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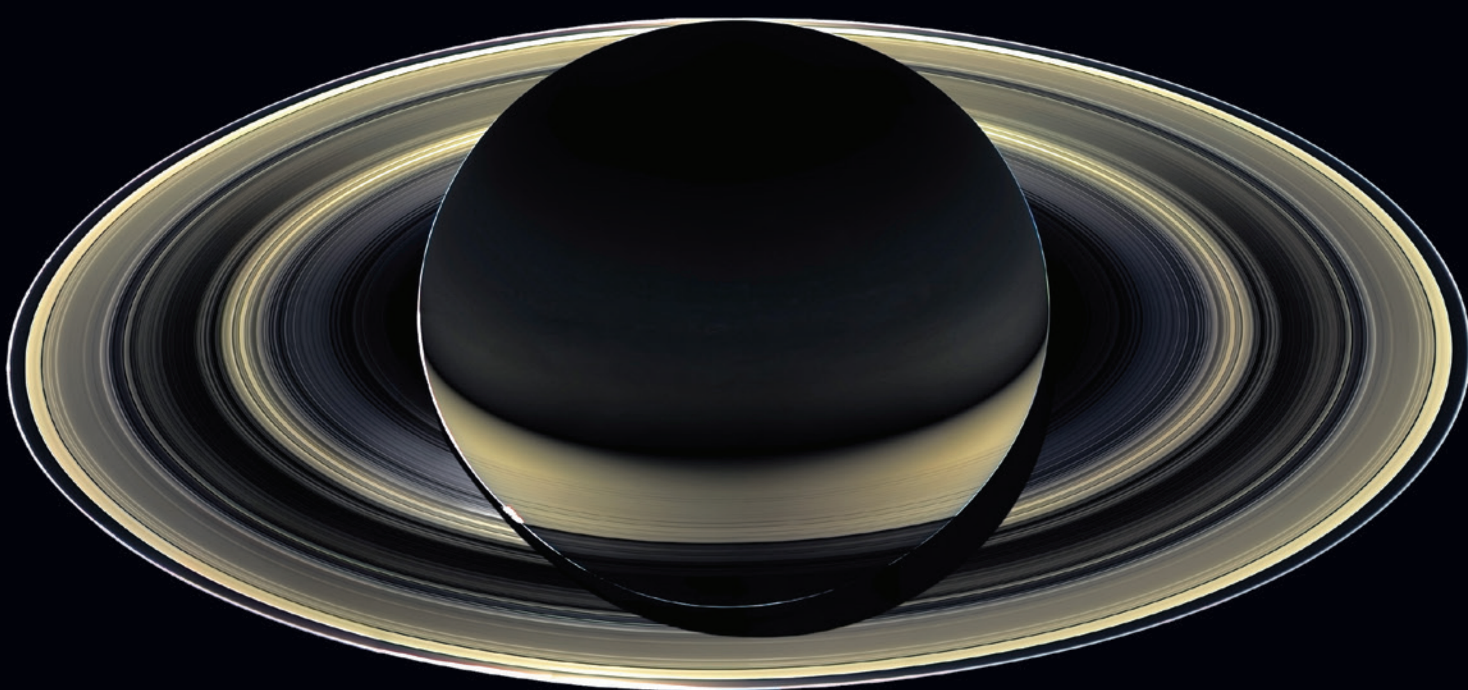
FAREWELL, *CASSINI*

CELEBRATING A LEGACY OF DISCOVERIES



ATMOSPHERIC CHANGES ✲ DYNAMIC RINGS ✲ COMPLICATED TITAN ✲ ACTIVE ENCELADUS

LINDA J. SPILKER *is* Cassini *project scientist at the Jet Propulsion Laboratory.*

IN 2004, *Cassini*, the most distant planetary orbiter ever launched by humanity, arrived at Saturn. For 13 years, through its primary and two extended missions, this spacecraft has been making astonishing discoveries, reshaping and changing our understanding of this unique planetary system within our larger system of unique worlds. A few months ater arrival, *Cassini* released *Huygens*, European Space Agency's parachuted probe built to study the atmosphere and surface of Titan and image its surface for the very first time.

ABOVE *As* Cassini *plunges into Saturn's cloud tops, it will continue to return data on the planet's atmosphere. When the spacecraft loses its radio connection to Earth, it will burn up like a meteor in Saturn's atmosphere.*

The Cassini-Huygens *mission is a cooperative undertaking by NASA, ESA, and the Italian space agency Agenzia Spaziale Italiana (ASI).*

Illustration: NASA/JPL-Caltech

Among its many offerings, *Cassini* has shown us three-dimensional structures towering above Saturn's rings, and it imaged a giant Saturnian storm circling the planet for most of 2011.

We now know that Titan's hydrocarbon lakes and seas are dominated by liquid ethane and methane, and that complex prebiotic chemicals form in its atmosphere and rain onto its surface. On Titan, methane plays the role that water plays on Earth, raining from the sky, carving river channels, and filling its lakes and seas, while a subsurface ocean resides beneath its icy crust.

Cassini's revolutionary findings at tiny Enceladus include a subsurface, global, salty ocean containing organics, ammonia, hydrogen, and silicates, with hydrothermal vents on its seafloor. As a bonus, it has revealed jets of water vapor and ice particles shooting out of fractures at the moon's south pole.

These discoveries have fundamentally altered many of our concepts of where life may be found in our solar system. *Cassini*'s observations at Enceladus and Titan have made exploring these ocean worlds a major focus for planetary science. New insights from these discoveries also have implications for potentially habitable worlds beyond our solar system.

In this special issue of *The Planetary Report*, a handful of *Cassini* scientists share some results from their studies of Saturn and its moons. Because there's no way to fit everything into this slim volume, they've focused on a few highlights.

Meanwhile, *Cassini* continues performing its Grand Finale orbits between the rings and the top of Saturn's atmosphere, circling the planet once every 6.5 days. These unique orbits are enabling detailed gravity measurements to estimate the depth of Saturn's winds, the size of its rocky core, and mass of the rings. Magnetic field measurements are determining Saturn's internal rotation rate and dynamic magnetic field structure. These final orbits are providing the first *in situ* measurements of the ionosphere, innermost radiation belts, and ring particle composition, as well as direct sampling of Saturn's upper atmosphere. Some of the highest-resolution measurements of the rings and Saturn are occurring as the spacecraft flies closer to the planet and rings than ever before.

The *Cassini* mission will end on September 15, 2017 as the spacecraft plunges into Saturn's atmosphere at 122,000 kilometers (76,000 miles) per hour. On that last day, with *Cassini*'s final heartbeat, our close, personal connection to Saturn will be lost. However, *Cassini*'s findings will continue to unfold, stoking the passion for discovery in the hearts of established and budding young scientists alike for many years to come.

ON THE COVER: *Cassini-Huygens* first became a gleam in mission planners' eyes in 1982, after the *Voyager* flybys whetted appetites for a closer look at the Saturn system. Now, 20 years after it launched, we say farewell and celebrate a mission that leaves a rich scientific and engineering legacy. On April 13, 2017, *Cassini* captured the 96 digital images that went into this Grand Finale portrait of Saturn. All components of the main ring system are visible here, illuminated from behind. Here, the more translucent rings shine brightly while the thicker, more opaque rings appear dark. *Mosaic: NASA/JPL/Space Science Institute/Ian Regan*

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It Takes Time

Such Is the Nature of Exploration

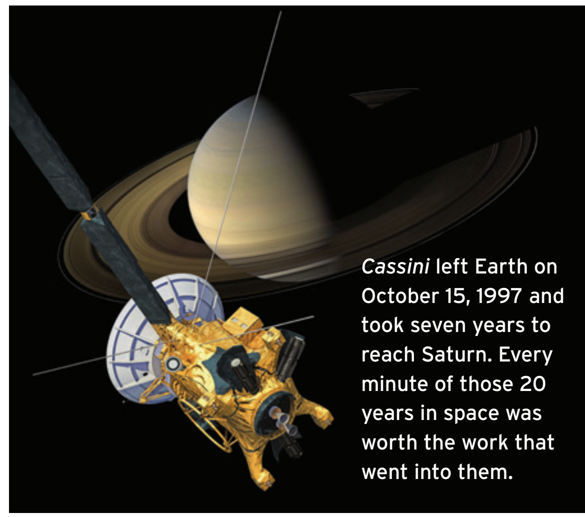
AS I WRITE, the *Cassini* spacecraft is making its last orbits around Saturn before it plunges into the planet's atmosphere. The data that come back and the scientific discoveries that will be made as a result will comprise the farewell address of this remarkable mission. Our spacesuit helmets are off to the men and women who made the *Cassini/Huygens* mission possible. Congratulations, and thank you. This issue of *The Planetary Report* is dedicated to the fruits of your labor.

When I reflect on the accomplishments of *Cassini*, I often have to stop myself and recognize how long it took to get that mission off the ground and into orbit. It flew for almost exactly two decades and, for me, this represents the nature of planetary exploration and science. It takes time, time, time to make the discoveries that amaze and humble us.

As a Planetary Society member, you have supported *Cassini* since its inception. You have supported exploration for its own sake and, especially, the exploration of our neighboring worlds. This focus goes back to the Society's original vision, a vision that lives on in the work that we do. This work is made possible by you. Thank you.

And we are especially grateful to you today as we prepare to launch our own spacecraft, *LightSail 2* (see the back cover). We will send this one higher and farther into space. We will experiment with untested maneuvering techniques. We will engage as many people as possible so that we may one day discover more about our place in space.

On a related note, in late September I will have the honor of delivering a Highlight Lecture at this year's International Astronautical Congress (IAC) in Adelaide, Australia. The topic is "LightSail® and Innovations in Solar Sailing." I will discuss how essential citizen involvement is for space exploration. At IAC, heads of agencies will address the global community. Industry leaders and young professionals will share their latest plans and innovations. And The Planetary Society will represent you, the people who make space exploration possible. While there, we will meet the fine citizens of South Australia through the generosity of the embassy and aboriginal community members. The Society has always been dedicated to its global role, and we are taking new steps to advance our mission and include people from all over this planet.

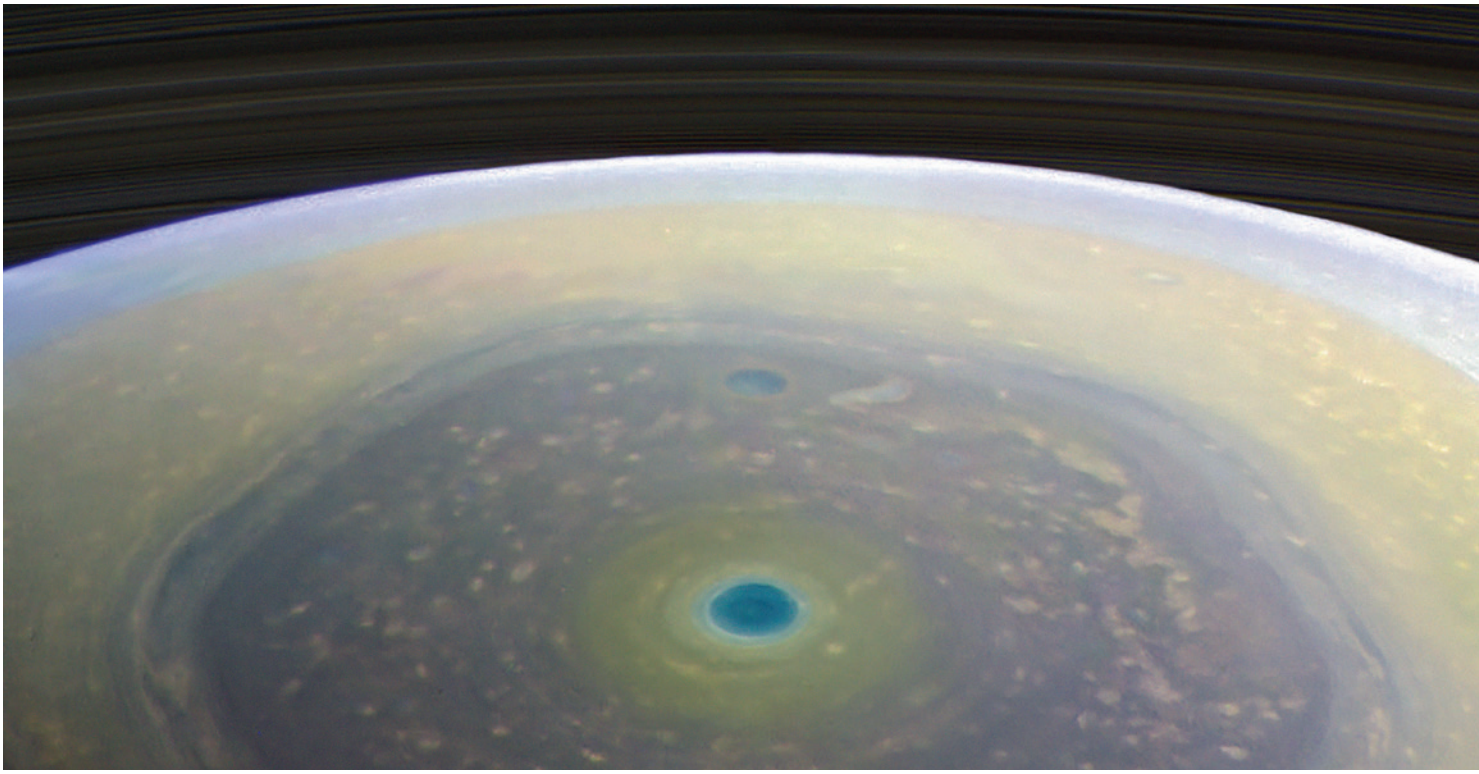


Cassini left Earth on October 15, 1997 and took seven years to reach Saturn. Every minute of those 20 years in space was worth the work that went into them.

Illustration: NASA/JPL-Caltech

You and I, and the *Cassini* team, share the understanding of how difficult and how rewarding planetary exploration can be. Let's go. Let's discover something astonishing out there.

LEIGH FLETCHER *is a planetary scientist at the University of Leicester.*



The Seasonal Giant

Exploring Saturn's Atmosphere and Weather with *Cassini*

SATURN HAS ORBITED THE SUN almost 14 times since Galileo Galilei first glimpsed the ringed world in 1610. He was puzzled by its "strange appendages," but the variable appearance of those rings over the planet's 29.7-year orbit revealed to later astronomers that Saturn has an axial tilt not unlike our own, subjecting the gas giant to seasonal extremes. While sunlight illuminates one hemisphere, the winter hemisphere is shrouded in years of polar night and ring shadows. Earth-based observatories and the *Pioneer 11* and twin *Voyager* spacecraft, between 1979 and 1981, provided increasingly clear snapshots of Saturn's hazy atmosphere, but a systemic understanding of how a gas giant's climate, meteorology, chemistry, and clouds respond to seasonal extremes has had to await the *Cassini-Huygens* mission. *Cassini*'s remote sensing instruments stripped away Saturn's serene mask, revealing a dynamic and ever-changing atmosphere shaped by physical processes that are both eerily familiar and altogether alien. Put simply, *Cassini*'s unprecedented longevity has delivered the most comprehensive characterization of a seasonal giant planet ever obtained.

Cassini's stint at Saturn began in July 2004, not long after winter solstice in the northern hemisphere (October 2002), when the south pole was basking in summer sunlight. Over the next five years, Saturn's rings appeared narrower and narrower to Earth-based observers as the planet's tilt progressed toward northern spring. The equinox came in August 2009, and the rings began to open up again.

ABOVE *The unique, six-sided jet stream at Saturn's north pole was first imaged in 1980 by* Voyager 1. *The giant storm is about 32,000 kilometers (20,000 miles) wide and has at its center a cyclone that swirls directly over the planet's pole. Scientists have a number of theories as to why the hexagon exists, and why there are no others like it in the solar system. Data returned from* Cassini*'s final orbits might provide more insight on this mysterious feature.*

Image: NASA/JPL-Caltech/Space Science Institute/Don Davis

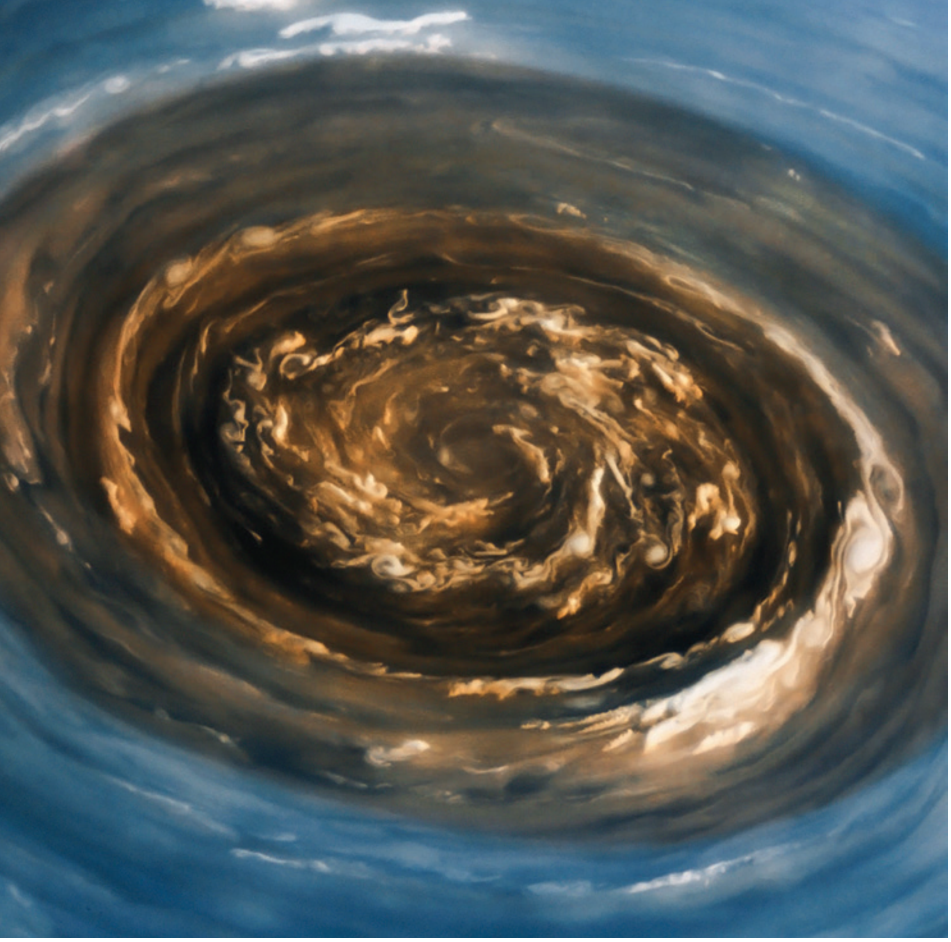


Image: NASA/JPL-Caltech/Space Science Institute/Alexis Tranchandon/Solaris

ABOVE *At center of Saturn's hexagonal crown lies a swirling maelstrom, a fast-moving storm eye about 2,000 kilometers (1,250 miles) across, with cloud speeds as fast as 150 meters per second (330 miles per hour).* Cassini *captured this infrared view of the vortex on November 27, 2012 from a distance of 400,000 kilometers (250,000 miles).*

On May 24, 2017, as Saturn reached northern summer solstice, *Cassini* was conducting its rapid, final orbits between the planet and the innermost rings. Thanks to *Cassini*'s long stay, humankind has had a robotic explorer bearing witness to every Saturnian season from solstice to solstice, gathering data from vantage points impossible from Earth.

DYNAMIC WEATHER PATTERNS

Cassini's ultraviolet, visible, infrared, and radio-wave eyes allowed scientists to reconstruct the atmosphere in three dimensions, from the roiling cloud-forming troposphere, through the stable stratosphere, and up to the tenuous thermosphere. We see that the vast hydrogen-helium bulk is slowly contracting as the planet ages, relinquishing stored energy as heat. The released heat makes Saturn self-luminous at infrared wavelengths (a trait shared with all giant planets except Uranus). Essentially, the meteorology and chemistry of the atmosphere are controlled by two factors: (a) convection of primordial energy upward from the planetary depths and (b) seasonal sunlight.

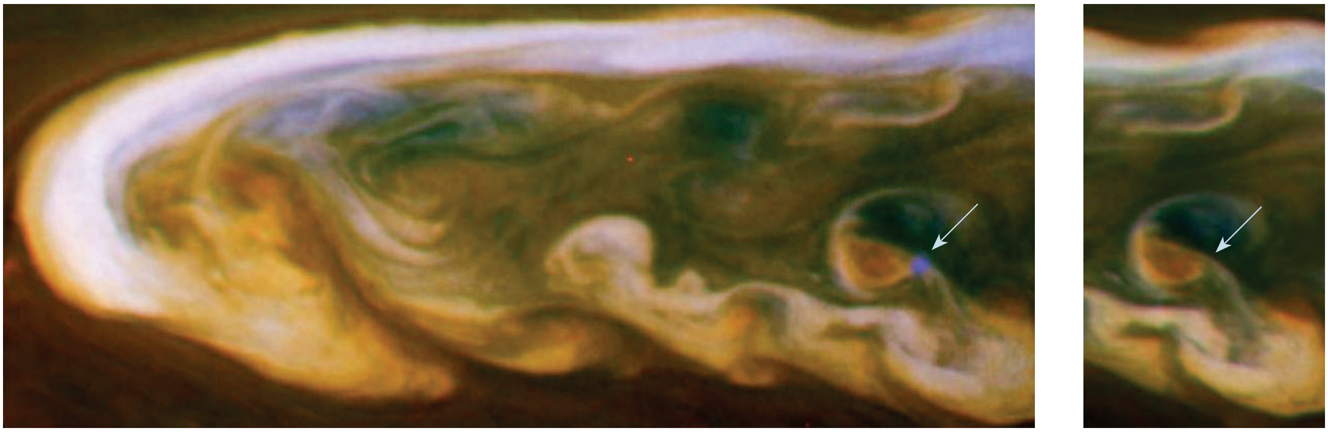
Convection, combined with Saturn's rapid 10-hour rotation, organizes the deep cloud structures into bands that encircle the globe, separated by powerful eastward and westward winds. These bands are sometimes disrupted by distinct clouds and oval-shaped vortices, deriving their energy from unstable eddies and ascending plumes. Unlike Jupiter's colorful cloud bands, which only extend from the equator to mid-latitudes, Saturn's more subdued banding reaches all the way to the highest latitudes, culminating in a cyclone at each pole. These cyclones, which have continued throughout the mission, feature concentric circular walls of towering clouds encircling a region of warmer temperatures and depleted atmospheric gases—a profile suggesting sinking motions at each pole.

Bizarrely, Saturn's north pole hosts a unique wind feature: a meandering jet that takes on a hexagonal appearance when viewed from above. The hexagon is long-lived (it was first observed by *Voyager 1*) and moves very slowly. Debate rages as to why it is there, why nothing like it is seen on the south pole (or at Jupiter's poles, for that matter), and whether the hexagon is a shallow feature or extends deep into the planet. *Cassini* has peered down into Saturn's polar cyclones and the hexagon. With even closer views expected during the final orbits, we may soon have a better understanding of what goes on at the top and bottom of this intriguing world.

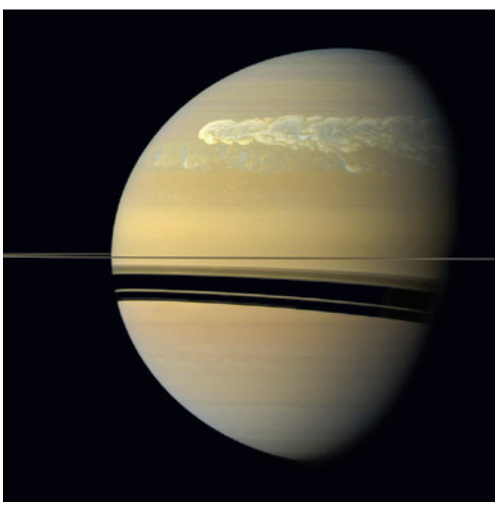
SEASONAL CYCLES

At low altitudes, we don't see strong effects from the change of seasons on Saturn. The dynamics in the low cloud-forming region are primarily influenced by convection processes, transporting energy and material from below. However, that is not true of the chemistry and

LEIGH FLETCHER *specializes in exploration of the giant planets. He is a co-investigator on the Cassini CIRS (thermal-infrared) instrument, and Interdisciplinary Scientist for ESA's JUpiter ICy Moons Explorer (JUICE) mission. Follow his research on Twitter (@LeighFletcher).*



aerosol properties of the upper troposphere and stratosphere, where north-south hemispheric differences observed at the start of the mission have now reversed.



Besides hydrogen and helium, Saturn's atmosphere comprises a host of trace species formed from the universe's most commonplace elements (C, O, N, S, P) in their chemically reduced and hydrogenated forms (methane, water, ammonia, hydrogen sulphide, phosphine). Some—such as water, hydrogen sulphide, and ammonia—are volatile species that condense in Saturn's atmosphere to form a stack of cloud decks. The topmost of these clouds are thought to contain ammonia ice, although it has only been definitively detected in regions of powerful convection.

Where there is condensation, gases are only really detectable below their respective clouds, and for this reason Saturn's water (which condenses deep below observable levels) is hard to measure from *Cassini*. Methane, on the other hand, doesn't condense and is well-mixed throughout the atmosphere. At high altitudes, exposure to ultraviolet light can split the methane molecule apart, generating a veritable soup of hydrocarbon species in Saturn's stratosphere, which are stirred around by giant circulation patterns. The efficiency of the chemistry and the strength of atmospheric circulation vary from place to place due to seasonal differences in sunlight (and maybe even ring shadowing). Seen as a whole, Saturn's atmosphere is an intricately connected system that shows distinct seasonal cycles.

We see these cycles in color differences between summer (the familiar yellow-ocher) and winter (blue hues more like Uranus and Neptune). *Cassini* has shown that chemically produced hazes are less prevalent in winter, leaving clear air with lots of red-absorbing methane, which reflects blue light. The summer air is hazier and scatters light, so it reflects as yellow.

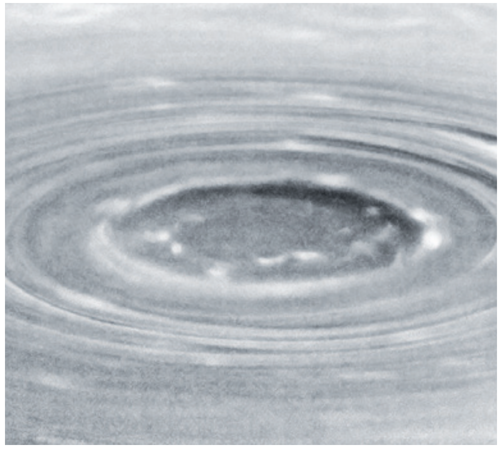
We see cycles in summer polar vortices—broad air-masses in the stratosphere that form after spring and dissipate in autumn/winter. At the time of writing, *Cassini* was still waiting for a stratospheric vortex to form over Saturn's north pole, which would mirror the one we saw over the south pole at the start of the mission.

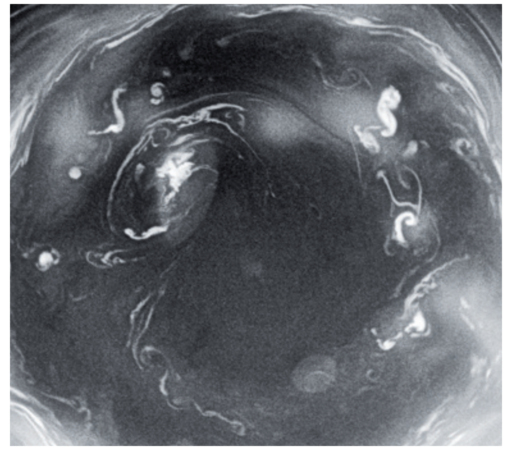
We see seasonal cycles also in the abun-

LEFT *In December 2010, scientists observed the beginning of what would evolve into the largest, most intense Saturnian storm ever observed by* Voyager *or* Cassini. *The planet's powerful winds blew the storm east and west, causing it to evolve into a snake-like structure that eventually grew to encircle the globe (left).*

ABOVE *These close-ups of the same planetwide storm show the spot where* Cassini *captured a flash of lightning as discharged. The lightning shows as a blue spot in the image at left. At right, the same area imaged one hour later, shows no trace of the lightning.*

Images: NASA/JPL-Caltech/Space Science Institute





ABOVE LEFT *The subtle bands of Saturn's atmosphere culminate in cyclones at both poles. This photo of the south polar vortex shows the shadows of concentric circular walls, or eyewalls, of tall clouds around a warmer, and gas-depleted area that suggests sinking motion. Such is the case at the north pole as well.* Cassini *took this image from a distance of 778,000 kilometers (483,000 miles).*

ABOVE RIGHT *This higher resolution view looks down into the south polar vortex from above. The white features that looked like puffy clouds at lower resolutions are actually an inner ring of vigorous convective storms. This picture was captured from an altitude of 392,000 kilometers (243,000 miles). Both images were taken in mid-July 2008.*

Images: NASA/JPL-Caltech/Space Science Institute

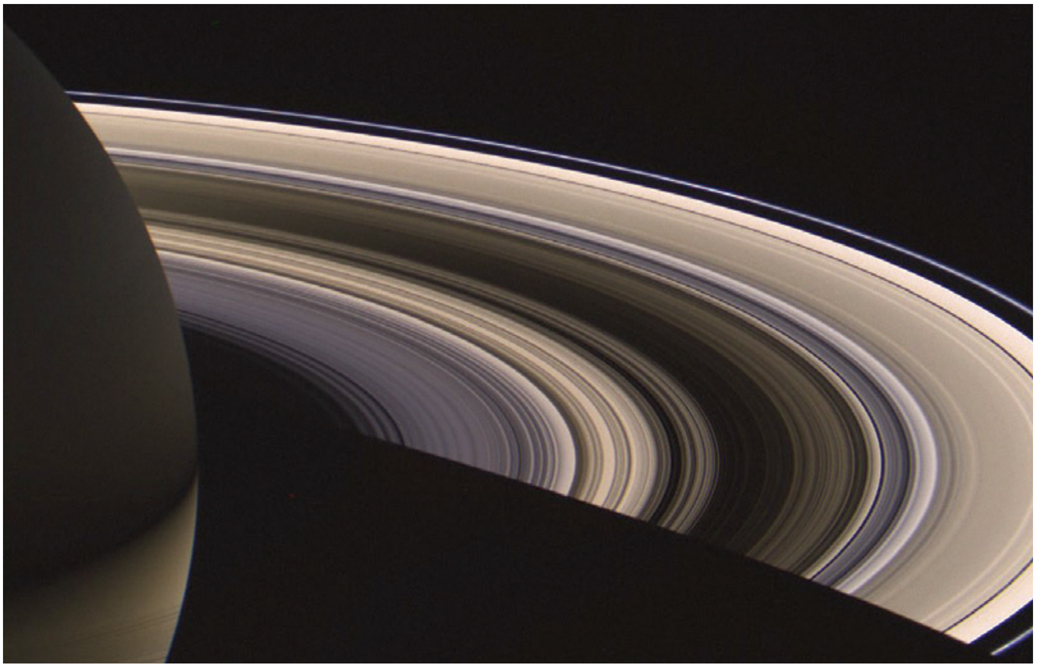
dances of chemical species, with the summer sun helping to increase production of certain gases (such as hydrocarbons) while helping to destroy others (such as phosphine or ammonia). And we see cycles of atmospheric wave activity over Saturn's equator, where a stack of alternating eastward and westward wind regimes move slowly downward, modulating equatorial temperatures and wind speeds, over a 15-year period. As a result, the stack of winds over the equator looks different today compared to its structure in 2004. Saturn's equatorial oscillation mirrors those found on Earth (the Quasi-Biennial Oscillation) and Jupiter (the Quasi-Quadrennial Oscillation), showing that atmospheres with quite different environmental conditions can share common physical phenomena.

The cycles of the seasonal giant are perhaps most evident when a massive, planet-encircling storm bursts forth from the deep atmosphere–once every Saturnian year. The annual great storm usually occurs after northern summer solstice, but in 2010 the storm erupted in early northern spring in the northern mid-latitudes. *Cassini* was there to witness the ensuing maelstrom. Tremendous lightning crackled in *Cassini*'s radio detectors. Plumes of ices unusual for Saturn were lofted high above the clouds. Powerful winds whipped the new material east and west to create a snake-like structure, with the head eventually devouring the tail and forming a new, whitish band encircling the globe. Waves radiated by the powerful plumes dumped energy high in the stratosphere, generating an enormous vortex, nicknamed "the beacon," that was 80 degrees Celsius (176 degrees Fahrenheit) warmer than its surroundings. The storm raged for months, enthralling *Cassini* followers and revealing the dramatic power trapped beneath Saturn's veil of clouds.

BEYOND SUMMER

September 16, 2017, marks the first day of the post-*Cassini* era. Our robotic explorer will no longer keep track of Saturn's evolving atmosphere, with its dramatic storms, polar cyclones, banded clouds, and brews of seasonal chemistry. What comes next? There is no shortage of ambitious ideas for our return to the Saturn system. For Saturn's atmosphere, the next step is to find out what lies beneath the clouds, in reservoirs beyond the reach of remote sensing. Those hidden depths hold the secrets of Saturn's formation: how did the planet form, does it have a core, and did it migrate through the young solar system after its birth? For answers, we must send a probe into Saturn's atmosphere, descending by parachute and directly sampling the composition. Until then, telescopes on Earth and in orbit (such as the James Webb Space Telescope) will continue to build on *Cassini*'s legacy of discoveries, watching the northern summertime evolve toward the next seasonal milestone: the autumnal equinox and ring plane crossing in 2025.

LUKE DONES *is a principal scientist at the Southwest Research Institute in Boulder, Colorado.*



Saturn's Rings

What *Cassini* Has Taught Us

THE *CASSINI* MISSION HAS given us our closest look yet at Saturn's fascinating rings. Even though the chunks of ice that make up the rings are too small—ranging from marble- to house-sized—for our instruments to see individually, we have learned a great deal about dynamics in Saturn's ring system and studied the strange effects that result, including viscous-overstability ripples, self-gravity wakes, and elongated features known as propellers.

Cassini also observed tiny moons in the ring system. In the outer part of the bright rings, we can make out two small moons that orbit within gaps, like runners in clear lanes around a track. Farther from the planet, bigger moons orbit within faint rings. However, there is no large moon close to the planet, and that is a key to understanding the nature of planetary rings.

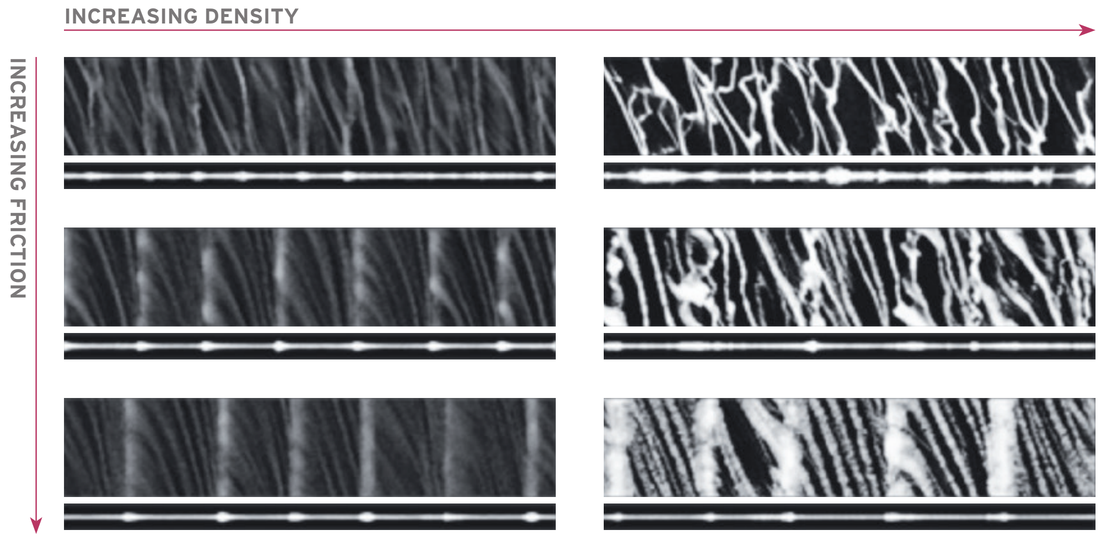
In its 13 years at Saturn, *Cassini* has taught us far too much to discuss in such a short article. Instead we will focus on phenomena in a ring system, particularly how rings behave when there is no moon big enough to cause a major disturbance.

NO BIG MOON NEAR THE PLANET

First, why don't any big moons orbit close to their planets? The answer is tides—that is, the changes in shape of a body (a body of water or, in this case, a moon) caused by the gravitational force from another body (Saturn). The gravitational pull of our Moon is responsible for the tides in Earth's oceans. Now think about the much larger effects that would be exerted on a moon close to Saturn. This imagined moon would be held together by its own gravity and by material strength (molecular bonds). Saturn's gravity would stretch the moon along a line between the center of the moon and the center of Saturn. The amount of stretching is small for distant moons, but would be very large

ABOVE *In July 2006,* Cassini *took this image of Saturn's night side and the northern side of its rings. For the first five years of the mission (2004 to 2009,) the Sun illuminated the southern side of the rings. The B ring, the densest part of the ring plane, is dark in this image because little light filters through it. Saturn's globe casts a shadow on the rings and is illuminated by light reflected off the rings, especially in its southern hemisphere (below the ring plane).*

Image: NASA/JPL-Caltech/Space Science Institute/Björn Jónsson



ABOVE *Computer simulations provide a visual catalog of the ring particle distribution patterns observed by* Cassini *at Saturn. Jostling one another in orbit, particles collided, clumped, spread out, and sometimes tilted. These six panels show a small patch of Saturn's rings, with different assumptions made about the nature of the particles: smooth and porous (upper left), rough and porous (lower left), smooth and solid (upper right), and rough and solid (lower right). In each panel, distance from Saturn increases from left to right. The six large images show simulated views of the rings from above, while the smaller strips underneath show side views. In some of the simulations, the rings reveal vertical "stripes," due to viscous overstability. In others, we see tilted structures –self-gravity wakes. Both types of structure are visible in all of the simulations.*

Computer simulations: Ronald Ballouz, University of Maryland

for any moon too close to Saturn.

Edouard Roche, a French scientist and mathematician, showed in 1849 that a moon with no material strength (a fluid body) would be pulled apart by its parent planet if it orbited closer than about 2.5 times the distance from the moon to the center of the planet. A moon can resist being pulled apart somewhat closer to the planet if it is made of strong materials, like a solid piece of rock. However, Saturn's small moons are mostly water ice.

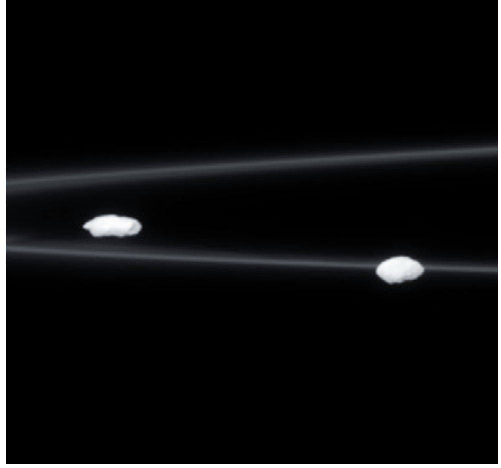
The critical distance of roughly 2.5 planetary radii is called the Roche limit. Within the Roche limit, tidal forces make it impossible for two like-sized bodies orbiting Saturn to collide and merge to form a larger body. Short-lived aggregates of ring particles called self-gravity wakes can form within the Roche limit, but they last for only about the time they take to complete one orbit around Saturn (less than an Earth day). This division between temporary aggregates and sustainable moons appears clearly in computer simulations and *Cassini* observations. No moons are known to exist in the rings within about 2.3 Saturn radii of the planet's center. Two small moons, Pan and Daphnis, orbit within gaps in the outermost part of the A ring.

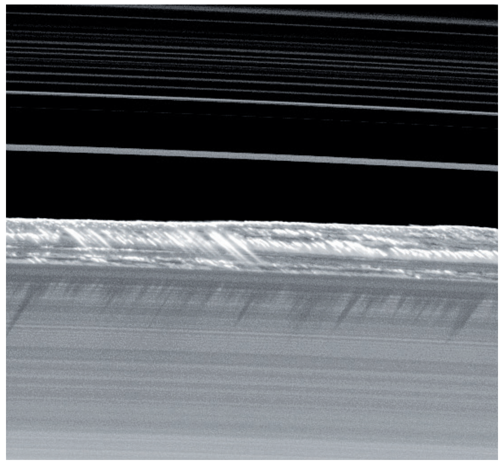
At about 2.4 Saturn radii, the narrow, ever-changing F ring is disturbed by the gravitational pull of Prometheus, a nearby moon whose gravity draws streamers of material out of the ring. The F ring might be the result of a collision between Prometheus and Pandora, a moon that orbits just outside the F ring. Farther from Saturn, beyond the main rings, we see only moons and tenuous rings. These rings consist of small, scattered fragments knocked off the nearby moons by interplanetary particles hurtling through the Saturn system.

THINGS IN THE RINGS

As ring particles orbit Saturn, they gently jostle and gravitationally attract each other. *Cassini* was able to measure these effects from two kinds of structures that form in dense rings. The first type of pattern is the elongated self-gravity wakes about 100 meters across, which are most prominent in the outermost main ring, the A ring. Originally inferred from telescopic observations in the 1970s, self-gravity wakes are temporary groupings of ring particles that form as the particles attract each other. Particles closer to Saturn orbit faster than those farther from Saturn. This leads to a specific tilt, or orientation, for self-gravity wakes (see images above). Even though an individual wake is too small for *Cassini* to see,

Voyager 1 *flew by Saturn during* **LUKE DONES'** *first semester in graduate school, where his PhD thesis involved dynamical and photometric modeling of Saturn's rings. He is a member of the* Cassini *Imaging Team.*





the wakes are so numerous that they cause a systematic change in brightness with longitude in the rings. At some longitudes, the observer looks across the wakes and sees more ring material, while at others, the observer looks along the wakes and the emptier regions between them, and so sees less ring material. *Cassini* confirmed the presence of self-gravity wakes in occultation experiments, in which a star passes behind the rings. Wakes constantly develop and then dissipate because Saturn's tides pull them apart.

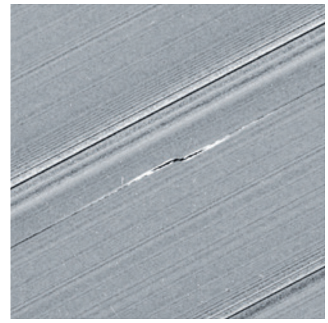
The second type of structure is rapidly alternating circles of more particles and fewer particles. Seen in *Cassini* occultation experiments as well as in the highest-resolution images, these alternating low-/high-density structures are thought to form due to "viscous overstability." These features form as follows: In most parts of the rings, collisions between ring particles cause them to move into regions where there are fewer particles, in the same way that billiard balls spread across the table during a game of pool. In a dense ring, this spreading can overshoot, causing a sort of wave in which ring particles rush from a dense region to a less dense region and back again. Overstability features, most prevalent in the outer B ring, probably play a role in creating many of the brighter and darker bands in the ring.

Both the viscous-overstability and self-gravity wake structures occur in Saturn's brightest rings, the B and A rings. When and where they form depend on details such as densities of ring particles (solid or porous), and their surfaces (smooth or rough).

"Propellers" are yet another type of structure seen in Saturn's A ring. They are somewhat like self-gravity wakes, creating adjacent areas of light and dark, but can persist for years. Near its midpoint, a propeller has a moonlet or very large ring particle—with a radius greater than about 50 meters—which stirs up nearby ring material. The moonlet is "trying" to open a gap in the rings but is too small to succeed. Instead it creates regions of lower density just inside and outside its orbit (the brighter parts in the image above on this page), and a denser region near the moonlet (darker part of the propeller). A moon has to be bigger than about 1 kilometer (.6 mile) in radius to clear a gap all the way around its orbit. Pan and Daphnis are the only known examples of moons within the rings that clear gaps.

LOOKING BACK, AND AHEAD

For many members of the *Cassini* mission team, and doubtless many readers of this magazine, the first sight of Saturn's rings through a telescope was a transformative moment—making the planets of the solar system suddenly real. You saw a point of light in the sky; in the eyepiece, the golden world itself. The *Cassini* mission has been like that telescope, bringing us in close to Saturn—close enough to measure and study scientifically—and yet seriously multiplying the excitement of discovery. *Cassini* has taught us a lot. But there are breathtaking moments still to come, in new findings to be mined from *Cassini* data and in future explorations of the ringed planet.



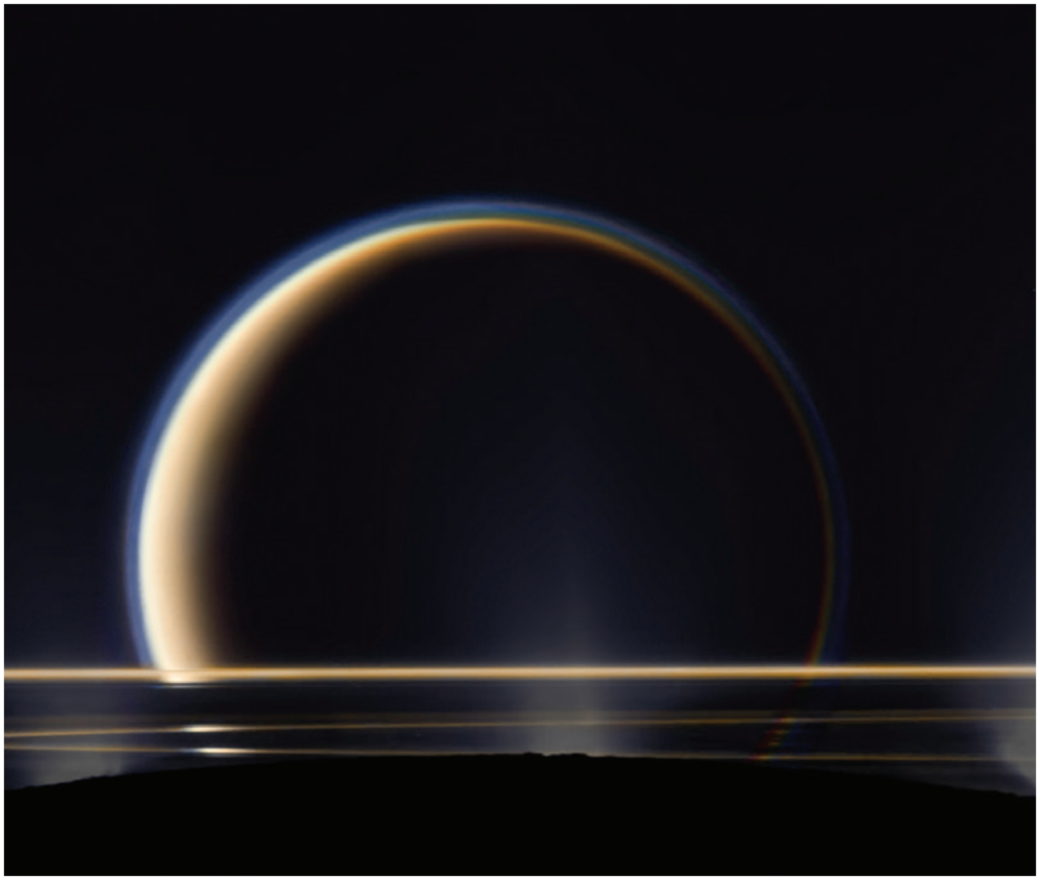
ABOVE *The unlit face of Saturn's A ring shows the largest known propeller, Blériot, which has been observed by* Cassini *since 2010. A moonlet (not visible here) about 500 meters in radius is thought to exist near the center of Blériot.*

TOP LEFT *Prometheus (left) and Pandora (right) are moonlets that orbit inside and outside Saturn's F ring, respectively. Prometheus is 148 by 68 kilometers (92 by 42 miles) in size and Pandora is 110 by 62 kilometers (68 by 38.5 miles). To watch a movie of Prometheus "herding" the F ring, go to* **planet.ly/herdingfring**.

BOTTOM LEFT *Shadows are cast by vertical structures that rise as high as 2.5 kilometers (1.5 miles) from the ring plane, near the edge of the B ring. This image was taken in July 2009, two weeks before the equinox when the Sun passed through the ring plane.*

Images this page: NASA/JPL-Caltech/Space Science Institute

SARAH HÖRST *is an assistant professor in the Department of Earth and Planetary Sciences at Johns Hopkins University.*



ABOVE *Titan has the most complex atmospheric chemistry in the solar system. In this view captured by* Cassini *on May 17, 2010, Titan rises above Saturn's ring plane and the night side of Enceladus. Data from* Cassini*'s Plasma Spectrometer indicate that the oxygen needed to make the moon's atmospheric carbon monoxide comes from Enceladus' plumes, visible here over its dark horizon.*

NASA/JPL-Caltech/Space Science Institute/Don Davis

Titan's Atmosphere

Identifying the Chemical Precursors of Life

IN 1944, GERARD KUIPER published "Titan: A Satellite with an Atmosphere" detailing his discovery of methane around Titan, which turns out to be the only moon in the solar system with a thick atmosphere. The *Voyager* flyby in the early 1980s found an impenetrably hazy world with organic (carbon-bearing) molecules in its atmosphere, indicating that Titan is one of the most astrobiologically interesting worlds in the solar system. Inspired by data from *Voyager*, the *Cassini* orbiter and its *Huygens* probe were launched in 1997. Since its arrival in the Saturn system in 2004, the *Cassini-Huygens* mission has unveiled a remarkable world that is simultaneously Earth-like and completely alien, presenting scientists with a new set of challenges. There is not nearly enough room here to do justice to everything we have learned about Titan's atmosphere from *Cassini-Huygens*, but below are some highlights.

BEGINNING WITH A FEW BASICS

Most (98 percent) of Titan's atmosphere is molecular nitrogen (N_2). We have known since *Voyager* that the surface pressure on Titan is 1.5 bar, which is 1.5 times the pressure at sea level on Earth. These two facts taken together make Titan a really interesting world, because the only other thick atmosphere made mostly of molecular nitrogen in our solar system is ours here on Earth. On top of that, Titan is the only moon in our solar system with a substantial atmosphere.

The other main constituent of Titan's atmosphere is methane (CH_4), which makes up the other 2 percent. The temperature at Titan's surface is 94 kelvin (–179 degrees Celsius, or –290 degrees Fahrenheit). This pressure and temperature combination is close to the triple point of methane, which means that methane can exist as a gas, liquid, or solid. Earth's surface conditions are similarly close to the triple point of H_2O, so water cycles back and forth between the atmosphere and surface—for example, in falling rain and evaporating dew. On Titan, similar cycling occurs with methane (except that most of Titan's methane is in its atmosphere, while most of Earth's water is on the surface). From *Cassini* we have observed the formation of large methane storms and seen evidence of rain by watching how the surface changed after the storm.

MOLECULE-BREAKING AND BUILDING

Light from the Sun and energetic particles from Saturn's magnetosphere break molecular nitrogen and methane into pieces that are very reactive and thus ready, when they run into other pieces (molecules, atoms, ions), to form new molecules. One of the most common of these reactions is conversion of two methyl radicals (a methyl radical is a methane molecule that has lost one hydrogen atom) into two new molecules: an ethane (C_2H_6) and a hydrogen (H_2). Since Titan is not very massive, gravity is not strong enough to hold on to the hydrogen, so it escapes into space. However, the ethane condenses when it reaches the cold lower atmosphere and ends up as a liquid on the surface, where it stays.

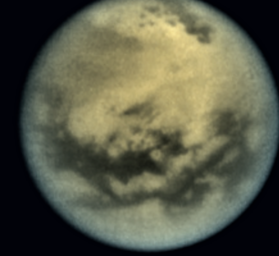
This reaction means that methane is being irreversibly destroyed in Titan's atmosphere, because the products are lost to space or to the surface. Methane must be resupplied from somewhere if Titan's atmosphere has had methane for the whole history of the solar system. We hoped that data from *Cassini-Huygens* would finally solve the mystery of the methane source, but unfortunately we still do not know where the methane comes from.

The chemistry in Titan's atmosphere builds molecules as well as breaking them apart. Eventually some molecules grow bigger and bigger until they turn into the particles that make up Titan's thick haze layer—the haze that prevented detailed studies of the surface until the arrival of *Cassini-Huygens*. We think that chemistry similar to what is currently happening in Titan's atmosphere also happened on the early Earth, before life started producing molecular oxygen (O_2). Molecular oxygen prevents Titan-like chemistry from occurring.

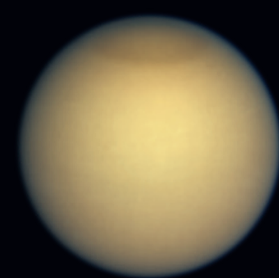
Titan is the best place in the solar system to learn about processes that likely occurred in the atmosphere of the early Earth; understanding Titan's atmosphere improves our understanding of the conditions that were present for the origin and evolution of life on Earth. We are interested in learning more about the complex chemistry that occurs in Titan's atmosphere because we want to understand the kinds of molecules that life might have available to start or evolve from, not just on the early Earth but also on Titan or extrasolar planets.

AN UNUSUALLY BUSY UPPER ATMOSPHERE

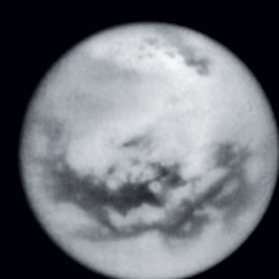
One of the most interesting and surprising of the mission's discoveries is that there are very heavy (large) ions, very high up



SURFACE IN PSEUDO COLOR [CB3/MT1/MT3]



ATMOSPHERE IN NATURAL COLOR [Red/Green/Blue/UV]

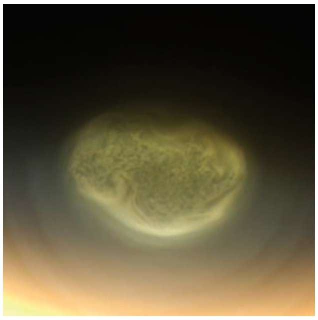


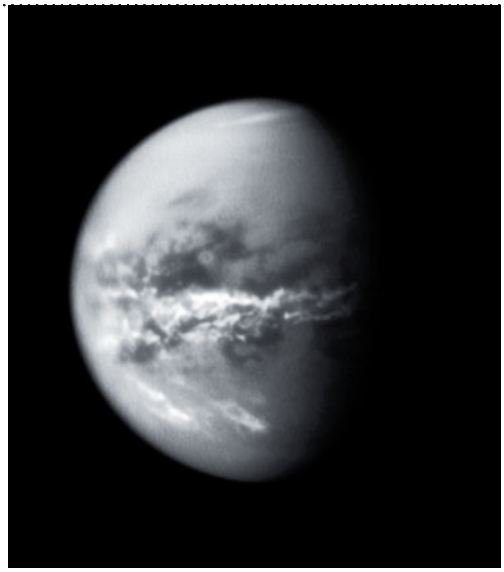
ENHANCED SURFACE RATIO [CB3 stack ÷ MT1]

ABOVE *The enhanced surface view of Titan at top has been colorized using data from methane filters that mimic natural color. The middle image shows how Titan would look to human eyes, while the version at bottom reveals surface details visible in infrared observations.*

Images: NASA/JPL-Caltech/Space Science Institute/Ian Regan

SARAH HÖRST *studies Titan's complex atmospheric chemistry using laboratory experiments and computer models. Although she is not a member of the* Cassini *team, much of her work over the past 13 years has been inspired by* Cassini's *measurements.*





ABOVE *Cassini's long-lived mission allowed scientists to observe Titan at both its poles and learn that a vortex forms at its winter pole. The south polar vortex was imaged close up for the first time by* Cassini *in June 2012.*

ABOVE RIGHT *The chemistry of Titan's atmosphere and surface share a unique and complex connection. Here extensive methane clouds at a number of latitudes show a shift in the clouds' location after Saturn's 2009 equinox, indicating that Titan's clouds change with the seasons.*

in Titan's atmosphere (1,000 kilometers, or 620 miles, above the surface). They range in size from things like CH_4 (which has only one heavy atom, carbon) to small particles (things that have 700 or 800 heavy atoms). As far as we know, Titan is the only world in the solar system with this complexity of chemistry happening in its atmosphere. The instrument that revealed the presence of these ions, the Cassini Plasma Spectrometer (CAPS), was not designed to study Titan's atmosphere or to measure such heavy ions, so we are not able to identify any of the ions that it sees; we only know that they are there.

However, we know that high in the atmosphere there are very energetic photons and electrons available to break up the N_2 in Titan's atmosphere, so molecules made high in the atmosphere probably contain a lot of nitrogen. All of life on Earth is based on a handful of molecules, and those molecules are composed of a handful of atoms (CHNOPS), including nitrogen. So we are particularly interested in understanding the complex chemistry occurring in Titan's upper atmosphere, but identifying these large ions will require a future mission.

The detection of oxygen ions flowing into the top of Titan's atmosphere by CAPS did help solve a 30-year-old mystery about the origin of Titan's carbon monoxide. CO is one of the most abundant of the trace gases in Titan's atmosphere, and the oxygen needed to make it seems to be coming from another of Saturn's moons. Enceladus has a subsurface liquid-water ocean, and in 2005 *Cassini* spotted a huge plume of vapor jetting from its south polar region. Some of the water sprayed into the Saturn system by the plumes of Enceladus eventually falls into Titan's atmosphere, where it participates in chemistry that forms carbon monoxide. The origin of carbon monoxide helps us understand how Titan's atmosphere formed, and also leads to questions about how the oxygen from Enceladus may get incorporated into other molecules, which might be interesting for understanding the origin of life.

LONG-TERM INVESTMENT PAID OFF

The length of the *Cassini* mission has been hugely important scientifically. It allowed us to watch Titan for half a Titan year and see the seasons change. Seasonal changes are like natural experiments on a world, providing us a chance to test our understanding of the chemistry and dynamics of an atmosphere. Titan has a tilt similar to Earth's, so it experiences strong seasonal changes–affecting the locations and frequency of methane storms, the temperature structure of the atmosphere, and the location of the vortex that we now know forms at the winter pole because we were there long enough to observe it at both poles. At the south pole, we even watched the formation of the vortex and its accompanying giant hydrogen cyanide ice cloud!

As with all successful missions to fascinating places, we have a new set of questions about Titan. One of those questions, as you might have guessed, is: What are those surprisingly large ions at the top of Titan's atmosphere, and what happens to those molecules when they eventually reach the surface? The answers to some old questions, like the origin of Titan's atmosphere (and, more specifically, its methane) remain tantalizingly out of reach. We are already working on concepts for future missions as our unanswered questions about Titan continue to tug at our minds and our hearts.

Images: NASA/JPL-Caltech/Space Science Institute

ELIZABETH TURTLE *is a planetary scientist at the Johns Hopkins Applied Physics Laboratory.*

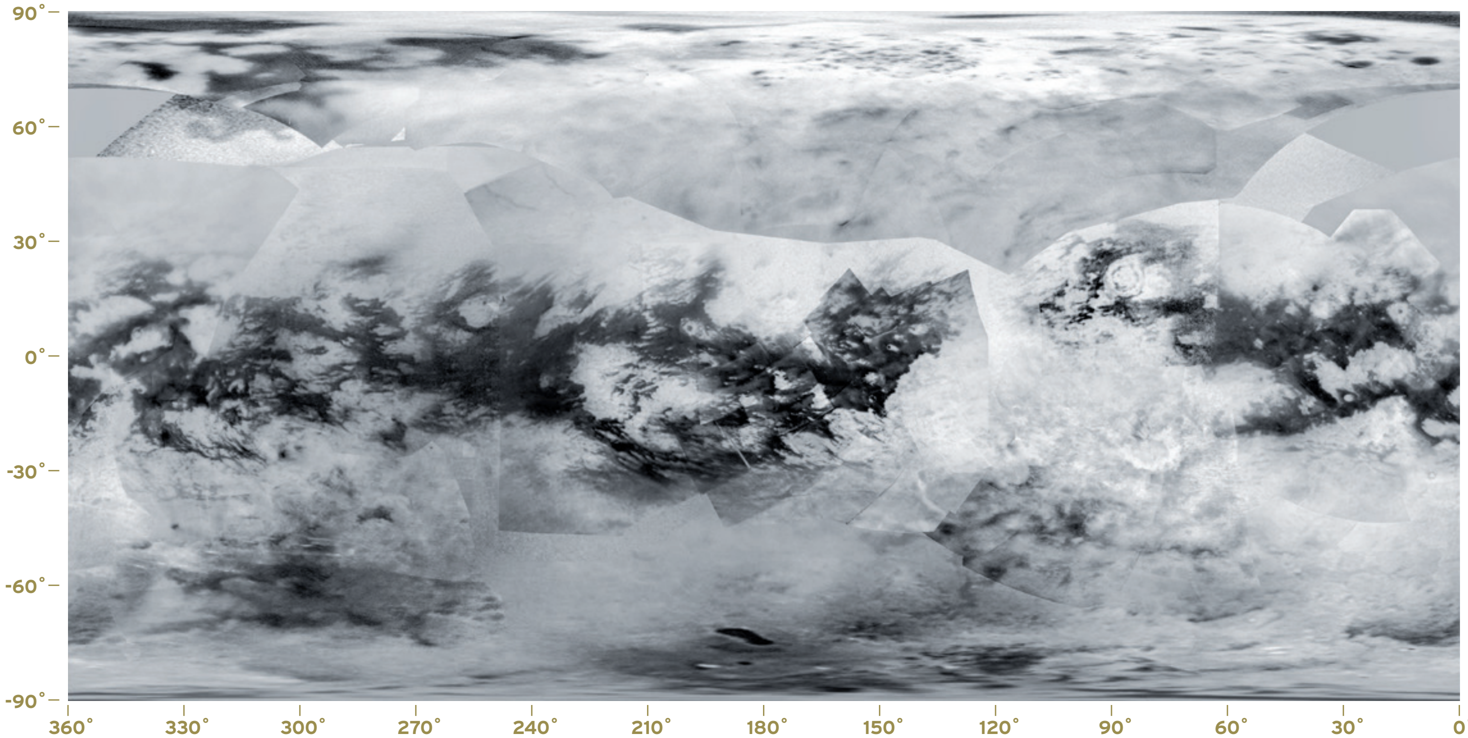


Image: NASA/JPL-Caltech/Space Science Institute

Titan's Surface

Observing a Landscape Sculpted by Wind and Rain

BEFORE THE ARRIVAL of the joint NASA and ESA *Cassini-Huygens* mission in 2004, little was known about the surface of Titan. It had long been a target of interest, especially because of the potential for lakes and seas, or even a global ocean, of liquid hydrocarbons. But Titan's atmosphere scatters light so effectively, particularly at visible wavelengths, that the solid body of the moon remained hidden.

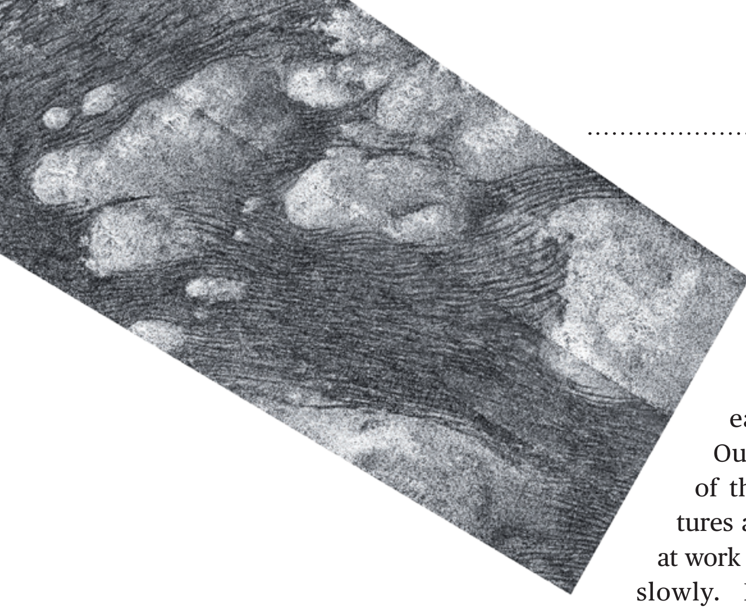
Voyager 1 was almost (but not entirely) unable to discern Titan's surface during its encounter with the Saturn system in 1980. Over the next 20 years, observations at infrared wavelengths by the Hubble Space Telescope (HST) and by ground-based telescopes using adaptive optics, along with Arecibo radar observations, brought large-scale features into view with resolutions of a few hundred kilometers. In these images, we saw dark terrain wrapped around much of Titan's equatorial region and interrupted by a large, bright area more than 3,000 kilometers (about 1,860 miles) across, now named Xanadu.

THE HAZE LIFTS SLOWLY

Cassini began distant observations of Titan in April 2004, during the lead-up to orbit insertion around Saturn. Instruments onboard were designed to obtain images at radar wavelengths as well as in the infrared, where there is less scattering by atmospheric haze. The plan was for the *Cassini* orbiter to map Titan's surface during 44 close flybys. In addition, ESA's *Huygens* probe was equipped to take measurements during descent through Titan's atmosphere and on the surface. So little was known about the environment *Huygens* would encounter that the probe was designed to float in case it landed in liquid.

Cassini's first few close flybys revealed

ABOVE *In the decades since* Voyager *first visited Titan, our view of the Saturnian moon has sharpened from a fuzzy orange globe, to the soft, dark and light patches imaged by Hubble, to a world of distinct and varied surface features. This global map of Titan's surface, composed of images taken by* Cassini*'s imaging science subsystem (ISS), was produced in June 2015 from data collected through April 2014. The location where the* Huygens *probe landed is 10 degrees S, 192 degrees W.*



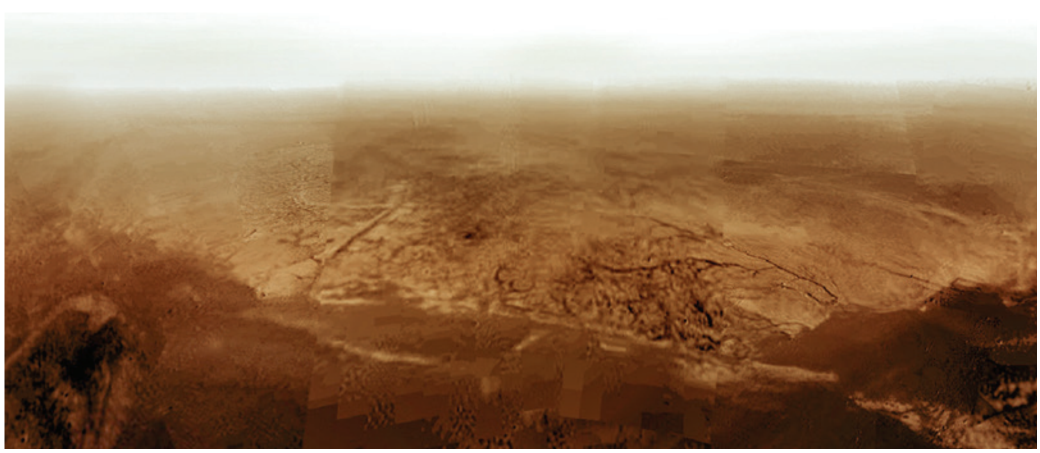
details that were intriguing but not always easy to interpret. Our understanding of the geologic structures and the processes at work on Titan unfolded slowly. Images showed fluvial channels and hinted at other types of flows, potentially the result of volcanism—or more specifically cryovolcanism, given Titan's low temperatures, with lava flows that would consist of liquid water. After months of debate among mission scientists over the early images from the orbiter, *Huygens* delivered in January 2005, revealing vistas of instantly recognizable features, including dendritic channel networks and a cobble-strewn floodplain. Subsequent *Cassini* images finally showed features identifiable as impact craters, and we learned the dark regions around the equator, discovered by HST in the 1990s, were vast seas of organic sand. The long-sought surface liquids would take a while longer to find.

The original *Cassini* mission, scheduled to last four years, was extended through Saturn's northern vernal equinox in August 2009 and later through the northern summer solstice in May 2017. As a result, we now have *Cassini* observations from 126 close flybys of Titan, in addition to the data from *Huygens*, providing global and detailed views of the geology of the solar system's second-largest ocean world. Although mysteries remain, we now have solid evidence to work with in understanding Titan's long-hidden surface.

SEAS OF SAND AND XANADU

Earth-like processes—predominantly deposition and erosion by wind and rain—shape the surface of Titan, despite the dramatic differences in surface materials between the two worlds. At a temperature of 94 kelvin (-179 degrees Celsius, or -290 degrees Fahrenheit), Titan's bedrock consists of rock-hard water ice. Liquid methane and ethane (liquid natural gas) form Titan's rain and rivers and fill its lakes and seas.

Dunes composed of organic sand cover much of the equatorial region. Up to a couple

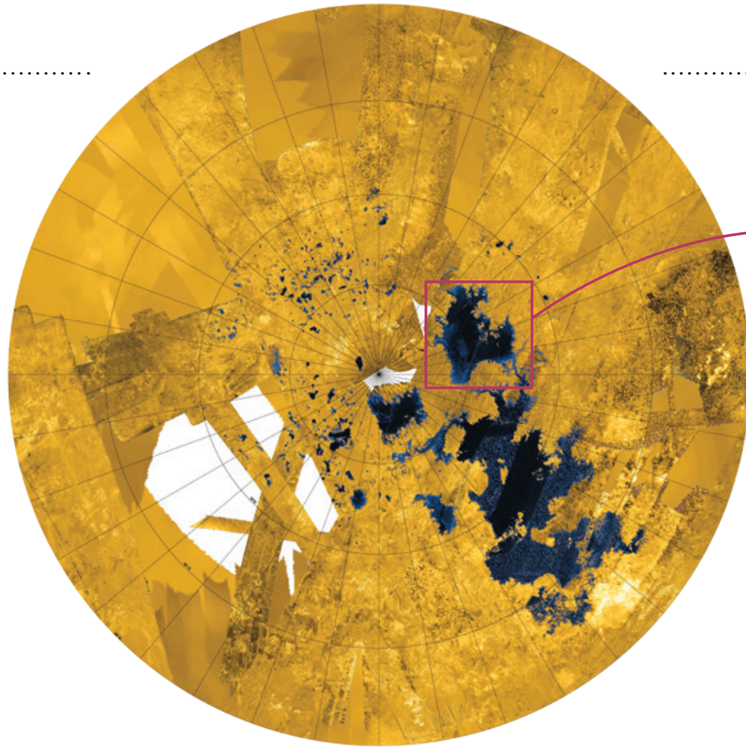


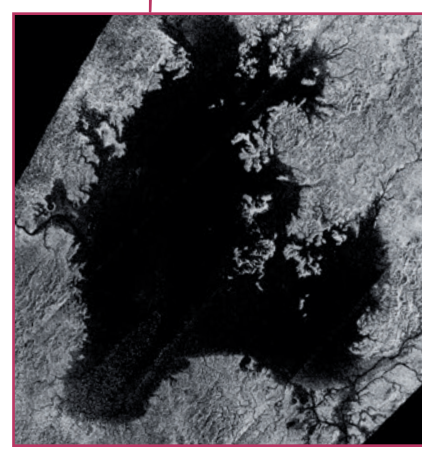
ABOVE *Hundreds of gigantic sand dunes (at least 90 meters, or 300 feet, high) undulate across Titan's face. Visible as dark lines in radar imagery, their paths around elevated features—which appear bright—show the direction of wind and sand movement across the surface. Titan's large Shangri-La Sand Sea, partly seen here, is located at the equator to the west of Xanadu.*

RIGHT *European Space Agency's* Huygens *probe took measurements and captured images as it parachuted to Titan's surface in 2005. This panorama, stitched together from* Huygens' *Descent Imager/Spectral Radiometer revealed a "shoreline" (foreground) and river channels wet with methane.*

Dunes image: NASA/JPL/ASI; *Huygens*: ESA/NASA/JPL/UA/image processing and panorama by René Pascal

ELIZABETH P. TURTLE*'s research combines remote-sensing observations and numerical geophysical models to study geologic structures and the surfaces and interiors of the planets on which they formed. She is the principal investigator of the Europa Imaging System (EIS) for NASA's upcoming* Europa Clipper *mission, an associate of the* Cassini *Imaging Science Subsystem (ISS) and RADAR teams, and a co-investigator of the* Lunar Reconnaissance Orbiter *Camera (LROC). She was also an associate of the* Galileo *Solid-State Imaging (SSI) team.*





of hundred meters high (the size of the largest dunes on Earth), the dunes are separated by flat inter-dune areas a few kilometers across. Titan's dunes are longitudinal, forming along the prevailing wind direction, like dunes in Namibia and some other locations on Earth. Dunes like these require consistent conditions over very long timescales to form, indicating that Titan's low latitudes have been primarily arid for quite a while. However, we also find channels in the low latitudes—for example, the site where the *Huygens* probe landed—so it appears that Titan's deserts are similar to terrestrial deserts, where rare rainstorms carve channels that are dry most of the time between rainfall.

The vast sand seas of the equatorial region drape and divert around most topographic features. The exception is Xanadu, which consists of deeply eroded terrain that generally sits slightly lower than surrounding areas and yet remains free of dunes, perhaps because ephemeral streams at the margins sweep sand away. Xanadu appears to be one of the older parts of Titan, preserving degraded circular structures that may be eroded impact craters.

Like Earth, Titan has relatively few preserved impact craters—a clue that points to modification of the surface by active geologic processes. Comparison of crater morphology on Titan to craters on other icy moons provides insight into the dominant processes at work. Analyses suggest that craters are modified primarily by aeolian deposition (winds) and fluvial erosion (streams and rivers).

In addition to breaking down ancient craters, erosion and deposition may have erased evidence of other geologic processes. In some places, we see chains of mountains that reach more than a kilometer high, but larger-scale patterns of tectonic activity are obscured by erosion and deposition.

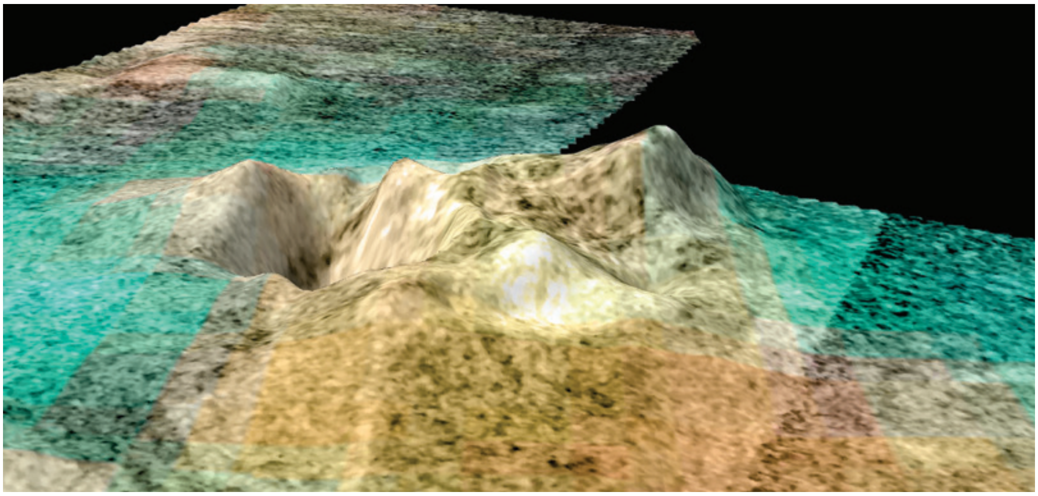
WHERE FLOWS GO: STREAMS AND LAKES

Channels are ubiquitous on Titan, with familiar dendritic patterns crossing almost all terrain types. At most latitudes, the channels appear to be empty of liquid, but even in the dry streambed at *Huygens*' low-latitude landing site, measurements that continued after the probe landed revealed the surface was damp with methane. And twice (so far) during the *Cassini* mission, we've seen darkening of the surface due to methane rainfall: once in 2005 near the south pole in late southern summer and once in 2010 about 30 degrees south of the equator shortly after the equinox. With the end of the mission nearing, it's a race against time to see if summer rainstorms will occur near the lakes and seas in the north before *Cassini*'s instruments make their final observations.

ABOVE *Ligeia Mare, filled with methane and ethane, is approximately 500 km across and has an estimated volume of 14,000 km^3, which is 2.8 times the volume of Lake Michigan. These images were obtained by the synthetic aperture radar instrument on* Cassini.

ABOVE LEFT *Most of Titan's hydrocarbon-filled lakes, and all three of its seas, exist near the moon's north pole, although its south pole has some lakes as well as depressions that may have once been ancient seas. Titan is the only world, other than Earth, with stable liquid on its surface.*

Globe mosaic: NASA/JPL-Caltech/ASI/USGS; lake close-up: NASA/JPL-Caltech/ASI/Cornell



ABOVE *Early* Cassini *images hinted at flows that suggested cryovolcanism, with lava flows of liquid water. Scientists believe this area, known as Sotra Patera, is the best case yet for an ice volcano region on Titan. To watch JPL volcanologist (and Planetary Society Advisor) Rosaly Lopes discuss cryovolcanism on Titan, go to* **planet.ly/titancryo**.

Titan's long-anticipated lakes and seas were found to exist almost exclusively at high latitudes, with some lakes near the south pole but most lakes and all three of the seas near the north pole. At low latitudes, there are some features that suggest lakebeds, but they remain unconfirmed. The south pole has depressions that may be the floors of ancient seas. The surprising asymmetry between the two poles may be the result of long-term climate variations similar to the Croll-Milankovitch cycles that drive glaciation on Earth.

Lakes often occur in steep, sharp-edged depressions as much as 600 to 800 meters (1,969 to 2,625 feet) deep (empty depressions are also common), with apparent similarities to terrestrial karst terrain. On Earth, karst forms in rock that can be dissolved by underground springs, streams, and caves, such as the limestone sinkholes that dot Florida; similarly, liquid hydrocarbons may be able to dissolve organic material on Titan's surface. However, we also see unexplained differences from terrestrial karst, for example raised rims, so work is still ongoing to understand these features.

Titan's three seas, Ligeia, Punga, and Kraken Maria, extend for hundreds of kilometers, with intricate shorelines similar to those seen on Earth in areas where terrain has been inundated by rising liquid levels, for example estuaries and reservoirs like Lake Powell on the Colorado River. *Cassini* radar measurements have detected the sea floors, providing bathymetry profiles that indicate depths of 100 to 200 meters (328 to 656 feet). *Cassini*'s longevity has made it possible to make repeat observations over time and, intriguingly, small transient bright patches have occasionally been observed on sea surfaces, the best explanations for which are waves, bubbles, or possibly floating particulate material.

NEXT STEPS

As the *Cassini* mission comes to an end, we have answers to many of the questions we asked two decades ago, but, inevitably, new knowledge also provokes new questions. Some, such as when (or whether) north-polar summer cloud outbursts might happen, can be addressed to a limited extent by monitoring using Earth-based telescopes. Other fundamental questions regarding Titan's methane cycle, deep interior water ocean, and composition beckon us. We now have a tantalizing glimpse of the complexity of the chemistry occurring in Titan's atmosphere, and the surface could host organic processes similar to those that occurred on the early Earth leading to the development of life, making Titan a particularly interesting destination to study astrobiology. An unparalleled opportunity to study prebiotic chemistry, and the possibilities for life on other worlds, is scattered on the ground, awaiting our return to Titan.

CANDICE HANSEN-KOHARCHECK *is a senior scientist at the Planetary Science Institute.*

The Source of Saturn's E Ring

Enceladus and a Mystery Solved by *Cassini*

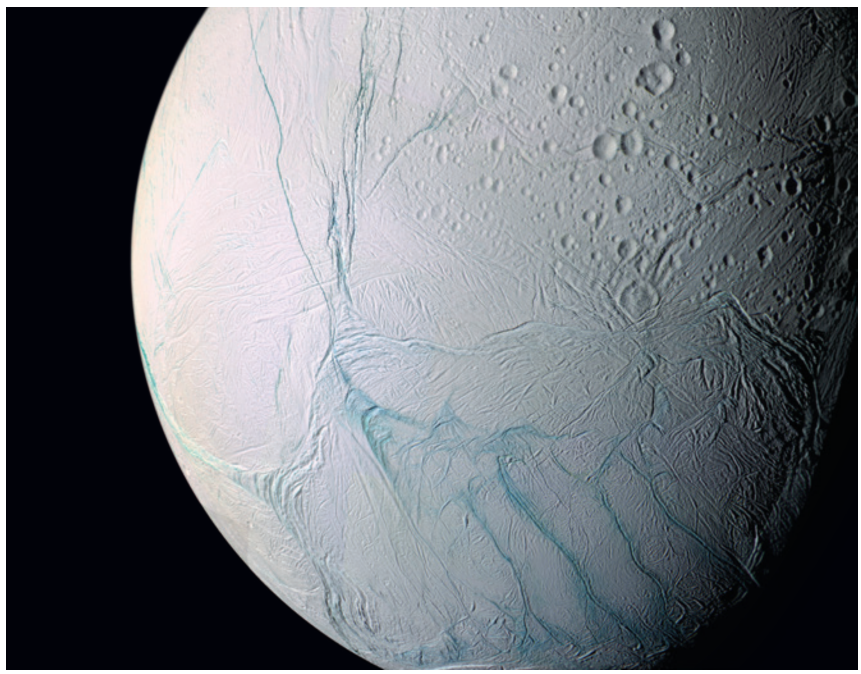
LONG BEFORE THE *Cassini* mission, Enceladus was an intriguing moon. Its youthful geology and the coincidence of Enceladus' orbit with the E ring led to suspicions that eruptive activity on Enceladus might be the source of Saturn's E ring. Thus, four close flybys were planned for *Cassini*'s prime mission.

In July 2005, *Cassini* flew by Enceladus and found that there is indeed a plume of water vapor and ice particle jets coming from the fissures (dubbed "tiger stripes") across the moon's south pole. This validated the hypothesis that Enceladus is the source of Saturn's E ring and raised a host of new questions. With every flyby of Saturn's active moon, *Cassini*'s new data has filled in our understanding of this remarkable phenomenon. By the time of *Cassini*'s demise, the spacecraft will have flown close to Enceladus 23 times.

A SUBSURFACE GLOBAL OCEAN

As in most moons in the solar system, the surface of Enceladus is solid water ice. Beneath Enceladus' icy crust is a layer of liquid water. Data from the radio science subsystem on the *Cassini* spacecraft show that there is a subsurface gravity anomaly consistent with a body of liquid water 30 to 40 kilometers (19 to 25 miles) below the south pole, extending up to about 50 degrees south latitude. Images taken for the study of Enceladus' libration confirmed that the crust is separated from the interior everywhere, so the liquid layer is global.

While we now know that the source of the erupting water is a subsurface global ocean, we do not know why the plume activity is concentrated at the south pole, where the crust is possibly as thin as 5 kilometers (3 miles). Ice particles and water vapor are propelled from Enceladus' interior out to the vacuum of space through the tiger stripe fissures about 130 kilometers (80 miles) long across the south pole of Enceladus from vents that are just 9 meters (30 feet) wide. In all, about 100 jets of ice particles have been identified along the length of the tiger stripes. Tidal flexing likely powers the plume and appears to affect the source rate for particles. The brightness of the jets, a proxy for the amount of material streaming out, varies with orbital longitude, implicating tidal stresses. More particles are ejected from Enceladus when it is at its most distant point from Saturn (apokrone) than at the closest point in its elliptical orbit (perikrone), by about a factor of three.

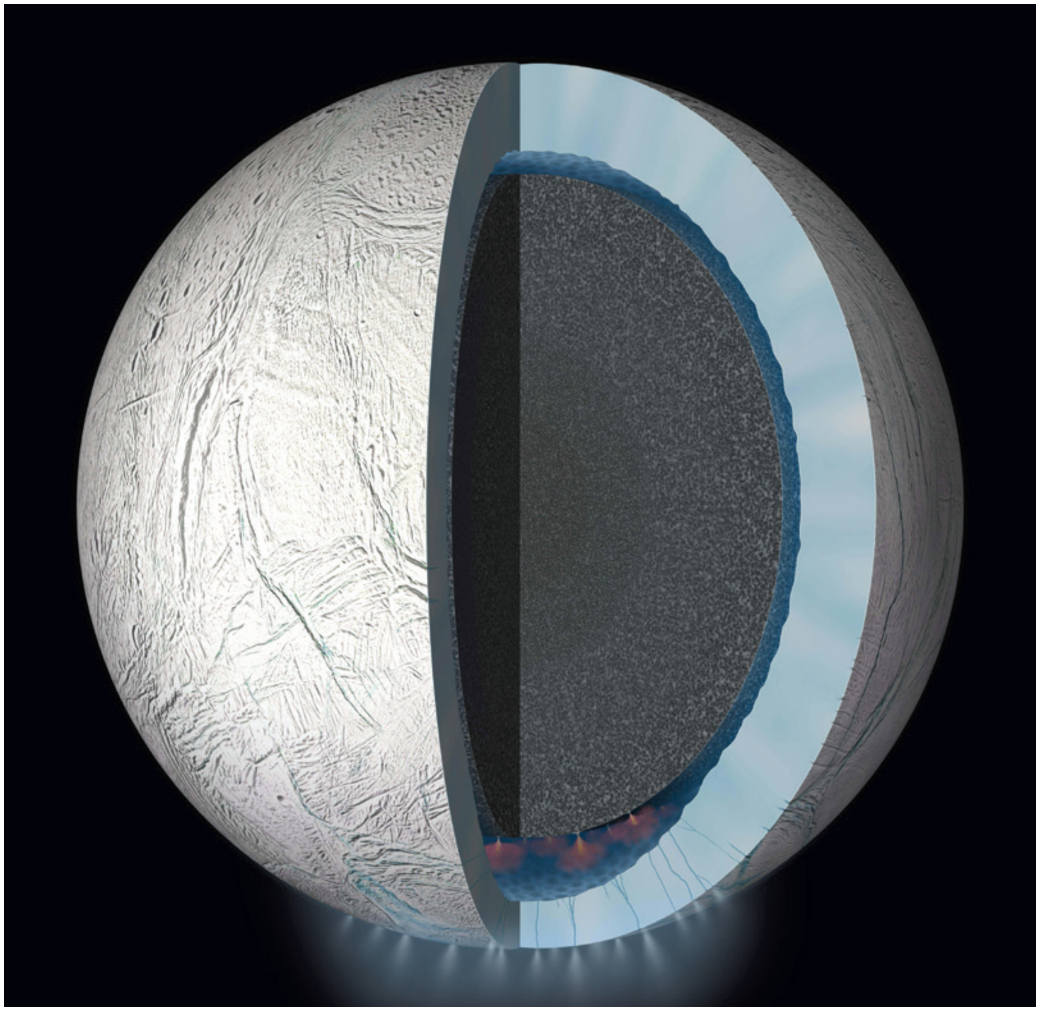


ABOVE *This enhanced color view of Enceladus highlights the bluish "tiger stripe" fractures that course across its south pole. From right to left they are named Alexandria, Cairo, Baghdad and Damascus. It is from these vents that Enceladus' distinctive plumes emanate.*

NASA/JPL-Caltech/Space Science Institute

UNDERSTANDING THE ICY JETS

Stars passing behind the plume (stellar occultations) observed by *Cassini*'s ultraviolet



ABOVE *This cutaway view shows Enceladus' plumes escaping from fractures in its icy shell. Beneath the shell lies a liquid water ocean over a rocky core. Hydrothermal activity at the ocean floor creates superheated water, powering the plumes.*

Image: NASA/JPL-Caltech

instrument show that the gas composition of the plume is dominated by water. Other molecular constituents, such as carbon dioxide, ammonia, and methane (CO_2, NH_3, and CH_4), and various other hydrocarbons detected *in situ* by *Cassini*'s Ion Neutral Mass Spectrometer, provide the remaining 5 to 10 percent. The stellar occultations also revealed highly collimated supersonic gas jets embedded within the overall plume. Assuming a source temperature of at least 170 kelvin (–103 degrees Celsius or –153 degrees Fahrenheit), all gas molecules leave with a velocity greater than escape velocity. These neutral water molecules flood the Saturn system.

Occultations observed from 2005 to 2017 show source rates with a variation of just 20 percent in over six years, representing a steady output of about 200 kilograms (about 440 pounds) of water vapor per second. The rate of fine material being ejected is not inconsistent with the gas rate, which has not been measured at apokrone. Rather, the combined dataset shows that material erupts from Enceladus steadily, but the rate is modulated as Enceladus orbits Saturn.

Several concepts have been proposed for the nature of the "plumbing" that connects the subsurface liquid reservoir to the escaping gas and particles. One idea is a "Perrier ocean" powered by escaping CO_2 as seawater nears the surface, pressure decreases, the dissolved gases come out of solution, and bubbles form. Another idea is that the gas is accelerated as it goes through nozzle-like channels from the ocean to the surface. Yet another idea is that water

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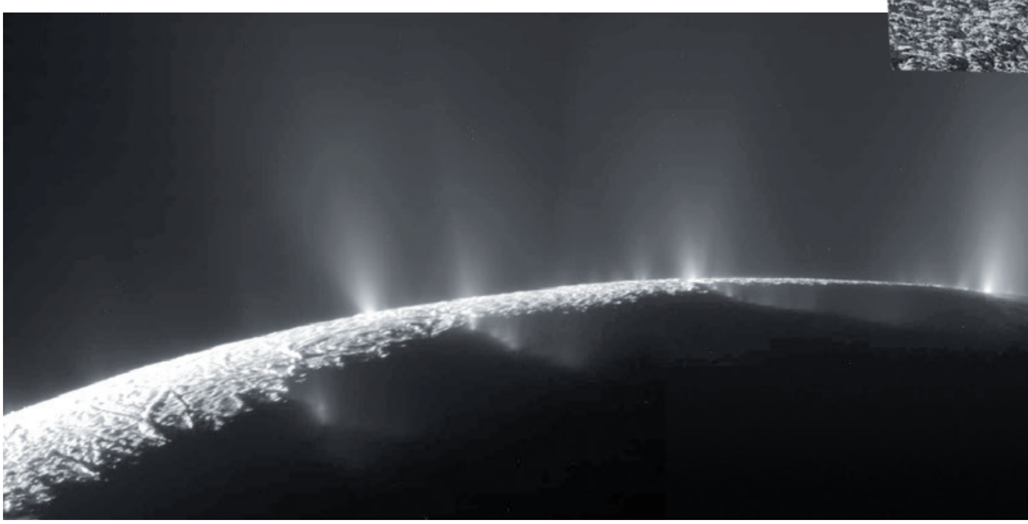
coming up from the ocean separates the solid edges of the fissures and that tidal stresses partially open and close the fissures, keeping the water from freezing. *Cassini*'s data is collected outside Enceladus, so we can only model what is going on below the surface and then ask whether the model is consistent with the dataset.

Cassini's dust analyzer has determined the particle size and compositional profile of the water ice particles fountaining from the tiger stripes. Their grain sizes are stratified: the smallest (smaller than 0.4 micron) pure-ice particles condense from gas in the plume, reach escape velocity, and go into orbit around Saturn, forming the E ring. In contrast, larger salt-rich particles come from liquid water that is in contact with a rocky core. These may originate as a frozen aerosol spray, which is then carried out by the escaping gas. These larger grains fall back to the surface and modify Enceladus' color.



ABOVE Cassini *captured the images that comprise this four-frame mosaic of the south polar tiger stripes during its close flyby on November 21, 2009.*

LEFT *This mosaic consists of two images of Enceladus' south pole, captured by* Cassini *on the same day. Tiny, pure ice particles condense from the gas in the plumes, reach escape velocity, and go into orbit around Saturn, forming the E ring.*

Plumes: NASA/JPL-Caltech/mosaic by Emily Lakdawalla; vents: NASA/JPL/Space Science Institute/mosaic by AstroO, unmannedspaceflight.com

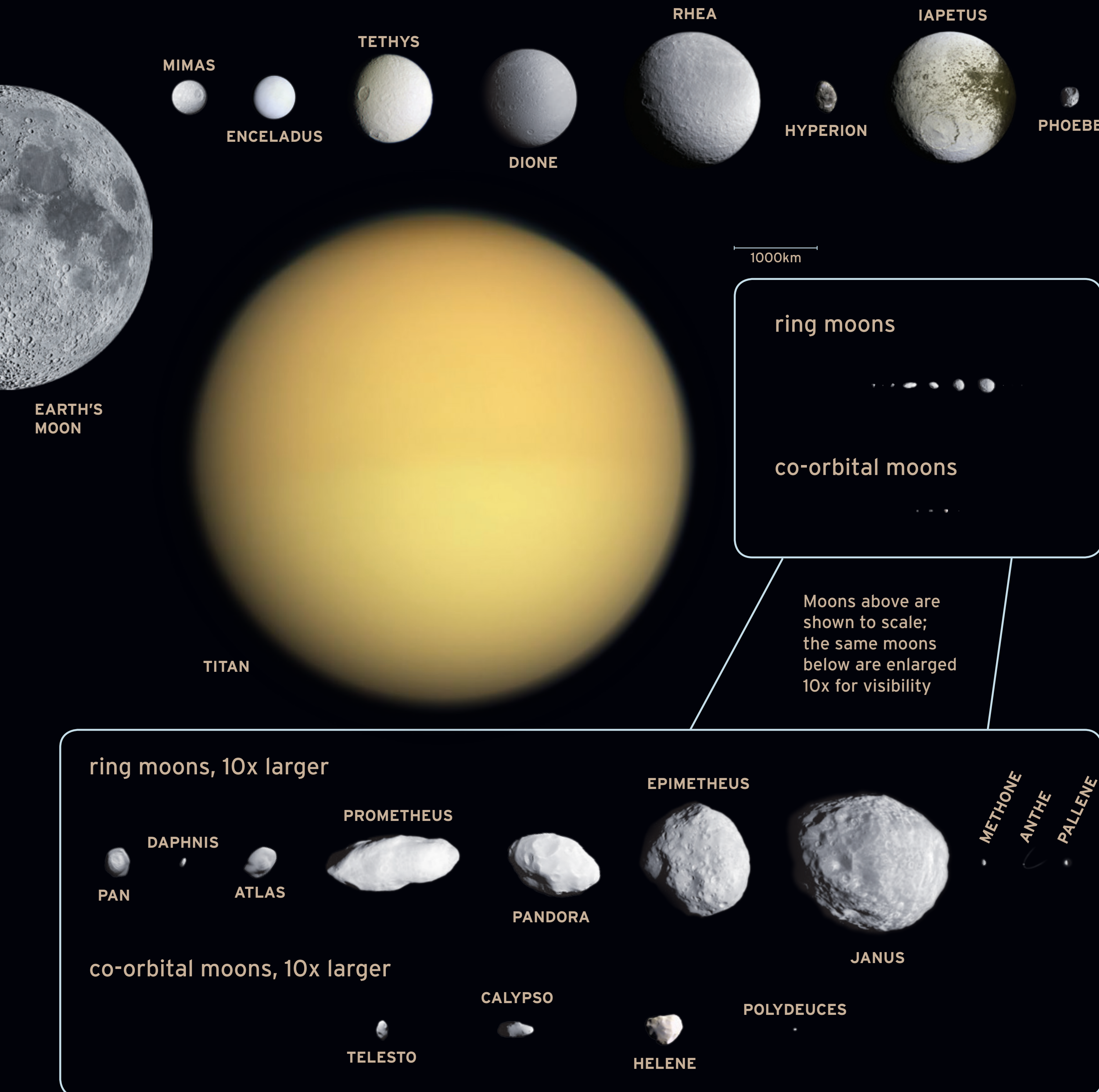
LIFE ON ENCELADUS?

The dust analyzer also detected silica nanoparticles, confirming that the liquid layer is in contact with the rocky core. Very hot (90 degrees Celsius or 194 degrees Fahrenheit) water is required for these particles to form, suggesting that Enceladus has hydrothermal vents on its seafloor. Furthermore, the abundance of methane gas in the plume can exist only if there are hydrothermal vents preventing the methane from being captured in the icy walls confining the ocean. In Earth's ocean, hydrothermal vents host abundant life thriving in that extreme environment.

Does Enceladus' internal ocean harbor life? Another piece of the puzzle is provided by the Ion Neutral Mass Spectrometer's detection of hydrogen (H_2). The process that likely provides the H_2, serpentinization of rock, could provide the chemical energy required for life. *Cassini*'s investigations have shown that Enceludus' ocean is a habitable environment. But is it inhabited? The answer to that question will have to wait for the arrival of a spacecraft with a payload of instruments specifically designed to look for life.

The Moons of Saturn

Throughout its 13-year mission, *Cassini* used repeated flybys of Saturn's many moons to build up global views of all of them. Each is a unique world. The larger ones have complex geologic histories, driven by heating and cooling of their interiors. But even the small ones have unique geologic stories, because of their different positions closer to or farther from Saturn, their embedment in different parts of the ring system, and their magnetic-field-driven particle motions. Here is a post-*Cassini* view of Saturn's moons, including several discovered during the mission. —*Emily Lakdawalla*



CASEY DREIER *is director of space policy for The Planetary Society.*

With *Cassini* Gone, Now What?

The Long Road to the Outer Solar System

Image: ESA/AOES

ABOVE *ESA's* JUICE *mission is planned to arrive at Jupiter in 2030 and settle into an orbit around Ganymede in 2032. There are as yet no confirmed plans by any space agency to return to Saturn.*

IN JUNE OF 1982, a joint working group from European Space Agency and NASA was formed to examine how the two space agencies could work together to explore the solar system. One recommendation was to orbit Saturn and its largest moon, Titan. A scant fifteen years (and many additional reports) later, *Cassini-Huygens* launched from Cape Canaveral.

Now that *Cassini* is gone, there is only one spacecraft operating in the realm of the gas giants. *Juno*, a product of NASA's New Frontiers mission line, will continue to measure the poles of Jupiter for a few more years. After that, humanity's robotic presence in the giant planets will end for the first time since 1973, when *Pioneer 10* emerged from the far side of the asteroid belt.

Fortunately, with the Europa Clipper project well underway, this retreat will be temporary. And should the mission utilize the heavy-lift capabilities of the Space Launch System and meet its target launch date of 2023, we could see a new spacecraft at Jupiter as early as 2026. ESA is working on its own Jupiter mission, the *JUpiter ICy moons Explorer*, or *JUICE*, which will arrive in 2030.

But there are no currently approved missions to Saturn or its moons.

That could soon change. NASA has opened competition for another New Frontiers-class mission to launch in 2024 or 2025. New Frontiers missions are cost-capped at $850 million and must target one of seven pre-approved destinations. Fortunately for Saturn fans, three out of the seven possible mission concepts would revisit the ringed planet.

Several mission concepts have been publicly announced. The Enceladus Life Finder would fly through the ocean moon's vapor plumes and analyze their contents for hints of life. Dragonfly would place a helicopter drone on Titan that would fly from site to site, sampling the moon's chemistry to determine its habitability. Oceanus would orbit Titan, mapping its surface at a high resolution and providing new insights into its unique chemistry and geology. SPRITE would descend into the clouds of Saturn, directly measuring their structure and chemistry, helping to advance our understanding of how the solar system formed.

NASA plans to announce several New Frontiers finalists by the end of this year. Each finalist will then spend next year refining its mission concept and submitting it to a series of independent reviews. Using this feedback, NASA will commit to a single mission by mid-2019.

Assuming a Saturn-centric mission is selected (which is no sure thing), the team would spend five years building the spacecraft, followed by roughly a decade of travel time. So the earliest return to the Saturn system would be 2034—seventeen years from now.

This process is both a reminder of how good we had it with *Cassini*, and how hard it is to systematically explore the farther reaches of our solar system. The *Cassini* team demonstrated the payoff of this patience, and scientists will pore through the mission's data for decades to come. Saturn may be quiet now, but we will return, and the payoff will be extraordinary.

Learn more about the projects competing to be the next New Frontiers mission at planet.ly/newproposal

The U.S. Senate advanced a funding bill providing $19.5 billion for NASA in 2018. Read the details at planet.ly/2018budget

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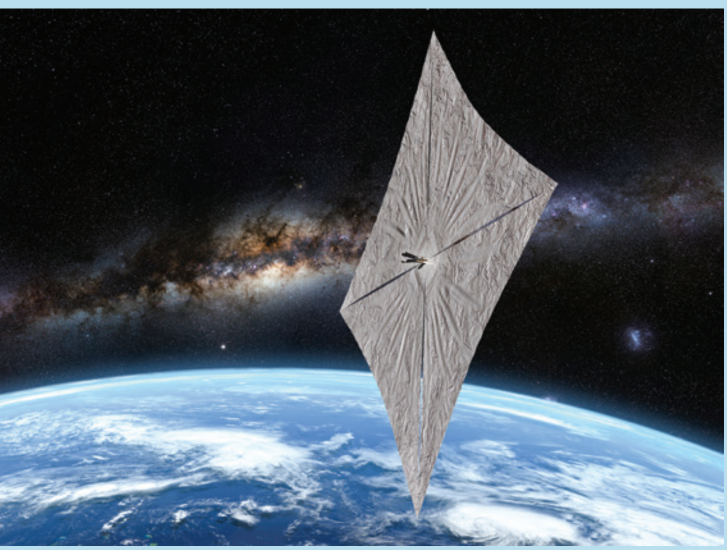
Help *LightSail 2* Get to the Launch Pad!



ABOVE *Powered only by sunlight,* LightSail 2 *will demonstrate controlled solar sailing in Earth orbit.*

Illustration: Josh Spradling

Thanks to the support of our members, we will soon make space exploration history with our *LightSail 2* mission! If successful, *LightSail 2* will be the first CubeSat spacecraft to demonstrate controlled solar sailing.

Recently, we received an update from the United States Air Force—*LightSail 2*'s launch date is set for no earlier than April 30, 2018, while SpaceX continues preparing its Falcon Heavy rocket for its inaugural flight.

Given the lessons we learned from *LightSail 1*'s 2015 test mission, this additional time has turned into an immense opportunity. Extensive upgrades and progressive testing have enabled us to make more enhancements, including a suite of new software and hardware, automated-repair watchdogs, and comprehensive testing of the attitude determination and control system that will swing the spacecraft's solar sail into and away from the Sun's photon stream with each orbit.

Solar sail popularity continues to grow because the technology offers the potential to travel through space without fuel and at a much lower cost. In fact, NASA recently approved a solar sail mission with a design similar to *LightSail*: Near-Earth Asteroid Scout.

With the unexpected costs of additional testing and enhancements, we need your help to keep the *LightSail 2* mission on track. Learn more about our current appeal to members at **planetary.org/lightsail**.

Onward,

Richard

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