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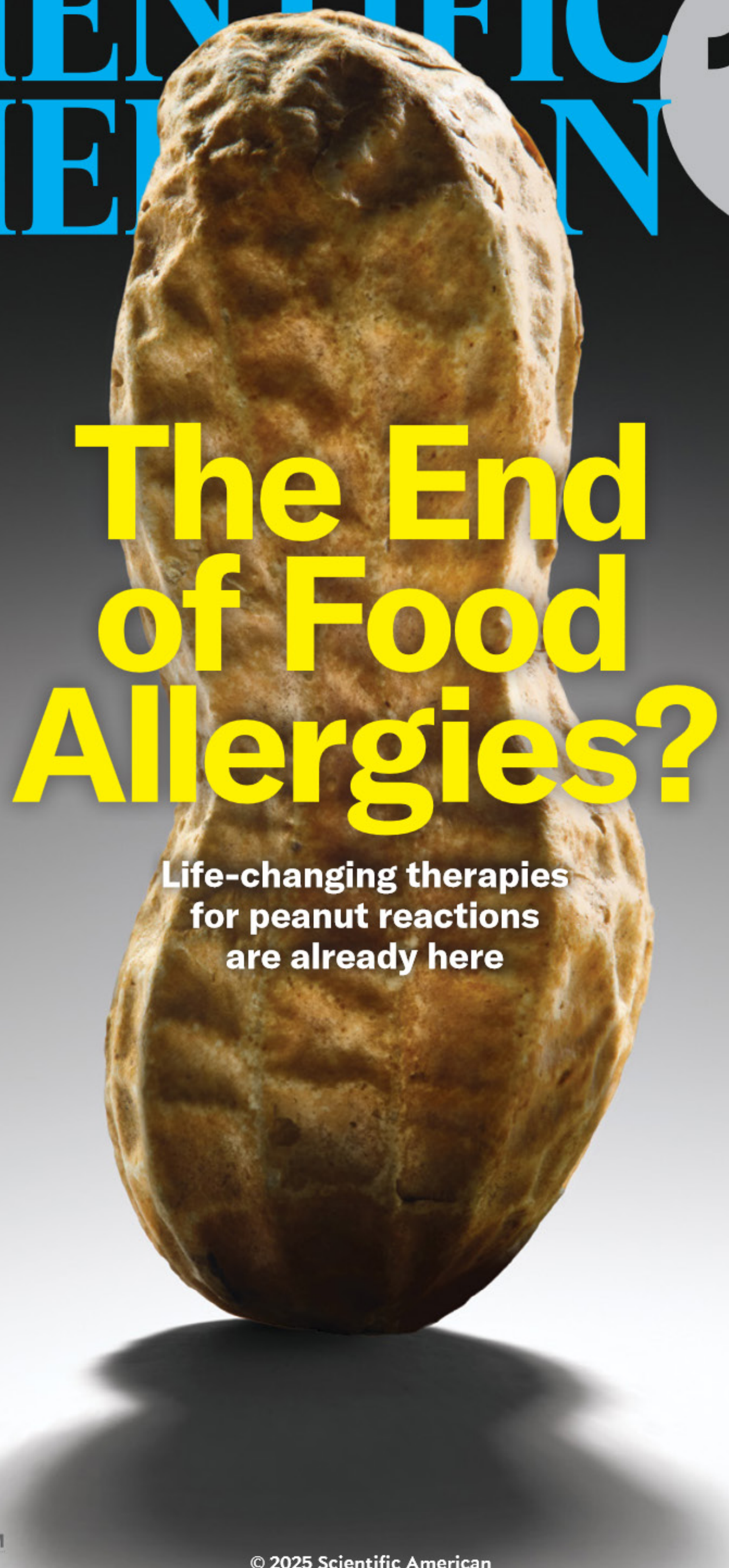

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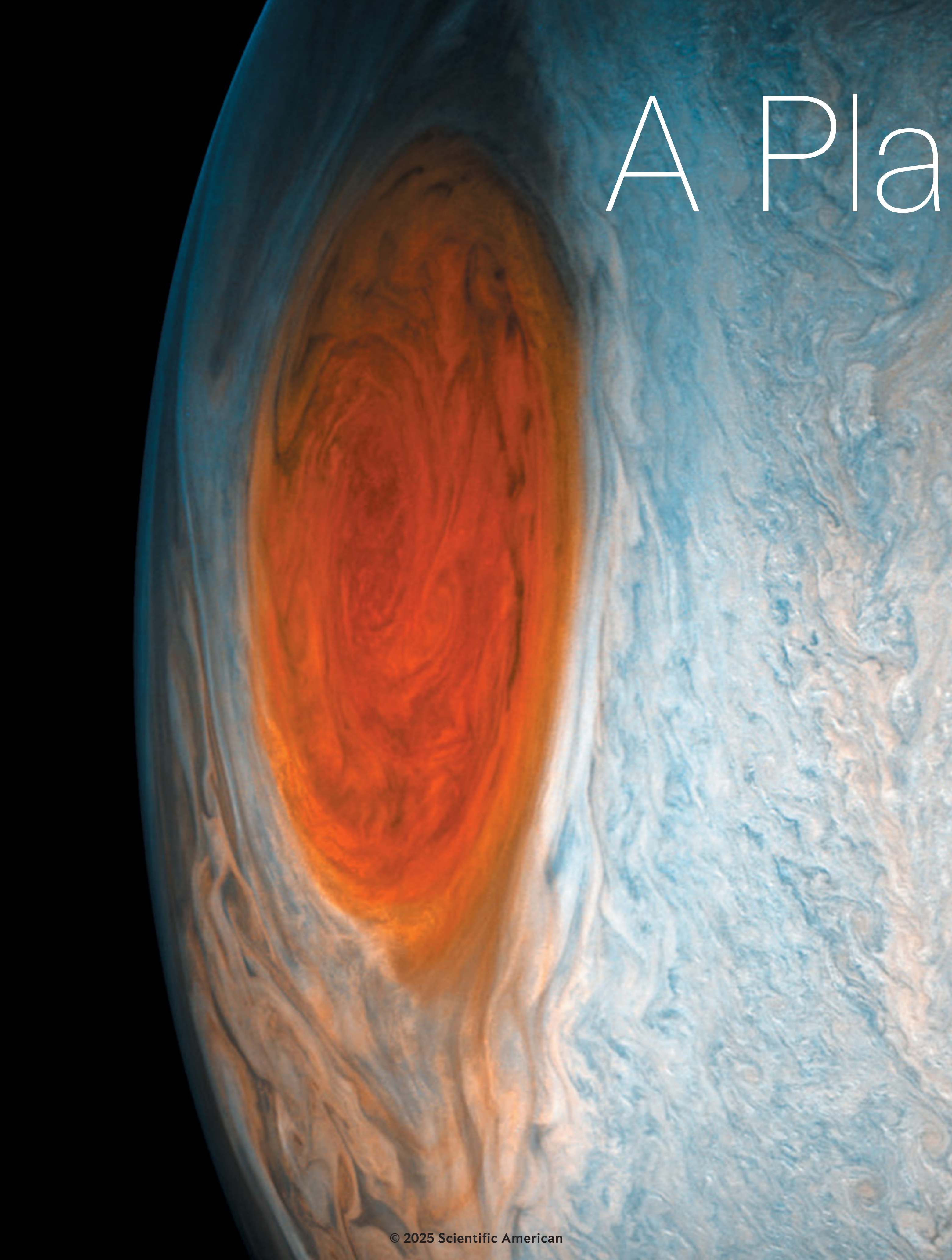

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PLANETARY SCIENCE

net Revealed

The Juno spacecraft has rewritten the story of Jupiter, the solar system's undisputed heavyweight BY ROBIN GEORGE ANDREWS

Jupiter's Great Red Spot glows in this image created from Juno observations.

THE NASA SPACECRAFT tasked with uncovering the secrets of Jupiter, king of the planets, is running out of time. The Juno probe has already survived far longer than anticipated—its path around the solar system's largest planet has repeatedly flown it through a tempest of radiation that should have corroded away its instruments and electronics long ago. And yet here it is: one of the greatest planetary detectives ever built, still pirouetting around Jupiter, fully functional.

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But it may not be for long. September 2025 marks the end of Juno's extended mission. Although it could get another reprieve—an extended-extended mission—the spacecraft cannot carry on forever. Eventually the probe is fated to plunge into Jupiter's stormy skies, to lethal effect. Regardless of when that happens, the spacecraft's legacy is indelible.

It revealed a whole different Jupiter than scientists thought they knew. Oddly geometric continent-size storms, in strange yet stable configurations, dance around its poles. Its heaviest matter seems to linger in its skies, while its abyssal heart is surprisingly light and fuzzy. Its innards don't resemble the lasagnalike layers found in rocky worlds; they look more like mingling swirls of different kinds of ink.

And Juno wasn't simply trying to understand Jupiter. It set out to uncover how the entire solar system was born. Jupiter, after all, was the first planet to piece itself together after the sun exploded into existence. Hidden underneath the planet's cloud tops, there is a recording of the beginnings of everything we see around us. "That's the story behind why Juno was created: to go and look inside Jupiter every way we knew how, to try to figure out what happened in the early solar system that formed that planet—and what role that planet had in forming us," says Scott Bolton, the mission's principal investigator at the Southwest Research Institute in San Antonio, Tex.

Whenever a mission studies a planet or moon up close, "you're going to be surprised" at what it finds, says Juno project scientist Steve Levin of NASA's Jet Propulsion Laboratory. But what you really want is "to make the theorists throw everything out the window and start over." Juno has torn up more textbooks than any other planetary science mission. "It's been quite a ride," Levin says. And scientists will never look at Jupiter, or the solar system, in the same way again.

JUPITER, THE ROMAN GOD, was often up to no good. According to myth, he obscured his mischief with a blanket of clouds so that nobody could see what he was up to. His wife, though, had the power to see through these clouds and monitor his shenanigans. Her name was Juno.

In the late 1970s the two Voyager space probes gave humanity its first spectacularly detailed look at the gas giant. Unlike the deific Juno, they couldn't see Jupiter's buried secrets—but they were sufficiently inspiring for Bolton, who was a college student at the time. "I had been a huge *Star Trek* fan and had fantasized about traveling around and wondering what the rest of the universe was like," he says. When someone from JPL gave a talk at his school and showcased Voyager 1's jaw-dropping shots of Jupiter and its maelstroms, he was sold. "I'd never seen anything like it."

In 1980 Bolton got a job at JPL, just as Voyager 1 was about to greet Saturn. Later he became part of the Galileo project, a mission to study Jupiter's atmosphere and magnetic field that orbited the

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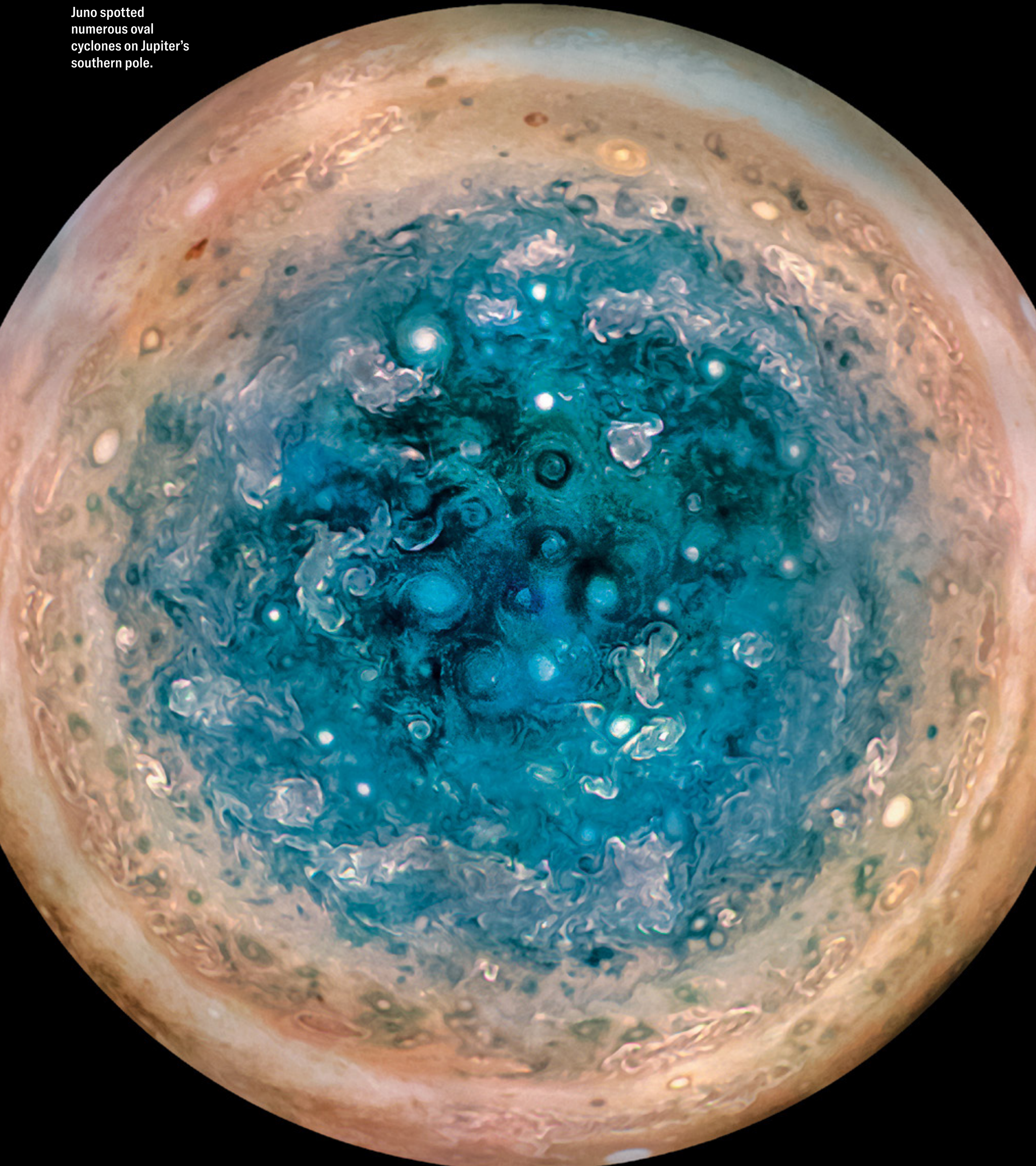
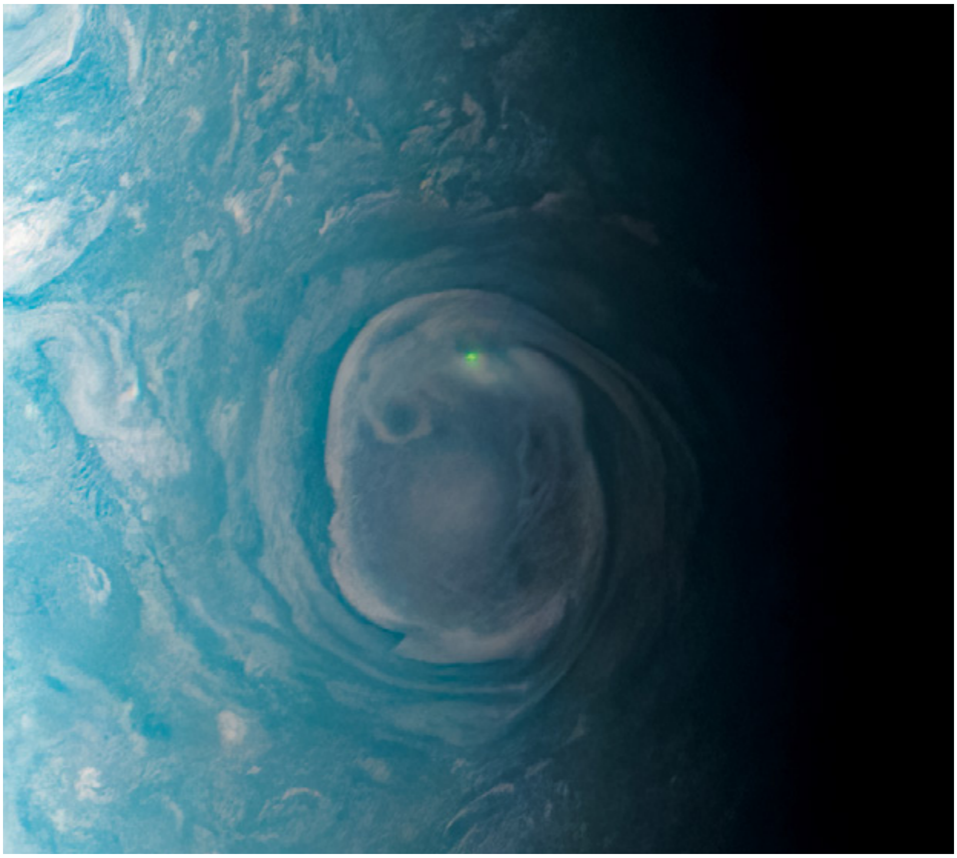


Juno spotted numerous oval cyclones on Jupiter's southern pole.



The glow from a bolt of lightning is clear in this image of a vortex on Jupiter's northern pole. Juno took the picture during a close flyby of the planet in December 2020.

planet from 1995 to 2003. It was the first spacecraft to orbit an outer planet and the first to drop a probe through its atmosphere. Although Galileo began to paint a picture of Jupiter in three dimensions, so much about the world—especially its core, the depth and nature of its storms, and its unseen polar regions—remained a mystery.

Bolton ultimately came to an inescapable conclusion: science needed to make the mythical Juno real. As the new millennium dawned a spacecraft took shape, to the tune of $1.1 billion. A triumvirate of solar panels powered a suite of cloud-piercing instruments, some able to pick up on different types of radiation emanating from deep within the planet. One piece of tech can measure how the spacecraft is affected by small changes in the planet's gravitational field, allowing scientists to determine Jupiter's inner structure.

Because every bit of added weight counts for a lot in spaceflight, the earliest Juno plans lacked a visual camera. It didn't need one to achieve its scientific objectives. But Candice Hansen-Koharcheck, a Juno team member and a senior scientist at the Planetary Science Institute in Tucson, Ariz., recalls Bolton saying: "We can't fly to Jupiter without a camera." The mission may be all about sensing what's below those clouds. But who doesn't want to catch a glimpse of alien hurricanes and vaporous whirlpools, too? JunoCam, led by Hansen-Koharcheck, was added to the payload.

The biggest issue mission designers faced was figuring out how to shield the probe. The space environment enveloping Jupiter is thoroughly unpleasant. A torus of radiation, not only deadly to humans but also highly degrading to any electronics, zips around the planet's equator. Eventually this radiation will murder any spacecraft in its wake. To delay the inevitable, Juno deploys two radiation-dodging tricks.

The first is to orbit in a way that repeatedly takes it over Jupiter's poles, where radiation is minimal. During each circuit, Juno gets as close as 3,100 miles to the planet's cloud tops, allowing it to conduct detailed scientific observations while spending a limited time bathed in aggressive radiation. The second is that its most vital electronics are encased inside a titanium vault. The spacecraft's hull is showered by more than 100 million dental x-rays' worth of radiation. Anything inside the vault receives about 800 times less.

Juno's mission team hoped these strategies would keep the spacecraft alive for at least a year, but the scientists had only educated guesses to work with. "No one's ever done a polar orbit. No one's ever slipped between the radiation belts," says Heidi Becker, a researcher at JPL and the member of the Juno team responsible for monitoring the radiation environment.

The only way to know was to go. "I've been looking up at Jupiter for a very long time," Becker says. She felt like the planet was teasing the Juno team before launch: "Okay, bring it. Let's see if you can do it."

Juno left Earth in 2011 and reached Jupiter after a 1.7-billion-mile journey. It quickly took up a polar orbit of the elephantine world, and Becker and the team were overwhelmingly relieved when they realized that the radiation hadn't immediately exterminated the spacecraft.

The scientists were also glad they'd packed that camera. The moment Juno opened its eyes, it witnessed a parade of colors rushing about with unrelenting force. The ever-changing landscapes weren't just painterly. "They're like works of art," says Bolton—impressionistic-looking spirals and streams, folding, arching and blooming in full view. Juno may be a scientific mission, but it also revealed Jupiter as a living van Gogh painting hanging in the sky.

WITHIN MOMENTS of falling into orbit, Juno revealed wonders—starting with the planet's freakish atmosphere and its gargantuan storms. When the probe peeked at Jupiter's poles, "we saw something nobody's seen before," Levin says. JunoCam and Juno's infrared mapping instrument, JIRAM, spied an octagonal collection of eight storms surrounding a central cyclone at the north pole. The south pole, meanwhile, had a pentagonal group of five storms circling another one in the middle. Each cluster of cyclones is larger than the U.S.

Graphic by Matthew Twombly

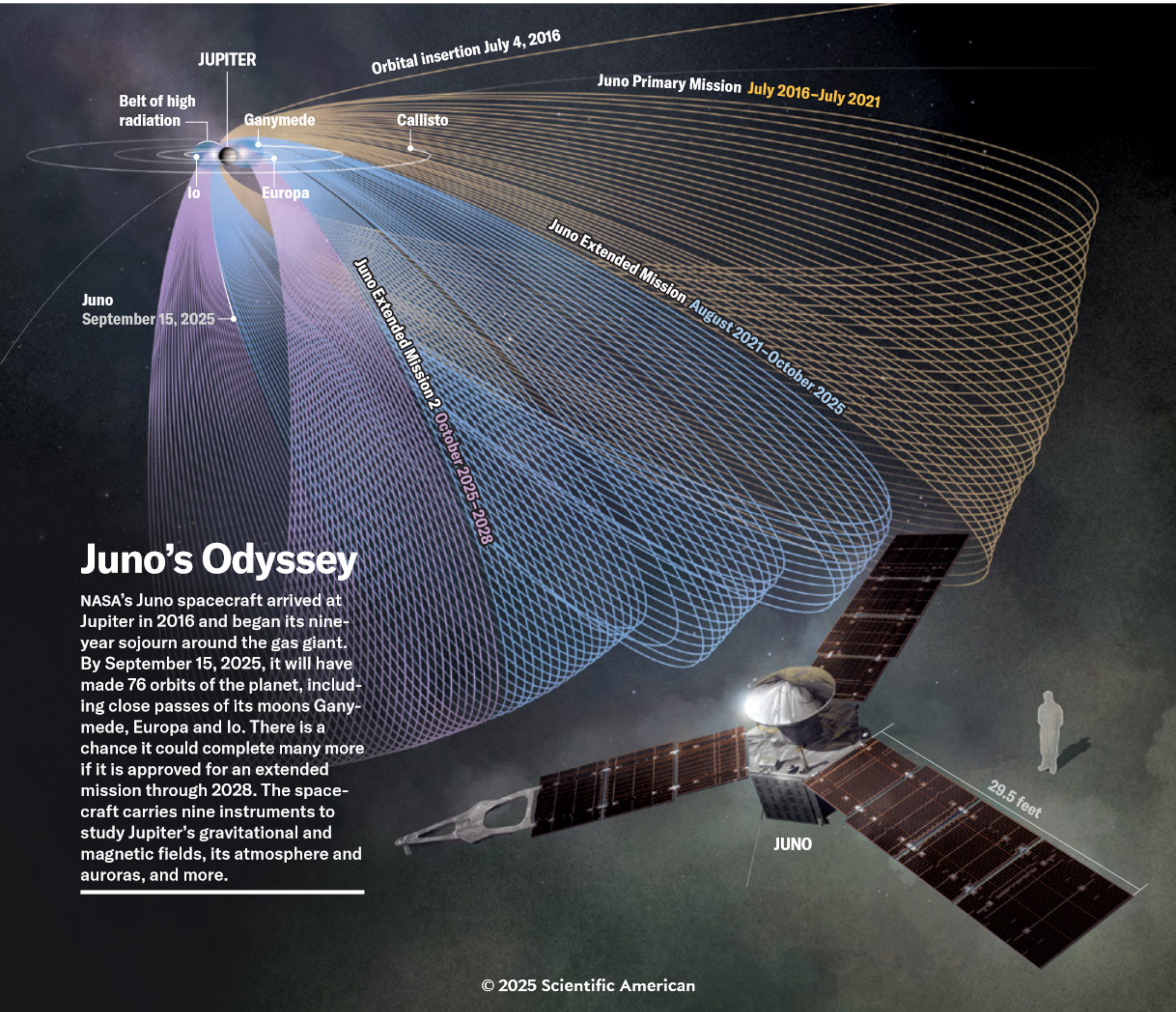
The JIRAM image of the northern circumpolar cyclones resembled a "beautiful, gigantic jack-o'-lantern in space," Becker says. These geometric storms didn't just look striking—they had no precedent. "The first time we saw the storms, I was with a bunch of people from the science team," Levin says. "Somebody literally said: 'Are you sure you got the right planet?' And they were only half joking."

The arrangement at each pole seemed oddly stable: storms moved around and jostled one another, but none disappeared. And to date, no one has a definitive explanation for why the number of storms at each pole differs, nor why their dance routine never seems to change. "The way those cyclones are stable at the poles is still a mystery," says Alessandro Mura, a researcher at the National Institute for Astrophysics in Rome and the lead for Juno's infrared mapping instrument.

The most famous storm on Jupiter is its Great Red Spot—a rust-hued monster large enough to encompass the entire Earth. First seen a couple of centuries ago, it's known to change shape over time, and one day it may vanish. But until Juno arrived, astronomers' knowledge of it was surficial. By probing the radiation emitted by the spot's churning gases and by measuring its gravitational pull, the Juno team realized it reached a depth of about 300 miles below the cloud tops—almost 55 times deeper than Mount Everest is tall.

Unsurprisingly, for a planet wreathed in storms, Jupiter experiences a lot of lightning; the Voyager missions caught bolts flashing through its clouds back in 1979. But Juno "discovered a type of lightning that doesn't exist on Earth," Becker says, which seemingly defied the laws of physics.

Like many spacecraft, Juno has a star camera, an instrument that uses those

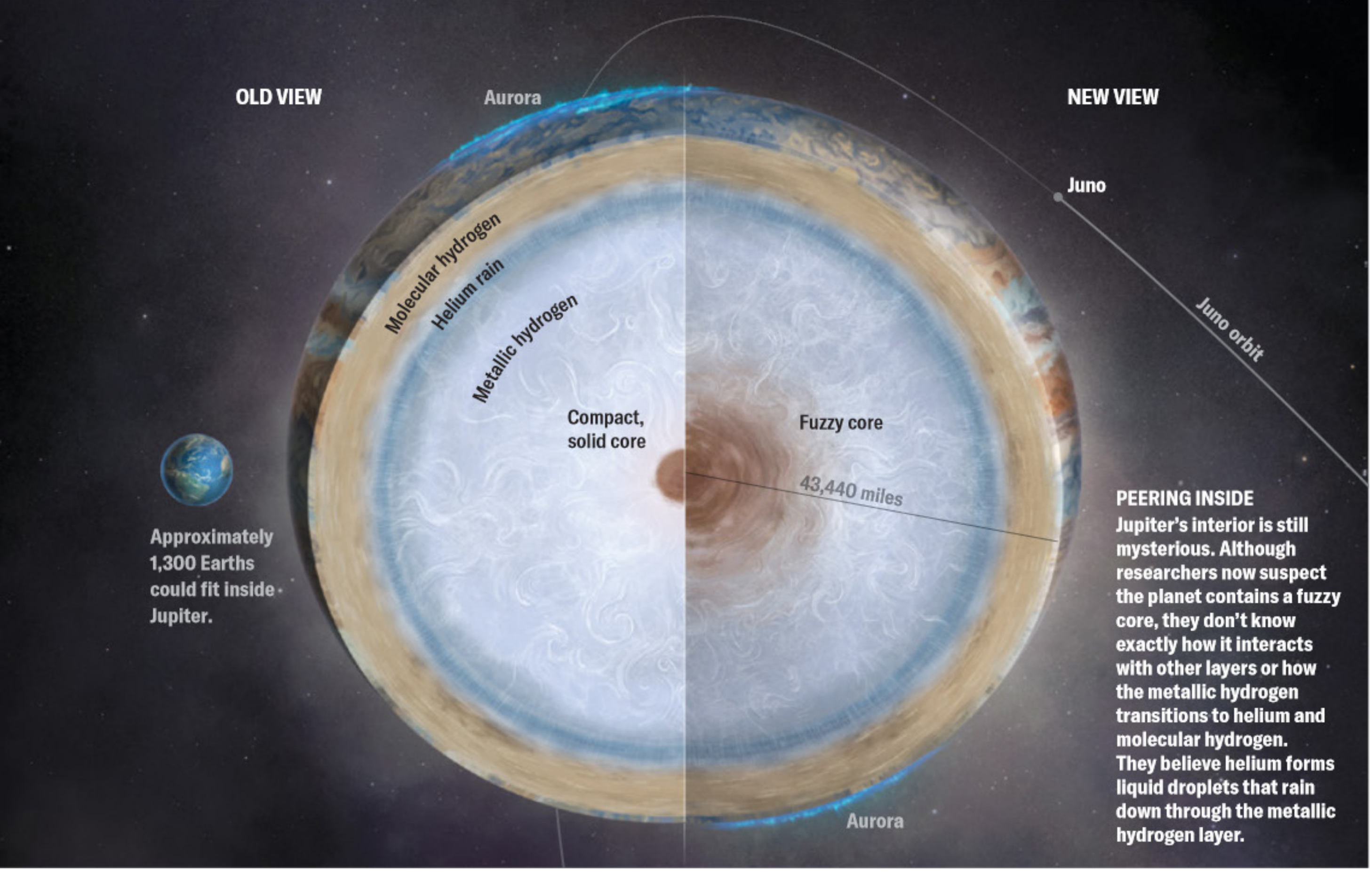


Juno's Odyssey

NASA's Juno spacecraft arrived at Jupiter in 2016 and began its nine-year sojourn around the gas giant. By September 15, 2025, it will have made 76 orbits of the planet, including close passes of its moons Ganymede, Europa and Io. There is a chance it could complete many more if it is approved for an extended mission through 2028. The spacecraft carries nine instruments to study Jupiter's gravitational and magnetic fields, its atmosphere and auroras, and more.

Jupiter's Interior

Juno's investigation of the gas giant has rewritten textbooks on the planet. Before the probe arrived, scientists thought Jupiter might contain a solid rocky core like many other planets in the solar system—or perhaps no core at all. Instead Juno found evidence for a bizarre fuzzy core that seems to be blending into its surrounding layer of liquid metallic hydrogen.



diamantine dots to determine its orientation in space and aid its navigation. The camera can also spot lightning, which appears as bright specks. When Juno looked at the dark side of Jupiter, it spied tiny little flashes made by very high-altitude lightning bolts.

That didn't make any sense. To produce lightning, liquid water needs to collide with ice crystals to create a spark. In 1979 the Voyager mission detected lightning coming from deep water clouds, where the suffocating pressure of the overlying atmosphere created temperatures high enough for liquid water to exist. But the lightning flashes picked up by Juno came from the upper echelons of Jupiter's atmosphere, a location so frigid that only ice crystals should exist there.

After studying Jupiter's titanic clouds for a time, the Juno team worked out what was happening. The planet's cloud tops contain plenty of ammonia, and storms can launch ice into the sky that then binds to that ammonia. The chemical acts like antifreeze on the water-ice, causing it to turn into liquid droplets. And when those droplets smash into the upwardly propelled ice crystals, you get electricity—and vertiginous lightning.

But this epiphany brought another mystery into focus. Sure, ammonia-ice clouds likely dominate Jupiter's skyline—but Juno found that some parts of the uppermost atmosphere have a dearth of ammonia. That didn't track: Jupiter's atmosphere looks incredibly turbulent—like a thoroughly whisked raw egg—so all its components should be mixed up, with a more or less even distribution of gases. How can many parts of the planet have 90-mile-deep wells lacking ammonia?

"There was no theory that could even remotely explain this," says Chris Moeckel, a planetary scientist at the University of California, Berkeley. His first thought was that "there's no way this is right." But the data were sound.

A complicated idea arose to make sense of the phenomenon. When the sky-high ammonia turns upwelling water-ice into liquid, the water and ammonia bond to form a peculiar slush with a water-ice shell. Ultimately softball-size globules of slush encased in ice fall back into the planet, where they melt at depths thought to be too extreme for Juno's instruments to detect.

For a few years this theory seemed a bit too baroque to be true. But Moeckel and his colleagues became convinced thanks to the power of Juno's microwave radiometer. The instrument can

 Graphic by Matthew Twombly

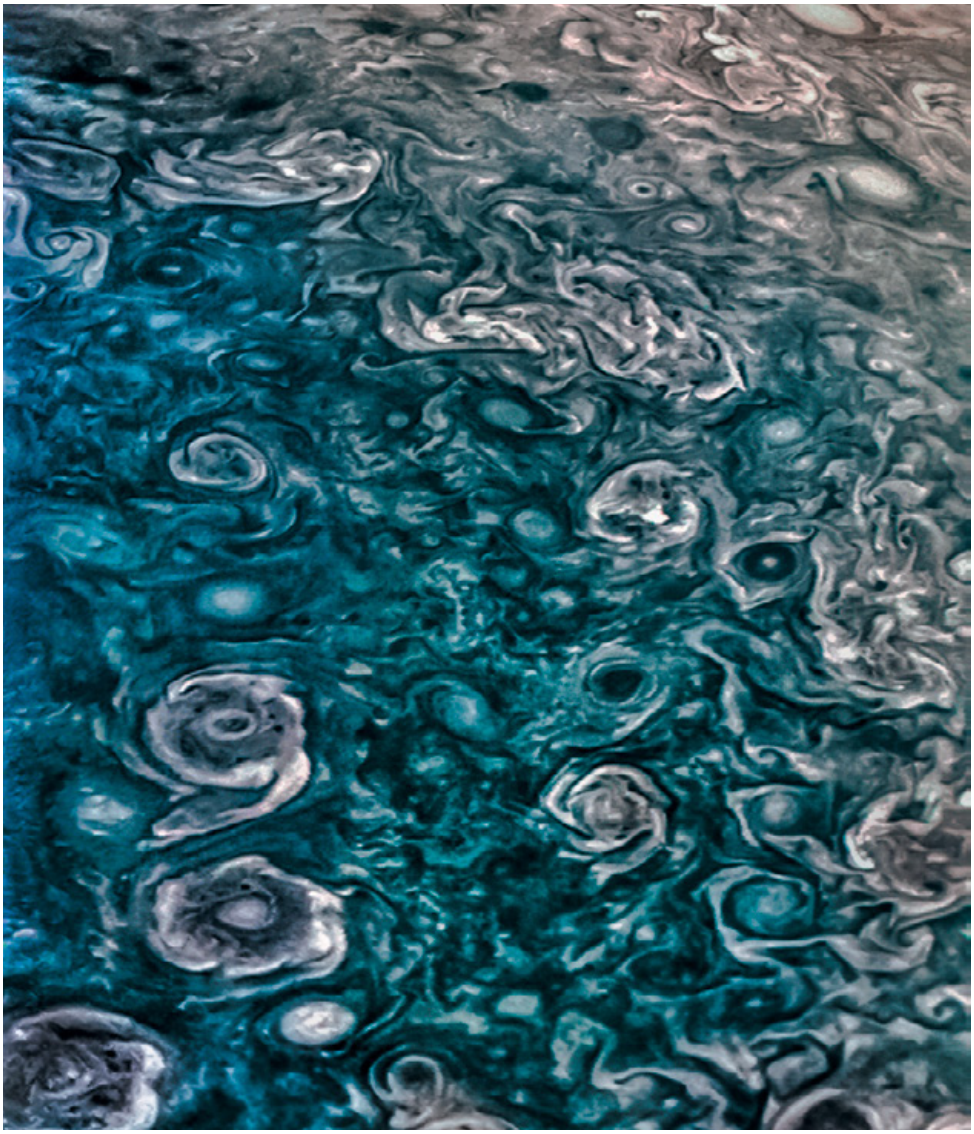
measure radio waves that betray the presence of different chemical compounds. During one of its orbits, Juno noted a burst of ammonia production at an exceptional depth within the planet. According to Moeckel, this was a telltale sign that icy orbs had rained down from the sky and thawed, releasing their trapped water-ammonia slush. Researchers referred to this unique weather phenomenon as mushballs. "It's such a stupid name," Moeckel says. "But it works."

JUNO ALSO TRAINED its instruments on Jupiter's magnetic field, the largest structure in the solar system, which reaches at least as far as its neighboring planet, Saturn. But Juno discovered that Jupiter's magnetic field is wonky and asymmetric—more messy in the northern hemisphere than the south. There is also an intense concentration of magnetism near the equator, a patch (confusingly) called the Great Blue Spot.

These characteristics are odd, but the existence of such a gargantuan field at all is the really strange part because Jupiter lacks the sloshing liquid iron and nickel responsible for Earth's magnetic field. Instead Jupiter contains an ocean of hydrogen, one under so much pressure that electrons are torn off individual hydrogen atoms, transforming it into an exotic, metal-like electrical fluid that generates its mighty magnetic field.

Below the hydrogen sea lies an even bigger mystery—the question of what's inside the planet's innermost core. What Juno found there left scientists reeling.

Before the spacecraft arrived, there were two prevailing notions about Jupiter's interior. The first was that the planet may have a compact core of rocky and metallic matter, not dissimilar to the cores of other worlds. If such a core exists, then Jupiter likely formed through the gradual clumping together of gas and solid matter, like the planets of the inner solar system. The second hypothesis was that there is no core at all. Instead Juno might find a ball of hypercompressed gas, suggesting Jupiter's formation was a bit like a failed star, one that didn't gather enough gas to trigger a thermonuclear ignition.

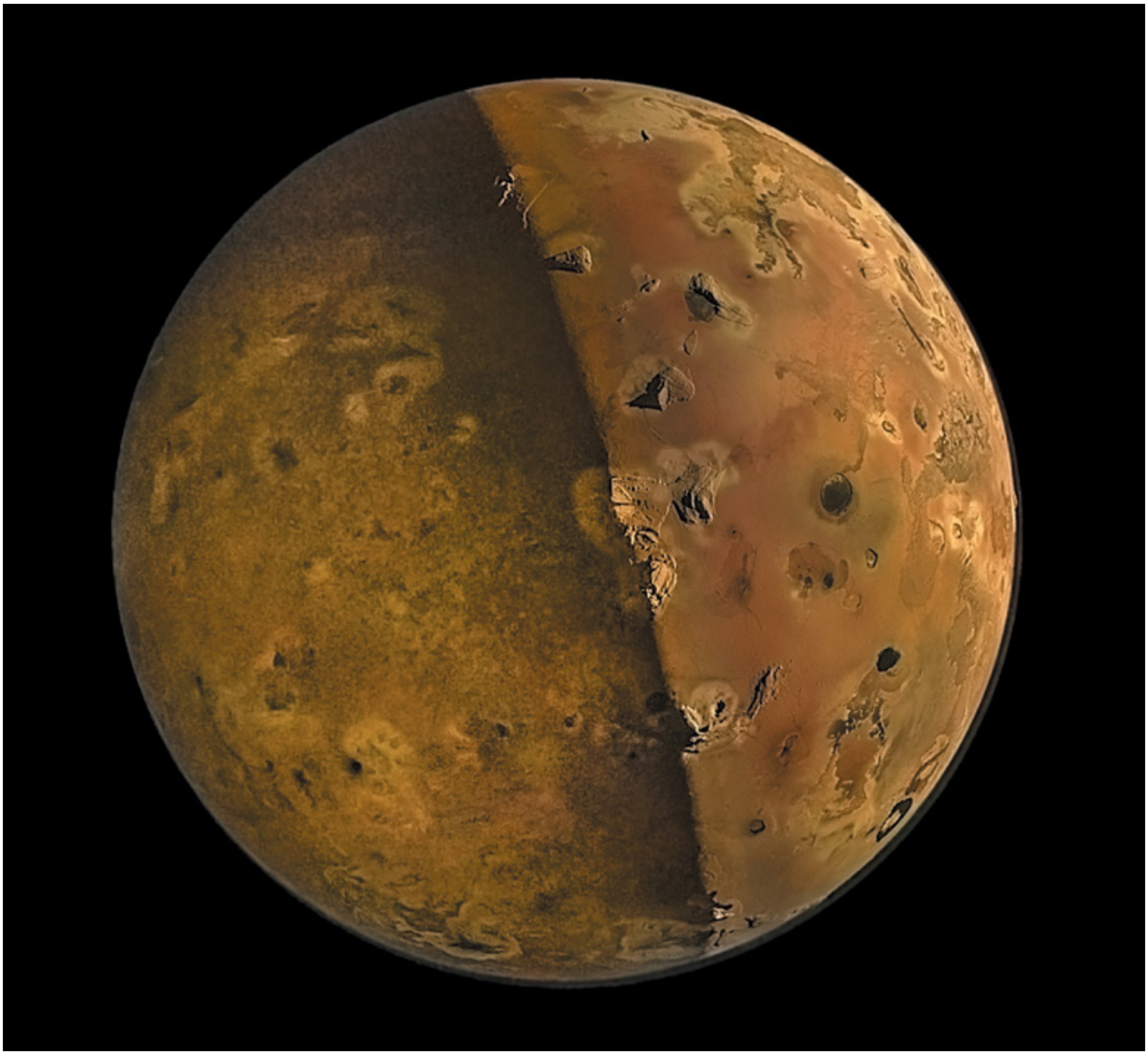


Violent storms swirl across Jupiter's northern pole. The storms are mysteriously stable over time, and each cluster of cyclones is larger than the continental U.S.

"Actually neither of those was true," Bolton says. Juno used gravitational detective work to sense the core. The spacecraft is constantly communicating with Earth using radio waves. Jupiter's uneven mass means that Juno speeds up at times and slows down at others, depending on the strength of the gravitational pull it's experiencing. These speed changes cause subtle shifts in the wavelengths of the radio transmissions Juno sends and receives—effects that scientists can use to determine the internal structure of Jupiter.

What they found was at first nonsensical. Deep within the metallic hydrogen ocean Juno detected an innermost core of, well, *something;* it's probably solid, but researchers can't tell. "It's blending gradually into the surrounding layers," says Ryan Park, a researcher at JPL and one of the leads on the gravity experiment on Juno. The hydrogen and the core material seem to mingle. The situation is very different from Earth's depths, where a lighter rocky mantle floats atop a denser iron and nickel core, between which is a distinct and definitive boundary. "We frankly don't know how to explain that," Levin says. And it gets weirder still.

The sun and Jupiter are rich in both hydrogen and helium but are also expected to contain a smattering of heavier elements. Jupiter, a huge planet that most likely ate up rocky and icy planet-size shards during its formation, should contain far more heavy elements than the sun. And indeed, Juno found that Jupiter has three to four times as



NASA/JPL-Caltech/SwRI/MSSS (*image data*); Emma Wälimäki © CC BY (*image processing*) (*Io*); NASA/JPL-Caltech/SwRI/MSSS (*Ganymede*)

many heavy elements as our star. The problem, though, is that these elements appear to be found in the upper atmosphere—and the innermost core is comparatively lacking. All that heavy stuff should sink, via gravity, into the core. But apparently it hasn't. If the core is so light, then what could it possibly be made of?

Scientists are scrambling for answers. This fuzzy core doesn't fit with anyone's model for planetary formation. Some scientists have suggested a giant meteor crashed into a once solid core, smashing it up and forcefully mixing it with the metallic hydrogen ocean. Levin wonders whether we simply don't understand the physics yet. "We're talking about temperatures and pressures much higher than anything we're used to," he says—conditions so severe that it's difficult to create them in laboratories.

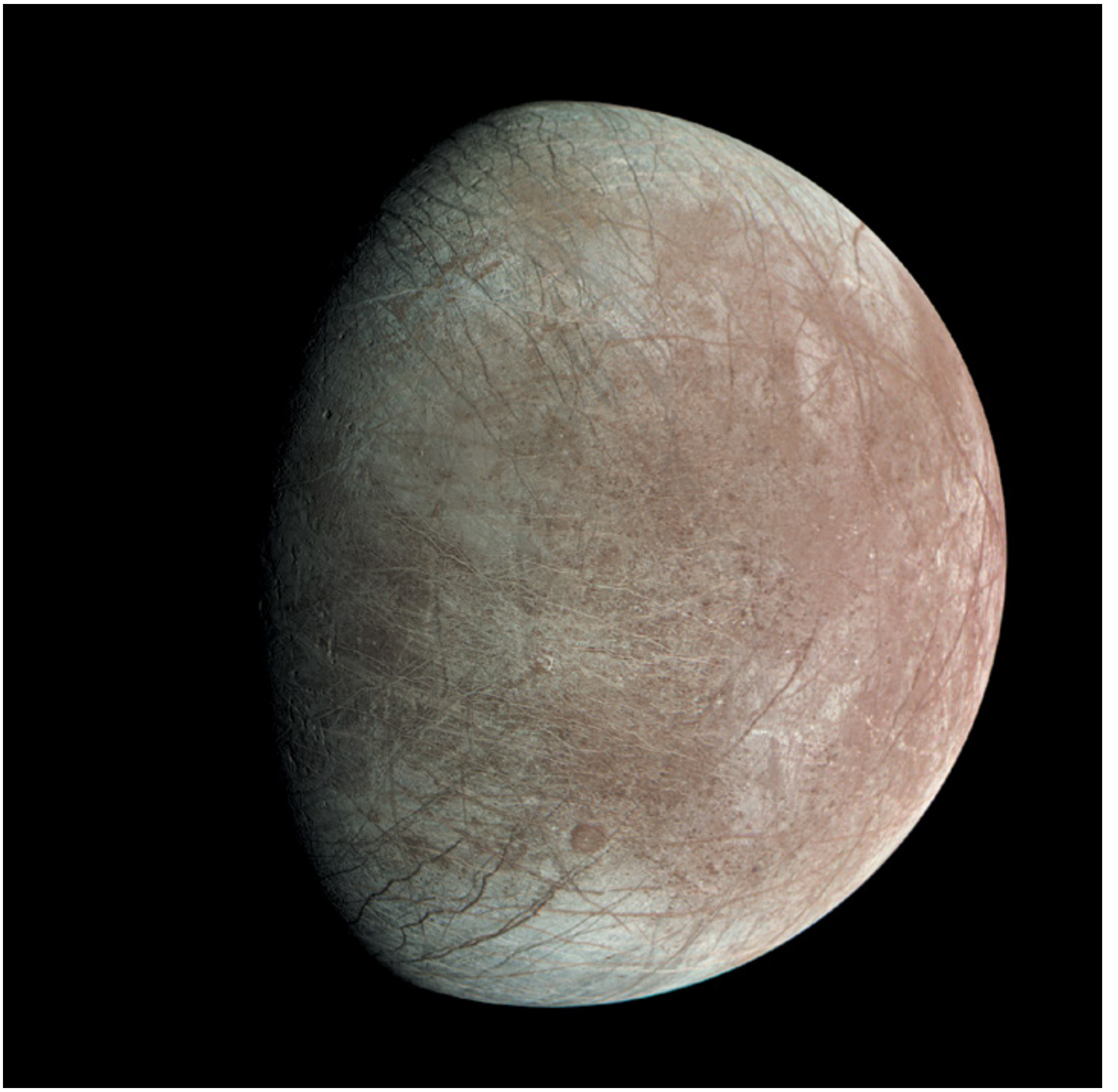
FROM OUR ARCHIVES
Missions to the Moons. Jonathan O'Callaghan; May 2023. ScientificAmerican.com/archive

OTHER BLOCKBUSTER FINDINGS from Juno concern Jupiter's moons. The probe's reconnaissance of two icy orbs—the pockmarked Ganymede and the ocean-concealing Europa (the target of a recently launched NASA habitability mission)—created breathtaking portraits of these dynamic worlds while also revealing some unusual chemistries. But a moon named Io got most of Juno's attention—and, consequently, generated the most shocking surprise.

"Io is a very peculiar moon because it's the most volcanic body of all," Mura says. Its surface, an amalgam of burnt orange, sickly yellow and crimson hues, is covered in rocky cauldrons filled with lava, as well as volcanoes whose explosions propel magmatic matter into space. Up there the material is ionized by sunlight before plunging into Jupiter's skies, creating extremely bright auroral lights.

Since the 1970s scientists have understood that Io's volcanism is powered by its elliptical orbit around Jupiter. When it's closer to Jupiter, it gets a bigger pull from the planet's gravity; when it's farther away, that pull is weaker. This back-and-forth kneads the moon like putty, creating tides in solid rock more than 300 feet high. All that motion creates a lot of friction, an abundance of heat—and a plethora of magma.

Many thought that this mechanism, known as tidal heating, was so powerful that it created a continuous ocean of magma under the surface rather than the smaller, individual magma reservoirs that fuel Earth's volcanoes. The Galileo mission seemed to back that idea up: it detected an electrically conductive layer under Io's crust suggestive of a magma sea.



Juno made close flybys of three of Jupiter's moons (*left to right*): Io, Ganymede and Europa. Io is the most active volcanic world in the solar system and features the largest volcanic eruption ever recorded. Ganymede is a pockmarked place much like our moon, and Europa boasts a hidden ocean under its crust.

NASA/JPL-Caltech/SwRI/MSSS (*image data*); Björn Jónsson CC BY 3.0 (*image processing*) (*Europa*)

But when Juno flew perilously close to Io on two occasions, getting within 900 miles of the violent surface, it found no trace of a shallow magma ocean. Mura now suspects Io's magma is partitioned into a maze of rocky tunnels, occasionally bubbling up into open rocky maws wherever the tunnels reach the surface.

Nobody knows for sure; in typical Juno style, the observations have raised more questions than answers. But at least while scientists ponder possible solutions, they can marvel at Io's unbound ferocity.

"We discovered the largest eruption ever recorded," Bolton says. In December 2024 Juno's infrared instrument detected a heat spike in the moon's southern hemisphere that briefly blinded the spacecraft's JIRAM instrument: a paroxysmal outpouring of lava spread over 40,000 square miles, enough to cover a quarter of California. It's producing more energy than the total annual energy output of humanity. "And we still see it going on," Bolton adds.

BY ALL ACCOUNTS, Juno should be dead by now. The radiation should have already broken it or at least one of its instruments. Somehow it lasted well beyond its prime mission timeline, which ended in 2021.

If an additional three-year extension is approved, Juno could get a better look at the planet's ghostly ring system, and some of its lesser-known innermost moons. But there's no telling how long the aging spacecraft could survive. "It could grow old, and something could fail," Bolton says. Perhaps "the radiation will kill something so important that we can't function anymore." Whenever the vehicle's end comes, it will go out in flames, spiraling toward the gas giant it spent its entire life interrogating. "Eventually Juno will crash into Jupiter on its own," Bolton says.

But the spacecraft's legacy is already clear. Juno revealed Jupiter to be a far more confounding place than anyone dared imagine, forcing scientists to throw out reams of outdated ideas about planetary formation. It's also revealed how future spaceflight missions can defend themselves from the worst radiation in the solar system. The Juno team, having emulated its namesake's god-defying powers, is openly proud, Becker says. "What an amazing success story for NASA." ■