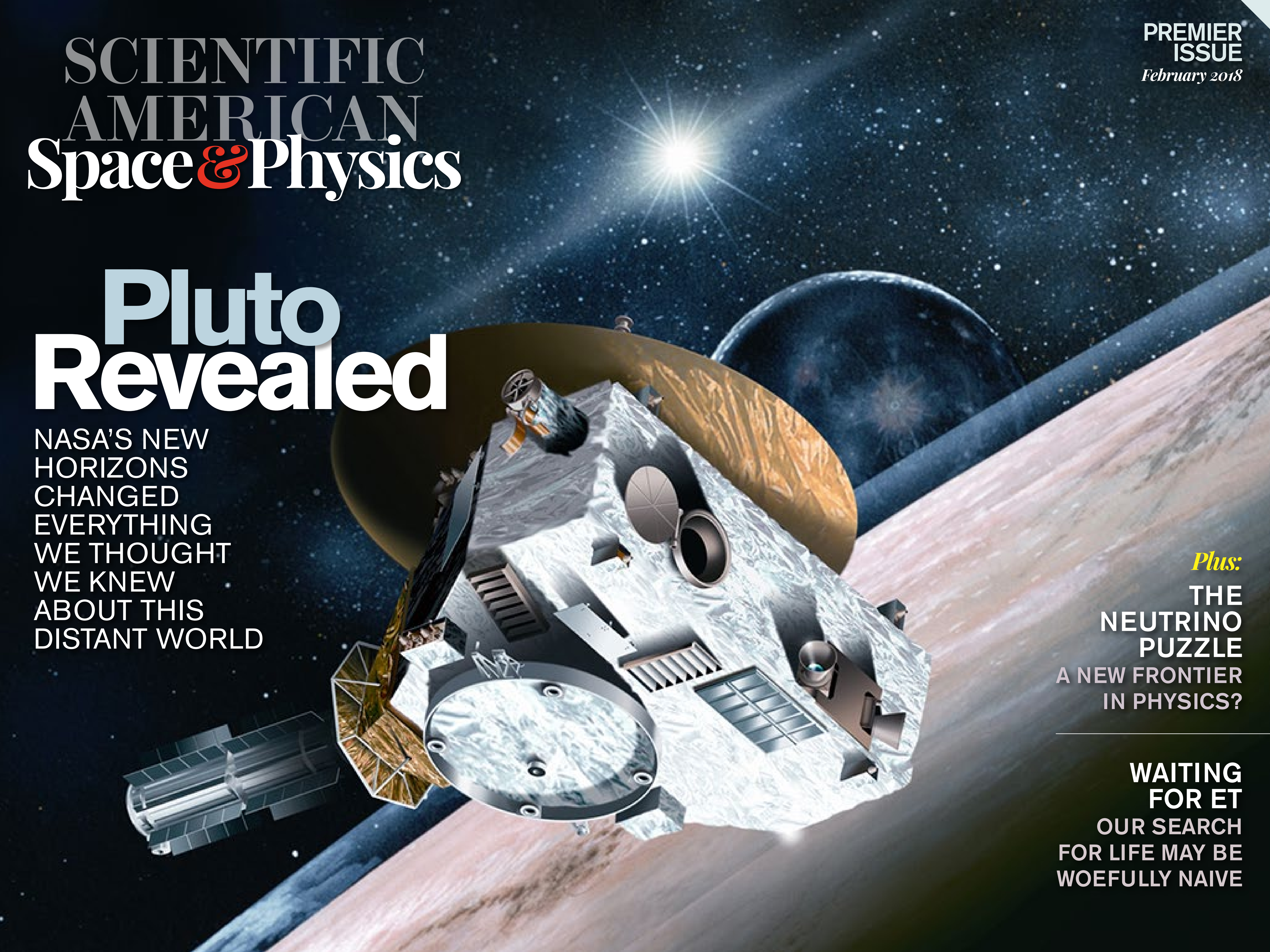


PREMIER ISSUE
*February 2018*

# SCIENTIFIC AMERICAN Space & Physics

# Pluto Revealed

NASA'S NEW HORIZONS CHANGED EVERYTHING WE THOUGHT WE KNEW ABOUT THIS DISTANT WORLD

*Plus:*

## THE NEUTRINO PUZZLE

A NEW FRONTIER IN PHYSICS?

## WAITING FOR ET

OUR SEARCH FOR LIFE MAY BE WOEFULLY NAIVE

# Cassini
# At Saturn

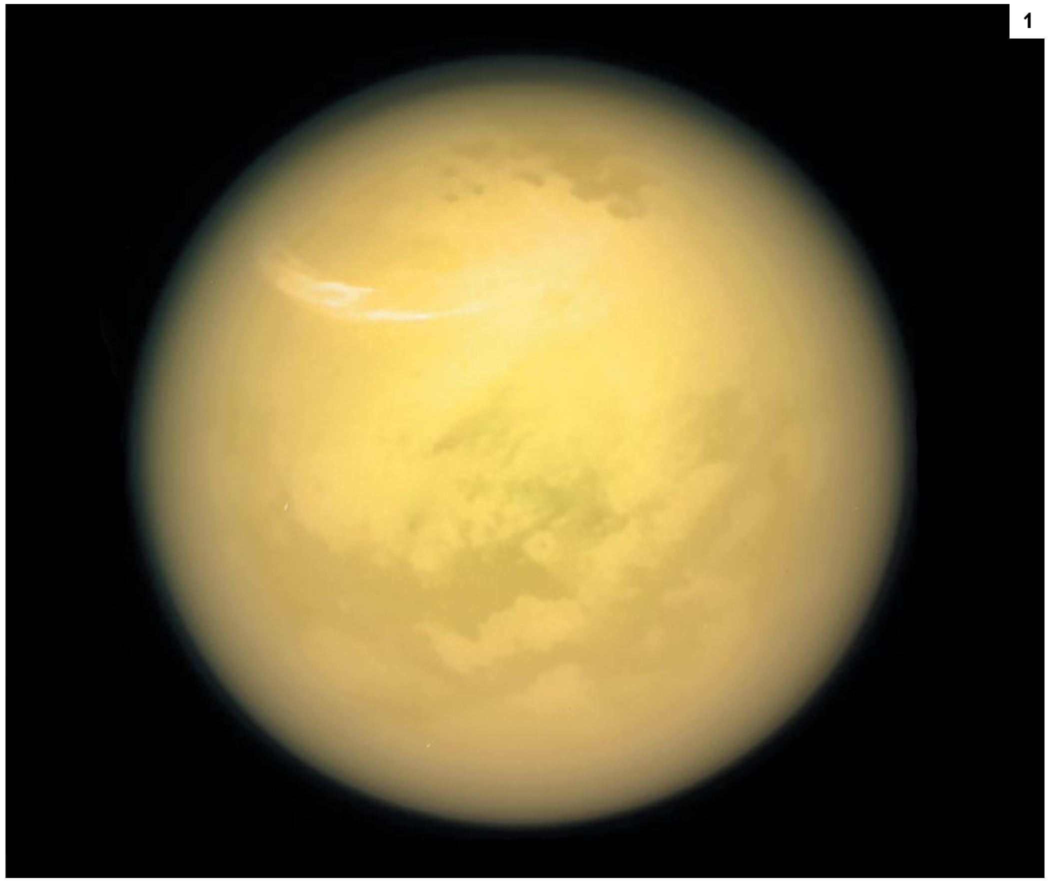
**A historic exploration of the ringed planet, unprecedented in magnitude and spectacle, comes to an end**

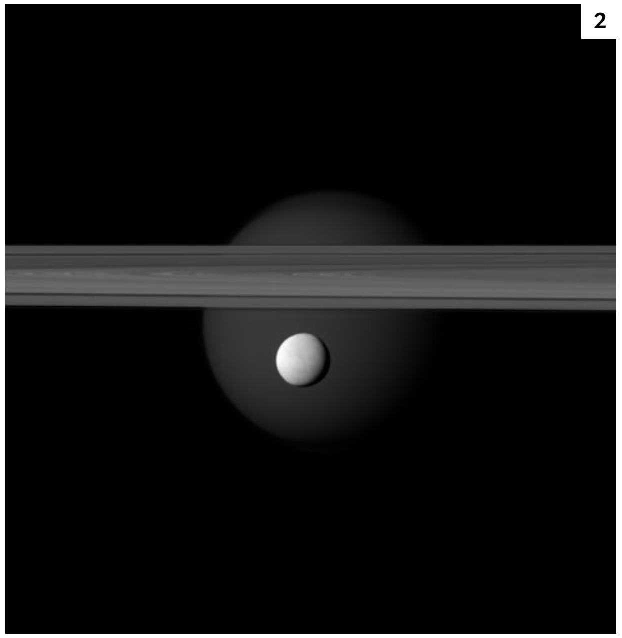
*By Carolyn Porco*

COURTESY OF NASA, JPL AND SPACE SCIENCE INSTITUTE

**Carolyn Porco** is a planetary scientist at the Space Science Institute in Boulder, Colo., and leader of the Cassini mission's imaging team. She is a visiting scholar at the University of California, Berkeley, and a member of Scientific American's board of advisers. This article was written, in part, while she was the science writer in residence at the Huntington Library, Art Collections, and Botanical Gardens in San Marino, Calif..

SOME EVENING WHEN SATURN IS HIGH IN THE SKY and the night is clear and dark, take a look through a backyard telescope. When you have had your fill of the planet's awe and beauty, search online for images that NASA's Cassini spacecraft has returned over the past 13 years in its travels around this ringed wonder. It will likely hit you hard: how far we have traveled, how proficient we have become as interplanetary explorers and how extraordinary an accomplishment it has been to come so intimately to know a world as distant as Saturn.





TITAN, Saturn's largest moon, shines in a false-color image (1) and looms in the distance (2) behind the smaller moon Enceladus and Saturn's rings.

Last September Cassini finished its travels around Saturn by diving, on command, into the planet's atmosphere. It was incinerated in a fireball ensuring that it will never accidentally hit and thereby contaminate any Saturnian moons that might harbor conditions suitable for life.

As the leader of the mission's imaging team, I, along with many of my colleagues on both sides of the Atlantic, began working on Cassini in late 1990, when it was still nothing more than an idea, a vision in the mind. I saw it through the planning and construction process, watched in person as the spacecraft launched on October 15, 1997, from Cape Canaveral, Fla., endured its seven-year voyage to Saturn and had a front-row seat as it arrived at its final destination in 2004. There and then Cassini began revolutionizing our view of Saturn and everything that surrounds it.

No mission has ever explored a planetary system as rich as Saturn's in such depth for so long. On its moon Titan, we found seas of hydrocarbons and a surface environment whose complexity rivals that of Earth. We observed the meteorology of Saturn's atmosphere and witnessed the birth, evolution and demise of giant storms. We saw new phenomena in Saturn's rings that told of the processes involved in the formation of solar systems, including our own. Like the cartographers of old, we mapped the moons of Saturn for future explorers and uncovered new ones, including an entire class of small bodies embedded within the rings themselves. And

## IN BRIEF

- **After 13 years** in Saturn's orbit, the Cassini spacecraft ended its mission in September 2017 by diving into the planet's atmosphere.
- **Over the course** of its voyage Cassini surveyed Saturn's atmosphere, rings and moons in exquisite detail. In 2005 Cassini's Huygens probe descended to the surface of Saturn's moon Titan.
- **Among its many** discoveries, Cassini found liquid-methane lakes on Titan and a buried liquid-water ocean on the moon Enceladus that escapes to the surface via geysers. Scientists suspect this underground sea might be capable of hosting alien life.
- **Cassini also** uncovered mountainous waves of rubble and "moonlets" in Saturn's rings and an effect that turns its atmosphere blue in the winter.

COURTESY OF NASA, JPL-CALTECH AND SPACE SCIENCE INSTITUTE (1); COURTESY OF NASA, JPL-CALTECH, SPACE SCIENCE INSTITUTE

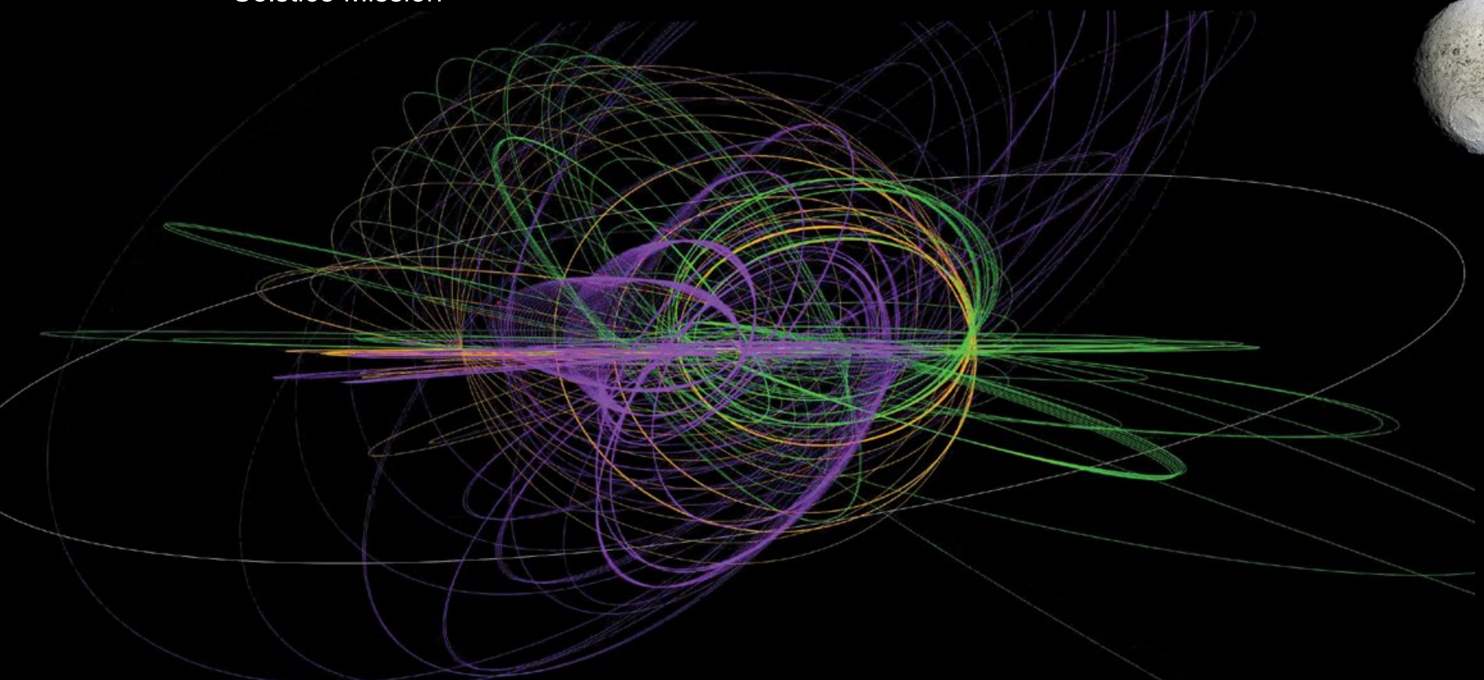
# 13 Years at Saturn

With its fuel source dwindling, the Cassini spacecraft dove into the atmosphere of Saturn in mid-September after 13 years in orbit. Over the course of its mission the probe delivered unprecedented discoveries about the complex planet, as well as about its varied moons and rings. It revealed worlds where rivers of methane flow into vast lakes, where jets of ice crystals from an underwater ocean spew into space, and where a single storm can encircle a giant planet. Here are some highlights. *–Edward Bell*

## SPACECRAFT

Since Cassini took up residence around Saturn on June 30, 2004, its 293 orbits of Saturn varied in size, orientation and angle to give it both up-close and panoramic views of many locales in the system. The spacecraft completed its four-year initial Prime Mission in 2008 and then began a two-year Equinox Mission, followed by a second extension running seven years called the Solstice Mission.

**Cassini Orbits**
- Prime Mission
- Equinox Mission
- Solstice Mission

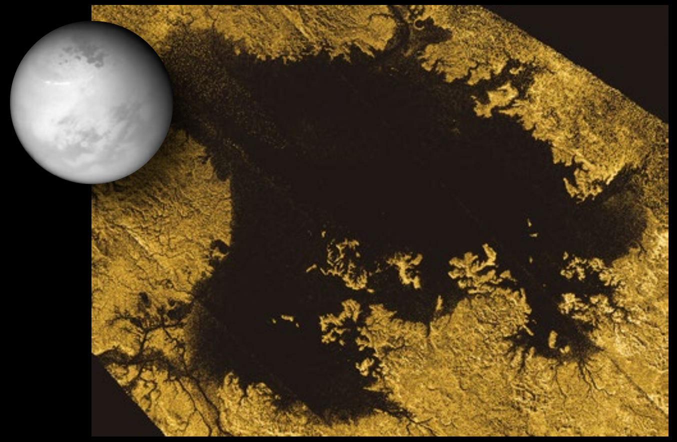


***Ron Miller*** (Enceladus surface illustration)***; NASA,JPL-Caltech,ASI And Cornell*** (Titan surface)***;***
***COURTESY OF NASA, JPL-Caltech and Space Science Institute*** (all other photographs)

## MOONS

### ENCELADUS

On this moon Cassini found towering geysers erupting from the south polar region, as seen in this artist's rendering. Evidence suggests they spring from a global subsurface water ocean that contains organic compounds and may be capable of hosting life.



### TITAN

Saturn's largest satellite is the only place in the solar system other than Earth that has known stable liquid on its surface. Titan has many geologic and atmospheric processes similar to those on our planet, which generate methane rains that build river channels and form lakes and seas containing liquid methane and ethane. One lake is shown here in this false-color radar image from Cassini.

### IAPETUS

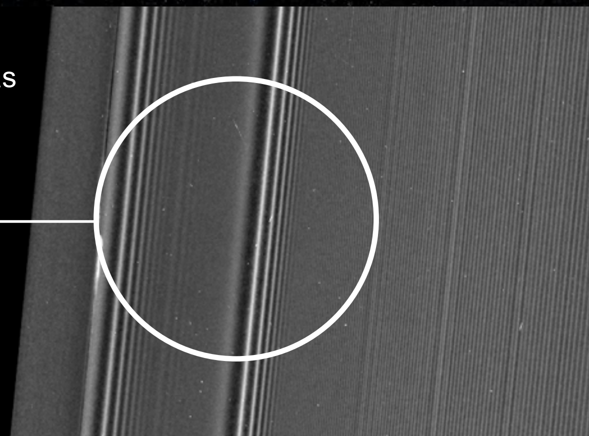
This odd moon presented a mystery with its two-faced surface, which is half black and half white. Dark dust in Iapetus's orbital path lands on the leading face of the moon, and a thermal process transfers ice from the dark face to the light. This close-up image reveals that the same thermal process acts on small spatial scales as well.

### HYPERION

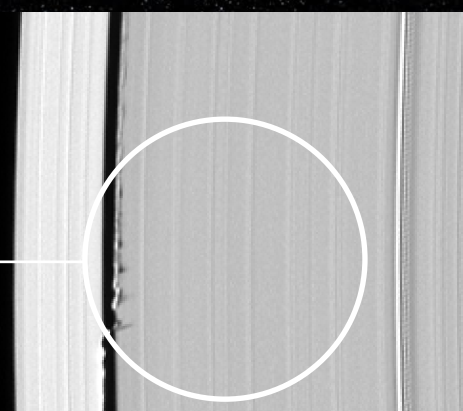
Cassini found this hamburger-shaped moon is pockmarked like a sponge. Scientists think that its unusually low density causes impacts to indent the surface rather than excavating it.

## RINGS

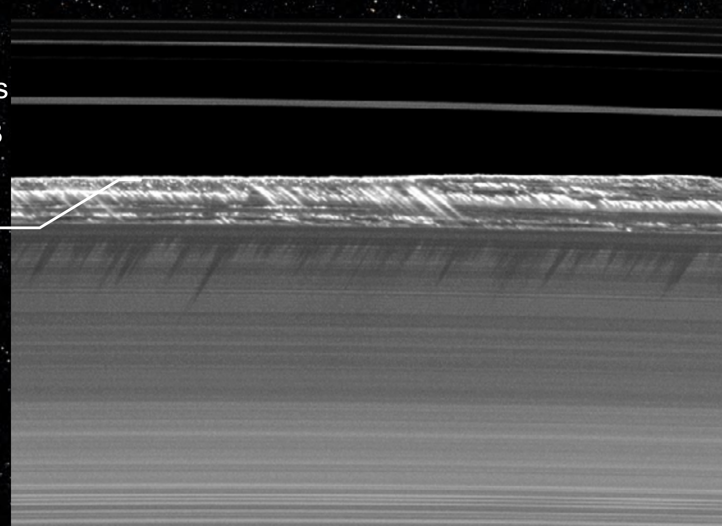
Cassini's close examination of Saturn's rings found that propeller shapes such as this one are gravitational disturbances caused by a moonlet too small to clear the area.



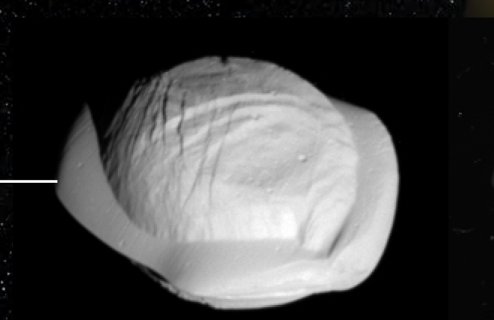
The tiny moon Daphnis, seen as a small dot in the Keeler ring gap, makes waves in the edges of the rings as it passes through.



A mountainous wall of ring rubble rises vertically in places 3.5 kilometers from Saturn's B ring and stretches at least 20,000 kilometers across.



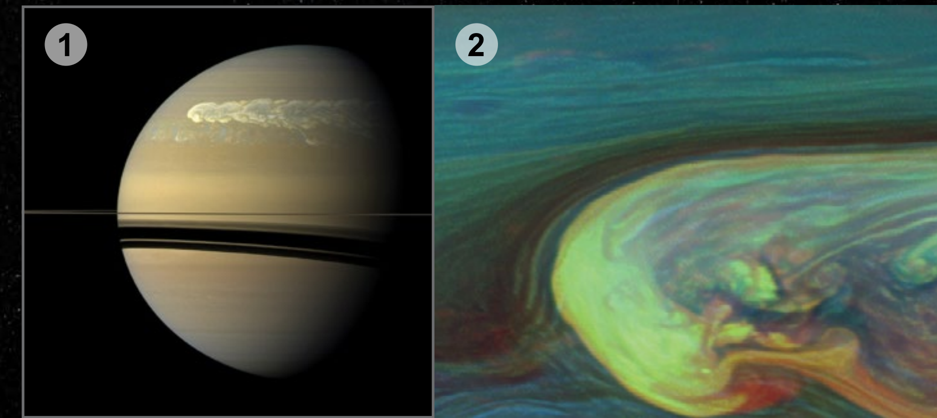
Pan, a 28-kilometer-wide moon in the Encke gap, got its cartoonish configuration from ring material falling onto it.

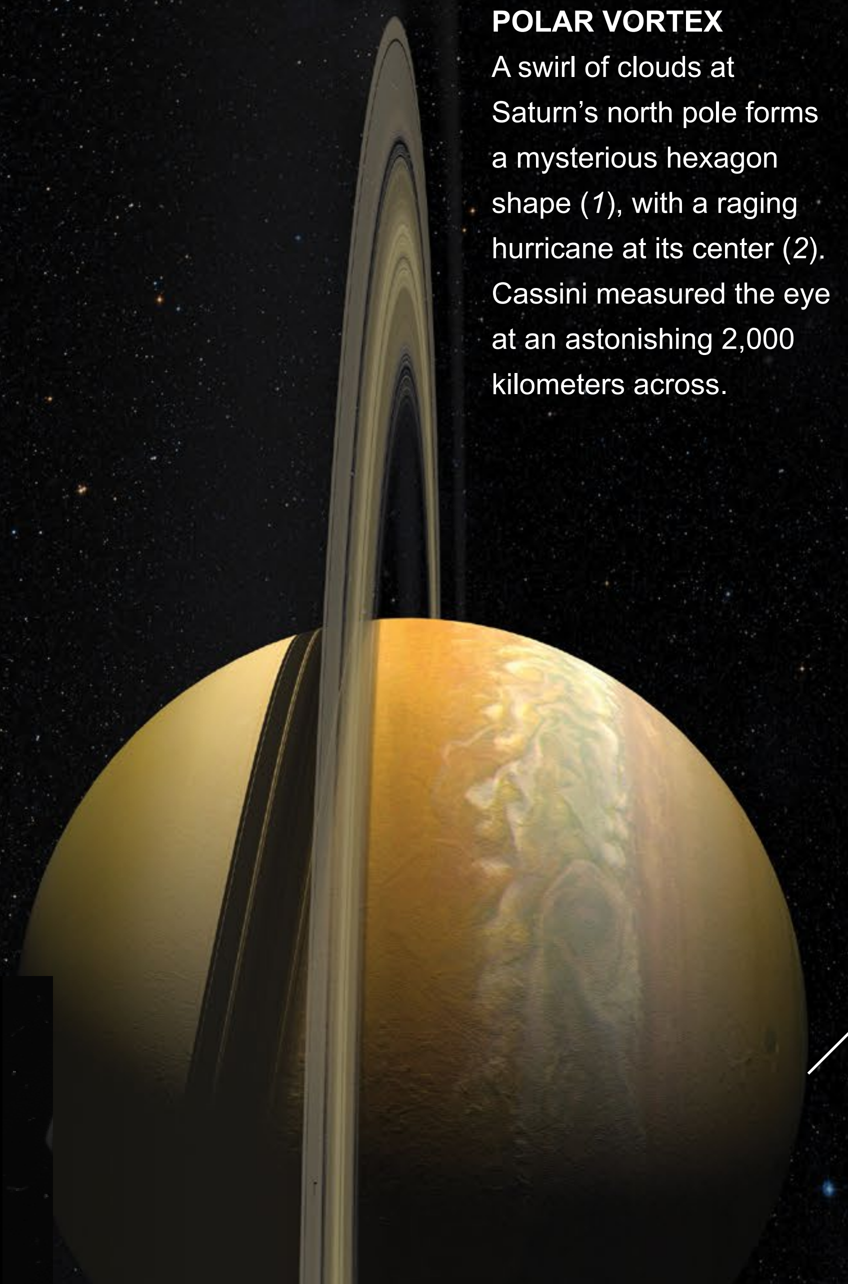


## ATMOSPHERE

### SUPERSTORM

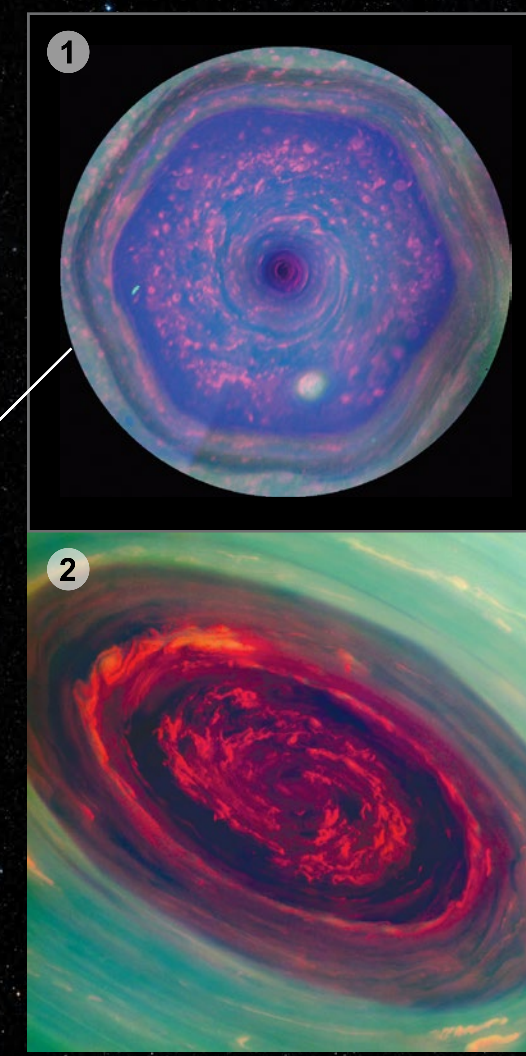
In 2010 Saturn's atmosphere erupted with an immense storm that began to spread around the planet (*1*). Within months this storm grew to encircle the globe, eventually meeting up with itself. Cassini imaged a false-color detail of the storm's various cloud layers (*2*).



### POLAR VORTEX

A swirl of clouds at Saturn's north pole forms a mysterious hexagon shape (*1*), with a raging hurricane at its center (*2*). Cassini measured the eye at an astonishing 2,000 kilometers across.



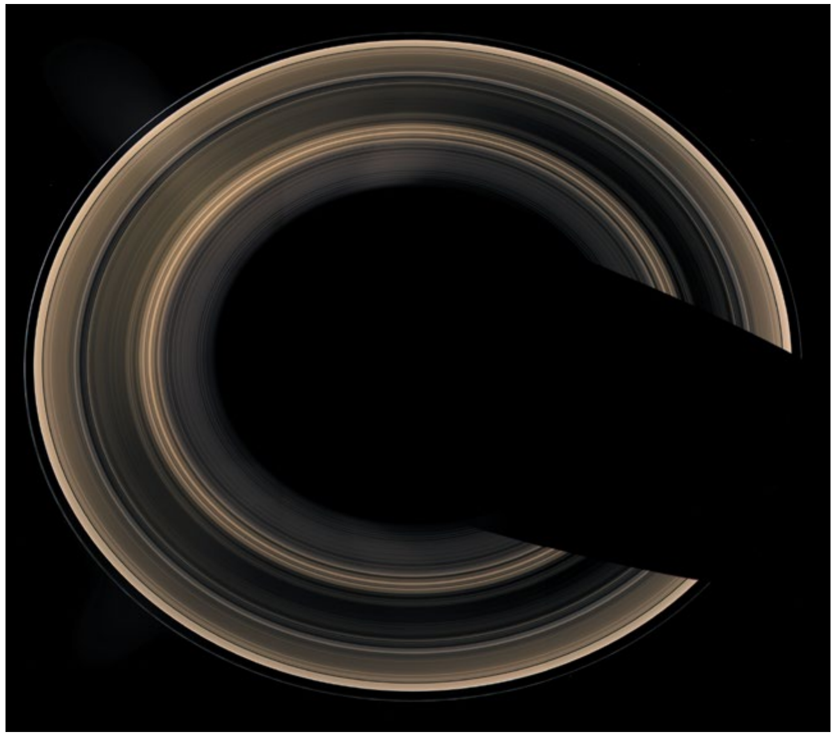

***Edward Bell*** (Saturn vertical composite)
***COURTESY OF NASA, JPL-Caltech and Space Science Institute*** (all other photographs)

then there is what I regard as Cassini's most profound discovery of all: at the south pole of the moon Enceladus, more than 100 geysers spouting from an underground ocean that could be home to extraterrestrial organisms. For 13 years my life has been lived out there in the outer reaches of the solar system. And now that bountiful scientific expedition has come to an end.

## AN INTIMATE VIEW

THE NEED FOR A DETAILED, comprehensive examination of the Saturn system became clear during the early 1980s, after the two Voyager spacecraft made flybys of the planet. These celebrated events were the opening acts in the story of humanity's exploration of Saturn. They gave the planet dimension and personality but left behind questions that demanded answers. Voyager found Saturn to be a planet with a complex interior, atmosphere and magnetosphere. In its rings—a vast, gleaming disk of icy rubble—the mission recorded signs of the same physical mechanisms that were key in configuring the early solar system and similar disks of material around other stars. Voyager's passage through Saturn's inner system exposed diverse moons with dynamic forces at work. Titan, Saturn's largest moon, whose surface remained invisible through its thick, ubiquitous haze, nonetheless teased observers with hints of a possible ocean of liquid hydrocarbons. Altogether the Saturn system seemed an ideal destination for further in-depth study and exploration.

Cassini was an international undertaking, led by nasa and the European Space Agency and designed to be, in every dimension, a dramatic advance over Voyager. At the size of a school bus, it was bigger than Voyager and outfitted with the most sophisticated scientific instruments ever carried into the outer solar system. Cassini also carried the Huygens probe—a four-meter-wide, aerodynamically shaped device, equipped with a six-instrument payload, that descended to the surface of Titan.



SATURN'S RINGS are made of countless icy particles, some as big as houses, and contain gaps due to the gravitational tug of moons. Credit: Courtesy of NASA, JPL and Space Science Institute

After traversing the solar system, Cassini flawlessly took up residence around Saturn on June 30, 2004. Its trajectory around Saturn was both convoluted and precise, unfurling over the course of its 13-year tour like the opening petals of a blossom. To enable close-up viewing of everything in the inner Saturnian system, its orbits varied in size, tilt and orientation. We also had the luxury of modifying orbits to dive in for another look—in some cases, many looks—at things we had discovered earlier.

The length of Cassini's stay at Saturn was also critical to our success. Prolonged monitoring is the only way to catch unpredictable processes such as meteoroid impacts on Saturn's rings. Furthermore, the slow, steady orbital migrations of Saturn's moons, along with atmospheric changes that arise from the large seasonal variations in solar illumination, required us to collect observations over as lengthy a time span as possible. Cassini's nominal mission was four years long and slated to end on June 30, 2008. But the spacecraft's resounding triumphs in that time and the indisputable logic of keeping such a productive asset at work helped us press the case for continuing Cassini's mission. Our arguments were successful, garnering several extensions and ensuring, for example, that we witnessed the rare illumination conditions of Saturn's equinox in August 2009, when the sun's shallow rays on Saturn's rings revealed the presence of vertical structures protruding above the ring plane that cast long, easily seen shadows.

Ultimately Cassini's orbital operations ended nearly one half of a Saturnian year (or, on Earth, 13 years and two and a half months) after they began. We arrived a bit past the height of the planet's southern summer, and the mission will close at the height of its northern summer. This time frame allowed us to observe over almost a full seasonal cycle: we watched Saturn's and Titan's southern hemispheres go from summer to winter and their northern hemispheres go from winter to summer. It was somewhat of a cosmic cheat, but it worked.

## THE MOONS

Before the space age, scientists thought the moons of the outer solar system would be featureless, geologically dead balls of ice. Voyager proved that assumption wrong; Cassini's mission was to survey Saturn's horde of satellites and return some understanding of their histories. In some cases, those histories turned out to be remarkable.

Take Iapetus. The origin of its two-toned appearance—one hemisphere as white as snow and the other deep black—was a long-standing mystery. From Cassini's high-resolution images, we learned that even on small scales, the moon is a piebald mix of dark and light patches. Together Cassini's cameras and thermal instrument showed us why this is so. Both the hemisphere-scale color variations and the local piebald patches are caused by a runaway thermal process found only on the slowly rotating Iapetus. Regions that start out dark get hot enough to sublimate ice and thus become darker and hotter. Regions

COURTESY OF NASA, JPL AND SPACE SCIENCE INSTITUTE that start out white are colder and become the sites where those sublimated vapors condense. Over time all the ice in the dark region disappears and reaccumulates in the white regions. How did an entire hemisphere partake in this process? In its orbit around Saturn, Iapetus barrels through a cloud of dark, fine-grained material originating from Phoebe, one of Saturn's outer irregular satellites. This cloud turns Iapetus's entire leading hemisphere dark, keeping it warmer and ice-free. Mystery solved.

Another standout moon is Titan. Cassini's visible and near-infrared cameras as well as its radar instrument were able to cut through Titan's haze. And, of course, the early 2005 descent of the Huygens probe through Titan's atmosphere for two and a half hours captured panoramic images and measurements of atmospheric composition, transparency, winds and temperature before the probe came to rest on the moon's surface. In all, what Cassini found on Titan was a world out of science fiction, where the scenery—landforms and clouds—are recognizable but made of unusual substances, where the look of the place is familiar but the feel is not.

Titan, we discovered, has lakes and seas made not of water but of liquid methane. At the moon's south pole, Cassini's high-resolution camera sighted such a liquid body close to the size of Lake Ontario (and hence named Ontario Lacus) amid a district of smaller similar features. Other Cassini instruments later verified that Ontario Lacus indeed holds liquid methane. We have since found many bodies of liquid methane of varying sizes; for some reason, they mostly inhabit the high northern latitudes. Radar observations have revealed craggy, rocky shorelines that resemble the coast of Maine. In contrast, the equatorial plains, where the Huygens probe landed, are dry and covered with dunes that continue for long stretches, interrupted here and there by higher ground, all the way around the moon.

The lakes and seas of liquid organics on Titan's surface have naturally raised speculation about whether they might contain life. But the surface temperature on Titan is exceedingly cold: −180 degrees Celsius. It would be surprising to find chemical reactions similar to those we believe are required for water-based biochemistry operating at such temperatures. But should we ever detect truly "alien" biochemistry thriving in methane, it would be a remarkable and historic find.

In my mind, though, the site of Cassini's greatest discovery is without question Enceladus, an icy moon a tenth the size of Titan. There Voyager had laid bare vast, surprisingly smooth stretches that told of a past marked by intense internal activity and maybe even a liquid-water layer buried below its icy shell—both on a moon seemingly too small for such phenomena.

The first inkling we had of any activity on Enceladus came early in the mission, in January 2005, when we discovered a plume of icy particles coming off the south pole. Our images were immediately made available to the public, and Cassini followers on the Internet pulsed with excitement. Very soon thereafter other Cassini instruments confirmed that the plume was indeed real. Cassini's operators responded quickly, altering trajectories to have a closer look. What we learned about Enceladus during that early part of the mission absolutely astounded us, but it was not until after 2008, when we received nasa's blessing to extend the mission, that we were able to devote significant time and resources to examining this fascinating place.

Enceladus, we now know, is a moon being flexed and pulled by the gravitational tidal forces of Saturn. This tidal energy produces more than enough internal heat to create a global water ocean, possibly as thick in places as 50 kilometers, buried under an outer layer of ice a few kilometers thick. More than 100 geysers spout from four prominent fractures in the south polar terrain, creating a plume of tiny ice particles and vapor that extends hundreds of kilometers above the surface. Most of the solid mass in this plume falls back to the surface, but a small fraction extends farther to form Saturn's diffuse but large E ring.

Cassini was able to fly through the plume a dozen times and analyze its material. We found that the particles seen in our images, which were droplets of ocean only hours earlier, bore evidence of large organic molecules and compounds that indicated hydrothermal activity similar to that observed at deep-sea vents on Earth's seafloor. They also indicated an ocean salinity comparable to Earth's. The vapor accompanying these particles was mostly water but contained trace amounts of simple organic compounds, as well as carbon dioxide and ammonia—all ingredients important for the sustenance and even origin of life.

Cassini's results point clearly to a subsurface environment on Enceladus that could contain biological activity. We now must confront the goose-bump-raising questions: Did this small icy world host a second genesis of life in our solar system? Could there be signs of life in its plume? Could microbes be snowing on its surface? No other body so demonstrably possesses all the characteristics we believe are necessary for habitability. It is, at present, the most promising, most accessible place in the solar system to search for life. And some of us are so enthralled by this possibility that we are designing return missions to Enceladus to find out.

## THE RINGS

The rings, of course, are what make Saturn the glorious spectacle it is, and understanding their intricate workings was a major objective for Cassini. They are the natural end state of the collapse of a rotating cloud of debris, and as such, they are the closest analogue to the rubble disk we think provided the raw ingredients for our own solar system. They are also a model for the protostellar disks from which new solar systems are born and even for the billions of pinwheels of dust and gas we call spiral galaxies. Of all there was to study at Saturn, the rings presented the greatest scientific reach, extending from our local neighborhood to clear across the cosmos.

Through Cassini's measurements, we have come to understand the origin of most of the structure in the rings of Saturn. In certain places, we find that the gravitational handiwork of some distant orbiting moon has disturbed the orbits of ring particles, creating sharp edges or wave disturbances that propagate out in a spiral pattern. In others, where moons are embedded in the rings, gravity has nudged particles into beautiful structures. Pan, for instance, a roughly 30-kilometer-wide moon in the Encke ring gap, has done this to the particles in its vicinity; in turn, infalling ring material has reshaped Pan, making the moon look as if it were wearing a tutu.

In regions of the rings where particles are especially dense, we uncovered self-generating waves, with wavelengths ranging from 100 meters to hundreds of kilometers, propagating through the disk. These waves can reflect off sharp discontinuities in particle concentrations and interfere with themselves and one another, creating a chaotic-looking geography. And our understanding of ring structure now includes the gratifying confirmation of a prediction Mark Marley, now at nasa's Ames Research Center, and I made in 1993: that acoustic oscillations within the body of Saturn could also create features in the rings. In this way, Saturn's rings behave like a seismograph.

Cassini found its most stunning ring surprises during the time surrounding the August 2009 equinox. Along the sharp outer edge of the most massive ring (the B ring), we found an incredible 20,000-kilometer-long continuous string of spiky shadows betraying the presence of "ring mountains"—waves of particles extending three kilometers above the ring plane. These formations might result from the extreme compression of material passing around small "moonlets" that have been caught in the resonance at the ring's edge like rushing water splashing against a large cliff face on the shore.

In another revelation, we saw a very subtle, tightly wound spiraling pattern continuing without interruption for 19,000 kilometers across the inner C and D rings. Some meticulous sleuthing by Matt Hedman, now at the University of Idaho, and his colleagues revealed that an impact of cometary debris within the inner rings in 1983 likely forced all the ring particles in the impact region into tilted orbits; these orbits precessed like a top, the inner ones precessing faster than the outer ones. Since then, this disturbance has wound up ever tighter, creating a three-meter-high spiral corrugation pattern in the rings. This structure did not even exist during the Voyager flybys. The solar system, we have come to see, is a dynamic marvel, and in their myriad and fluid forms, Saturn's rings are an object lesson in the universality, scalability and endless complexity of gravity. No artist could do better.

## THE ATMOSPHERE

Cassini has also investigated the makeup and behavior of Saturn's atmosphere in great detail, uncovering some unexpected features in the process. Its instruments were able to study Saturn's atmosphere at a wide range of altitudes, revealing its global circulation patterns, composition and vertical structure. The atmosphere is divided into wide bands like Jupiter's, although Saturn's bands are less obvious from the outside because of a thick layer of haze lying above the upper ammonia cloud deck. When Cassini probed below the haze and into the troposphere, it revealed that the width of Saturn's bands alternates with latitude: narrower ones are darker and coincident with rapid jet streams, and the wider bands tend to be brighter, aligned with jets that are slower and maybe even stationary, relative to the general rotation of the planet. Overall, Saturn's atmosphere seems fairly static over time—even the surprising hexagon-shaped jet stream over the north pole has changed little, Cassini showed, since Voyager first sighted it. We are learning that stability is a common feature of large-scale atmospheric systems in the giant planets: with no solid surface underlying the gas, there is no friction to dissipate atmospheric motions. Once started, they endure.

We were delighted to find, however, that Saturn's atmosphere is not totally unresponsive to the changing seasons. Above the clouds in the northern winter hemisphere, the planet was putting on quite the unexpected show when Cassini first arrived: it was blue! Because the two Voyager flybys occurred near an equinox and thus returned no views of winter, this extreme coloration came as quite a surprise. Our best guess is that the lower flux of ultraviolet radiation during the winter, along with the sun-blocking effect of the ring shadows on the winter hemisphere, reduces the production of the overlying haze. A clearer atmosphere means better opportunity for Rayleigh scattering, the process that turns our own atmosphere blue, and for methane in the atmosphere to absorb the red rays of the sun. The gorgeous sliver of azure that colors the winter hemisphere in our images of Saturn is, in effect, a slice of Neptune's atmosphere spliced onto Saturn's. Who knew?

One distinctive property of Saturn, which has been known for a century, is that on timescales of decades, it is prone to the eruption of colossal storms. So we were thrilled to greet one such storm in late 2010. Over a period of about 270 days, we watched this thundering, lightning-producing behemoth be born as a small disturbance in the northern hemisphere, then grow, spread clear around the planet until its tail met its head, and eventually fade. This was yet another phenomenon that no spacecraft had ever witnessed. We suspect that water, the constituent of Saturn's deepest cloud deck, can suppress convection in the lighter hydrogen atmosphere for a period of decades, until finally buoyancy wins out and a large convective outburst ensues.

### SURVEYOR OF WORLDS

From its inception in 1990 to its final dramatic conclusion last September, Cassini has been a major, extraordinarily successful component of humanity's six-decade-long exploration beyond our home planet. Its historic expedition around Saturn has shown us intricate details in the workings of an alluring and remarkably alien planetary system. It has expanded our understanding of the forces that made Saturn and its environs, our solar system and, by extension, other stellar and planetary systems throughout the cosmos what they are today.

It is doubtful that we will soon see a mission as capable as Cassini return to Saturn. To have been part of this magnificent adventure has been to live the taxing but rewarding life of an explorer of our time, a surveyor of distant worlds. I sign off now, grateful in knowing that the story of Cassini is one that will inspire humankind for a very long time to come. ■

## MORE TO EXPLORE


- Saturn's Curiously Corrugated C Ring. M. M. Hedman et al. in *Science,* Vol. 332, pages 708–711; May 6, 2011.
- Enceladus's Measured Physical Libration Requires a Global Subsurface Ocean. P. C. Thomas et al. in *Icarus,* Vol. 264, pages 37–47; January 15, 2016.
- Could It Be Snowing Microbes on Enceladus? Assessing Conditions in Its Plume and Implications for Future Missions. Carolyn C. Porco et al. in *Astrobiology.* Published online August 11, 2017.