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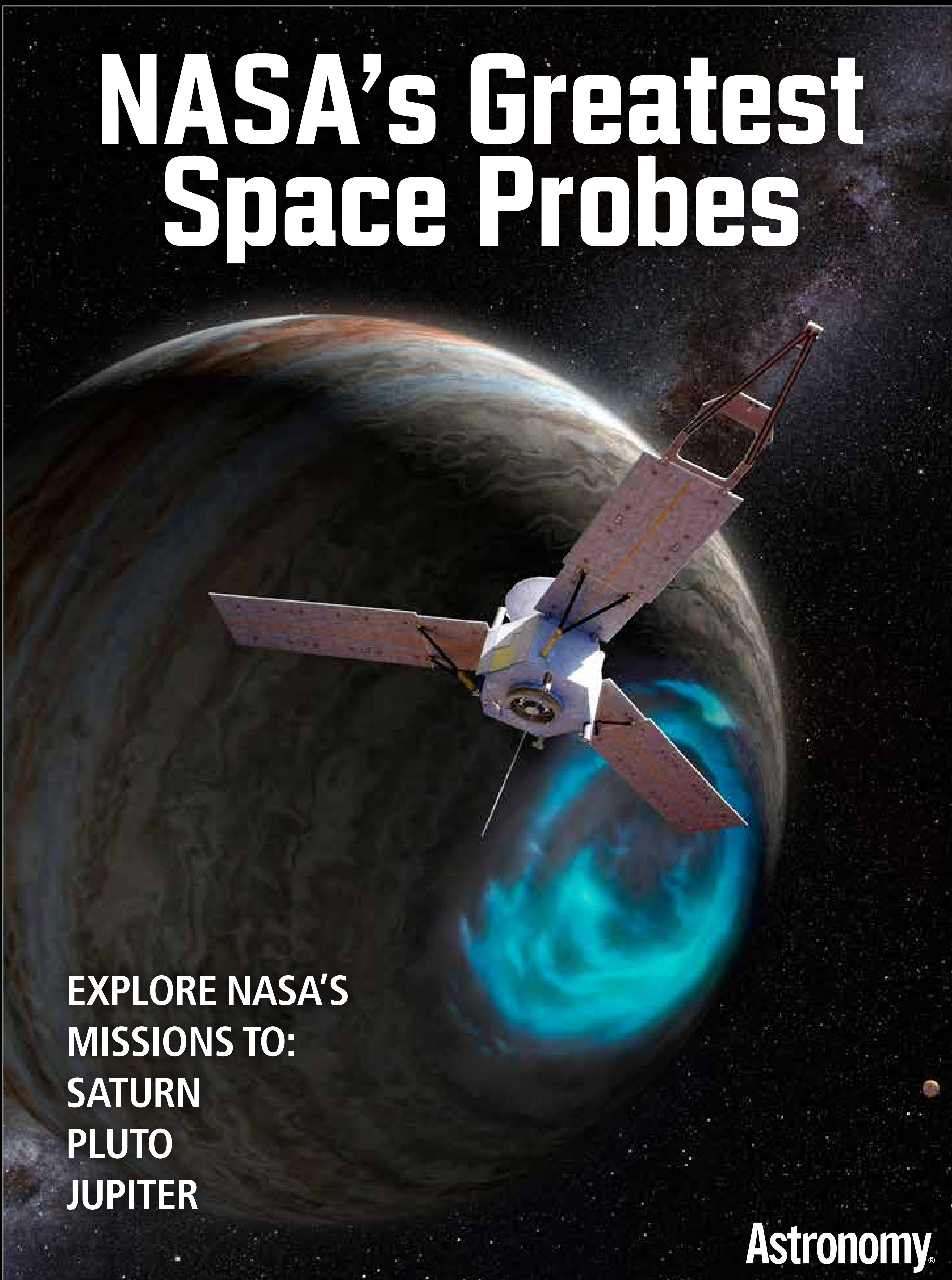

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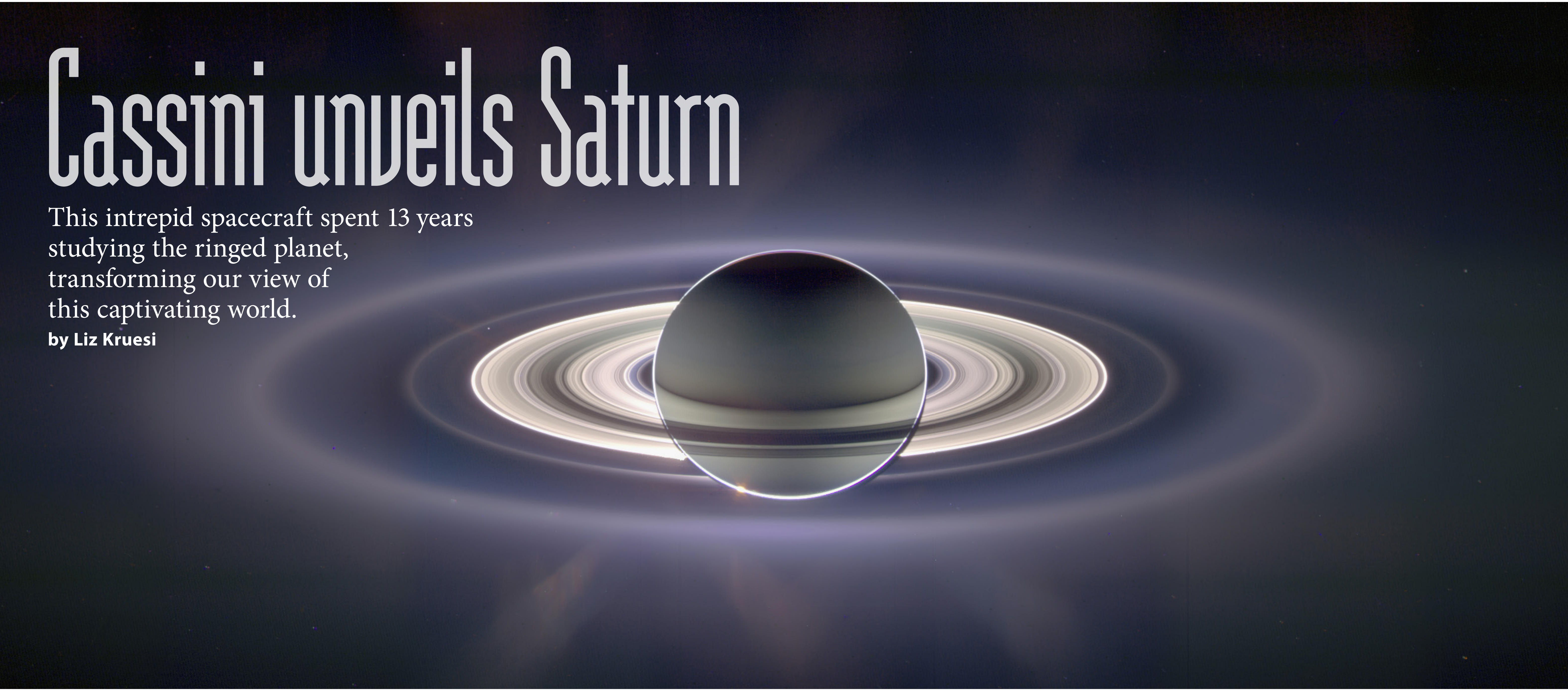
Cassini unveils Saturn

This intrepid spacecraft spent 13 years studying the ringed planet, transforming our view of this captivating world.

by Liz Kruesi



Saturn's globe blocked the Sun while Cassini captured this panoramic view showing the planet's ring system in exquisite detail. The imaging team created this mosaic from 165 separate images taken over a three-hour period. NASA/JPL-CALTECH/SSI

On the evening of September 11, 2017, Griffith Observatory hosted an enthusiastic group of observers. The assembled crowd looked through the 12-inch Zeiss refracting telescope, the centerpiece of the venerable public astronomy venue in Los Angeles. They watched as light from Saturn and its largest moon, Titan, passed through the telescope's optics, where lenses bent and focused it onto their eyes.

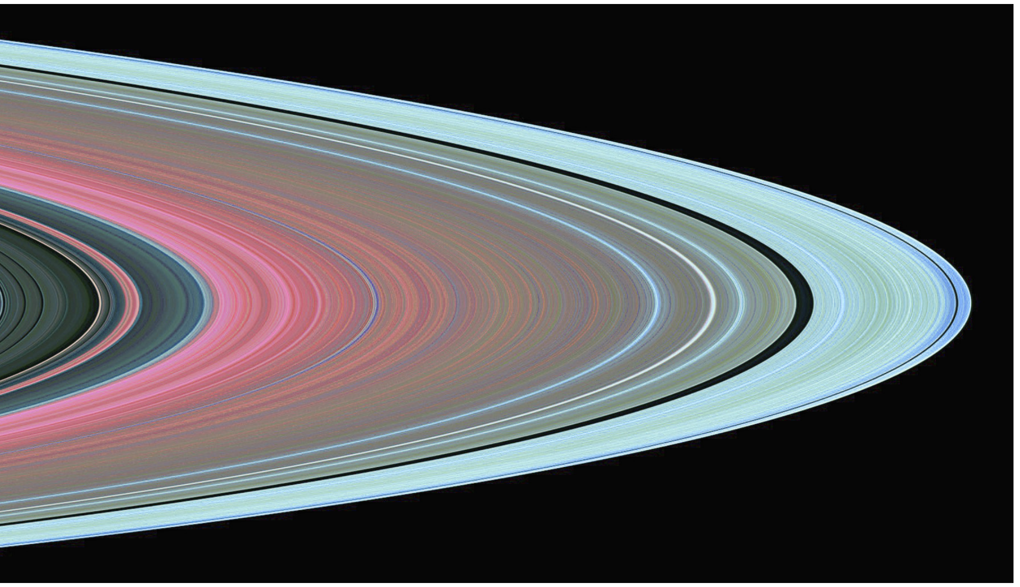
The onlookers could see the beautiful rings circling Saturn, the planet's yellowish cloud bands, and the orange-tinged dot of the big moon near the planet; what they couldn't make out was a much smaller, human-made target. On that late summer evening, the Cassini spacecraft was just 75,000 miles (120,000 kilometers) from Titan on its final path toward Saturn. The spacecraft and Titan had enjoyed their "goodbye kiss," as the astronomers and engineers on the mission called the last gravitational yank that would send the spacecraft into the planet it had been studying for 13 years.

These observers at Griffith were no ordinary members of the public. They were members of Cassini's Project Science Group, watching their beloved spacecraft on its final journey around the giant world. "It was a magical evening," says Cassini's Project Scientist Linda Spilker.

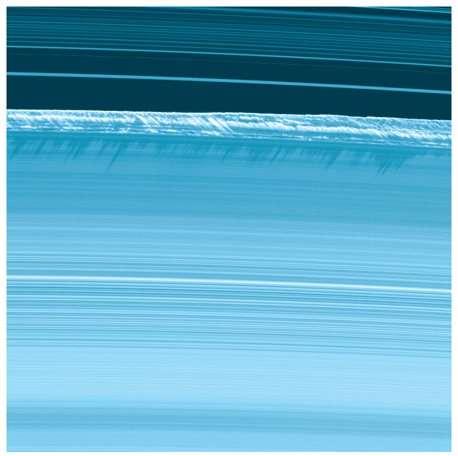
Over the next few days, hundreds of scientists and engineers on the Cassini mission team would reminisce about the spacecraft, which had launched from Cape Canaveral, Florida, nearly 20 years earlier. But their thoughts were not all on the past: Cassini was still collecting data and sending it back to Earth.

On September 15, at 3:31 A.M. PDT, Cassini entered Saturn's upper atmosphere at a shallow angle. It would travel through the gas for nearly 1½ hours. The team members were gathered at NASA's Jet Propulsion Laboratory in Pasadena, California, where they watched and waited. "The room got quieter and quieter as we got down to those final minutes," says Spilker. At 4:55 A.M. PDT, they saw the last signal from Cassini fade away on the screen. The room erupted in applause — not for the end of the mission, but for what the spacecraft and those hundreds of people had achieved.

Cassini revealed surprise after surprise at Saturn: an incredibly complex system of moons and moonlets, rings that change structure on hourly timescales, and a beautiful atmosphere wracked by huge storms. The 13 years of images and measurements changed humanity's view of the ringed world. But there's still more to learn from



Above: Cassini could probe Saturn's ring structure by sending radio signals through the rings. In this simulated view of the A ring and the Cassini Division (at left center), red denotes particles 2 inches (5 cm) or more in diameter; green indicates particles less than 2 inches across; and blue signifies particles less than 0.4 inch (1 cm) across. NASA/JPL-CALTECH



Right: Vertical structures at the B ring's outer edge cast long shadows onto the rings two weeks before Saturn's August 2009 equinox. The structures rise some 1.6 miles (2.5 km) above the rest of the rings, which average about 33 feet (10 m) thick. NASA/JPL-CALTECH/SSI

the last several months of data that Cassini collected. Scientists hope those final observations will tell them about Saturn's interior — in particular, how it generates a magnetic field and how its mass is distributed.

An extended stay

Spacecraft already had visited Saturn three times before Cassini arrived in mid-2004, so scientists had some inkling of what they might find. But as with any new mission — especially one involving a machine with 12 sophisticated instruments that would remain in orbit instead of flying past as its predecessors had — Cassini revealed a complex planet full of surprises. And that's a good thing. "If Saturn had been exactly as expected, it would have been a lot more boring," says Spilker.

Cassini arrived at Saturn for a primary mission set to last four years. But when mid-2008 came, the spacecraft continued with its Equinox Mission extension. And in September 2010, the mission began its Solstice extension, which ultimately bled into the Grand Finale. This final stage commenced in April 2017 and featured 22 close-in orbits that skimmed just above Saturn's cloud tops.

Because Cassini's 12 instruments were attached directly to the spacecraft, the entire contraption had to rotate for an instrument to point toward a specific target. That meant multiple instruments couldn't observe the same spot at the same time. Instead, while one looked at a moon, another might observe Saturn's rings. And that made the last five months of the mission — the Grand Finale — a work of impressive coordination. Although 22 orbits might sound like a lot, they aren't much to work with when you have to divide the limited time during those close flybys among the full instrument lineup.

Rings, rings, and more rings

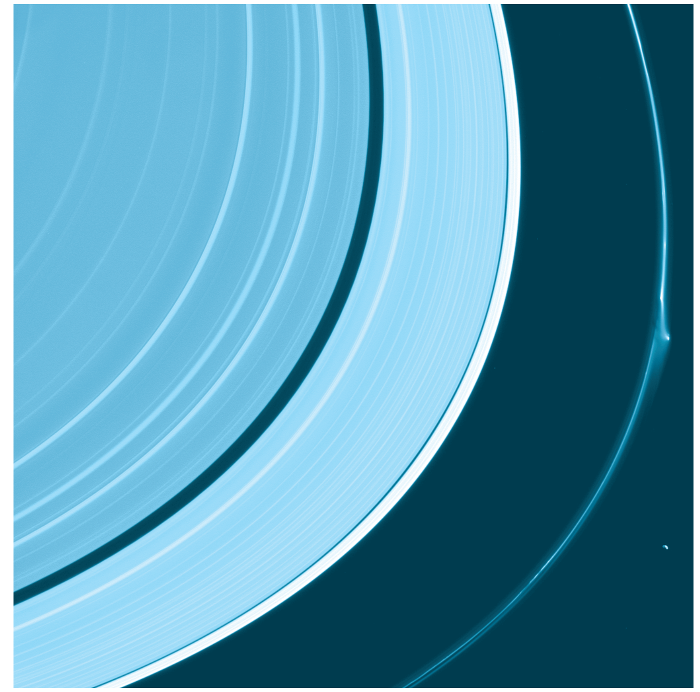
Saturn's rings are the planet's defining characteristic. From afar, they look like a vinyl record circling the yellow gas giant. But bring a camera close to Saturn, and the smooth disk resolves into belt after belt after belt, with spaces separating them. That was the view revealed by the Voyager flybys in 1980 and 1981, which led scientists to think the rings were probably made of tiny ice particles that slowly bump into one another as they orbit the planet.

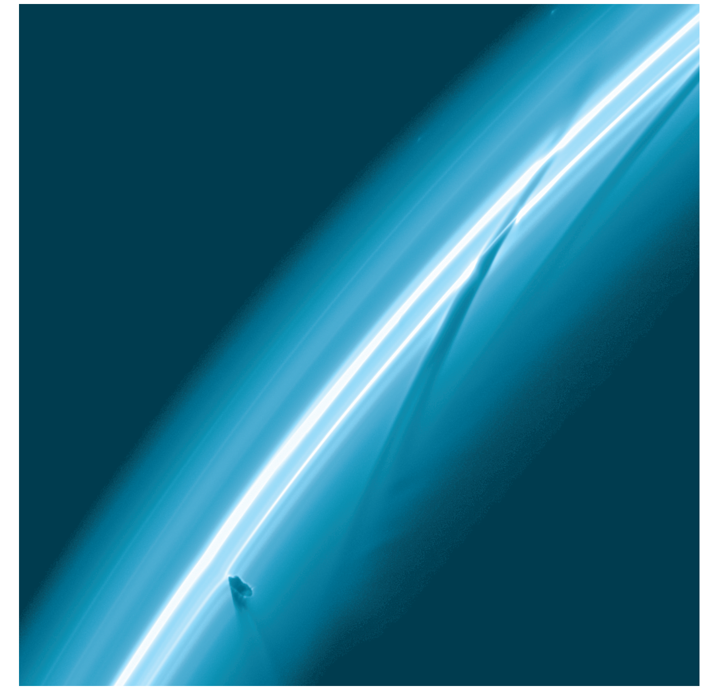
Use Cassini's instruments to watch as the rings filter light from a background star, however, and all of a sudden those belts become far more complex. The particles clump together and form bigger bodies. The gravity of those objects — boulders and minimoons — controls the rings, herding smaller particles and building structures and patterns. And they change quickly, says Larry Esposito, principal investigator on Cassini's Ultraviolet Imaging Spectrograph, who has studied Saturn's rings for more than four decades. "Structures develop within hours in the rings."

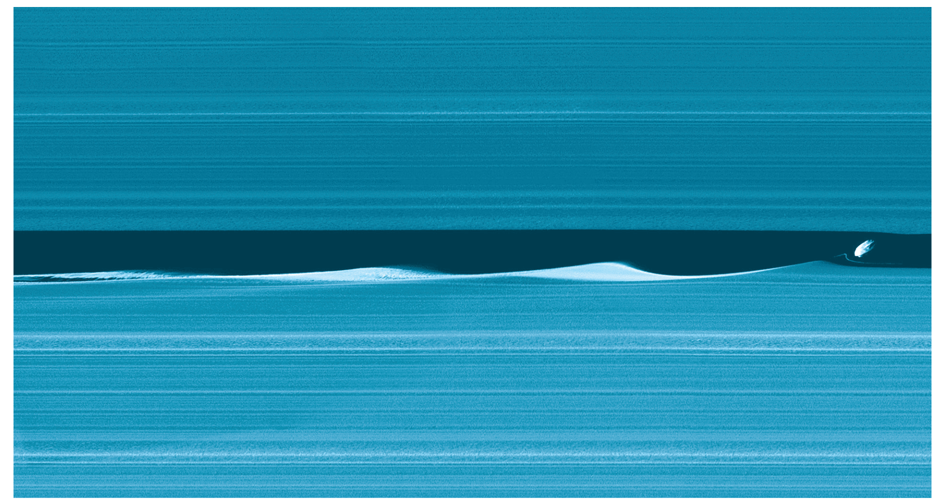
Planetary scientists have identified several different types of structures. Some, which come and go and come back again, are called kittens — "because they seem to have multiple lives," says Esposito. Others, called propellers, migrate slightly inward or outward. They are consequences of gravitational interactions between a small moon embedded within the rings and the ring particles themselves. The moon tries, unsuccessfully, to clear away the particles and create a gap.

Bigger moons tend to have more noticeable effects. Prometheus, for example, whose diameter averages 53 miles (86 km), "dips in almost to the edge of the F ring and pulls out streamers," says Spilker. Several other moons also leave their gravitational imprints. Scientists had long known that Mimas creates the Cassini Division — like the spacecraft, named for the 17th-century Italian-French astronomer Giovanni Cassini — the broadest gap in the rings. But it took data from the Cassini probe to reveal that seven midsized moons combine to keep the outer A ring from dispersing.

The rings also contain density waves that show up as variations in brightness and thickness. After studying these patterns, scientists, including the University of Idaho's Matt Hedman, showed that these brightness changes are tied to Saturn's interior. The researchers used fine-scale density variations in the rings as a seismometer of sorts to learn about how the planet's interior oscillates, in much the same way







Above left: A disturbance in Saturn's narrow F ring appeared April 8, 2016. The disorder likely arose when a small body embedded in the ring interacted with material at the ring's core. The small moon Pandora (lower right) was a mere bystander. NASA/JPL-CALTECH/SSI

Above right: Potato-shaped Prometheus (lower left) dips into the F ring's inner edge once each 15-hour orbit, pulling particles into a streamer. This image captures the moon as it creates a new streamer; the dark streamers at upper right formed during the moon's previous two incursions. NASA/JPL-CALTECH/SSI

Left: Tiny Daphnis orbits in the Keeler Gap near the A ring's outer edge. Here, the 5-mile-wide (8 km) moon makes waves from the fine particles at the gap's edge. The waves dissipate quickly, however, as the moon travels toward the image's right side. NASA/JPL-CALTECH/SSI

that solar astronomers have studied how brightness variations at the Sun's surface correspond to its inner pulsations.

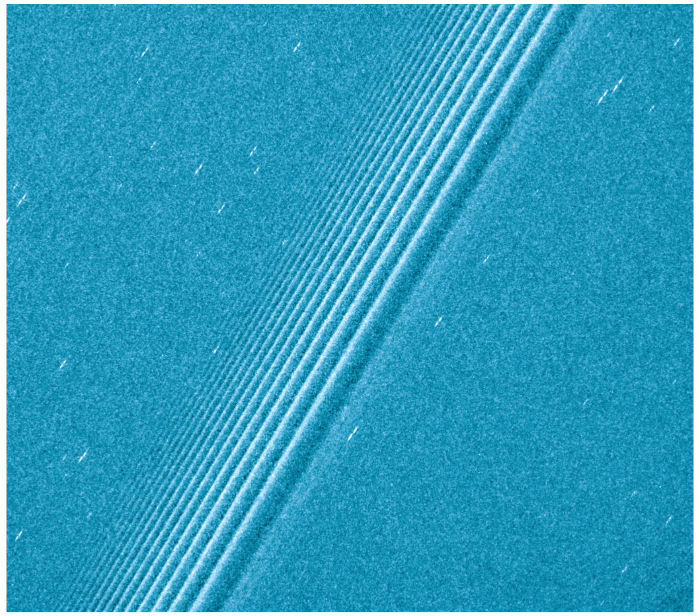
Despite all the incredible ring structure that Cassini's cameras and spectrometers resolved, scientists still have questions. The biggest one concerns the ring system's mass. They don't want to know this mass just for knowledge's sake. Instead, the mass is linked to the age of the rings and how they formed.

This is important because Saturn's rings are the closest example astronomers have of astrophysical disks — such as the flattened disks of gas and dust out of which solar systems form. "It's not the same, but it's analogous," says Hedman. And this means, "if we don't understand what's going on in the rings, we could be missing things about, say, how the solar system formed." The processes going on in the rings could give astronomers valuable insights into how planetary systems develop.

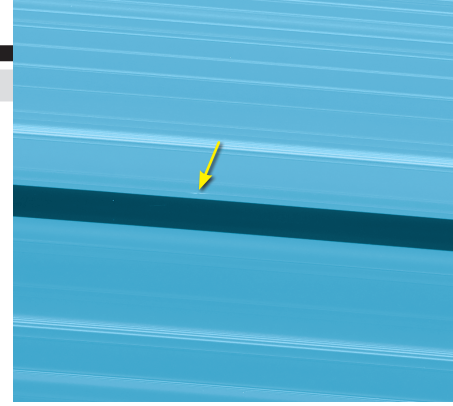
The Grand Finale data are getting scientists closer than ever to figuring out the rings' mass. During those final months, Cassini flew between the inner rings and Saturn's upper atmosphere 22 times. Throughout the previous 12½ years of Saturn exploration, the spacecraft stayed outside the rings, and thus it felt the combined pull from Saturn and the rings. "When you are between the rings and Saturn, the rings are pulling in one direction, and Saturn is pulling in the other, so you can disentangle the two effects," says Luciano Iess, who is leading Cassini's gravity data analysis. Disentangling the two will not be easy, however. The preliminary analysis, he says, "seems to indicate that the rings did not form with Saturn." It will take more research to firm up this result, and to find out when and how the rings formed.

Cloudy weather

Beneath Saturn's majestic rings lies the planet's equally magnificent cloud tops. Cassini unveiled churning and swirling clouds in the upper atmosphere, and places where warm gases rise up through cooler layers and erupt into long-lasting thunderstorms. Cassini resolved these thunderstorm clusters into minute detail, watching



Dozens of small propellers occupy the so-called propeller belts in the middle of the A ring. The propellers look like double dashes and appear on both sides of the density wave that cuts diagonally across this scene. NASA/JPL-CALTECH/SSI



Tiny embedded moonlets create "propellers" as they unsuccessfully try to open gaps in the rings. In one of its final images, Cassini captured one such feature just above the Keeler Gap in the outer A ring. NASA/JPL-CALTECH/SSI

The informally named Earhart propeller resides in the A ring just inside the Keeler Gap (right). Earhart is the attempt of an unseen moonlet to create a ring gap, but the large mass of the surrounding material quickly fills the nascent breach. NASA/JPL-CALTECH/SSI

them evolve and listening to the radio static from lightning flashes.

While normal photos painted pretty pictures of the whirling atmosphere, infrared images let scientists see below the cool cloud tops to warmer regions beneath. "And that's our secret weapon for how to analyze the depths of Saturn," says Cassini scientist Kevin Baines. "[It's] how Saturn was revealed to be not this nice demure place, but this roiling dynamic place." He and his colleagues watched as clouds in the upper atmosphere blocked heat from below. They also identified vortices and a giant cyclone at each of Saturn's poles, though only the north pole features a hexagonal jet stream.

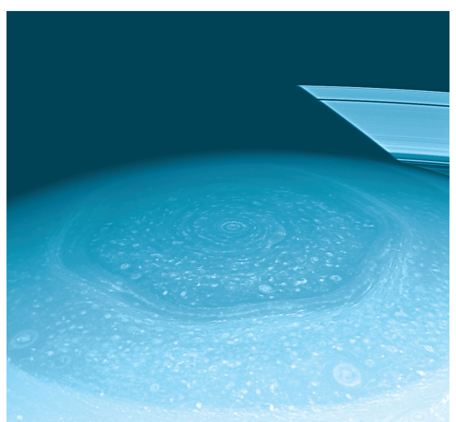
But one storm stood out from all the others. The Great White Spot erupted unexpectedly December 5, 2010. Earth-based observations of Saturn over the past 140 years had shown that a giant, long-lasting storm pops up every 30 years or so, alternating between cloud bands in the northern hemisphere and near the equator. In 1876, one appeared at the equator; in 1903, another developed at mid-northern latitudes; and in 1933, a storm emerged back at the equator. The pattern continued over the decades, and scientists expected the next storm would arrive around 2020 — after Cassini's reign. But it fortuitously arrived 10 years early, and gifted Cassini scientists with an up-close look at how these giant storms evolve.

Cassini's imaging camera first saw the storm December 5, at the same time another instrument heard it — or at least, the radio bursts created by its lightning. A similar phenomenon happens on Earth. If you have ever been in a car listening to an AM radio station during a thunderstorm, you probably heard what sounded like static. "That static is not actually static," says William Kurth. "It's actually radio emissions from the lightning strokes and the thunderstorm, and they propagate at the speed of light." Kurth is the principal investigator of Cassini's Radio and Plasma Wave Science (RPWS) instrument, which listened in on the Great White Spot's high-frequency radio emissions created in lightning strokes.

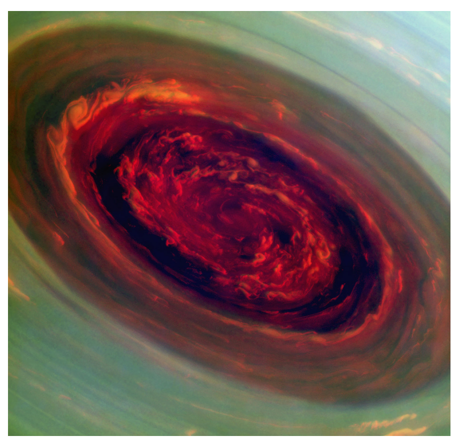
The jet streams in Saturn's atmosphere carried the northern hemisphere storm along its cloud band. By late January 2011, it wrapped around the planet and stretched 9,000 miles (15,000 km) north-south. As the storm progressed, scientists used the imaging instruments and RPWS to view it. In summer 2011, after some 200 days of roiling, swirling, and spreading, the storm died out and the atmosphere cleared. The region, says Baines, "has been very boring ever since."

Because scientists could watch the great storm evolve with Cassini's broad array of instruments, they could piece together a coherent picture of what causes these long-lived events. Caltech's Andrew Ingersoll and his then-graduate student Cheng Li put forth the most likely theory. They say it's due to a convective competition between water-rich clouds and the lighter-weight atmosphere of mostly hydrogen and helium. The heavier, wet clouds can't rise until the lightweight upper clouds become denser and sink.

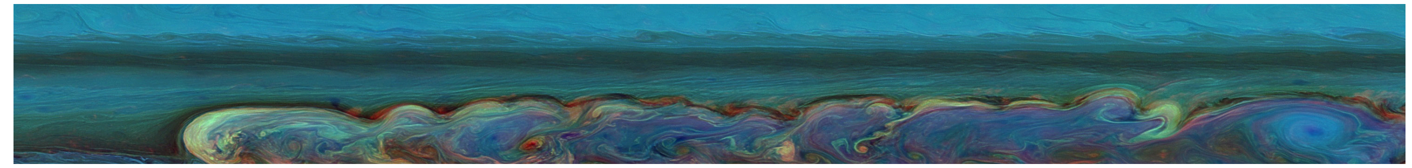
But this competition is a marathon. "The air above has to cool off, radiating its heat to space, before its density is greater than that of the hot, wet air below," said Li in a press release. "This cooling process takes about 30 years, and then come the storms." Once the storm rains out its water content, convection shuts down, and the storm stops.



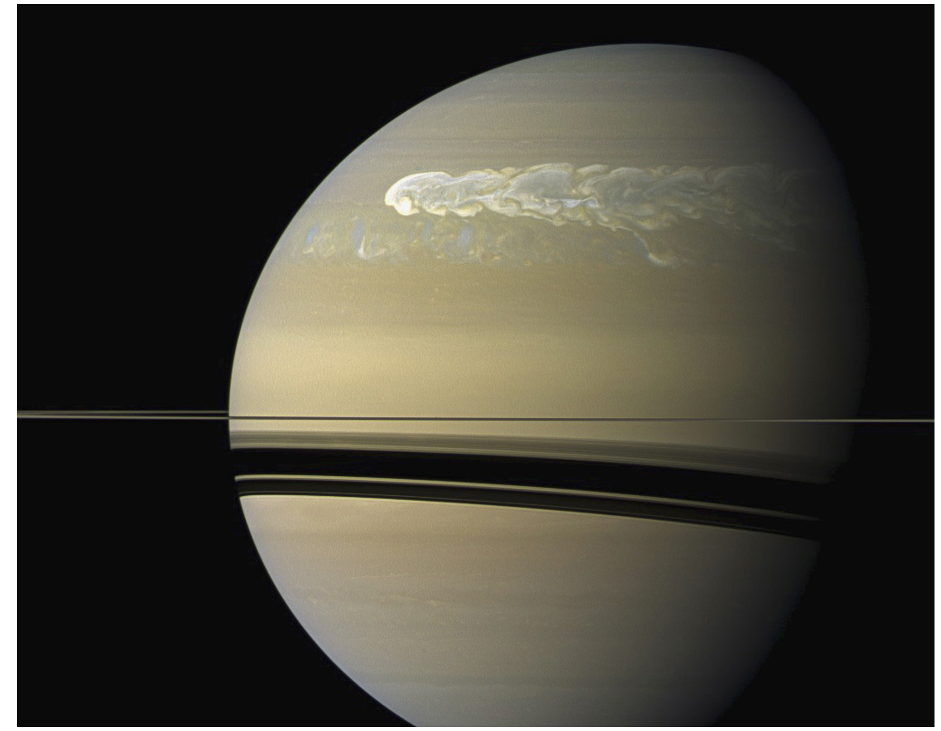
Saturn's north polar hexagon is a meandering jet stream near 77° north latitude. Each side of the hexagon measures slightly longer than Earth's equatorial diameter. NASA/JPL-CALTECH/SSI



A giant vortex resides at Saturn's north pole. The storm, which appears red in this false-color image, spans 1,250 miles (2,000 km) and has winds up to 330 mph (540 km/h). NASA/JPL-CALTECH/SSI



The Great White Spot appears as a multihued snake in this false-color mosaic from February 2011. Yellow and white reveal high, thick clouds associated with thunderstorms; red shows deep clouds with no towering tops; and blue areas are cold spots. NASA/JPL-CALTECH/SSI



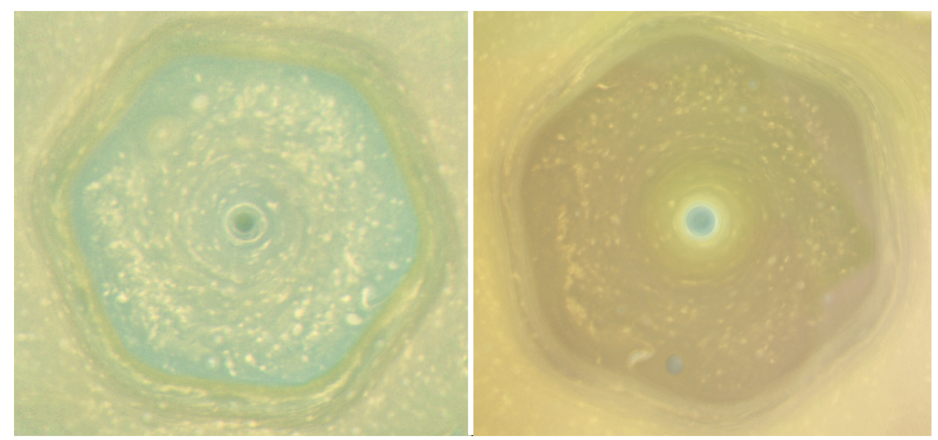
The Great White Spot erupted in December 2010 and quickly evolved into a massive storm. By the time Cassini captured this image 12 weeks later, Saturn's jet streams had carried the storm completely around the planet. NASA/JPL-CALTECH/SSI

Magnetic makeup

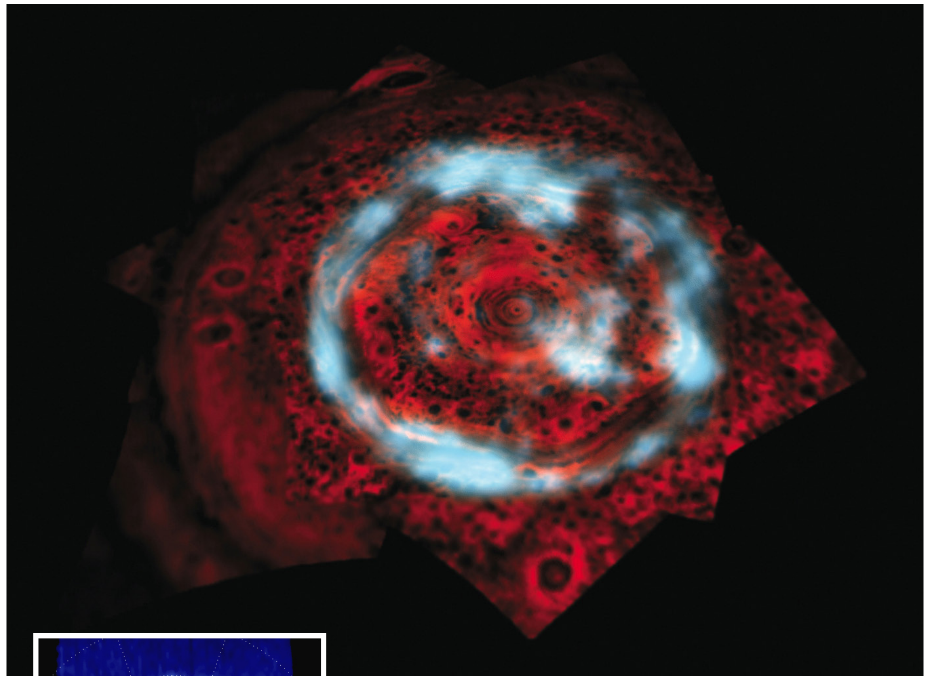
When you think of Saturn, the ornate rings and cloudy atmosphere likely come to mind first, but no object exists in isolation. So, how does the giant planet affect its surroundings? That's where Saturn's magnetic field factors in, and it's why Cassini brought along instruments to study it and the region the field controls, called the magnetosphere.

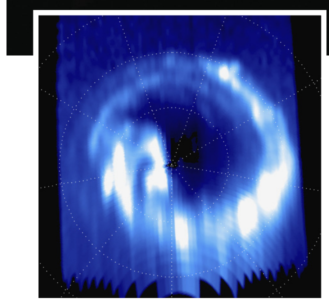
Previous observations of Saturn had shown aurorae at the planet's poles, similar to the northern and southern lights seen in Earth's polar regions. Cassini's RPWS instrument monitored auroral activity by detecting the radio waves that aurorae generate, in much the same way it heard radio flashes associated with lightning. "We've been able to use the intensity of these radio emissions as a proxy," says Kurth, to address questions of "how intense are the auroras and is there a lot of activity going on." RPWS also monitored how Saturn's magnetosphere and aurorae changed when the Sun delivered a burst of high-energy particles and radiation.

But how does Saturn produce its magnetic field? To find out, scientists used Cassini's magnetometer. This instrument measures the strength and location of the planet's magnetic field lines, which trace how charged particles travel. Electrons, for example, have a negative charge, and they always move toward a magnet's positive pole. Both Saturn and Earth are essentially giant dipole magnets: They have a positive pole and a negative one. Each planet generates its magnetic field deep in its interior. For Earth, researchers have a pretty good idea of how it happens. "You have heat, you have convection taking place in the interior, you have rotation in the interior, and



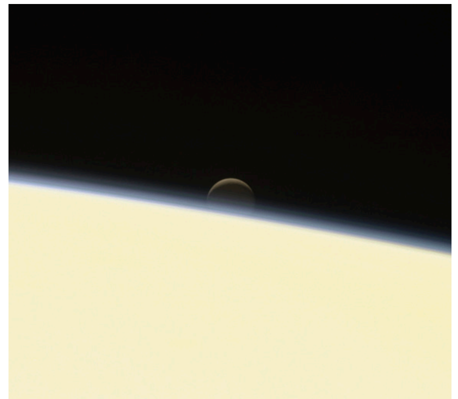
Although Saturn's north polar hexagon has lasted for at least 35 years (the Voyager spacecraft first imaged it in the early 1980s), it does change. These natural-color views show the hexagon in June 2013 (left) and April 2017. Scientists think an increase in solar radiation during those four years caused yellowish smog to form. NASA/JPL-CALTECH/SSI/HAMPTON UNIVERSITY





Above: Saturn's aurora glows blue while the underlying atmosphere appears deep red in this infrared composite image. As on Earth, the aurora arises as Saturn's magnetic field funnels energetic solar particles to the polar regions. NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA

Left: Cassini captured the ultraviolet glow from Saturn's aurora one day before the spacecraft crashed into the planet. The north pole lies at the center of this image, while the bottom faces the Sun. NASA/JPL-CALTECH/UNIVERSITY OF COLORADO/UNIVERSITY OF LIEGE-LPAP



Enceladus prepares to set behind Saturn's limb September 13, 2017. This was one of the last images Cassini took of the geologically active moon before the probe crashed into the gas giant September 15. NASA/JPL-CALTECH/SSI

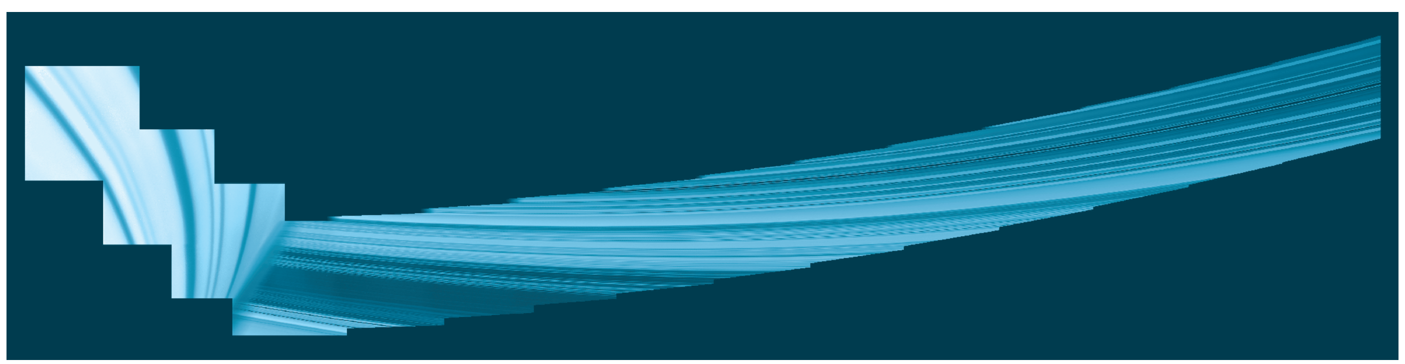
you have flowing electrical currents," says Michele Dougherty, principal investigator of Cassini's magnetometer. "All of those combine to give you the magnetic field that you measure outside the planet."

A key component in understanding Saturn's magnetic field is the length of a saturnian day, and this was a major question scientists hoped Cassini would resolve. This shouldn't be a difficult question, right? It's just the rotation period. But that's a much harder problem to solve for gas giant planets than it is for Earth. The cloud tops rotate at different speeds, and the thick atmosphere hides the planet's solid core — assuming it has one.

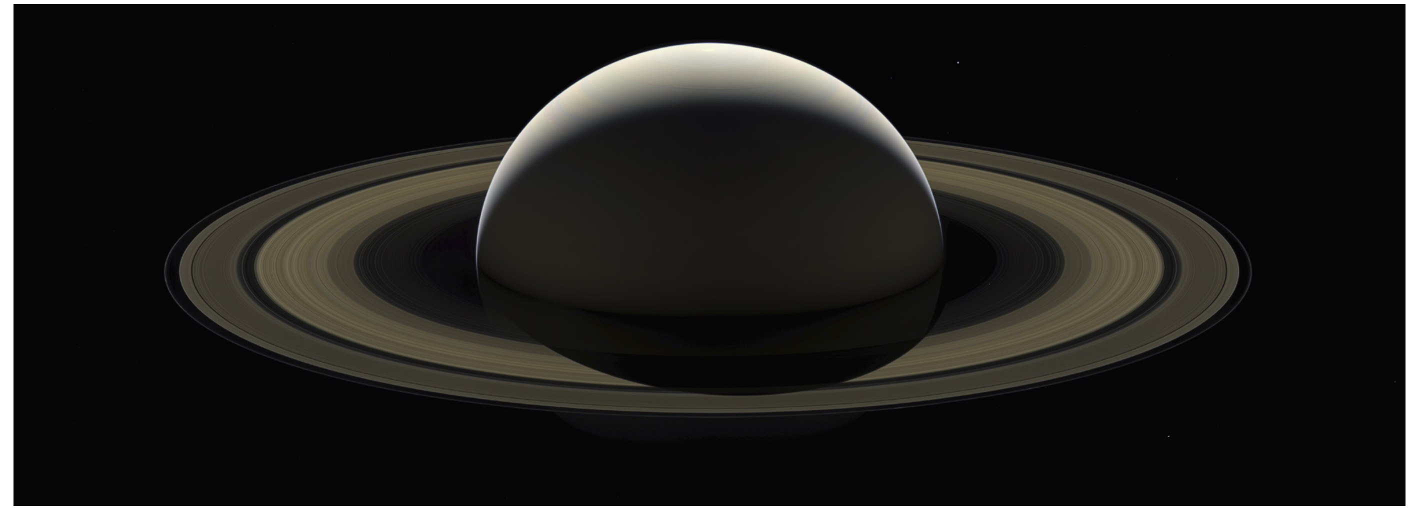
To measure Jupiter's day, for example, scientists track the magnetic axis and find it wobbles with respect to the planet's rotation. The magnetic field's axis and the rotation axis tilt relative to each other, and that wobble relates directly to how fast the planet's core is spinning. The problem with Saturn, though, is that the two axes are nearly perfectly aligned. This makes it awfully hard to find that wobble.

The precise alignment also perplexes researchers because it implies that the magnetic field should be decaying — and scientists have seen no evidence of a diminishing magnetic field at Saturn. When Cassini flew close to Saturn during the Grand Finale, the magnetometer collected data about the magnetic field. "We really expected these Grand Finale orbits to clearly measure the tilt, and all we've been able to do so far is put a limit on it," says Dougherty. The angle between the two axes must be less than 0.06°.

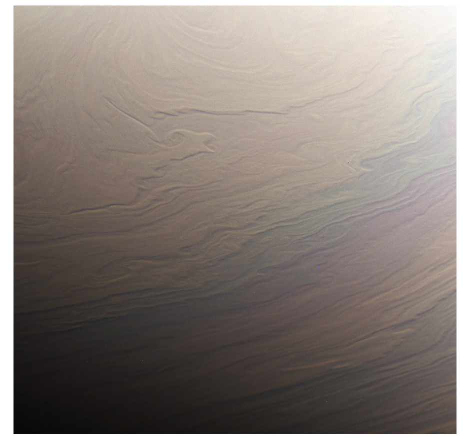
The team has had the data for only a couple of months, however, and Dougherty is confident that after she and her colleagues complete their careful and thorough analysis, they'll know what Saturn's internal magnetic field is like. The biggest hurdle is accurately calibrating the instrument. The analysis requires absolute precision — the exact location and timing of the spacecraft's trajectory, and knowledge of where Cassini was when the instrument collected each bit of data. Researchers have *predicted* orbits, positions, and times, but they have to know whether Cassini's *actual* orbit followed them precisely. For example,



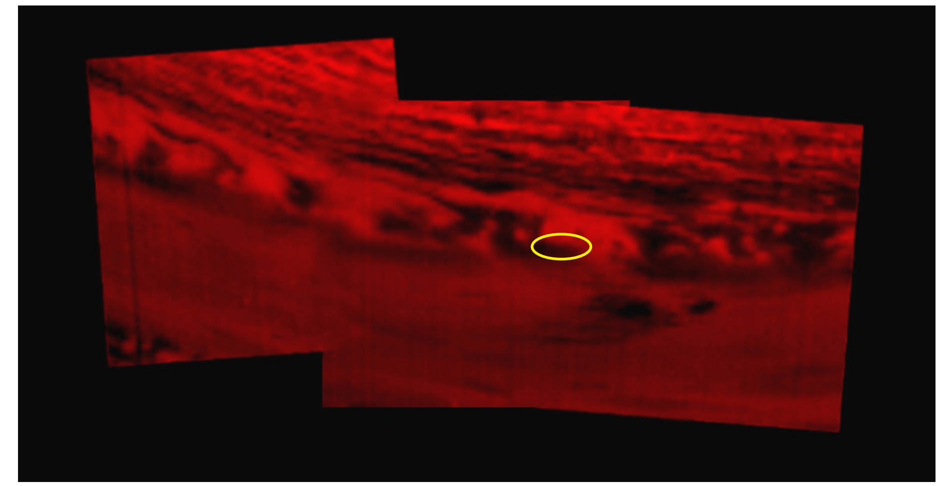
On May 28, 2017, Cassini flew between Saturn's rings and its cloud tops, capturing the images for this mosaic. Saturn appears in the left foreground, adorned with shadows cast by the rings. The rings themselves emerge from behind the planet's limb and extend to the right. NASA/JPL-CALTECH/SSI



Saturn posed for Cassini one last time September 13, 2017. The imaging team assembled this natural-color mosaic from 42 wide-angle images taken through three color filters from about 15° north of the ring plane. NASA/JPL-CALTECH/SSI



During its Grand Finale mission, Cassini captured subtle atmospheric details. In this view, the Sun shines at a low angle near Saturn's terminator, where day turns to night, and some high clouds cast shadows on lower regions. NASA/JPL-CALTECH/SSI



Cassini crashed into Saturn's atmosphere September 15, 2017, at the spot marked by the oval. This nighttime infrared view shows heat coming from the planet's interior in red; the dark regions are silhouetted clouds. NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA

might there have been a half-second delay because the craft felt more drag from the atmosphere than expected? "It's a really complicated process," says Dougherty of the analysis. "It's like trying to find three or four needles in a haystack that's changing shape and size at the time."

Mapping gravity's pull

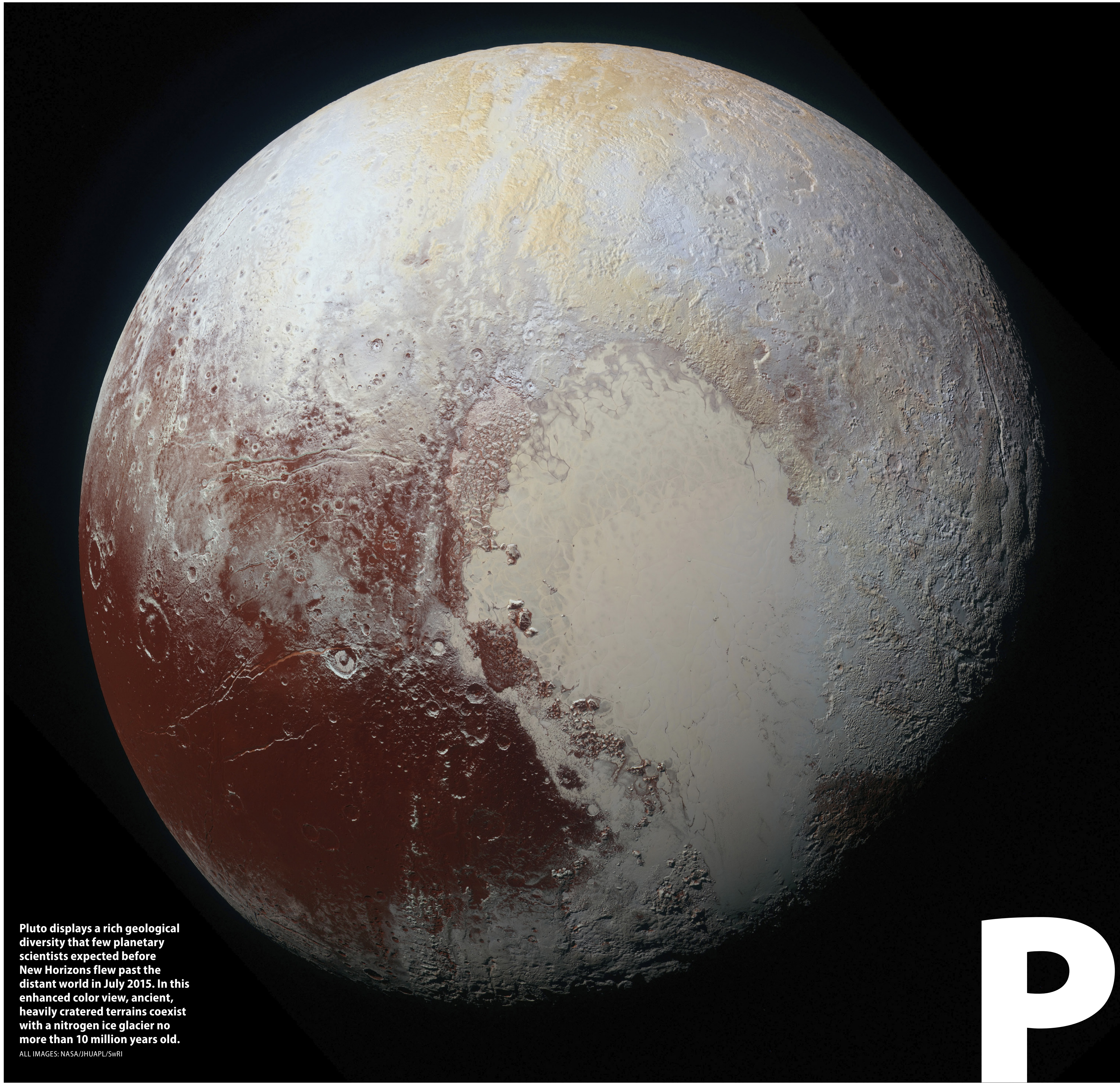
The magnetic field analysis isn't the only one proving to be extremely complex and requiring precise calibration. Scientists also want to know about Saturn's interior, and in particular, how the planet's mass is distributed. To do that, they need to measure the planet's gravity. That's not as simple as it might sound. "There is no instrument aboard a satellite which can reveal the gravity field by itself," says Iess. Instead, scientists passed radio signals between Earth and Cassini and measured the slight changes in radio frequency. Those changes arose from gravitational tugs of mass pulling on the spacecraft — the more mass, the bigger the tug. So Iess and his colleagues can use those tiny frequency changes to map the distribution of mass within Saturn. Because Cassini skimmed the planet's cloud tops during its final months, it felt a stronger gravitational pull from those mass distributions, and was able to sense finer details.

Precisely understanding those Grand Finale orbits is crucial to the gravity analysis of Saturn. So far, the team has learned that theoretical models of Saturn's gravity do not match the data. "The gravity field of Saturn is surprising," says Iess. "We found Saturn has features that can be explained only by differential rotation," meaning some portions or layers of the planet move at different speeds than others. The researchers still have more orbit trajectories to calibrate, and thus are still months away from a major announcement.

Revealing that the interior doesn't align with models would be a fitting discovery from a mission that already has found so many surprises at the Saturn system. Cassini's suite of instruments offered the flexibility that allowed scientists to make those discoveries. The mission's scientists and engineers worked in sync for decades to perform what Spilker calls Cassini's "intricate ballet."

"It's for the unknown, the unexpected," she says. "That's why you do science."

Contributing Editor **Liz Kruesi** *writes about distant objects from her Earthbound home in Austin, Texas.*



Pluto displays a rich geological diversity that few planetary scientists expected before New Horizons flew past the distant world in July 2015. In this enhanced color view, ancient, heavily cratered terrains coexist with a nitrogen ice glacier no more than 10 million years old.
ALL IMAGES: NASA/JHUAPL/SwRI

PUZZLED BY PLUTO

Far from the inert ball of ice some scientists expected, this distant world boasts unique landscapes, recent geological activity, and a possible underground ocean. **by S. Alan Stern**

The exploration of Pluto by NASA's New Horizons spacecraft revolutionized our knowledge of this small planet and its system of five moons. But it also did much more. The encounter showed us again that there is no substitute for going to the planets to learn about them, and it proved once more how first flybys thoroughly shatter scientific paradigms.

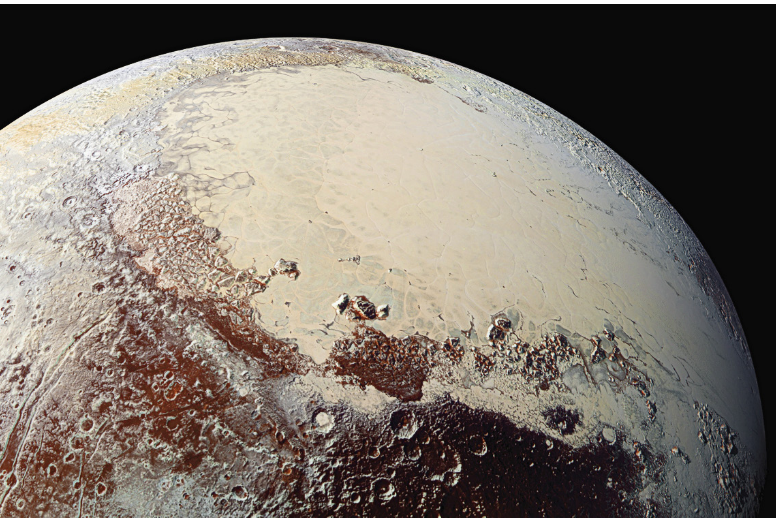
Every time we used the cameras, spectrometers, and other onboard sensors on New Horizons, we made discoveries about the Pluto system. We found that the planet's four small moons — Nix, Hydra, Kerberos, and Styx — are as old as Pluto itself, and all are covered in water ice that somehow is kept clean or is eternally refreshed to produce astonishingly high surface reflectivities. We also learned that these satellites surprisingly rotate much faster than they orbit Pluto, and that they are not accompanied by still more small moons as many of us had expected.

Pluto's giant moon, Charon — the other member of the binary planet at the heart of the Pluto system — also surprised us. It displays an old surface sporting a dark, red northern polar cap unlike anything seen elsewhere in the solar system, flooded plains of water ice, and vast extensional tectonic features — which form under stress as the moon's surface spreads apart. Charon even shows evidence of a possible internal ocean in its youth.

And then there is Pluto — geologically alive on a vast scale and displaying a range of landforms that rivals Mars, the solar system's other red planet. No one really expected any of these big-ticket Pluto surprises. And few anticipated the complexity we see in Pluto's suspended haze layers, the blue color of its sky, the almost 1,000-times lower atmospheric escape rate than predicted, or the evidence seen on the surface that Pluto's atmospheric pressure has been, apparently, sometimes tens to thousands of times higher than what we see today. Yet we found all of this, and much, much more.

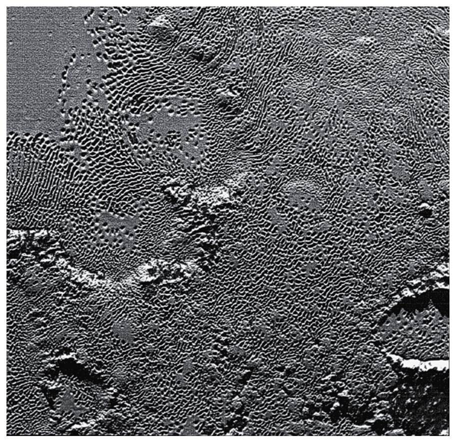
The entire data set from New Horizons is now on Earth, and is archived in the open-access NASA Planetary Data System. Researchers on our science team have examined all of the 400-plus observations made by our seven scientific instruments and written over 50 technical papers detailing early findings. But there is much more to do to understand Pluto, and to extend those findings to a better understanding of the other small planets in the Kuiper Belt.

In *Astronomy*'s May 2016 issue, I wrote "Hot results from a cool planet," detailing many of the initial findings we made as the Pluto system data began raining down from the Kuiper Belt. Here, I will supplement those early findings with four



Above: The nitrogen ice glacier Sputnik Planitia covers some 400,000 square miles (1 million square kilometers) of Pluto's surface. It is the largest glacier known beyond Earth and appears devoid of craters, implying that some process continuously renews it. (All feature names in this story are informal.)

Right: The cellular patterns seen in western Sputnik Planitia suggest that convective motions within the ice constantly renew the surface by replacing older ice with fresher material from below.



Hundreds of sublimation pits dot the "coastline" of Sputnik Planitia. Scientists think these pits form when nitrogen ice turns directly into gas. New Horizons captured this high-resolution view just 13 minutes before closest approach.

overarching results that stand out from the first exploration of Pluto.

Unique landforms

One of the biggest surprises in the imagery that New Horizons returned is the many new kinds of landforms seen on Pluto's surface. Yes, Pluto displays heavily cratered terrains, polar deposits, canyons, glacial channels, mountain ranges, and even chaotic mountain blocks like those seen on Mars and on Jupiter's moon Europa, and we didn't expect to see so many of these landform types. But even more surprising are the exotic new types of landforms on Pluto.

The star of this show is the vast, 400,000-square-mile (1 million square kilometers) nitrogen glacier informally called Sputnik Planitia (SP), which forms the western lobe of Pluto's "heart." No nitrogen glacier has been seen elsewhere in the solar system, and no glacier of this extent has been seen anywhere beyond Earth.

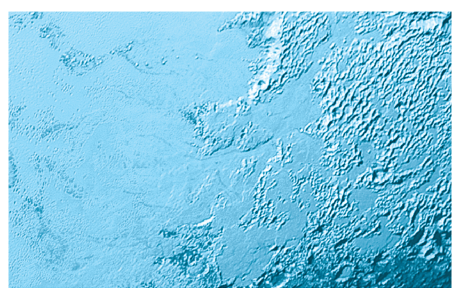
Several features within SP enhance its exotic nature, including cellular structures on its surface (which indicate convective motions in the ice), recharge zones found along its edge, hundreds of mile-wide sublimation pits formed where nitrogen ice has turned directly into a gas, and clear evidence of glacial flow against the surrounding mountains near the northwestern shoreline. Also surprising is the complete lack of craters on SP, indicating that this gargantuan feature renews itself continuously despite a temperature of just 40 kelvins (72° F above absolute zero)! More on that later.

Another completely unique landform on Pluto is the widespread "bladed terrains" of the region informally called Tartarus Dorsa. These long, 1,000-foot-high (300 meters) linear ridges made of methane ice are unlike anything seen elsewhere in our solar system. Moreover, the bladed terrains appear to extend far beyond Tartarus Dorsa and cover wide expanses of the low latitudes on the far-side hemisphere that we imaged only at low resolution. The bladed terrains may even be one of the dominant landform types on Pluto. What causes this terrain? Some scientists suggest that these structures may be penitentes — blades of ice that form in high deserts under sunlight-driven sublimation. Others suggest that they may be the result of wind sculpting or glaciation. There are several ideas, but no clear favorite yet.

New Horizons also discovered unique terrain types on Charon. Although this moon has much the same size, density, and surface composition as some of the mid-sized icy satellites of the giant planets, it shows two types of surface features not seen elsewhere. One is the dark, red polar stain I mentioned earlier. The best theory is that it formed when gases escaped from Pluto, condensed onto Charon's cold poles, and then were chemically altered by solar radiation. Charon's other unique feature is a handful of "moated mountains," each surrounded by a quasi-circular trench. The cause of these structures remains a mystery.

Clinching the giant impact

It has been more than 30 years since planetary scientists like Bill McKinnon first suggested the Pluto-Charon binary formed in a giant impact. In this scenario, a collision between Pluto and another small planet launched material into orbit around Pluto that then accumulated to form Charon.



Nitrogen ice flows from the highland region on the right side of this image onto the frozen plains of Sputnik Planitia through narrow valleys just 2 to 5 miles (3 to 8km) wide.

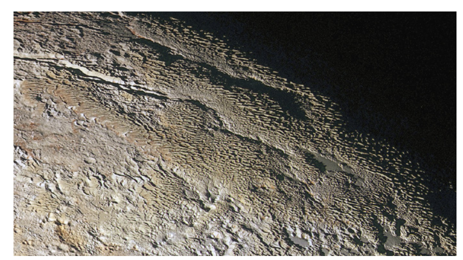
New Horizons helped clinch the case that Pluto's satellite system formed as a result of a giant collision between a rogue Kuiper Belt object and the young Pluto. Debris from the impact formed a disk around the battered Pluto that eventually coalesced into Charon and its cohort of four much smaller moons.

RON MILLER FOR *ASTRONOMY*

Early clues supporting this formation hypothesis included the large mass of Charon relative to Pluto and the off-the-charts specific angular momentum (the angular momentum per mass) of the binary. Further evidence arrived in the 1990s with the discovery of the Kuiper Belt, which provided a source population for the necessary impactors, and the Hubble Space Telescope's discovery of Pluto's four small moons all in the same orbital plane as Charon.

New Horizons data add to the case for a giant impact origin in three significant ways. First, the spacecraft revealed the compositions of Nix and Hydra for the first time, showing they are covered in water ice. This is exactly what numerical simulations had predicted a giant impact would produce. Second, New Horizons images more precisely determined Charon's volume and thus refined this large moon's density. The improved density measurement indicates Charon is more icy and thus less rocky than Pluto, which is just what you would expect from a giant impact on a Pluto differentiated into a core, mantle, and crust.

Finally, New Horizons imaged Nix and Hydra in sufficient detail to allow scientists to count craters on their surfaces and thus estimate their ages. (A surface accumulates more craters over time.) This let us compare the surface ages of Nix and Hydra to the age of Charon, similarly derived from New Horizons images. When our science team completed these studies last year, we found that all of these objects are equally old — providing yet another link to their common origin. Together, these latest clues make it all but impossible to imagine any other formation scenario for the Pluto system than a giant impact.

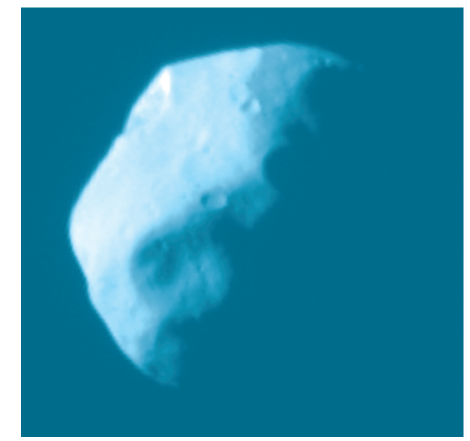


Scientists have seen nothing like the so-called bladed terrains of Pluto's Tartarus Dorsa region elsewhere in the solar system. These ridges rise some 1,000 feet (300 meters) above their surroundings in this enhanced color view.

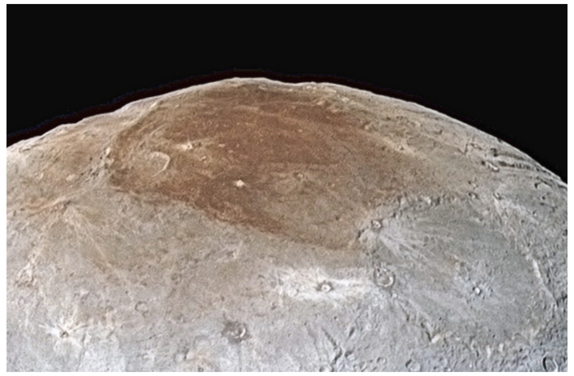
Time-variable Pluto

Another big surprise we found on Pluto is widespread evidence for temporal changes on its surface. This evidence comes in several forms.

SP provides some of the best examples. As I noted earlier, it has no detectable craters on its surface and cannot be older than perhaps 10 to 30 million years. This means it either was created recently or, more likely, continuously renews itself. The cellular patterns of ice convection may be an indication

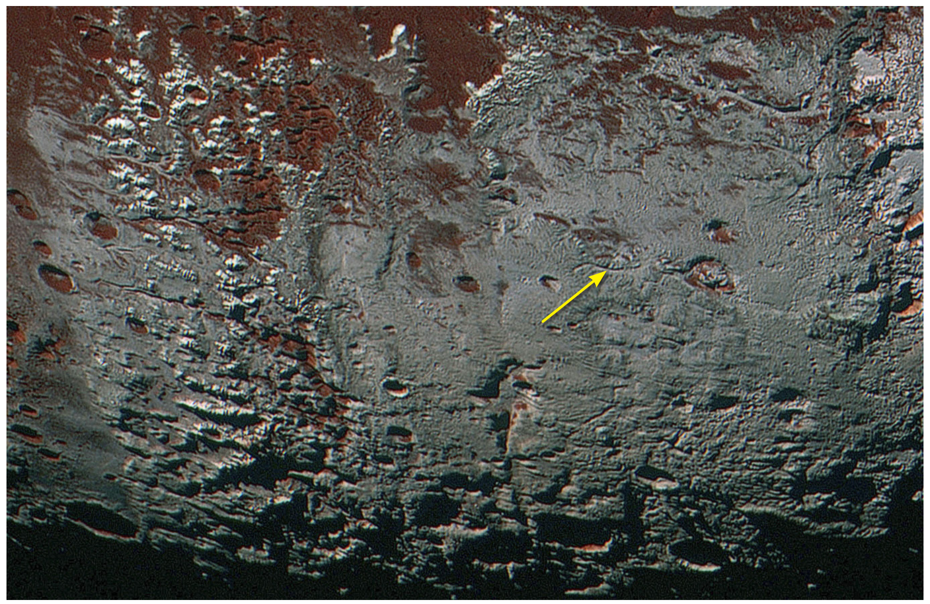


Pluto's small moons, including Nix (pictured) and Hydra, bolster the case that a giant impact created the entire satellite system. New Horizons showed that water ice covers both moons, and both are the same age as the large moon, Charon — exactly what you would expect from a giant impact origin.



Above: Pluto's large moon, Charon, also possesses some unique landforms. The dark, red stain that covers the satellite's north polar region appears to be material that originated in Pluto's atmosphere and then condensed on Charon's cold polar terrains. Exposure to solar radiation then darkened and reddened the material.

Left: Charon's other unique landforms are several "moated mountains" like the one seen at the top left. In these features, a quasi-circular trench some 0.6 to 2 miles (1 to 3km) deep surrounds the mountain.



Valley networks that appear to have been cut by flowing liquids or ices provide some of Pluto's best evidence for temporal changes. The one here (arrow) lies south of the equatorial band Cthulhu Regio.

of this renewal process. But the evidence for temporal change on SP goes well beyond that. In fact, we see signs for both glacial recharge in the form of recent flows down the slopes of the surrounding mountains and for currents in SP's nitrogen ice. The currents themselves are a form of temporal change as the ice moves and possibly slides under some of the mountains that SP abuts.

More evidence for temporal change appears on the flanks of the feature informally called Wright Mons. Wright Mons is a caldera-like structure that likely formed by cryovolcanism — the eruption of water or other volatile liquid. And Wright Mons is huge, rivaling Hawaii's Mauna Loa in scale. But strikingly, its flanks show essentially no evidence of cratering, which implies that either the mountain itself is young or it has been active recently, resurfacing the flanks.

Although the signs of large-scale temporal changes in SP and on Wright Mons are impressive, in my book, the most interesting evidence for such changes on Pluto is something else entirely. Across the surface, we see geological features that strongly resemble sloping valleys and dendritic valley networks on Earth and Mars. On those other two planets, flowing liquids or ices create such structures via erosion. We also see one surface feature, informally called Alcyonia Lacus, that appears to be a frozen lake nestled in a low-lying part of the chaotic mountain blocks that make up the informally named al-Idrisi Mountains. This 19-mile-long (30km) feature is replete with a smooth surface and distinct shorelines.

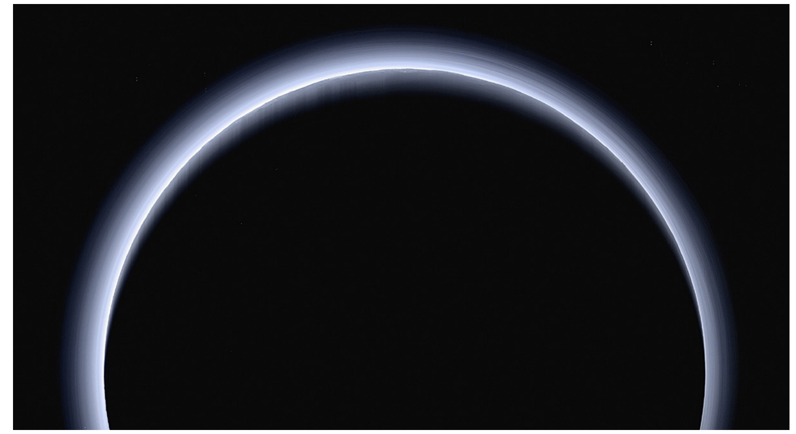
Perhaps the strangest aspect about the possibility that liquids once existed on Pluto's surface is that both the temperature and surface pressure today are far too low to allow liquids. In fact, for liquids to exist on Pluto's surface, temperatures and pressures must exceed the triple point — the conditions under which the solid, liquid, and gas phases of a substance can coexist in equilibrium — of molecular nitrogen, carbon monoxide, or methane. But this in turn requires atmospheric pressures exceeding 100 millibars — about 10,000 times Pluto's current surface pressure of 11 microbars. How can this be?

Scientists discovered in the 1990s that the tilt of Pluto's axis varies by more than 20° every 3 million years. A similar process on Earth, called Milankovitch cycles, causes our own polar tilt to change, but by about 10 times less. Still, even that small shift creates significant climate variations on Earth. In a recent paper in *Icarus* on which I was lead author, we modeled the kind of atmospheric pressure and temperature variations that Pluto's much larger polar tilt variations may cause. We found it is plausible that such cycles caused conditions on Pluto to sometimes exceed the pressures and temperatures of the nitrogen triple point. If further modeling bears us out, this would allow liquids to be stable and even flow on Pluto's surface thousands of times in the past!

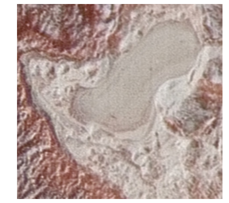
Ocean worlds?

At the dawn of the Space Age, Earth was the only known world to have an ocean. Later, increasingly detailed studies of Mars by spacecraft revealed that it almost certainly once had vast seas or oceans of water that have long since disappeared. But to our great surprise, spacecraft also found that many worlds with icy surfaces — including Enceladus, Europa, Ganymede, and Titan — show evidence for internal oceans.

Why should this be so? First, water ice is common to the surfaces and interiors of virtually every solid world in the middle and outer solar system. Second, pressures and temperatures increase with depth, meaning that the water ice often reaches a liquid state in the interiors of these worlds. This typically occurs tens to hundreds of miles below the surface, creating the conditions for global interior oceans with depths



Above: New Horizons found lots of evidence that liquids once existed on Pluto's surface. For this to be so, the atmosphere — seen here as a bluish arc in one of the spacecraft's parting shots — must have been much warmer and denser in the past.



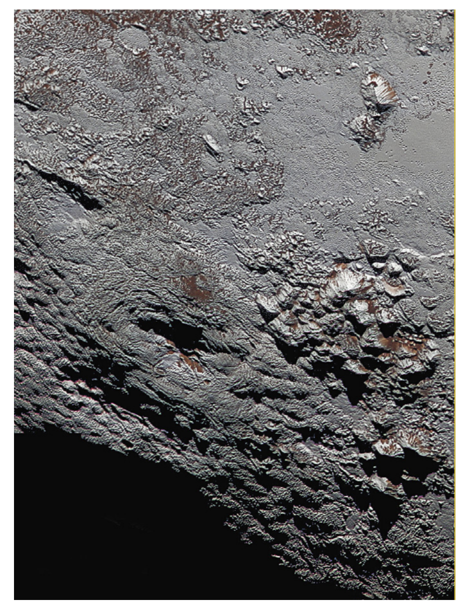
Right: Alcyonia Lacus lies in the mountains just north of Sputnik Planitia. The feature appears to be a frozen, former lake of liquid nitrogen.

The huge tectonic belt that runs along Charon's equator provides dramatic evidence that this moon's interior once held a large water ocean. Scientists think the belt formed from stresses when the water froze and expanded.

and volumes that are, in some cases, even larger than Earth's.

Evidence for these oceans was once only theoretical, coming from computer calculations of interior conditions. But later we found water geysers erupting from the interiors of Enceladus and Europa, and magnetic field variations that suggest electrical currents in salty interior oceans in three of Jupiter's Galilean satellites.

A few years ago, geophysical models indicated that Pluto and Charon might be able to host interior water oceans, or at least to have done so in the past. But when New Horizons arrived, it revealed new evidence that such oceans are actually likely.



The 90-mile-wide (150km) Wright Mons (shown at lower left) appears to be a shield volcano complete with a deep central pit at its summit. The mountain's flanks show no evidence of impact craters, suggesting that it either is young or has recently erupted.

In the case of Charon, a primary sign for an ancient interior ocean is the giant extensional tectonic belt that girdles the moon's equator. Our team suspects the belt originated from stresses created long ago when liquid water in Charon's interior cooled, expanded, and froze after the satellite's violent formation in a giant impact.

The case for an ocean inside Pluto is more nuanced. SP suspiciously lies diametrically opposite to Charon. (Pluto and Charon are tidally locked and thus keep the same faces toward each other.) The odds of this occurring randomly are small. But if there is an interior water ocean that wells up under SP, it would create an excess of mass there because water is denser than water ice. Tidal forces would then naturally reorient SP to just the location we see it — opposite Charon. Of course, this evidence is only circumstantial. If we return someday with an orbiter that can map gravity anomalies, search for magnetic variations, and perhaps even carry a surface-penetrating radar, we can definitively test for this ocean.

The value of exploration

Clyde Tombaugh discovered Pluto 85 years before New Horizons flew past it. During those 85 years, the distant world never appeared as more than a smudgy disk in images. Yes, from afar we learned its basic surface composition, that it has a nitrogen-dominated atmosphere, and that it forms a binary planet with Charon. Yes, from afar we learned Pluto's rotation period and polar tilt, and that it has four small moons. And yes, from afar we learned that the surface is reddish with brighter and darker areas, and that Pluto's interior is made primarily of rock.

But frankly, despite the vast advances in observing capabilities from 1930 to 2015, there wasn't much more we learned about the Pluto system from Earth or Earth orbit. I doubt that if I lived to be 120, we could have learned as much in all those years as we found out in a matter of days while New Horizons zipped by. The lesson of New Horizons is that it took a mission of close-up exploration to really determine Pluto's basic nature.

And so, while I am sure that new tools like the James Webb Space Telescope and the planned 30-meter-class telescopes on the ground will add some detail, I doubt that we will learn much more until we follow up New Horizons with an orbiter or orbiter-lander pair. I also doubt that we'll ever know as much about the other small planets of the Kuiper Belt as we now know about Pluto unless we send probes to fly by them as well. New Horizons re-emphasized the lesson that all those first missions to explore the closer planets in the 1960s, 1970s, and 1980s taught a previous generation of scientists and scientific enthusiasts: There is no substitute for spacecraft exploration.

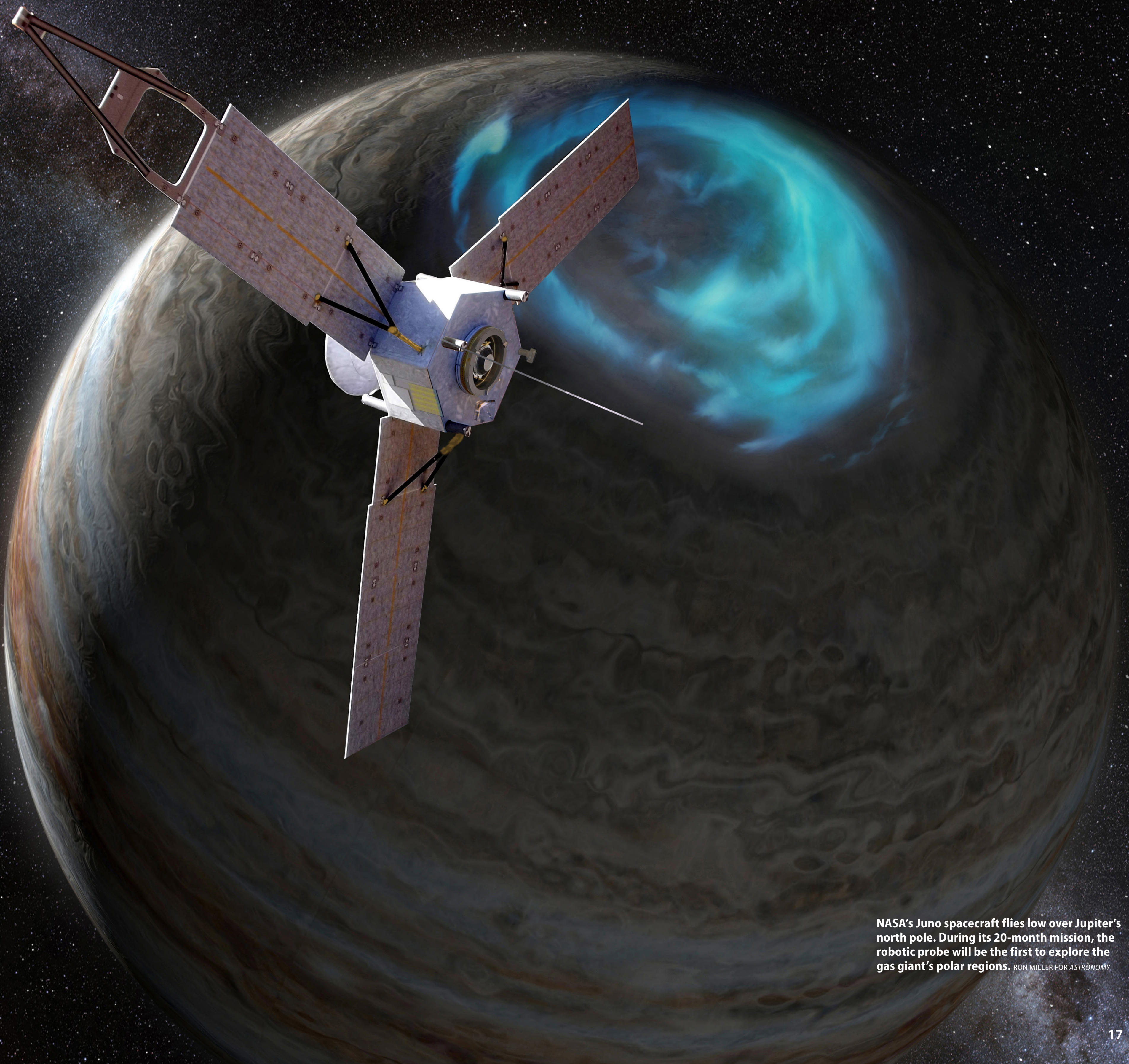
S. Alan Stern *of the Southwest Research Institute in Boulder, Colorado, is a planetary scientist and the principal investigator on New Horizons.*

Juno sets its sights on Jupiter

Despite eight missions to Jupiter, scientists still know little about the planet's origin and evolution. NASA's Juno spacecraft aims to change that. by Ben Evans

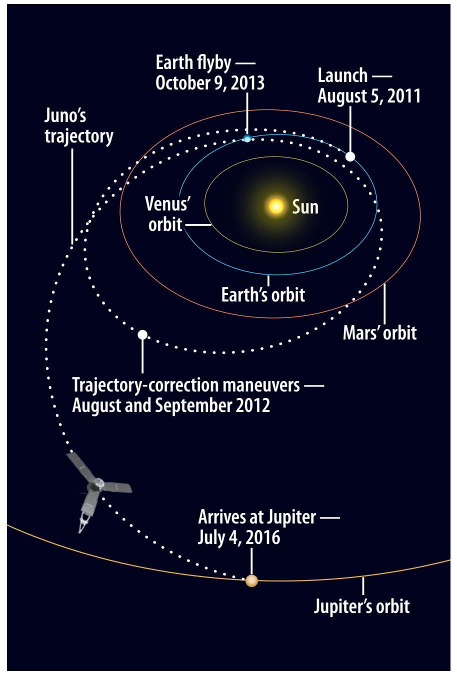
IN MYTHOLOGY, JUNO WAS WIFE TO the king of the Roman pantheon, the sky-god Jupiter, who had a reputation for seducing mortal mistresses and committing all manner of earthly mischiefs. Yet Juno retained an uncanny ability to see through the cloak of clouds that Jupiter frequently drew about himself to hide these indiscretions.

Their tumultuous relationship will be spotlighted this summer when the solar system's largest planet receives a robotic visitor, appropriately named Juno. The probe will explore the giant world's composition, its gravitational and magnetic fields, and its deep winds. And, like its long-suffering mythological namesake, it will seek to understand how Jupiter came to be.



NASA's Juno spacecraft flies low over Jupiter's north pole. During its 20-month mission, the robotic probe will be the first to explore the gas giant's polar regions. RON MILLER FOR *ASTRONOMY*

The Juno spacecraft lifts off from Cape Canaveral, Florida, on August 5, 2011. The Atlas V rocket used is the most powerful Atlas in NASA's inventory. PAT CORKERY (UNITED LAUNCH ALLIANCE)



Juno took a circuitous route to Jupiter during its nearly five-year journey. It flew past Earth in 2013 for a gravity assist so it could reach the giant planet more quickly. *ASTRONOMY*: KELLIE JAEGER

In the past five years, the six-sided Juno spacecraft has voyaged 1.74 billion miles (2.80 billion kilometers) to a world whose colossal bulk could swallow every other solar system object apart from the Sun. Launched on August 5, 2011, Juno followed a long and circuitous route. Its initial trajectory took it beyond the orbit of Mars, where the spacecraft fired its main engine twice in the summer of 2012 to redirect it toward a flyby of Earth on October 9, 2013. The spacecraft stole a minuscule bit of our planet's orbital energy that day, gaining 8,800 mph (14,200 km/h) of speed that set it on course for Jupiter.

By July 4, 2016, Juno will be hurtling into the jovian system at more than 165,000 mph (265,000 km/h) — a record for the fastest-moving human-made object. The spacecraft will then fire its engine for 30 minutes, slamming on the brakes as it threads the needle between the planet and its lethal radiation belts. This will position the spacecraft in a 107-day capture orbit, split into two halves, that allows the science team to test the probe's instruments during a close pass by Jupiter before the main mission begins.

Settling into the science

Mission planners will refine this capture orbit in October 2016 to place Juno into its highly elliptical science orbit. It will sweep within 3,100 miles (5,000km) of Jupiter's cloud tops at closest approach and swing out well beyond the 1.17 million-mile (1.88 million km) distance of the outermost major moon, Callisto, at its farthest. Scientists had planned to have each orbit last 11 days, but they later adjusted that to 14 days. The longer orbit will allow Juno to build an initial global map of the planet's magnetic and gravitational fields by its eighth orbit, far sooner than originally planned. The new orbit also will prolong Juno's time at Jupiter from 15 to 20 months and increase its total number of orbits to 37.

> "Juno is basically an armored tank going to Jupiter. Without its protective shield or radiation vault, Juno's brain would get fried on the very first pass near Jupiter." — Scott Bolton

The extended science orbit will give the science team more time to react to unexpected conditions. "We have models that tell us what to expect, but the fact is that Juno is going to be immersed in a strong and variable magnetic field and hazardous radiation, and it will get closer to the planet than any previous orbiting spacecraft," says Juno Principal Investigator Scott Bolton of the Southwest Research Institute in San Antonio. "Juno's experience could be different from what our models predict. That's part of what makes space exploration so exciting."

Protecting the spacecraft from this harsh radiation is critical. Many of its electronics are composed of radiation-resistant tantalum, with wiring wrapped in copper and stainless steel braid, all shielded within the 0.4-inch-thick (1 centimeter) titanium walls of a 400-pound (180 kilograms) vault. "Juno is basically an armored tank going to Jupiter," says Bolton. "Without its protective shield or radiation vault, Juno's brain would get fried on the very first pass near Jupiter."

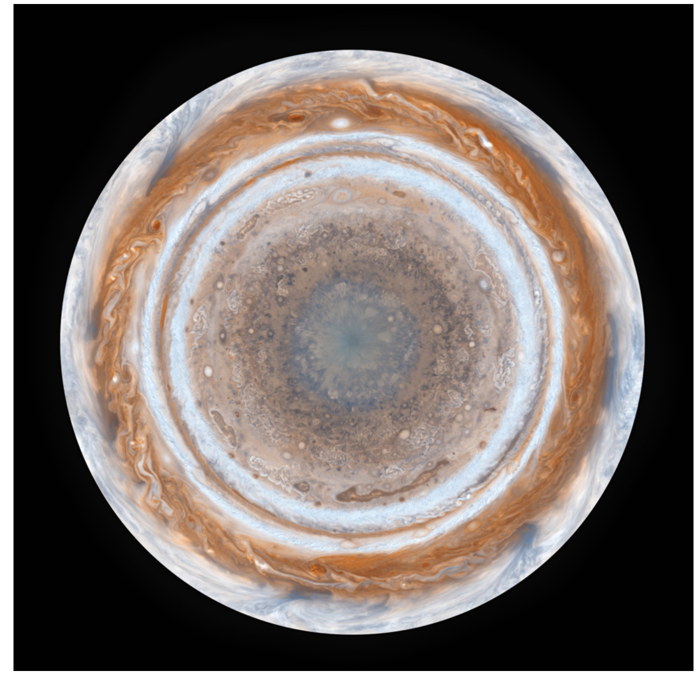
Over its lifetime, the spacecraft will endure the equivalent of 100 million dental X-rays. Although this is actually less than the radiation levels sustained by its predecessor — the equator-girdling Galileo orbiter, which circled Jupiter from December 1995 to September 2003 — the environment is so fierce that the visible-light camera known as JunoCam likely will survive only until the eighth orbit, while the microwave radiometer should make it through the 11th orbit.

An eye on the clouds

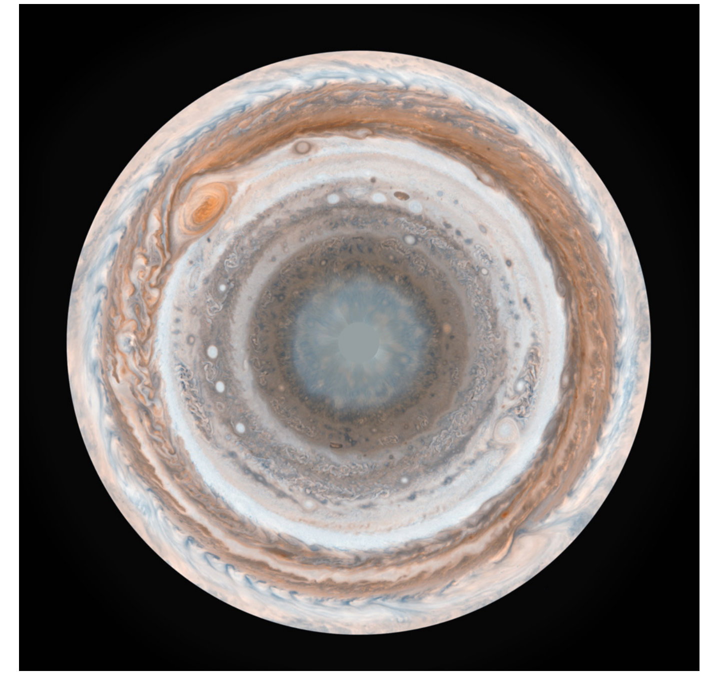
Nevertheless, JunoCam will play a pivotal role during the mission's early phases. Its 58° field of view will provide panoramic views of the jovian cloud tops, including the first ever of the largely unseen north and south polar regions. And the probe's elongated orbit will permit images with resolutions as high as 1.8 miles (3km) per pixel at closest approach, better than any previous spacecraft.

JunoCam also will allow the public to participate directly in the mission. "We are going to have to be choosy and select the places where we want to take pictures," says JunoCam team member Candice Hansen of the Planetary Science Institute. To help with the process, the Juno team has asked amateur astronomers to submit their telescopic images. The scientists hope these can be used to identify dynamic changes in the swirling bands, eddies, and spots that make up Jupiter's atmosphere.

In between the close Jupiter flybys — when Juno is too far from the planet for its camera to pick which features to capture — online discussions will help the scientists decide what should be targeted when the probe swings by again, Hansen says. "We are really counting on having help from ground-based observers." The process worked well during Juno's 2013 Earth flyby. To learn more about participating, visit www.missionjuno.swri.edu/junocam.



The Cassini spacecraft mapped Jupiter in December 2000. Scientists created this view of the planet's northern hemisphere (with the pole at center) from more than a dozen individual exposures. Juno promises much sharper views of the gas giant's polar regions. NASA/JPL/SSI



The Cassini spacecraft also mapped Jupiter's southern hemisphere (with the pole at center) as it flew by in December 2000. Notice the Great Red Spot near the 10 o'clock position and about two-thirds of the way from the pole to the equator. NASA/JPL/SSI

Described by Bolton as "the public's camera" and by Hansen as "science in a fishbowl," JunoCam is just one of nine science instruments aboard Juno. They receive power from a trio of 29-foot-long (8.9 meters) solar arrays — the first set of such arrays ever used this far from the Sun. Together, they produce less than 500 watts — no mean feat at Jupiter, where the Sun is barely 4 percent as bright as it is at Earth. That's about one-third the power delivered by a typical hairdryer.

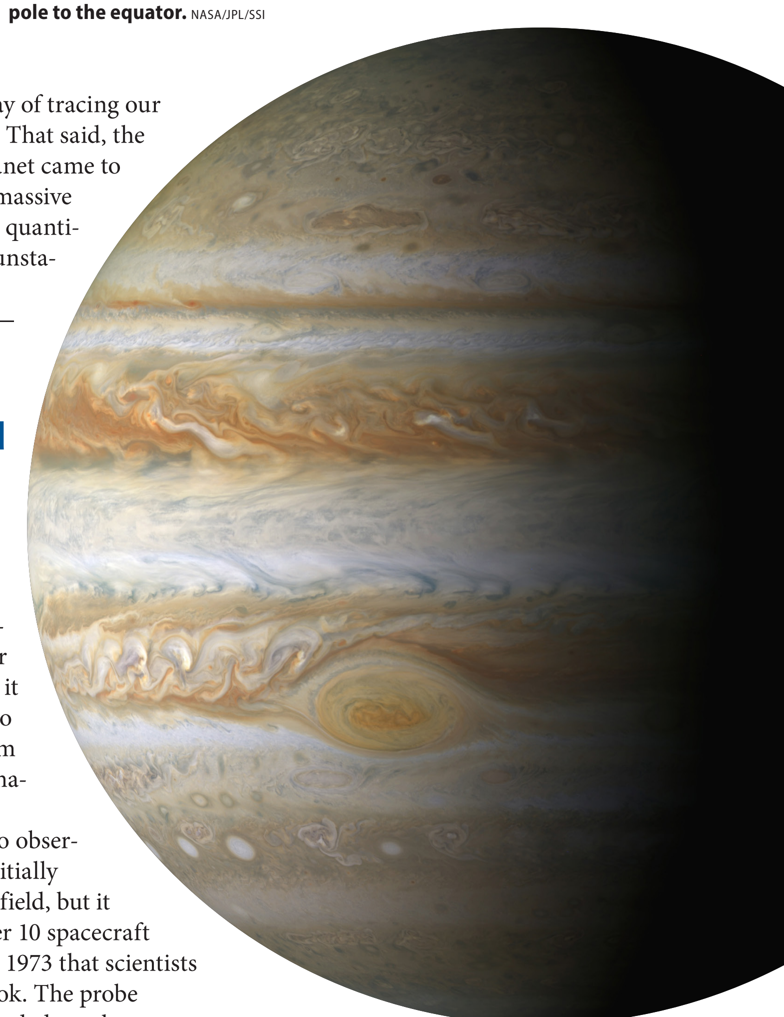
The science team designed the suite of instruments to address the mission's core goals: investigate Jupiter's deep interior, the nature of its hypothetical core, its global water and ammonia reserves, its deep winds — which can reach speeds of up to 384 mph (618 km/h) — and the origins of its internal magnetic field, vast magnetosphere, and powerful aurorae.

This multihued gaseous world consists largely of hydrogen and helium, like the Sun, suggesting that it formed early in the solar system's evolution by trapping much of the material left over from the Sun's birth. "Jupiter is the archetype of giant planets in our solar system," says Bolton. "Unlike Earth, Jupiter's giant mass allowed it to hold on to its original composition, providing us with a way of tracing our solar system's history." That said, the mystery of how the planet came to be — whether from a massive core that drew in huge quantities of gas or from an unstable region in the solar nebula that collapsed — remains unclear.

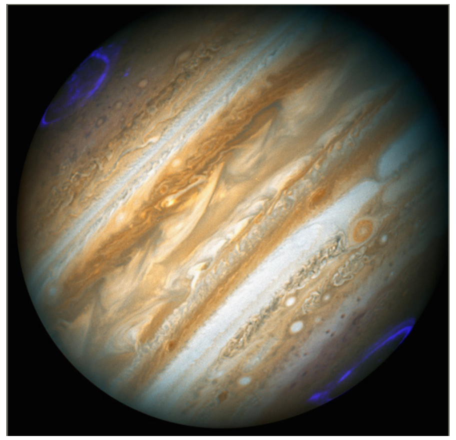
A powerful magnetic field

What is clear, however, is that Jupiter's internal magnetic field has no equal among the solar system's planets. It's thousands of times stronger than Earth's field, and it carves a vast cavity into the solar wind, a stream of charged particles emanating from the Sun.

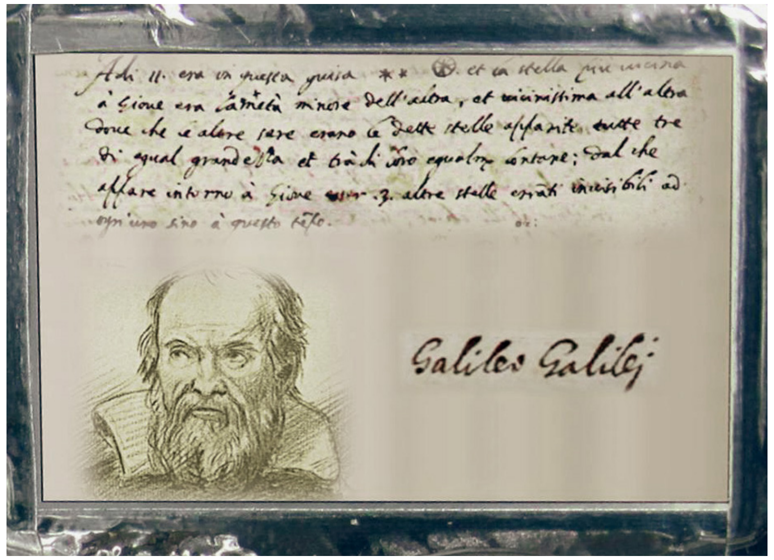
Ground-based radio observations in the 1950s initially revealed the magnetic field, but it wasn't until the Pioneer 10 spacecraft flew past in December 1973 that scientists got their first direct look. The probe showed the cavity extended nearly 5 million miles (8 million km) sunward, and it aroused speculation that a long "magnetotail" might trail off beyond the



Jupiter posed for this true-color portrait made by Cassini in December 2000, when the Saturn-bound spacecraft received a gravity assist from the giant world. NASA/JPL/SSI



Jupiter's aurorae stand out in this Hubble Space Telescope view that highlights the glowing gas. One of Juno's goals is to better understand how Jupiter produces its monster aurorae. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



The Juno orbiter carries this plaque, which shows a self-portrait of Galileo Galilei along with a passage he wrote in 1610 about his observations of Jupiter and its moons. NASA/JPL-CALTECH/KSC

planet. The magnetospheric radiation proved so intense that the electronics of Pioneer 10 and its twin — Pioneer 11, which flew past Jupiter a year later — sustained 1,000 times the lethal dosage for a human and endured multiple circuit failures.

In 1979, Voyagers 1 and 2 confirmed the magnetotail's existence and showed that it corkscrews backward, tadpole-like, out to at least Saturn's orbit some 400 million miles (650 million km) away. Subsequent missions refined scientists' knowledge of Jupiter's magnetic field. Ulysses briefly explored the planet's polar magnetosphere in 1992, Galileo surveyed the equatorial plane during its mission, and New Horizons traversed more than 100 million miles (160 million km) of the magnetotail in 2007. Despite these insights, however, Jupiter's magnetospheric dynamics remain mysterious, and Juno — the only spacecraft ever placed in orbit above the planet's poles — will execute the first global magnetic-mapping campaign.

Mapping this immense magnetosphere is one of just a few ways to understand the world's deep interior, including the origin of this magnetism and the nature of the core. Jupiter's powerful gravity so tightly compresses the atmosphere that it is virtually impenetrable to most sensing techniques.

Juno's twin magnetometers — located about 6.5 feet (2m) apart on a boom at the end of one of the solar arrays — will measure strong and weak emissions 60 times per second. Each instrument will back up its mate, guarding against one's failure and any spurious field the spacecraft itself might generate.

The magnetometer experiment has three goals: precisely map the magnetic field, determine the dynamics of Jupiter's interior, and ascertain the magnetosphere's three-dimensional structure above the poles. Timing is critical, with primary science observations collected within six hours of closest approach. "We're going to make very accurate measurements and basically envelop Jupiter in a dense 'net' of observations," explains magnetometer team leader Jack Connerney of NASA's Goddard Space Flight Center in Greenbelt, Maryland. "That will give us the ability to image what the magnetic field looks like down in Jupiter's core, where it is generated."

Deep inside Jupiter

Scientists hope these observations will yield improved constraints on the mass and radius of the core, whose very existence remains hypothetical. Many models of planet formation require a rocky or icy core with enough mass — perhaps 12 to 45 times Earth's mass, or up to 14 percent of Jupiter's bulk — to pull in the vast quantities of hydrogen and helium the planet possesses. But the imprecise nature of current gravitational measurements makes it equally plausible that there is no definitive core.

Probing Jupiter's hidden depths has always been difficult. The best data scientists have came from the Galileo mission, which dropped a titanium-skinned probe into the jovian atmosphere in December 1995. It survived for about 90 miles (150km) below the cloud tops, a region dominated by ordinary molecular hydrogen, before being crushed. Juno's microwave radiometer will determine how far down the atmospheric circulation Galileo measured extends. It also will profile temperatures inside the planet to a depth of roughly 220 miles (350km), where the pressure reaches 200 bars (about 200 times the atmospheric pressure at Earth's surface). These will allow scientists to construct three-dimensional images of Jupiter's internal structure.

> "Juno's extraordinarily accurate determination of the gravity and magnetic fields of Jupiter will enable us to understand what is going on deep down in the planet." — David Stevenson

Although mission planners expect the radiometer to survive only 11 orbits, it has another key role: to study the abundance and distribution of the planet's ammonia and water. The Galileo orbiter imaged clouds of ammonia, but water has proven surprisingly elusive. Scientists have seen only minor amounts of this substance in small pockets.

Astronomers know that hydrogen and oxygen are abundant in Jupiter. But by determining the ratio of oxygen to hydrogen and measuring how much water there is, Juno can shed light on how the gas giant world evolved. To Juno science team member Tobias Owen of the University of Hawaii, it evokes reminders of the mythological Juno, ever watchful of her husband's mischief. "Our Juno looks through Jupiter's clouds to see what the planet is up to," he says, "not seeking signs of misbehavior, but searching for whispers of water."

Farther down, conditions grow more hellish. Extreme temperatures and pressures, reaching as high as 4 million bars, strip molecular hydrogen of its electrons and force it into an electrically conductive state known as liquid metallic hydrogen. Although researchers have produced minute quantities of this exotic substance for brief periods in the laboratory, planetary scientists think Jupiter contains a large shell filled with it. "It's in this conducting shell that we think Jupiter generates its magnetic field," says Owen.

Jupiter's gravitational pull also will help unlock some of its core secrets. Scientists can peer inside the planet by carefully analyzing the radio signals the spacecraft returns — deviations in the probe's motion, caused by changes in Jupiter's gravity and thus mass distribution, will show up as a slightly altered signal. "Juno's extraordinarily accurate determination of the gravity and magnetic fields of Jupiter will enable us to understand what is going on deep down in the planet," says science team member David Stevenson of the California Institute of Technology. "These and other measurements will inform us about how Jupiter's constituents are distributed, how Jupiter formed, and how it evolved, which is a central part of our growing understanding of the nature of our solar system."

An ethereal glow

Back near Jupiter's cloud tops, the planet's magnetic field generates powerful aurorae that are thousands of times stronger than Earth's own. Voyager 1 first saw this auroral activity and found it covered an area larger than Earth. The observations suggested that material from Jupiter's volcanic moon, Io, flows along magnetic field lines into the atmosphere and helps trigger the aurorae. Galileo detected two-directional beams of electrons that poured up to a billion watts into the atmosphere. From Earth orbit, the Hubble Space Telescope revealed aurorae projecting hundreds of miles beyond the planet's limb while the Chandra X-ray Observatory has detected auroral X-ray emissions.

These three Lego figurines — Galileo Galilei (left), the Roman goddess Juno (center), and her husband, Jupiter (right) — are also along for the ride as Juno orbits Jupiter. NASA/JPL-CALTECH/LEGO

Juno's scientific prowess and unique orbit promise new insights into these phenomena. The sensors of the Jovian Auroral Distribution Experiment will examine the angular distributions, energies, and compositions of ions and electrons at relatively low energies. Complementing this experiment is the Jupiter Energetic Particle Detector Instrument — nicknamed the "hockey puck" because of its shape — which will examine the distributions and energies of hydrogen, helium, oxygen, and sulfur particles at higher energies, focusing on what accelerates them to such high velocities.

An ultraviolet imaging spectrograph will observe auroral emissions from the polar magnetosphere on both day and night sides of the planet, while the Waves sensor will measure radio and plasma emissions in the auroral region. Finally, the Jovian Infrared Auroral Mapper will investigate the dynamics of Jupiter's aurorae as well as identify water and ammonia abundances at depths of 30 to 45 miles (50 to 70 km) below its cloud tops. Located on Juno's bottom deck, this was the last instrument added to the payload, in 2007. "We entered the mission later," says Deputy Principal Investigator Alberto Adriani, "so there was no room in the big place where all the other instruments are. We had to run quite fast to keep pace with the mission."

And the pace of the mission will prove as critical as the science. Juno's exposure to high radiation levels creates an elevated risk of hardware failures. Moreover, the spacecraft's orbit crosses the paths of the moons Europa, Ganymede, and Callisto — all of which may harbor subsurface water and perhaps ancient or extant microbial life. That makes it imperative that NASA sends Juno to a grave in Jupiter's atmosphere when the mission ends in early 2018. This will eliminate the chance of the spacecraft impacting one of these moons and contaminating a possible ocean with toxic propellants and debris.

Juno's short life will blaze a trail of jovian exploration that dates back across four decades of space exploration and four centuries of telescopic observation. It carries a tiny aluminum plaque to honor Galileo Galilei, who discovered Jupiter's four large moons. The plaque includes a self-portrait of Galileo and, in his own hand, a passage written in 1610 that describes his observations of those moons.

Also tucked aboard are three aluminum Lego figurines. One represents Galileo himself, with a telescope in his left hand and a Jupiter globe in the right. The other two represent the Roman god Jupiter with his thunderbolt and his ever-vigilant wife, Juno, holding a magnifying glass with which to unravel her husband's secrets. In just a few months, her robotic embodiment should be achieving similar results with her spouse's celestial counterpart.

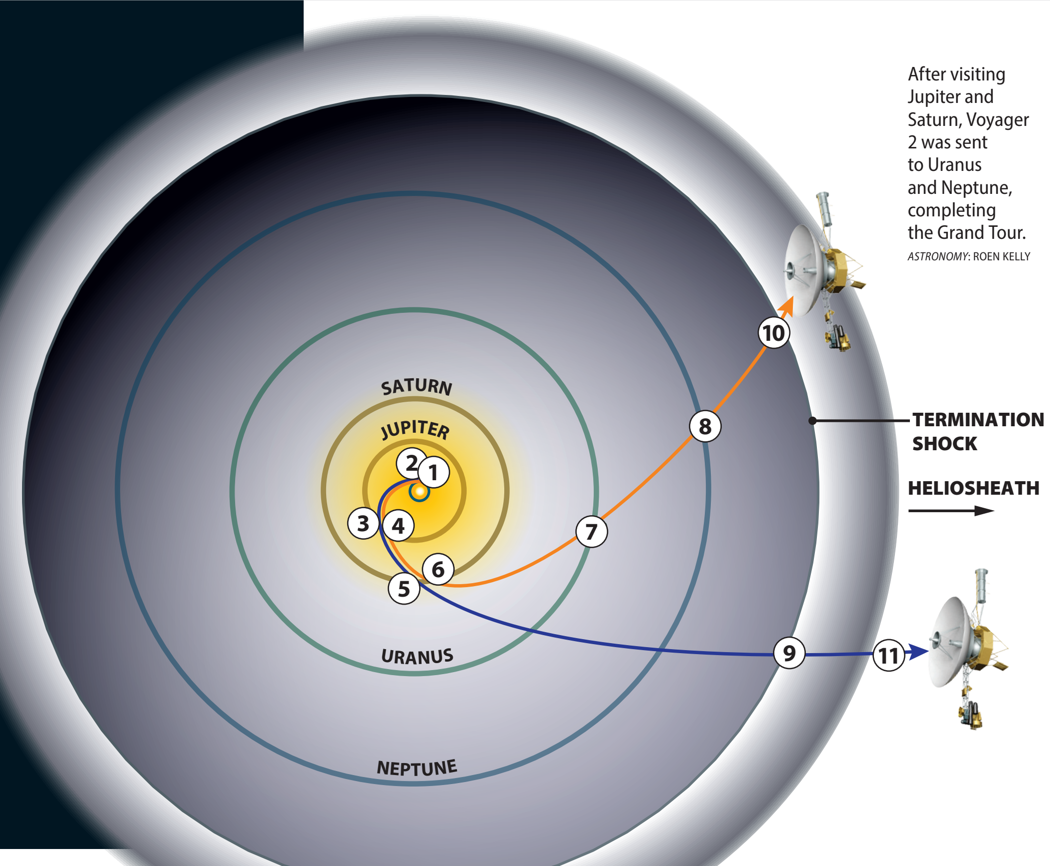
Juno's camera captured this view of Earth when it flew past October 9, 2013. The image shows Argentina's coast and the South Atlantic Ocean. NASA/JPL/SwRI/MSSS/"GERALD"

Ben Evans *is a British spaceflight writer and author of the multivolume* History of Human Space Exploration, *published by Springer-Praxis.*

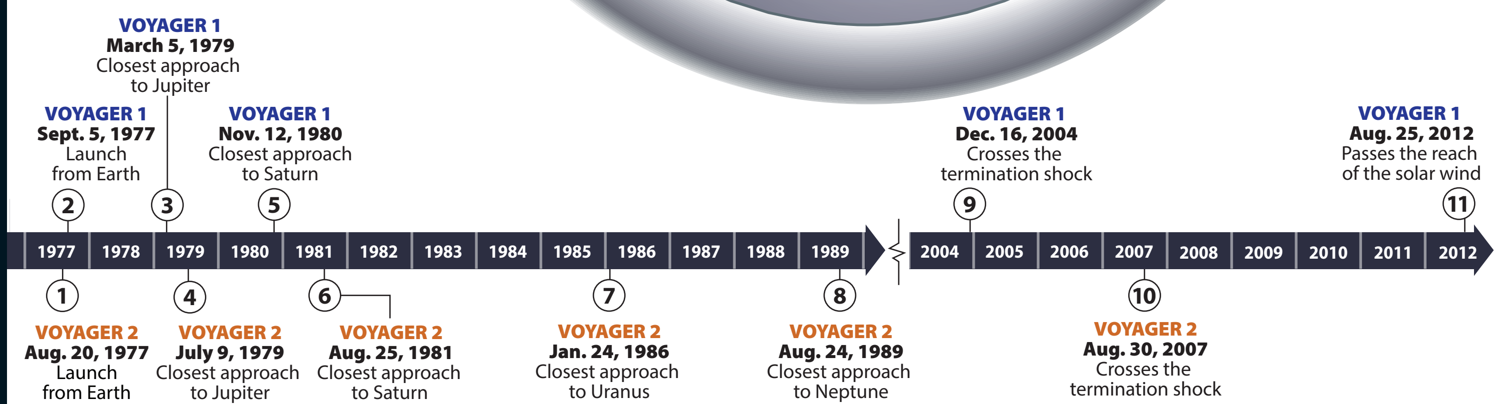
VOYAGER'S GRAND TOUR

The twin probes explored more planets, discovered more moons, and offered more breaking news than any other spacecraft.

by Michael E. Bakich



After visiting Jupiter and Saturn, Voyager 2 was sent to Uranus and Neptune, completing the Grand Tour. *ASTRONOMY*: ROEN KELLY



When NASA launched Voyager 1 and Voyager 2 in the summer of 1977, its engineers were sending the spacecraft on specific missions. Originally, the space agency tasked the Voyagers with conducting close-up studies of Jupiter and Saturn. They would compile data on magnetic fields, the Sun's influence, Saturn's rings, a few large moons, and send back lots of great images. To accomplish all this, engineers built into them a generous (for the 1970s) five-year lifetime.

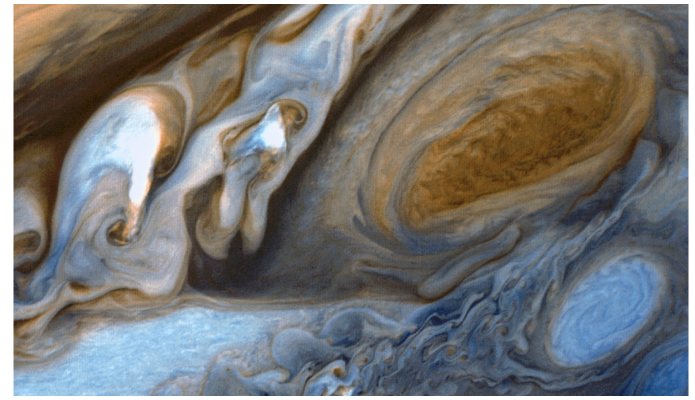
At Jupiter, and then Saturn, the mission achieved far more than its original objectives. Then came the big news: By carefully tweaking Voyager 2's flight path, flybys of Uranus and Neptune were possible.

The two-planet addition became the Grand Tour. The projected lifetimes stretched to 12 years for the Neptune encounter August 24, 1989. And that date would, in turn, become early history. As of 2018, both Voyagers have finished their fourth decade of operation — and they show no signs of stopping.

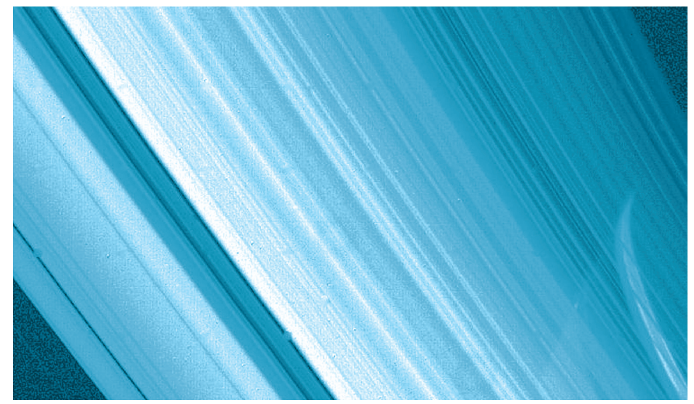
One surprise after another

The Voyager spacecraft made enough discoveries to fill this magazine — and we did just that for our October 2017 issue — but most scientists would view the following as the top 10.

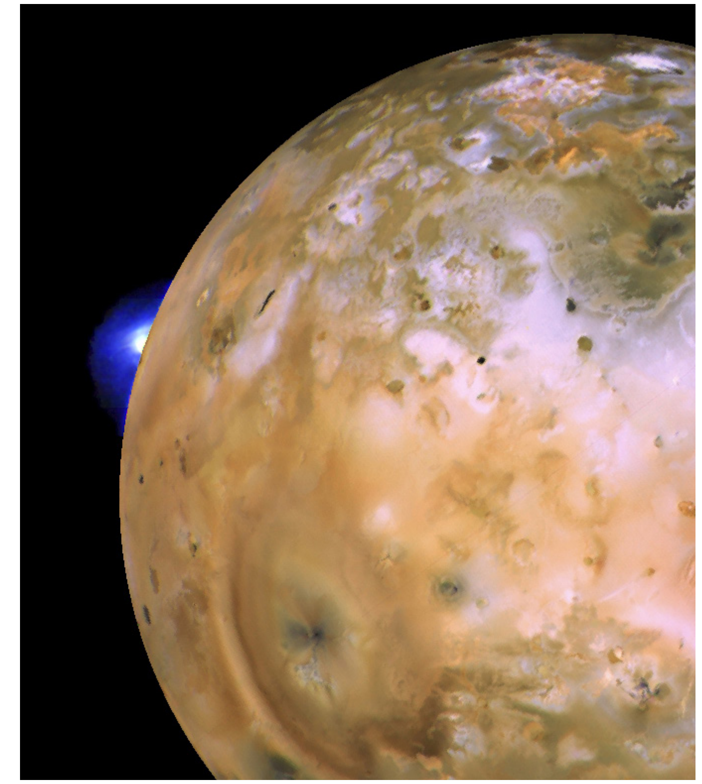
1) Volcanoes on Jupiter's moon Io. This was the biggie. While processing a Voyager 1 image, navigation engineer Linda Morabito discovered a feature along Io's edge. What she initially thought was a moon turned out to be a plume from an active volcano. Planetary geologists subsequently learned Io's interior is in turmoil: Jupiter's gravity stretches it differently depending on how far the moon is from the planet. Such an interaction creates intense heating due to friction. The result is that Io has 100 times as much volcanic activity as Earth.



The Great Red Spot is a spinning anti-cyclone in Jupiter's southern hemisphere. At the time Voyager 1 snapped this close-up of swirling clouds, the Great Red Spot was three and a half times the size of Earth. NASA/GODDARD SPACE FLIGHT CENTER



This Voyager 2 image is just one of hundreds of high-resolution views of Saturn's rings. The probe took this shot from a range of 2 million miles (3.3 million kilometers). At lower right, you can see the planet through the rings. The Cassini Division is the dark gap that extends from lower center to upper left. NASA/JPL



Above: As Voyager 1 flew by the jovian moon Io, it captured this image of an active plume (left edge, bluish white) coming from Loki, a volcano then on Io's limb, from 340,000 miles (490,000 km) away. The dark heart-shaped feature near the bottom shows fallout deposits from the active plume Pele. NASA/JPL/USGS

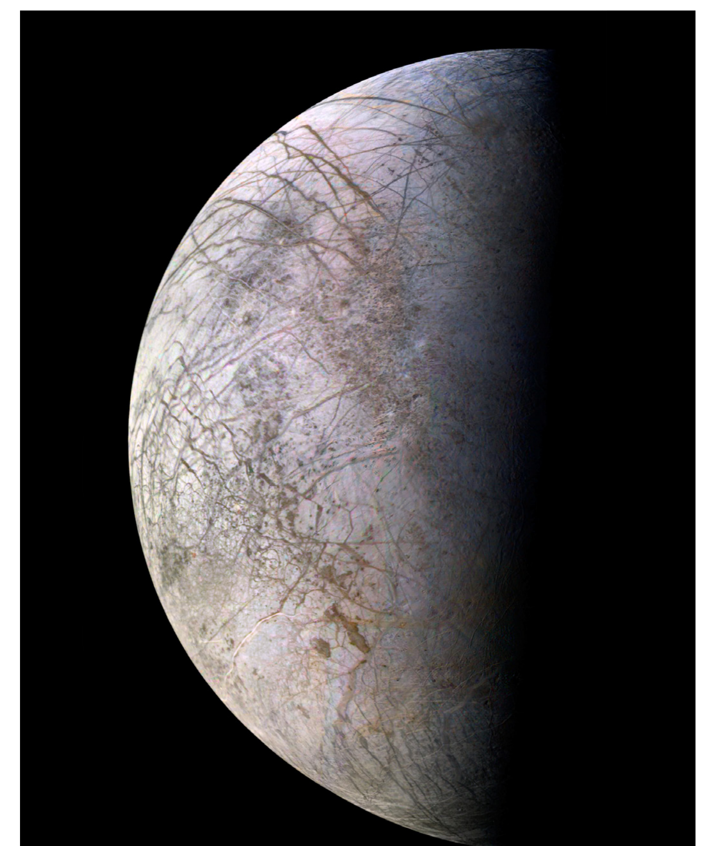
Below: Voyager 2 revealed Europa's surface to be devoid of mountains or craters as the spacecraft flew by the jovian satellite July 9, 1979. The main feature it did show was a network of crisscrossing streaks. The lines are where warmer ice broke through the colder surface when tidal forces from Jupiter and its other large moons cracked the outer layer of the moon. NASA/JPL/TED STRYK

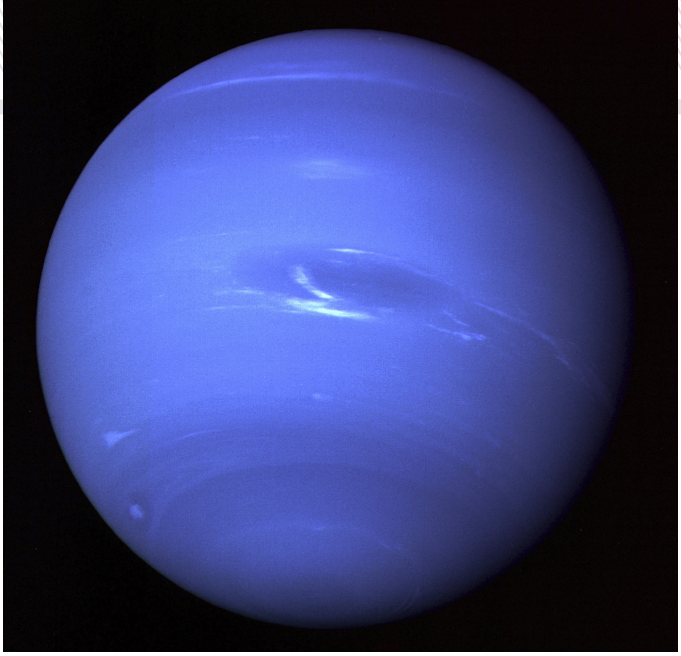
2) Jupiter's turbulent atmosphere. After watching the giant planet's cloud bands and Great Red Spot from afar for three centuries, scientists got their first up-close look with Voyager 1. They saw dozens of interacting hurricanes, some as large as planets. And the Red Spot itself displays layers of complex activity. It lies 5 miles (8 kilometers) above the surrounding clouds, and time-lapse movies confirmed its counterclockwise rotation.

3) An ocean within Europa? As the two spacecraft flew by the fourth-largest jovian moon, its icy crust showed a dizzying series of intersecting cracks. Calculations indicated the possibility of a liquid ocean deep beneath the ice. Such a feature likely exists because of the tidal interaction between the moon and Jupiter. But Europa's orbit is closer to circular than Io's, so the internal heating isn't enough to create volcanoes — just enough to melt vast quantities of ice.

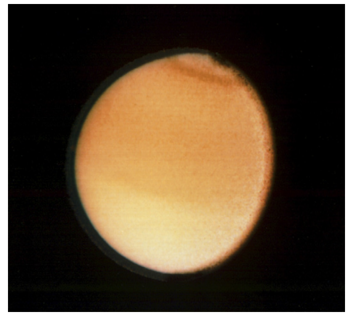
4) The Io torus. Voyager 1 found a thick ring of ionized sulfur and oxygen shed by Io that inflates Jupiter's giant magnetic field. The material originates within the moon's volcanoes, some of which are so powerful that they erupt it directly into space.

5) Saturn's ring structure. Before 1980, astronomers recognized fewer than six rings around Saturn. But Voyagers' cameras showed that each ring had numerous subdivisions. In addition, Voyager 1 discovered that the enigmatic F ring has two small "shepherding" satellites, Pandora and Prometheus, whose gravity keeps the ring in place.

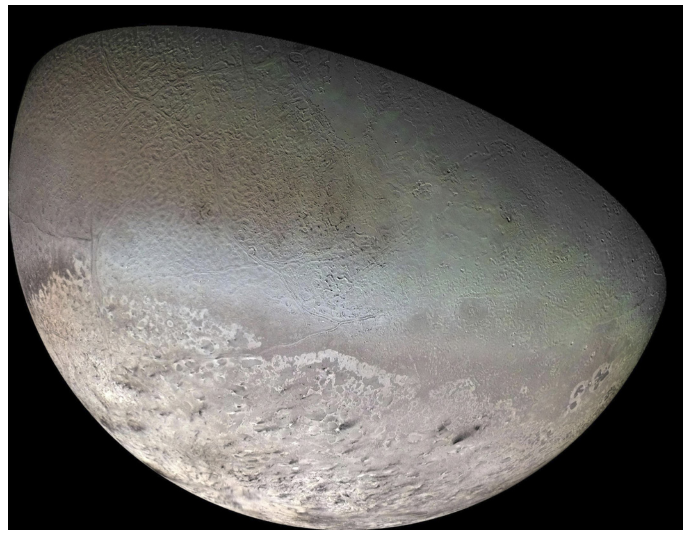




Astronomers created this image of Neptune from the last whole-planet exposures taken with the Voyager 2 narrow angle camera. The picture shows the Great Dark Spot and its companion bright smudge in the center, the fast-moving bright feature called "Scooter," and the little dark spot at lower left. NASA



This Voyager 2 photograph of Titan, taken August 23, 1981, from a range of 1.4 million miles (2.3 million km), shows some detail in the cloud systems on this saturnian moon. Titan's southern hemisphere appears lighter than its northern half in this image. It also shows a dark collar near the north pole. This large moon's atmospheric circulation is responsible for forming these bands. NASA/JPL



Voyager 2 took this global color mosaic of Triton, Neptune's largest moon. It is one of only three objects in the solar system with an atmosphere of mainly nitrogen. (The others are Earth and Titan.) But this moon is so cold (–391 degrees Fahrenheit) that most of the nitrogen has condensed on the surface as frost. NASA/JPL/USGS

6) Titan's atmosphere. Voyager 1 showed that Titan has a nitrogen atmosphere with a surface pressure 45 percent greater than on Earth. Voyager data hinted at the possibility (later confirmed) that this satellite experiences clouds of methane and other hydrocarbons, and that rain falling from those clouds creates lakes of liquid methane on the surface.

7) The Great Dark Spot. As Voyager 2 approached Neptune, scientists identified a gigantic dark feature. It was dubbed the Great Dark Spot, and researchers were at a loss to explain how such a storm could form given the small amount of energy Neptune receives from the Sun. Further study showed the Great Dark Spot, and similar features observed since Voyager 2 passed by, are cyclones that exist as holes in the planet's upper atmosphere.

8) Neptune's supersonic winds. The discovery of the fastest winds in the solar system in the atmosphere of the most distant planet was a stunner. Voyager 2 measured wind speeds of 1,100 mph (1,600 km/h) above Neptune. Because the planet radiates 2.6 times as much energy as it receives from the Sun, researchers think the decay of radioactive elements deep within Neptune powers the currents.

9) Geysers on Triton. In addition to observing clouds and hazes in the thin atmosphere of Neptune's largest satellite, Voyager 2 found evidence of cryovolcanoes — otherwise known as ice volcanoes. These active geysers within the moon's southern polar cap spew dust-laden nitrogen up to 5 miles (8 km) above the surface, which lies in perpetual cold at a temperature of 37 kelvins (–393 degrees Fahrenheit).

More than 40 years after their launches, Voyager 1 and Voyager 2 continue to go where no one has gone before.

10) The edge of the solar system. The Voyager spacecraft didn't stop working after their planetary encounters. In 2014, Voyager 1 passed an important boundary within our solar system called the heliopause. This is where the strength of the solar wind isn't powerful enough to overcome the stellar winds of nearby stars. Voyager 1 crossed another border, the termination shock, where the solar wind abruptly slows to subsonic speed, back in 2004. Voyager 2 followed in 2007. As each spacecraft crossed the heliopause, their Voyager Interstellar Mission commenced.

A new horizon

As of February 8, 2018, Voyagers 1 and 2 are 13.16 billion miles (21.18 billion km) and 10.91 billion miles (17.56 billion km) from Earth, respectively. And the craft are still making news. In 2011, Voyager 1 crossed into a zone astronomers call the stagnation region. There, at the boundary of interstellar space, the solar wind is less intense, but the magnetic field measures twice as strong.

Voyager 1 is leaving the solar system at about 320 million miles (520 million km) per year. Meanwhile, Voyager 2 is exiting at about 290 million miles (470 million km) per year.

Both spacecraft continue to study ultraviolet sources among the stars and the boundary between the Sun's influence and interstellar space. Communications will be maintained until the Voyagers' power sources no longer can run critical subsystems.

A legacy of discovery

The grand tour of the solar system (and beyond) continues. The primary explorers are two workmanlike spacecraft that achieved the goals scientists set before them, far surpassed their planned life spans, and adapted to new expectations by evolving technologically. Indeed, more than 40 years after their launches, Voyager 1 and Voyager 2 continue to go where no one has gone before.

Michael E. Bakich, *a senior editor of* Astronomy, *remembers the Voyager missions and the impact they had on visitors to the planetariums where he worked.*