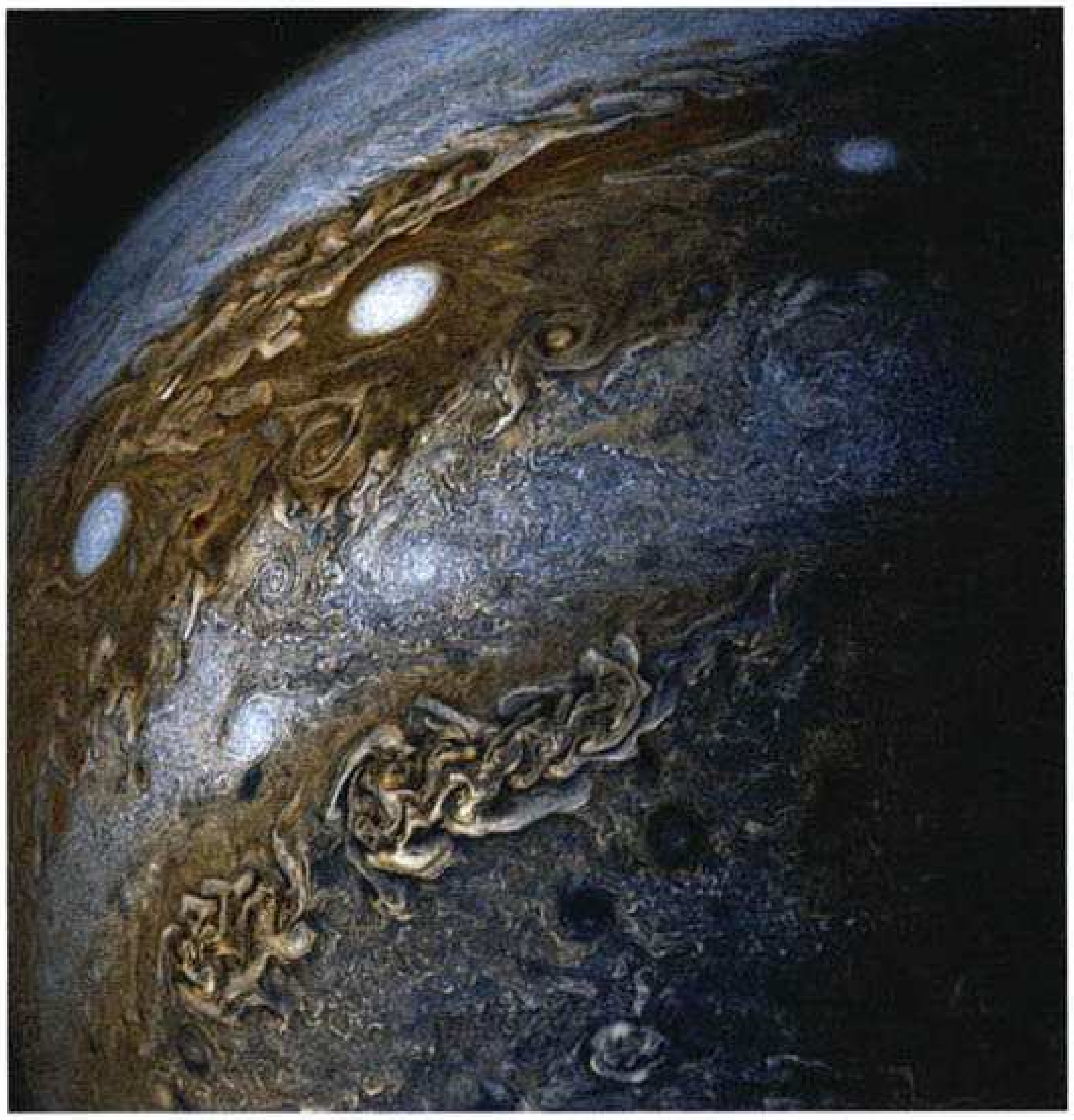
Jupiter Rediscovered

NASA's Juno mission is revealing that our solar system's largest planet is a fantastic, cyclone-festooned world with a strange interior. What's the scoop after 18 months in orbit?

For many of us, the planet Jupiter conjures mental images of a giant ball with latitudinal stripes of red and white all the way from pole to pole, with the most remarkable anomaly being the Great Red Spot. We've had little reason to question this scheme: The glimpses that previous spacecraft have caught of high latitudes looked striated.

But Juno changed that. Upon the spacecraft's arrival at Jupiter in July 2016, its JunoCAM wowed us with the first views ever captured looking directly down at the poles. Above about 50° latitude, it turns out, the planet darkens and takes on a blue tinge. Images show spectacular eddies and a chaotic mass of jostling storms.



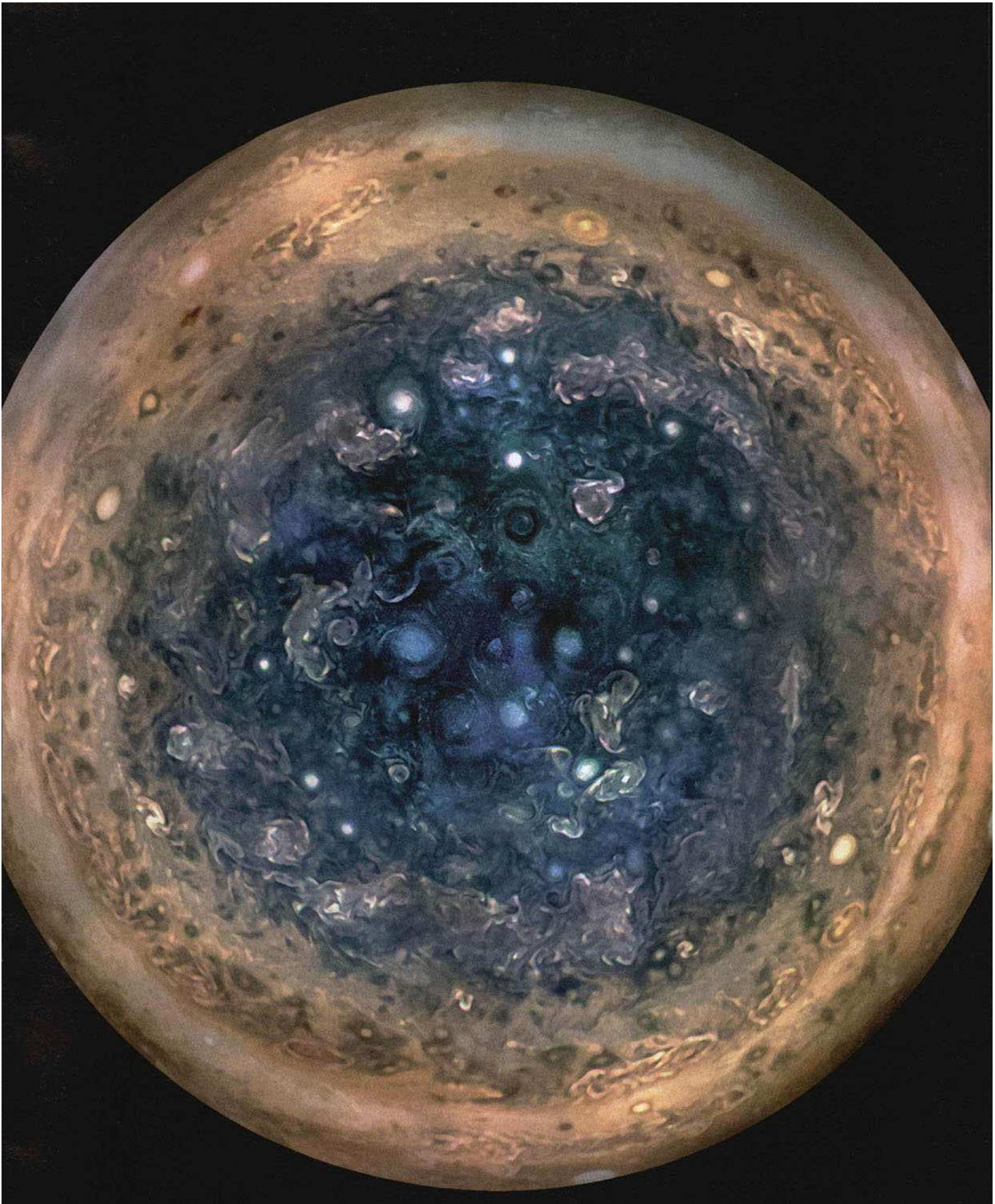
Particularly intriguing is the fact that Jupiter's polar regions are so different from Saturn's. While rotation dominates the atmospheric dynamics of both planets, their polar weather systems seem to be fundamentally different. Saturn has a single deep, fast vortex centered on each pole, top and bottom, with the north pole surrounded by a remarkably long-lived, hexagon-shaped wave. In contrast, we've found by comparing Juno images from orbit to orbit that Jupiter's numerous, smaller-scale polar vortices move around in a semi-random way. They remain tightly packed around the pole and do not merge.

Jupiter's poles are illustrative of Juno's early discoveries: The closer we look at this planet, the more structure we see. My article last year (*S&T:* July 2016, p. 18) listed Juno's scientific aims, including the determination of the planet's bulk composition and how much water is inside it. We cannot yet answer these two fundamental questions; first Juno will need to finish mapping the planet's gravity field and microwave emissions, respectively. Nevertheless, what we've learned from Juno's first seven flybys is enough to dazzle and amaze.

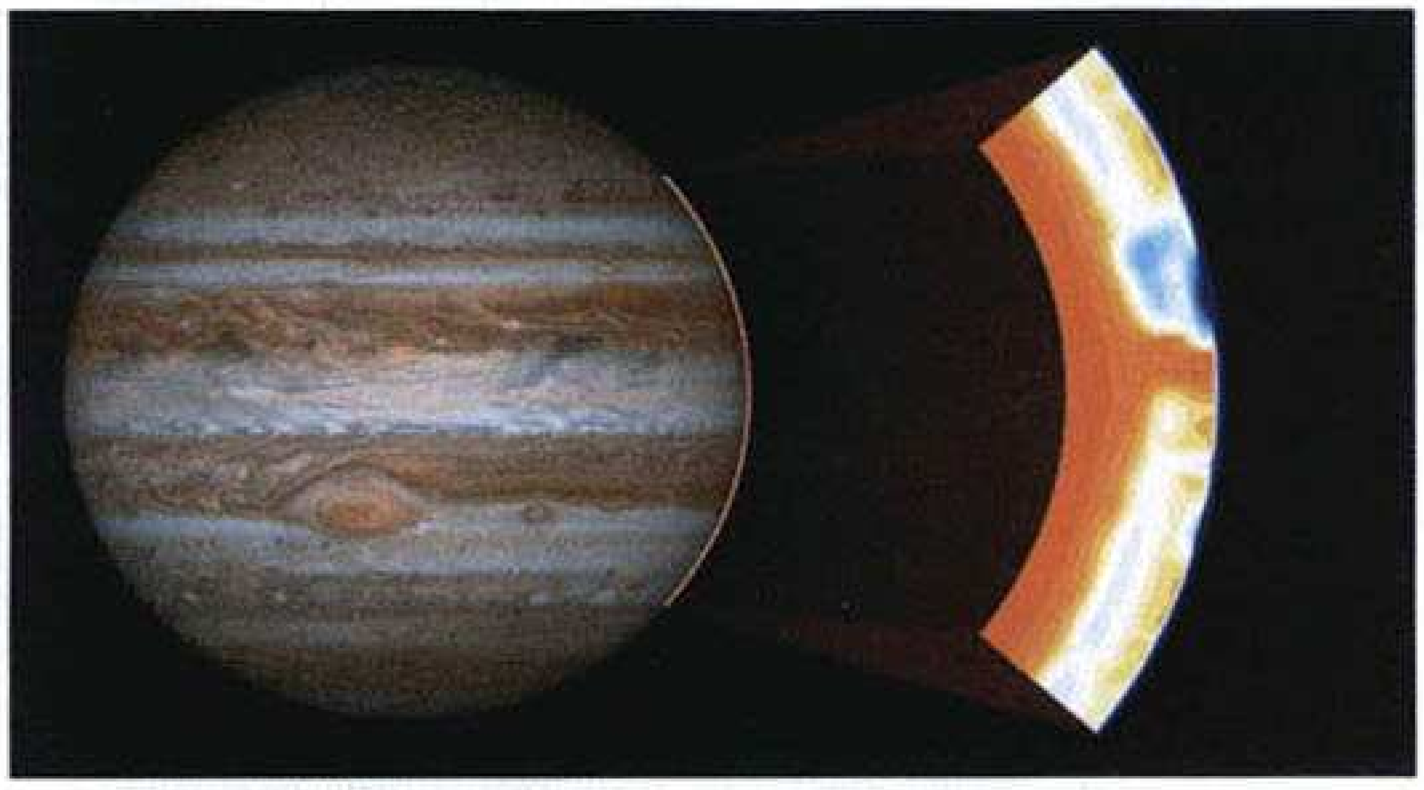
Swirls Within Swirls

Juno loops around Jupiter once every 53 days, whizzing in for a closest approach, or *perijove*, of about 4,300 km (2,700 miles) above the cloudtops. Although this might seem far away, it still gives us incredible close-ups of the planet — Voyager 1 was 65 times farther away on its 1979 flyby.

▲ **BEJEWELED** Three of the white oval storms known collectively as the "String of Pearls" appear near the top of this enhanced-color image, created by JunoCam participants Gerald Eichstädt and Seán Doran. Each of the alternating light and dark bands is wider than Earth. The lighter bands are regions where gas is rising; the darker ones, where gas is sinking. **Facing Page:** This enhanced-color mosaic combines images from three flybys to reveal the planet's nether regions, unseen until Juno. The ovals are cyclones, the largest 1,000 km (600 miles) wide. Juno took the images from 52,000 km above the south pole's cloudtops.



▲ **LO, THE GREAT RED SPOT** JunoCam took this true-color image *(top)* from 13,917 km (8,648 mi) above the cloudtops on July 10th. Contrast enhancements and white-balancing of another image from the same pass *(middle)* reveal glorious details the eye might overlook.



This dramatically smaller perijove gives Juno a much different perspective than the Voyager spacecraft had. The twin craft took weeks-long movies of Jupiter's dramatic global weather systems, showing bands of white clouds zooming left to right and deep red bands streaming right to left. It's interesting to contrast these Voyager movies with the still views Juno is getting 38 years later. On a spinning spacecraft and a 2-hour pole-to-pole dash, Juno's camera sees only snapshots of atmospheric activity. But these close-ups reveal small-scale structures that were blurred at Voyager's distance from the planet.

In fact on every scale, down to the 50-km resolution of JunoCAM, we see structure in Jupiter's atmosphere – vortices, thunder clouds, waves, and turbulence. In retrospect, we probably shouldn't have been so surprised, since nature across the universe tends to get more structured when we zoom in.

Jupiter is more than 11 times wider than Earth, yet it spins around in just under 10 hours – the shortest day of the major planets. This rotation drives the dynamics in the shallow, outermost layer of the mid-latitude atmosphere, where the multiple red "belts" and white "zones" mark striped weather systems. Convection and turbulence spur small-scale structure, and spots grow by merging together. We've seen large-scale order emerging from small-scale chaos in a number of planetary atmospheres, but Jupiter is the best example.

Why has Jupiter's rotation not smoothed out this small-scale structure? If you put milk in your coffee and give it a stir, it quickly becomes a uniform mixture. Jupiter has been "stirring" for billions of years, so what causes these structures to persist? The answer is similar to the ongoing activity in Earth's atmosphere. On Earth, the water cycle feeds weather patterns, keeping our atmosphere in a constant state of transformation. On Jupiter, ammonia plays a similar role as water on Earth. As a blob of air with ammonia vapor rises, it cools. Eventually the vapor condenses, releasing energy into the surrounding gas, making the gas rise higher in the atmosphere. Such feedback systems persistently drive small-scale structures and prevent the atmosphere from mixing into a great bland ball.

And then there's the Great Red Spot. On July 10, 2017, Juno flew directly over the giant storm that astronomers have observed since at least the 19th century (*S&T:* Mar. 2016, p. 18). More than 16,000 km across but less than 300 km deep, the GRS is like a spinning New York pizza – except it's made out of hydrogen. Voyager 2's movie of the Great Red Spot shows the vast storm gobbling up smaller eddies and sometimes spitting them out again. Juno's zoomed-in pictures show turbulent structure within the GRS's twirling vortex. To the south of the GRS, small, fresh, white clouds poke up like monsoon thunderheads on an afternoon in the Rocky

◀ **IN MICROWAVES** The cut-out shows data from Juno's Microwave Radiometer, which detects microwaves emitted from ammonia in Jupiter's atmosphere down to 350 km. Colors correspond to abundance, with orange being more and blue less. Scientists had thought the ammonia would be uniformly mixed, but the data reveal a deep circulation pattern, including an equatorial band (the prominence-like column).

TOP: NASA / JPL-CALTECH / SWRI / MSSS / BJÖRN JÓNSSON; MIDDLE: CREDIT: NASA / SWRI / MSSS / GERALD EICHSTÄDT / JUSTIN COWART; BOTTON: NASA / JPL-CALTECH / SWRI

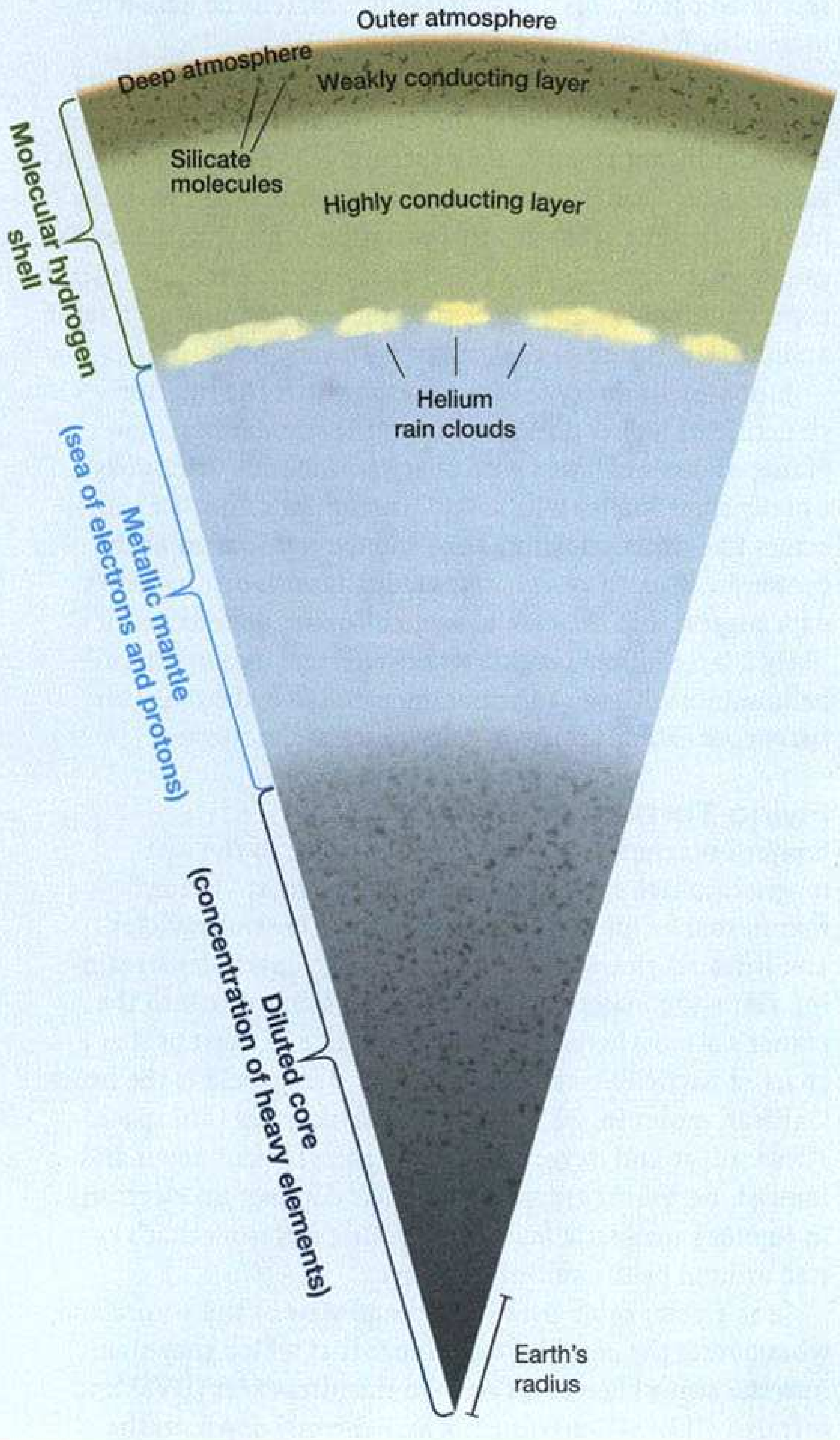
Mountains. The clouds we see on Jupiter are predominately ammonia (NH_3), and the red coloration of Jupiter's belts and the GRS are likely photochemical products (such as phosphine, PH_3) that have accumulated over years of exposure of the outer atmosphere to ultraviolet radiation from the Sun.

The Microwave Miracle

Juno also looks below the turbulent clouds. The beauty of the mission design was the realization that a microwave detector could see what's going on beneath the chaos of clouds. The Microwave Radiometer (MWR) instrument is revealing a totally different weather system down there. But it's not the uniform, static deep atmosphere imagined before Juno. The MWR data reveal an equatorial belly-band of ammonia, formed by a large, upwelling plume and extending down about 300 km. We don't know yet whether this deep circulation system varies around the planet, or whether it might extend toward the poles. It probably goes about its business unaffected by the belts and zones we see at the cloudtops.

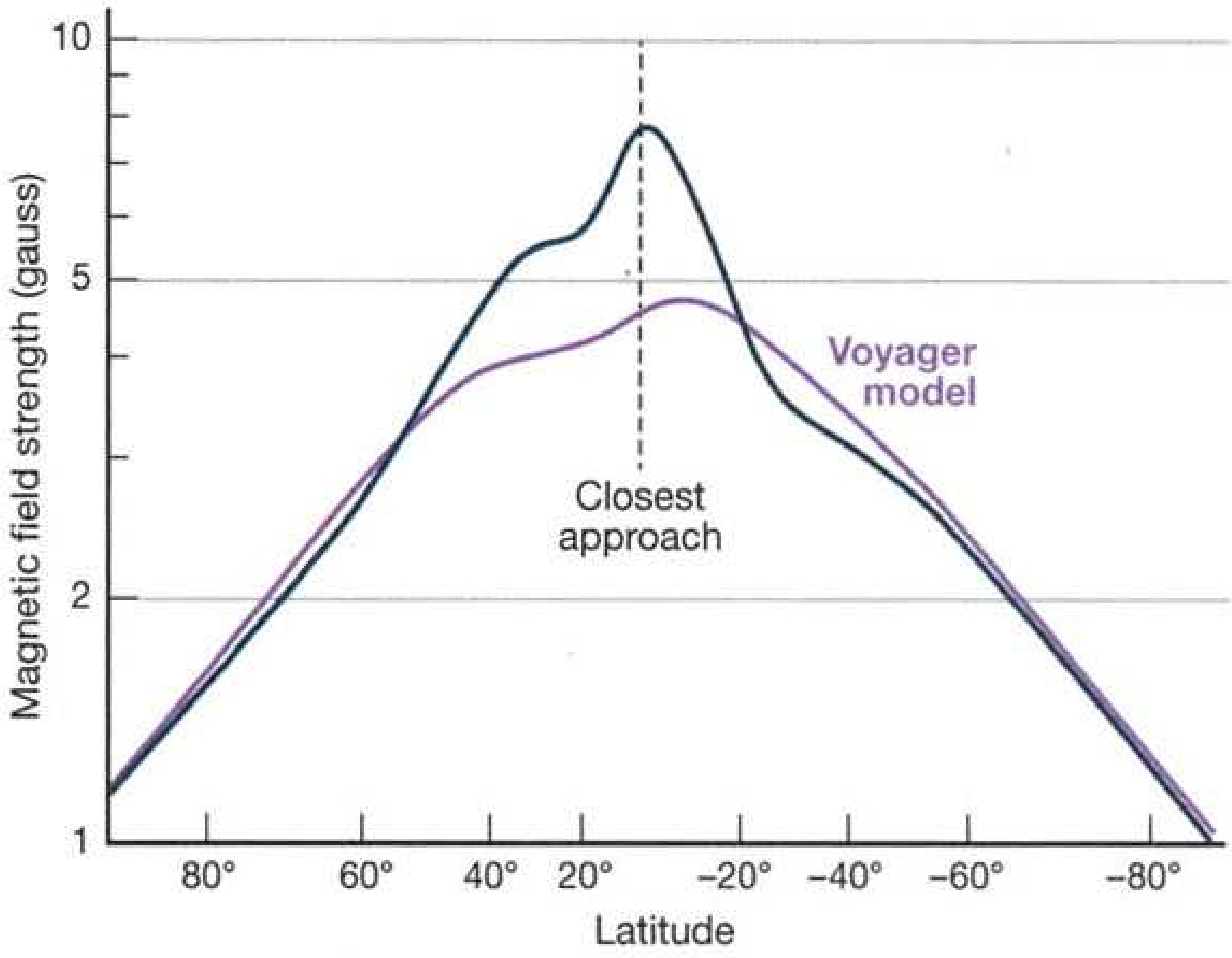
In some ways, Jupiter's upper weather patterns and the deeper circulation system can be compared with the combined system of Earth's atmosphere and oceans. Both have distinct layers, with the lighter gas above and the denser fluid below. These layers circulate on different temporal and spatial scales, separated but with some dynamical linkage. With further MWR observations, we aim to discover what scale the lower wind system operates on and just how separate the flows are from the familiar belts and zones above.

JUPITER'S LAYERS



GREGG DINDERMAN / S&T

- The **outer atmosphere** comprises molecular hydrogen with layers (from top to bottom) of ammonia clouds, ammonium hydrosulfide, and water. Zonal flows (the belts and zones) characterize the large-scale dynamics, accompanied by small-scale vortices and turbulence.
- The **deep atmosphere** extends about 300 km (200 miles) below the clouds. Microwave data suggest a separate flow regime, decoupled from the belts and zones above.
- The **weakly conducting molecular shell** lies above the magnetic-field-creating mantle, but it might be coupled to the magnetic field if its zonal flows are strong. The top of this region is defined by where the zonal flow weakens to less than about 1 m/s (2 mph). This is also roughly where the diffuse "rock clouds" of silicate molecules form. May extend down to about 2,000 km (the upper 3% of Jupiter's radius).
- In the **highly conducting molecular shell**, hydrogen is mostly in molecular form, but the molecules trade enough electrons to make the hydrogen electrically conducting — a prerequisite for a magnetic dynamo. Thus the shell might support magnetic dynamo activity, in addition to the mantle below it. It might extend from about 95% or 90% of Jupiter's radius down to 80%.
- The **metallic mantle** takes up most of Jupiter's volume. Here, high pressures break the hydrogen molecules apart to form a "sea" of electrons and protons. This makes the liquid electrically conducting. The combination of a big volume of conducting material, motions spurred by heat from below and cooling from above, and the planet's rapid rotation drives Jupiter's strong magnetic field. This region is bounded above by clouds of helium rain — the place at which helium becomes partly insoluble in hydrogen and, being denser, its droplets sink down until they hit the high-pressure metallic region.
- The **core** is an enrichment of elements heavier than hydrogen and helium near the center of Jupiter. It's probably not solid, nor does it consist purely of rock or ice-forming compounds. It doesn't have a clear outer boundary, either. It extends out to half the planet's radius yet still occupies only about 10% of the volume.



▲ **JUPITER'S MAGNETIC FIELD** Juno's magnetometer data from the first flyby reveal that the planet's magnetic field is stronger in some places than scientists predicted based on Voyager data. (The plot peaks at the equator only because Juno flies much closer to the planet there, not because the field is intrinsically stronger at the equator than the poles.)

The deep atmospheric layer might hold a bizarre twist. Scientists looking at the Juno data conjecture that there may be a layer of silicate molecules, perhaps primordial, perhaps coming from meteoritic impacts. Some people call these "rock clouds" — but don't conjure up visions of lumps of rock you can hit with a hammer or rock faces to climb in Jupiter's atmosphere! At most we are talking about traces of silicate molecules dispersed in the atmosphere as droplets — like the water raindrops we have on Earth, only made of very hot rock.

Digging Deeper

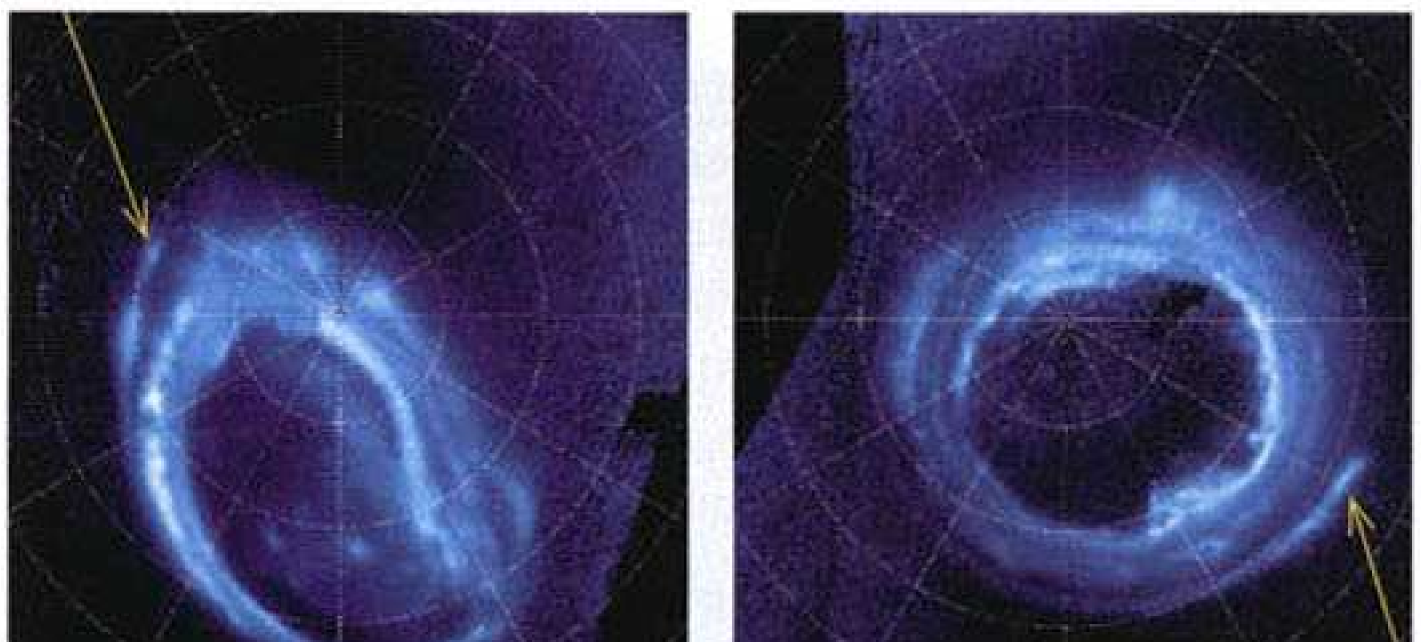
The microwave observations only probe the outermost skin of Jupiter — not even 1% of the way to the center. Below the deep atmosphere lies molecular hydrogen tainted with helium. According to atmospheric theory, as we descend pressures rise to such extremes that the hydrogen molecules break apart, creating a sea of electrons and protons. We call this substance metallic hydrogen, because the free-moving electrons make the liquid electrically conducting. The pressure also makes helium insoluble, and it precipitates out at this region's upper boundary as "rain." The metallic hydrogen mantle is the source of the planet's magnetic field.

To work out what Jupiter looks like deeper down, we need to consider the shape and strength of Jupiter's gravitational field. We map these by carefully measuring small variations in Juno's motion as it orbits the planet, using the same Doppler shifting of Juno's radio communication frequency as traffic police use with radar to check speeding cars.

For this mapping to work, it is vital to get up close to the planet. That's why we chose Juno's polar orbit to skim over the clouds and duck inside the radiation belt. We've spaced the north-south passes longitudinally such that we cut the planet into equal slices as Juno spirals around, with the first 8, then 16, and finally 32 passes following roughly equally separated paths. This allows models to match the data with increasing fidelity over the mission.

While we must patiently wait for Juno to finish mapping out Jupiter's magnetic field, the data from the first few passes show significant small-scale structure — a "patchy" field that varies up to 2 gauss from place to place. Combined with the field's surprising strength, this variation hints that the field's generator, or dynamo, lies closer to the surface than we might expect, perhaps extending beyond the metallic hydrogen layer and into the region of molecular hydrogen above.

Juno's preliminary results also show that the interior structure of Jupiter does not match the standard cartoon planet of distinct layers with sharp boundaries. Textbooks usually show Jupiter with a solid core of rock and "ice" (molecules like water and ammonia, though not frozen) at the center. Instead, things change gradually with depth. Juno's data suggest that the core has much fuzzier boundaries. It's likely a large, diluted region where elements heavier than helium mix with the surrounding metallic hydrogen. This fuzzy core extends roughly halfway up to the surface.



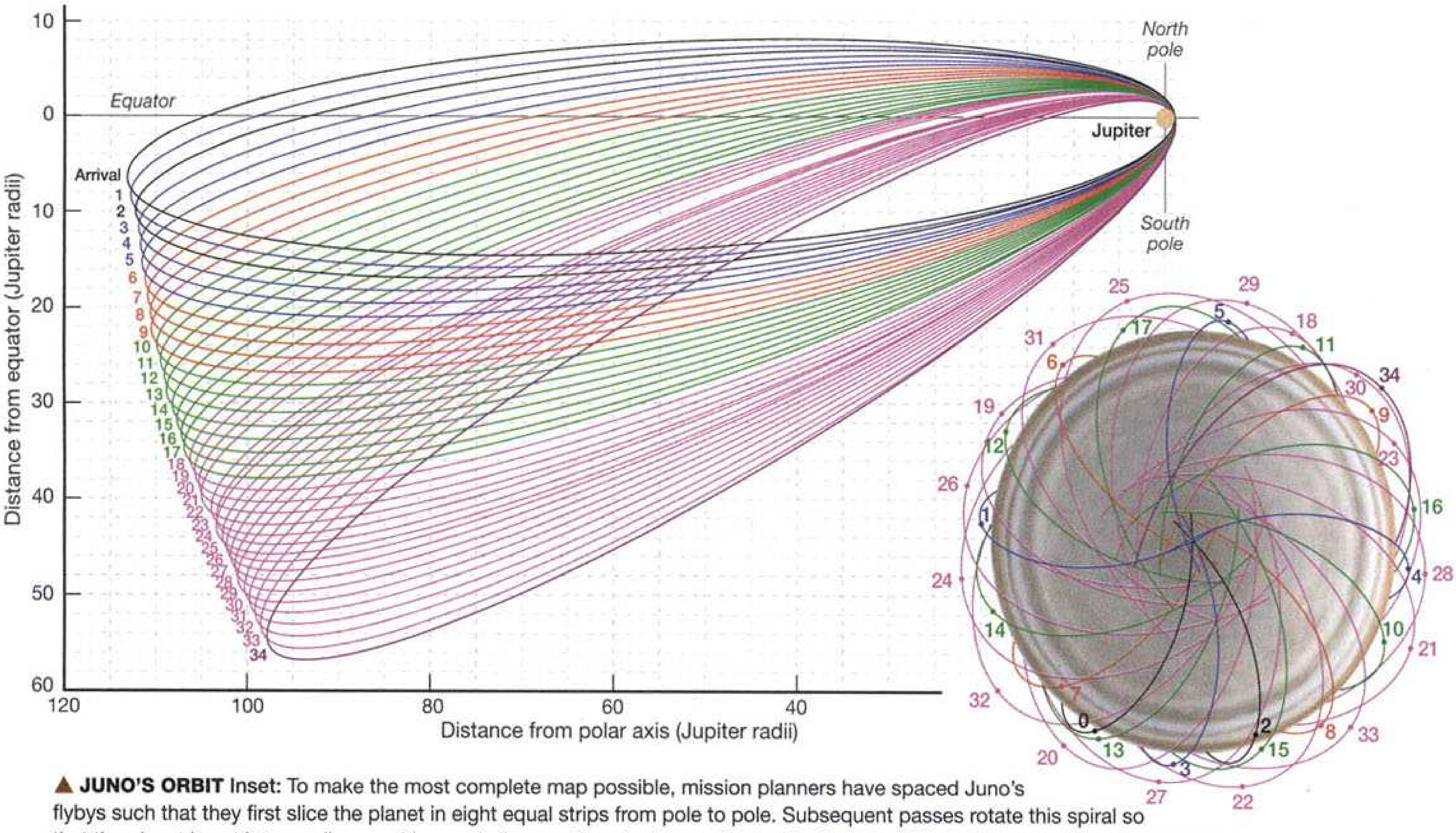
▲ **AURORAL OVALS** Images of Jupiter's northern (left) and southern aurora obtained by the Juno UVS instrument. Yellow arrows indicate emissions related to the moon Io.

Flying Through the Aurora

Jupiter's magnetic dynamo gives structure to the vast magnetosphere surrounding the planet, most "visibly" manifested by Jupiter's strong auroras. These ultraviolet and infrared glows are excited by charged particles streaming along the magnetic field lines and slamming into the planet's atmosphere. The ultimate source of most of the charged particles trapped in Jupiter's strong field is the inner Galilean moon Io, which spews volcanic gases into space. These sulfur and oxygen atoms are then broken down and ionized, becoming trapped with their companion electrons in Jupiter's magnetic field and forming a plasma that's carried around by the spinning planet.

Juno's polar orbit gives us a special view of the aurora and what boosts the particles to the speeds at which they slam into the atmosphere. Not only do the ultraviolet (UVS) and infrared (JIRAM) instruments look directly down on the

GRAPH: GREGG DINDERMAN / S&T, SOURCE: NASA / GSFC / SWRI / JACK CONNERNEY; AURORAS: JUNO UVS / VINCENT HUE (2)



▲ **JUNO'S ORBIT** Inset: To make the most complete map possible, mission planners have spaced Juno's flybys such that they first slice the planet in eight equal strips from pole to pole. Subsequent passes rotate this spiral so that the planet is cut into smaller, roughly equal slices as the mission continues. **Background:** Shown here are all planned flybys as seen from the side (looking along Jupiter's equator) and flattened into the same plane. Over time, the gravitational pull of the planet's equatorial bulge will cause the orbit to slowly precess downward, inevitably bringing the trajectory through the dangerous radiation belts, around the equatorial plane.

GREGG DINDERMAN / S&T; SOURCE FRAN BAGENAL AND JET PROPULSION LABORATORY (2)

auroral emissions, but the particle instruments JADE and JEDI simultaneously measure how many charged particles are streaming along the magnetic field. By pulling together the data from these different instruments, we can learn about the processes that accelerate the particles.

The most intense auroras on Earth are generated when electrons are accelerated in a region above one of Earth's poles where an electric potential exists between locations with opposite polarities – like a battery. Weaker terrestrial auroras are caused instead by electrons scattered by electromagnetic waves. As Jupiter's aurora is orders of magnitude more powerful than Earth's, we naturally assumed that the former process was responsible.

Yet Juno's results puzzle us. We do see potentials of up to 400,000 volts, 10 to 30 times larger than what's observed at Earth. But such static, high-voltage structures would produce beams of electrons all with about the same energy – something that's rarely observed by the JEDI instrument. More commonly observed by JEDI as it passes over Jupiter's aurora are electrons with a broad range of energies, which is what we'd expect if the electrons are interacting with – and getting an energy boost from – waves in the plasma above the aurora. But we still do not know what generates the waves.

What's Next?

These preliminary discoveries are only from Juno's first seven orbits, less than a quarter of the planned number of passes. Because Juno is staying in its 53-day orbit instead of closing in for the intended 14-day circuits, a plan shelved after an engine anomaly arose (*S&T:* June 2017, p. 8), it will take more than 4½ years to complete the 32 flybys that we need in order to fully map out the small-scale structure of the magnetic and gravitational fields. The initial plan envisioned Juno operating for less than 18 months in its tighter orbit.

Moreover, in 4½ years Jupiter covers over a quarter of its orbit around the Sun. Juno's orbit remains fixed with respect to space, but Jupiter's day-night terminator shifts. Thus even though Juno's flybys are spaced to see different parts of Jupiter, the local time of the pass wasn't originally supposed to shift much. But in the new situation, Juno will eventually pass closest to the planet near local noon and near midnight when at *apojove* – instead of the persistent dawn-dusk orbit orientation the mission planners designed for. Now the Juno team is juggling how to keep the solar-powered spacecraft oriented toward the Sun while optimizing observations of Jupiter with science instruments that were designed for the original geometry. Such is the business of space exploration.

We're still a long way from answering the fundamental questions Juno set out to answer. In the meantime, though, we have plenty of discoveries to chew on.

■ **FRAN BAGENAL** is a researcher at the University of Colorado, Boulder, and co-chairs Juno's Magnetospheric Working Group and Scientific Planning Working Group. For more information about Juno, visit **missionjuno.swri.edu** and **nasa.gov/mission_pages/juno**.