Uranus's hidden polar cyclone, revealed

Microwave observations peer into the atmospheric dynamics of the oddball seventh planet.

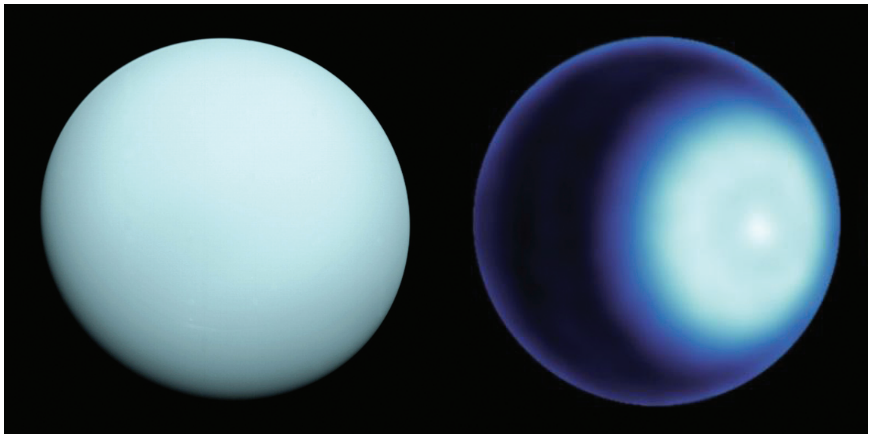

FIGURE 1. PALE BLUE DOT. When *Voyager 2* flew by Uranus in 1986, it sent back the visible-light photograph, shown here at left, of the planet's outer layer of methane clouds. In the decades since then, Earth-based observations at longer wavelengths have probed deeper and uncovered the planet's layers of hidden complexity. Shown at right is a new microwave image with signs of a cyclone at the Uranian north pole. (Left panel courtesy of NASA/JPL-Caltech; right panel courtesy of NASA/JPL-Caltech/VLA.)

Jupiter has *Juno*. Saturn had *Cassini*. Even tiny Pluto had *New Horizons*. But when it comes to exploration, Uranus and Neptune, the solar system's ice giants, have been left out in the cold. Neither has been visited by any spacecraft since (or before) *Voyager 2*, which flew by the former in 1986 and the latter in 1989.

Voyager 2 captured stunning photographs of the outer planets: Jupiter's mottled stormy surface, Saturn's elegant stripes and groovy rings, and Neptune's mesmerizing swirls of blue. Its images of Uranus, in contrast, weren't much to look at. As shown in figure 1 at left, the seventh planet appeared as a dull, pale sphere, as plain and featureless as a Ping-Pong ball.

But "boring," it turns out, is only skin deep. *Voyager 2*'s visible-light images show Uranus's surface layer of methane clouds. In the decades since the flyby, researchers have looked deeper into the planet by imaging it at longer wavelengths, and they've discovered that beneath the plain exterior lurks a complex and dynamic atmosphere. Now Alex Akins, of NASA's Jet Propulsion Laboratory, and colleagues have used the Very Large Array—a squadron of 28 radio dishes (one is a spare) spread over tens of kilometers on the plains of western New Mexico—to image Uranus at wavelengths from 0.7 cm to 5 cm. And they've uncovered a clear sign of a cyclone circling the planet's north pole.[1]

Polar cyclones exist on Earth—and on every other planet with an atmosphere in the solar system. But Uranus is unusual enough that it wasn't a given that one would be seen there. "In comparative planetology, we're interested in what changes in planetary systems under different conditions and what stays the same," says Akins. "So the observation of polar cyclones on every planet with a substantial atmosphere tells us that they're likely present on much of the exoplanet population as well."

Sideways seasons

Akins and colleagues' microwave images, including the one in figure 1 at right, show the Uranian north pole close to head-on. That's possible with an Earth-based telescope only because Uranus has an exceptional orbital geometry. Unlike most other planets, whose rotational axes are at least roughly parallel to their orbital axes, Uranus looks like it's been knocked on its side. During its 84-Earth-year orbit, its poles take turns pointing straight toward the Sun—and toward Earth.

The orbital configuration also potentially affects the Uranian seasons and atmospheric dynamics. On Earth and similar planets, the poles are colder than the equator because they get less direct sunlight. In response to the thermal imbalance, hot air rises at the equator, drifts to higher latitudes, and sinks. When that convection cycle interacts with Earth's rotation, it gives rise to the pattern of pressures and prevailing winds, including the Arctic and Antarctic polar vortices, that dominates our local weather and climate. (See the article by Thomas Birner, Sean Davis, and Dian Seidel, PHYSICS TODAY, December 2014, page 38.)

On Uranus, however, everything is different. Averaged over a year, the poles get more sunlight than the equator, not less. On the other hand, Uranus is 20 times as distant from the Sun as Earth is, so it gets barely 1/400 the sunlight. That may not even be enough to drive significant seasonal or regional variation.

The most recent Uranian equinox was in 2007. The current northern-hemisphere spring is the first time the north pole has been visible from Earth since 1965—and it's the first chance astronomers have had to get a good look at either pole since the south pole faded from view in the early 2000s.

Microwave-astronomy capabilities have improved a lot during those decades, including at the Very Large Array (shown in figure 2), which underwent a significant upgrade[2] that was completed in 2012. Akins and colleagues' new images show the north polar region in more detail than was possible before, and they're newly able to resolve the polar cyclone: the small bright spot right

FIGURE 2. RADIO FORMATION. The Very Large Array, a roughly two-hour drive outside of Albuquerque, New Mexico, is one of the world's foremost observatories for radio- and microwave-frequency astronomy. With all of its radio dishes aimed at the same spot on the sky, the array can capture images in exquisite detail, even resolving features on our solar system's outer planets. (Courtesy of T. Burchell, NRAO/AUI/NSF.)

at the pole encircled by a faintly darker collar at about 80° N. Those features, the researchers conclude, stem from the temperature–pressure pattern at the center of a cyclone, similar to the eye of a terrestrial hurricane.

Around again

Not everything in the new images is new. The Very Large Array has been fully operational since 1980, albeit with lower bandwidth and resolution than in recent years, and microwave observations of Uranus date back nearly that far—close to half a Uranian year. And they've consistently shown the same feature that dominates Akins and colleagues' images and constitutes one of the many mysteries of the Uranian atmosphere's circulation: The broad polar regions, with latitudes higher than about 45° north or south, glow brighter than the equatorial zone.

Microwave imaging records thermal radiation, not reflected light. So one reason the Uranian poles might be brighter than the equator is that they're hotter. They do get more sunlight, after all. But that explanation is less than satisfying because the brightness contrast persists regardless of the Uranian season, even for a pole just emerging from the dead of winter. And the temperature difference required to produce the contrast—several tens of kelvin—would be hard to explain in any circumstance.

The polar brightness could also be the result of a difference in chemical composition. Uranus is known as an ice giant because of its richness in ice-forming materials—such as water, ammonia, and methane, as opposed to the hydrogen and helium that dominate the gas giants Jupiter and Saturn—not because those substances are necessarily present in their solid form. The chemical diversity gives the atmosphere a complex layered structure, with water clouds at the bottom and methane clouds at the top. But the layers might not be the same everywhere.

Methane doesn't strongly absorb microwaves, but gases deeper in the atmosphere, such as ammonia and hydrogen sulfide, do. If those low-lying absorbers somehow got churned up to higher altitudes near the equator, they could block the microwave emissions and make that region appear darker. "The observations are consistent with a simple model of atmospheric circulation where air rises at lower latitudes and descends at higher latitudes," says Akins. Such a circulation pattern is familiar on Earth, with its warm equator and cold poles, but how the same phenomenon could arise on Uranus is less clear. "We're not exactly sure what causes it, especially since insolation is so weak," he adds. "I hope more folks in the community get excited about Uranus and can help provide some answers."

Another voyage

As the northern Uranian spring progresses into summer, keeping an eye on the polar cyclone could offer valuable new insights into how a polar atmosphere behaves after 42 continuous years in the dark—and what seasonal effects, if any, are present in Uranus's atmosphere. Although it's too soon to tell for sure, Akins and colleagues have already seen hints that the cyclone may have strengthened a bit during its short time in the Sun.

Ultimately, though, Earth-based observations can only do so much. They're limited in their resolution and spectral bandwidth, and they can't reach the meter-long wavelengths needed to image Uranus's deep water clouds. To really unravel the mysteries of the Uranian atmosphere, it will probably be necessary to get a close-up view once again.

Happily for seventh-planet afficionados, a Uranus orbiter and probe was deemed the top-priority flagship mission by the latest planetary science decadal survey, released in April 2022 by the National Academies of Sciences, Engineering, and Medicine. The recommendation alone is no guarantee that the project will come to fruition, but it bodes well. The top two priorities of the previous survey—a Mars sample-return mission and the *Europa Clipper*—were both funded, with launches planned in the next few years.

For Uranian science, time is of the essence. If launched in 2031 or 2032, a Uranus-bound spacecraft could capitalize on a gravity assist from Jupiter and reach its destination in a mere 13 years. If launched later, its journey will take much longer.

Johanna Miller

References

1. A. Akins et al., *Geophys. Res. Lett.* **50**, e2023GL102872 (2023).
2. R. A. Perley et al., *Astrophys. J. Lett.* **739**, L1 (2011).

Understanding how metal-nitride ferroelectrics switch their polarization

Transmission electron microscopy images and first-principles calculations suggest that the atoms adopt a disordered but low-energy configuration that facilitates the switching.

Studied for more than a century, ferroelectric materials exhibit a spontaneous polarization in one or more directions along a crystal axis. Thermodynamically stable, the polarized states can be switched from one to the other by applying an electric field that exceeds what's known as the coercive field E_c. That switchability provides the basis for the nonvolatile RAMs in computing. (See the article by Orlando Auciello, James F. Scott, and Ramamoorthy Ramesh, Physics Today, July 1998, page 22.)

Since the 1960s, electrical engineers have been designing memory elements based on conventional ferroelectrics such as the perovskite barium titanate. But manufacture is complicated by the challenge of integrating those materials with silicon-based semiconductors. What's more, the memory elements are difficult to scale down to atomic dimensions for energy efficiency. Between 2019 and 2021, researchers discovered that crystalline films of alloyed aluminum nitride are ferroelectrics that could solve both problems. Boron-doped AlN, in particular, is easy to integrate, as it consists exclusively of elements common in silicon electronics.

The discovery was a surprise to most scientists. The films were well-known pyroelectric and piezoelectric crystals, but few believed they could be ferroelectric, because their coercive fields are just too perilously close to the field at which the materials experience dielectric breakdown. Apply a high enough electric field to switch the polarization and you risk destroying the material.

Pennsylvania State University materials scientists Jon-Paul Maria, Susan Trolier-McKinstry, and Ismaila Dabo, who had demonstrated ferroelectricity in B-doped AlN two years ago,[1] have now teamed up with Carnegie Mellon University materials scientists Sebastian Calderon and Elizabeth Dickey to address the dielectric-breakdown problem.[2] The collaborators realized that if they understood the mechanism by which the polarization switches at the atomic scale, they could manipulate it—for example, by straining the film, growing it thinner, or altering its dopant concentration.

Such tricks may dramatically lower the coercive field from roughly 4–6 MV/cm in metal nitrides down to levels approaching 1 MV/cm. That transformation would render the new ferroelectrics more practical for applications in memory, energy-harvesting, and high-speed and high-power circuits.

Double duty

Fortunately, there are a few ways to ensure that the coercive field is lower than the dielectric breakdown field. At elevated temperatures, the margin separating E_c and the breakdown field increases, for instance.

As deposited on a tungsten electrode, $Al_{15/16}B_{1/16}N$ films grow with a polarization that points downward (into the substrate)—a configuration shown in figure 1a and referred to as N-polar growth. The image depicts the thickness of a film, grown upward from the bottom of the frame. The tetrahedron diagrams show the positions of the metal atoms Al or B (gray) relative to the N atoms (blue). The metal atom in each tetrahedron is bonded to four N atoms.

To experimentally study the films' local structure and polarization, the researchers used scanning transmission electron microscopy (TEM). And in a standard imaging mode known as differ-

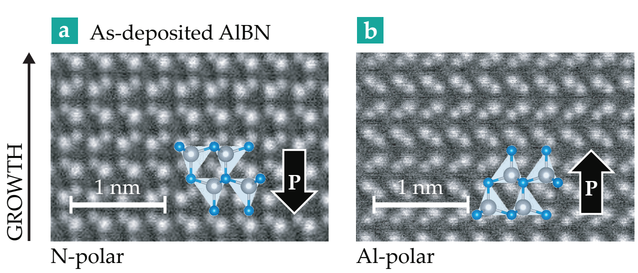

FIGURE 1. BEFORE AND AFTER polarization reversal. These transmission electron microscopy images are on-edge views of a boron-doped aluminum nitride film—a mere 6 nm thick—that show the projections of N, Al, and B atoms through the lattice. **(a)** In AlBN as it's deposited on tungsten, the polarization orientation **P** is down, or N-polar. **(b)** After the surface expels enough charge to exceed the coercive field, the polarization flips upward (Al-polar) and the angles between the N atoms and the Al or B atoms change their relative orientation. (Adapted from ref. 2.)