission to unravel the mysteries that still face scientists trying to understand the ice giants. Michael Carroll

Airy moons

The solar system is an amazing place. Not only do all the planets except Mercury have significant atmospheres, but so do two of its moons. The densest: the gloomy, nitrogen-rich atmosphere that enshrouds Saturn's moon Titan. Here, methane plays a role similar to water on Earth. It rains from the sky, pools at the surface, and evaporates to become clouds. Cassini's radar instrument detected river valleys and outflow regions. Despite evidence for flowing liquid, Titan's air currents may dry its equator. As on Venus, air rises over the equator, loops toward the poles, and then descends. The result: the equator dries out while moisture migrates poleward.

Neptune's big moon, Triton, has a thin atmosphere that exists only around the time of its equinoxes. When it's winter at one of the poles, the air freezes onto the surface. In this Voyager 2 view from Triton's farside, sunlight scatters through the hazy atmosphere. NASA/JPL

In March, an international team announced its discovery of a methane rainstorm on Titan. The researchers described how the surface darkened at locations associated with methane clouds. Team leader Elizabeth Turtle of Johns Hopkins University in Baltimore, Maryland, thinks Titan goes through shifting weather patterns during its equinox season. "Similar behavior is observed in Earth's tropics," she explains. "Surface winds from the north and south converge, causing upwelling. [Rainfall] shifts from one side of Earth's equator to the other each spring and fall. Our observations indicate that the same shift occurs on Titan."

The European Space Agency's Huygens probe, which landed on Titan in 2005 and survived for more than an hour, sampled the moon's winds and gases directly, detecting complex chemistry and moisture even at the surface. Super-rotating winds circulate at an altitude of 75 miles (120 km) and blow at more than 250 mph (400 km/h). Winds calm and reverse direction below an altitude of 5 miles (8 km). The weather report from the surface: a temperature of –290° Fahrenheit (–179° Celsius) and a pressure 1.47 times that at sea level on Earth.

Neptune's moon Triton has a far more tenuous atmosphere composed of nitrogen and methane. Like on Mars, Triton's air is tied to the freezing and thawing of polar ices, which on Triton consist mostly of nitrogen. Unlike Mars, however, Triton's entire atmosphere collapses twice each neptunian year, during winter at each pole. The moon only has weather during spring and fall because its atmosphere only exists during those seasons.

Understanding the weather on other planets and their moons is critical to our understanding of Earth's meteorology, says Ingersoll. "If all your theories are based on Earth, you can't really test them, so you go to another planet where you can learn things. They're full of surprises." These weather surprises undoubtedly will continue as we explore the skies of distant worlds.

A+ Read about the "Venus anomaly" and Saturn's day at www.Astronomy.com/toc.