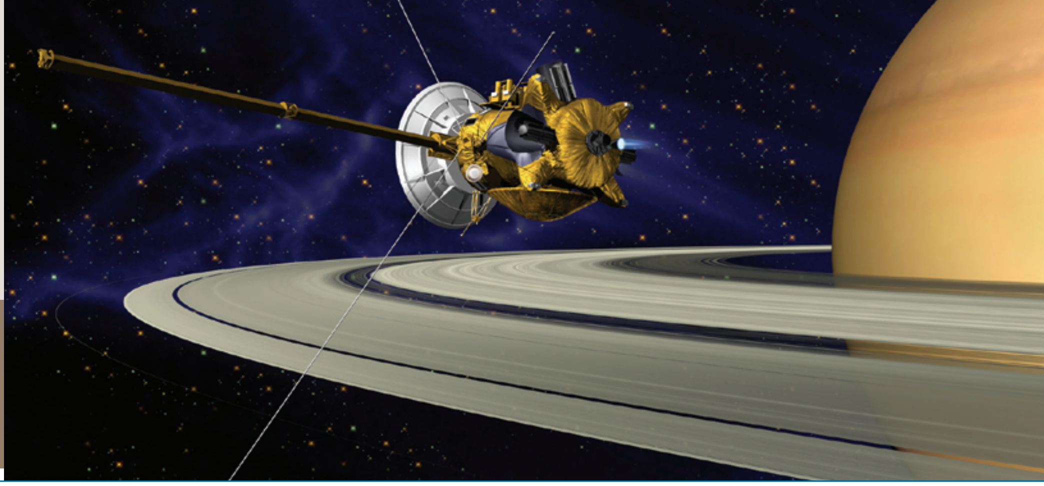
Cassini's Ringside Seat

Saturn's rings and moons are a model for how planetary systems may be forming around nearby stars. The Cassini spacecraft has been taking a close look at the rings of late, and it turns out that gravity and granules with momentum can do some amazing things.

Of all the planets in our solar system, only one's got a whole lot of bling. Yet, for most of human history, we didn't know about Saturn's luminous rings, even though the gigantic, gaseous planet is readily visible in the night sky. When Galileo became the first person to peer at Saturn through a telescope in 1610, he sketched a companion moon on each side. A couple of years later, he became utterly perplexed when the moons vanished. When the mysterious objects returned, he saw them as elliptical arms resembling handles. In 1655, Dutch astronomer Christiaan Huygens, using a better telescope, figured out that the arms were actually a flat ring and that, like the edge of a sheet of paper held horizontally at eye level, it disappeared from view when Saturn's tilt presented it to us edge-on. (The rings truly are paper-thin—a mere 10 to 20 meters thick on average, and yet so broad that they would fit neatly between Earth and

Opposite: Linda Spilker, Cassini's project scientist, with one of the Deep Space Network's 34-meter dishes at Goldstone, California.
Right: The Cassini orbiter.
Below: The anatomy of Saturn's rings. The planet itself is out of view to the left.

By Linda Doran



its moon.) Saturn's rotational axis is tilted by about 27 degrees, and the rings, which girdle Saturn's equator, are tilted by the same amount. Seasons change slowly on Saturn, with its nearly 30-year orbit; but once every 14 to 15 years, when the sun straddles Saturn's equator at the solar equinox, the rings vanish from view—they're pointed directly at the sun and more or less at us.

Seen through the 60-inch telescope at Caltech's Palomar Observatory, Saturn's rings beckon like diamond-paved, circular highways. (Every now and then, the Friends of Palomar Observatory get a tour that, weather permitting, includes an opportunity to turn that telescope on the heavens.) They nearly fill the telescope's field of view, and seem as close as the moon does in a pair of good binoculars. In reality, they're more than a billion kilometers away. If you were to count those kilometers at one per second, you'd still be counting three decades from now—an entire Saturnian year later. Put another way, Saturn is about 10 times farther away from the sun than Earth. Understanding something so remote is a challenge not only for parents with curious children—at Palomar and elsewhere—but for scientists as well. To this day, we're not even sure how old the rings are or exactly what they're made of.

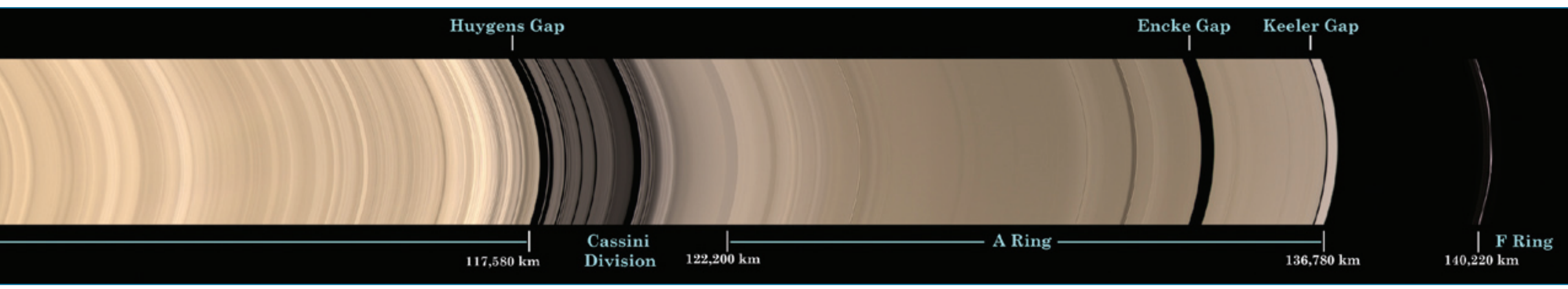
Our first clue came in 1675, when Giovanni Domenico Cassini, the founding director of the Paris Observatory under Louis XIV, observed not one bright ring but two, separated by a dark gap. The discovery of what's now called the Cassini Division, 4,800 kilometers wide, demonstrated that Saturn's rings were not a single, solid object. Quite perceptively, Cassini theorized that they were swarms of tiny moonlets too small to be seen from afar.

Three centuries later, spacefaring vehicles carried telescopic cameras to Saturn itself. Our first emissary, NASA's Pioneer 11, revealed in 1979 that the Cassini Division was not actually empty, but was merely a zone with a very low density of ring material. JPL's twin Voyager spacecraft, flying past Saturn in 1980 and 1981, showed that the rings are astonishingly complex. Astronomers and stargazers alike marveled at images of gaps swept clean by tiny moons, mysterious dark spokes whirling within the B ring as if it were a wagon wheel, and the "braided" multiple strands of the F ring. The Voyagers showed that Saturn's rings were really thousands of discrete ringlets, and confirmed that they are very nearly pure—99 percent—water ice. (We'll come back to that other 1 percent later.) The Voyagers also determined that the ring particles range from flecks the size of dust, about a millionth of a meter across, to chunks of ice as big as two-story houses. Most of them, however, run from pebbles to snowballs.

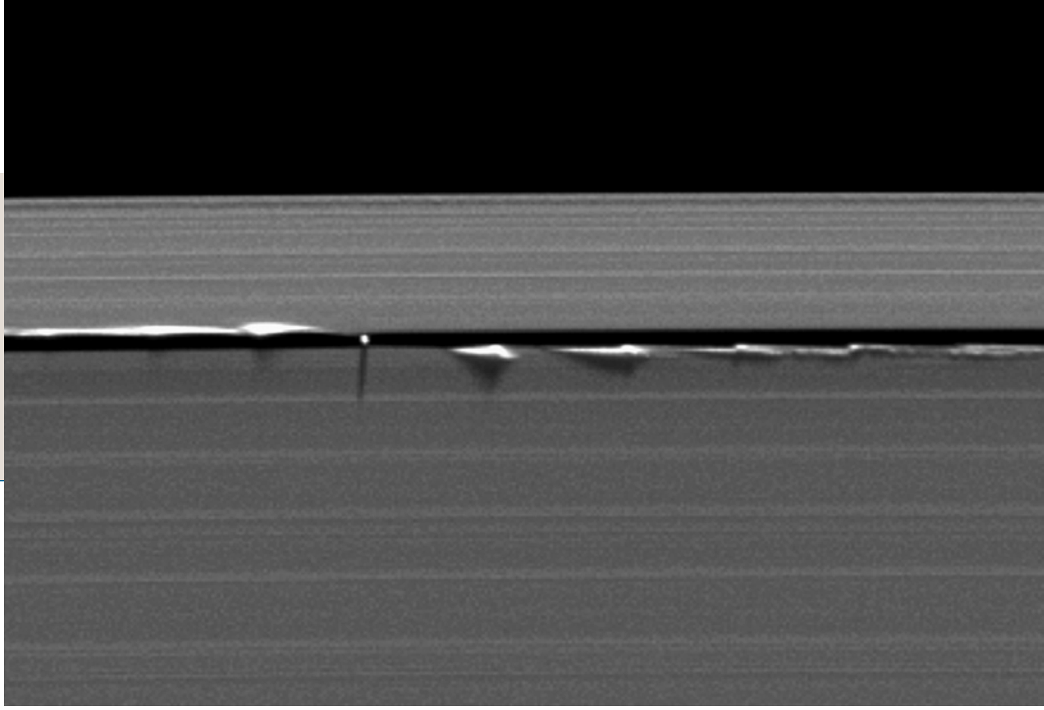
On June 30, 2004, a schoolbus-sized spacecraft named Cassini, a joint U.S.-European mission built and operated by the Jet Propulsion Laboratory, which Caltech manages for NASA, entered orbit around Saturn. Six months later, on December 25, Cassini released the European Space Agency's Huygens probe, which parachuted to the surface of smog-shrouded Titan. Discovered by Christiaan Huygens in 1655 and bigger than the planet Mercury, Titan is the second-largest moon in the solar system and has an Earth-like surface with highlands, lowlands, stream channels, and liquid methane–filled lakes. Huygens sent pictures and data back to Cassini during the entire journey down, and then continued to transmit information from the surface for some 70 minutes, until the mother ship flew out of range. Meanwhile, Cassini had settled into its four-year primary mission—a grand tour of a planet that many scientists regard as a miniature solar system in its own right. A team of navigators guides Cassini on the multiple loops of its itinerary, firing rocket thrusters to fine-tune its orbit and using the gravitational pull of Titan like a slingshot to adjust the spacecraft's path. Cassini's travels have taken it on equatorial orbits in the plane of Saturn's rings and moons, as well as on steeply inclined orbits above and below the plane in order to make observations from as many angles as possible. And Cassini will be going strong for years to come—in January 2010, NASA authorized a seven-year mission extension to follow Saturn through a complete change of seasons.

PLUNGING INTO THE DARK

Which brings us back to the solar equinox. In August 2009, for the first time in history, astronomers got a close-up look at Saturn's rings shrouded in darkness, just as they were when Galileo couldn't see



The gravitational pull of a tiny moon named Daphnis, only eight kilometers in diameter, sweeps stray material out of the 42-kilometer-wide Keeler Gap near the outer edge of the A ring. Cassini discovered that Daphnis's gravity also kicks up bright, white rooster tails in the ring material.



them. One of those astronomers was JPL's Linda Spilker, Cassini's project scientist. "At equinox, the sun is essentially edge-on to Saturn's rings," she says. "This is the time when the ring temperature is at its very coldest—down to 43 kelvins (–230 degrees C). In a sense, it's like experimentally turning off the sun. The rings are heated only by Saturn's thermal radiation and by sunlight reflected from Saturn." When Cassini arrived at Saturn, the rings averaged 90 to 110 K (–183 degrees C to –163 degrees C). During equinox, a 60-degree temperature drop happened overnight, as it were.

Spilker belongs to that generation of space explorers who spent July 20, 1969, in wide-eyed wonder in front of their television sets watching Neil Armstrong set foot on the moon. While an undergrad majoring in physics at Cal State Fullerton, she studied other space rocks at Caltech—helping her physics professor, Dorothy "Dotty" Woolum, who had been a postdoc at Caltech in the '70s, and Don Burnett, Caltech professor of nuclear geophysics, analyze the distribution of bismuth and lead in meteorites. Later, she worked on the Voyager mission, and she likes to tell her daughters that their births were literally based on the alignment of the planets. The girls were born between Voyager 2's flybys of Saturn in 1981 and Uranus in 1986—in other words, during the "cruise phase" when there wasn't so much going on.

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Spilker's fascination with destinations beyond Earth is a constant in her life. "If you could scoop up a particle out of Saturn's rings," she asks, "and hold it in your hand, what would it look like? Would you see this fluffy snowball? Would it have an icy core? If you could take your knapsack and collect particles as you collect shells on a beach, would you find different kinds of particles in each of the rings? I like being an explorer."

She has a partial answer to those questions as a result of data collected during the equinox. In addition to her management role coordinating Cassini's many investigations, Spilker is coinvestigator on an instrument called the Composite Infrared Spectrometer, or CIRS. Humans sense infrared light as heat. Like a snake's tongue, CIRS seeks out sources of heat, experiencing the world at wavelengths longer than those the human eye can see. As it distinguishes variations in infrared light, CIRS can map the temperature and composition of Saturn's rings because different materials emit and absorb heat in characteristic ways.

"I think that the outsides of Saturn's ring particles would certainly be very fluffy and porous," Spilker says. "That's based on the fact that they heat up and cool down very quickly, within about half an hour. They have what we call a very low thermal inertia—in fact, it's four orders of magnitude lower than that of a solid block of ice." Rapid heating and cooling implies a lot of surface area in order to exchange so much thermal energy with the surroundings so fast. That's why crushed ice in a glass of soda melts faster than cubed ice.

For about four days, the rings were cloaked in shadow. Indeed, sunlight on Saturn's rings during the equinox is so dim

Planetary scientist Carolyn Porco did her PhD thesis on Voyager's observations of Saturn's rings and spokes. She now leads Cassini's imaging team, which is headquartered at the Space Science Institute (SSI) in Boulder, Colorado. In 2009, she received the most prestigious award in scientific photography, the Lennart Nilsson Award, "for combining the finest techniques of planetary exploration and scientific research with aesthetic finesse and educational talent."

"From the very beginning of the Cassini mission," says Porco, "I took it as my personal goal that we on the imaging team would be the planetary equivalent of nature photographers. We would try to capture, whenever possible, images and movies whose primary purpose went beyond science and conveyed the sheer magnificence and otherworldly beauty to be found around Saturn."

The vast library of aesthetically striking images taken during equinox as well as throughout the mission is available for viewing at JPL's Cassini website and at the website of SSI's Cassini Imaging Central Laboratory for Operations (CICLOPS), where the images are processed. The images paint a portrait of a planetary system that, in Porco's words, "is so alien in comparison to Earth that we might as well have visited a planet around another star in another quadrant of the galaxy. When this mission is over, we will leave behind a stunning visual legacy, and a body of work that will guide future explorers, both robotic and human, in their excursions around the Saturn system."

A much sought-after speaker and Carl Sagan protégée who served as a consultant on the movie *Contact*, she also consulted with Industrial Light and Magic's visual-effects supervisor Roger Guyett on the recent *Star Trek* reboot. This picture, taken at ILM, shows her with some familiar faces from yet another blockbuster franchise. (Photo courtesy of Carolyn Porco and ILM.)

that the rings are nearly invisible in the raw camera images, even those taken from overhead. The only reason we can see them is that scientists led by Carolyn Porco (MS '79, PhD '83) digitally enhanced the shots from Cassini's wide-angle camera. (Porco, too, worked on the Voyager mission, and is now also working on NASA's New Horizons mission en route to Pluto.) To bring the rings to life, she and her colleagues at the Cassini Imaging Central Laboratory for Operations (CICLOPS) at the Space Science Institute in Boulder, Colorado, increased the brightness of the dark half of the rings by a factor of three relative to the half illuminated by Saturn-shine, and bumped up the brightness of the entire ring system by a factor of 20.

The photos revealed walls of icy rubble as tall as mountain peaks rising out of the ring plane. "It's like standing outside right before the sun sets," notes Spilker. "Your shadow gets very long. Anything that's a little bit bigger, or sticks up, casts shadows on the part of the ring that's behind it. We see what look like towering mountains, in some cases as high as four kilometers, created by the particles that Saturn's moon Daphnis is pulling out of the ring plane." This happens because Daphnis's orbit is slightly tilted with respect to the rings. When Daphnis crosses the ring plane, it drags some of the particles out of the plane. Like the rooster tail behind a speedboat at full throttle, this disturbance quickly subsides once Daphnis passes by. If you were a pilot flying above the great plains that are Saturn's rings, it would be a good idea to keep plenty of altitude over the landscape below, lest you crash into an icy curtain as tall as the Rockies.

As you kept an eye out for ice peaks, you might also notice regularly spaced basins and ranges. Close analysis of the Voyager pictures had revealed spiral density waves in the rings. These waves occur wherever one of Saturn's moons is in resonance with a region in one of Saturn's rings. Orbital resonance brings two bodies back to the same region of space over and over again—for example, if the ring particles travel around Saturn exactly twice for every orbit of the moon, they have a 2-to-1 resonance. The repeated gravitational tug at that location causes the ring particles to crowd together into a coherent spiral structure one or two kilometers wide. The resulting density wave sweeps through the ring material. As the crest overtakes the ring particles in their orbits, they get pushed together by the wave; once the wave passes, the trough pulls the particles back into their original positions relative to their fellows. These density waves are analogous to the arms of a spiral galaxy such as our own Milky Way, says Porco. "They're much more tightly wound than the spiral structures that you see in galaxies, but they are in fact the same creatures. The physics behind them is the same."

Spiral density waves are compressional, existing only in the two dimensions of the ring plane. But if the orbit of the resonant moon is slightly askew, yet another set of waves forms—this time, in three dimensions. The orbit of Saturn's moon Mimas also takes it above and below the ring plane, pulling ring particles out of the plane along with it. Orbital resonance then keeps these particles' orbits tilted relative to the plane, resulting in a towering spiral wave called a bending wave that wraps all the way around the ring. The density waves and the bending waves propagate in opposite directions, says Spilker, adding a further level of complexity to the rings' structure.

And now Cassini's equinox pictures show yet another kind of three-dimensional wave, heretofore undiscovered. These waves only rise about 100 meters above the ring plane, yet during the equinoctial photo session they too remained illuminated after the rings were plunged into darkness. "From high above, the rippled surface of Saturn's D ring looks like a corrugated roof," says Spilker. "The ripple extends for more than 17,000 kilometers across the ring system. When the Voyagers flew by, it wasn't there. Something caused this wonderful rippling to get started, and then it expanded outward all the way into the C ring. Based on computer models of the ripple's expansion, we can run the clock backward, and we think that it began some time in the early to mid-1980s." Scientists remain baffled about its origin, but one possible scenario has a meteoroid slamming into the rings—the pebble in the pond, as it were. Like the waves the Voyagers discovered, this ripple is also a tightly wound spiral. In fact, it has become more tightly wound over time. In Hubble Space Telescope images taken before Cassini's discovery and since reexamined, the ripples were farther apart.

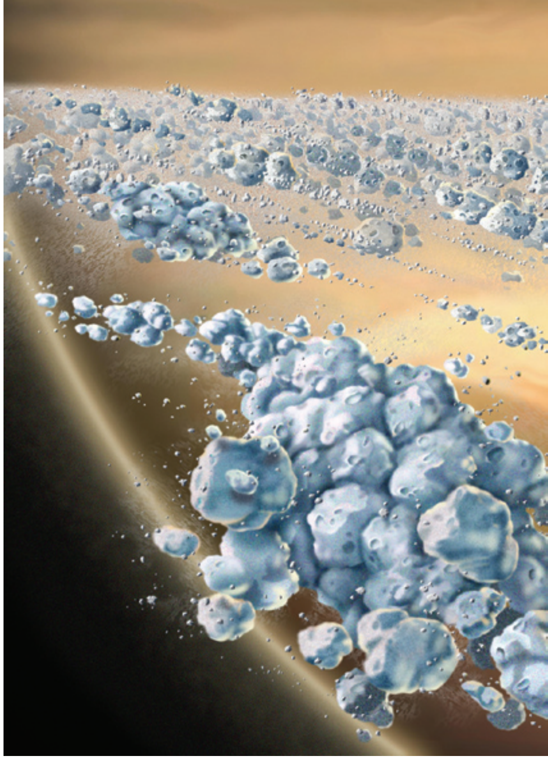
Cassini also got a close-up look at the mysterious "spokes" in Saturn's rings first observed by the Voyagers. These spokes may be the result of meteoroids hitting the ring and generating charged particles, says Porco. The particles levitate, in the same manner that a comb rubbed vigorously on a wool sweater will cause your hair to rise if held near your head, until eventually they lose their charges and settle back into the ring plane. The low-angled sunlight at equinox caught the high-flying spokes, setting them off against the shadowed rings below.

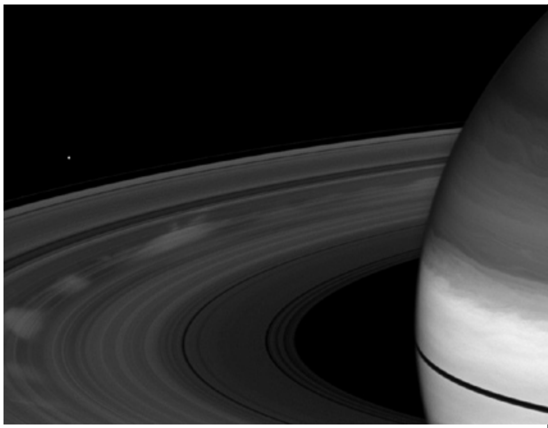
BLINKING IN THE SUNLIGHT

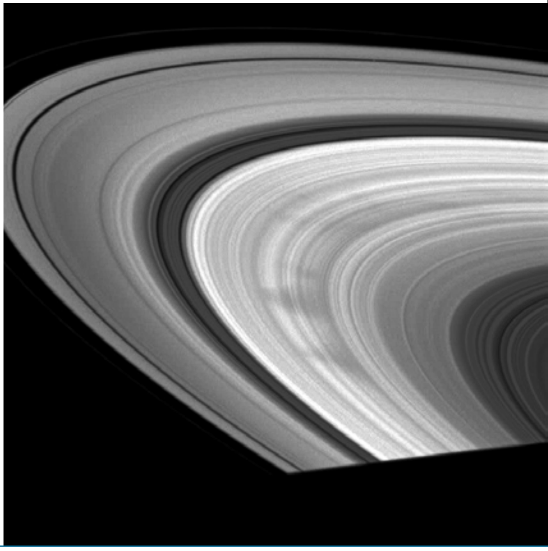
If, on a bright sunny day (you certainly wouldn't want to be using visual flight rules during equinox), you were to buzz down between the A and B rings through the Cassini Division, you would find that the rings' unlit side is not completely dark. Instead of being continuous, each of Saturn's ringlets is like a dashed line of clouds. "As we fly underneath," says University of Colorado at Boulder planetary scientist Larry Esposito, "we see flashes of sunlight come through the gaps. We originally thought we would see a uniform cloud of particles. Instead we find that the particles are clumped together with empty spaces in between." Esposito is principal investigator for the Ultraviolet Imaging Spectrograph, or UVIS, which sees light at wavelengths shorter than we can perceive—ultraviolet rays are what burn your skin if you forget the SPF 30. Esposito's team measured ultraviolet emissions from a distant star, Alpha Arae, which waxed and waned as the rings passed in front of it.

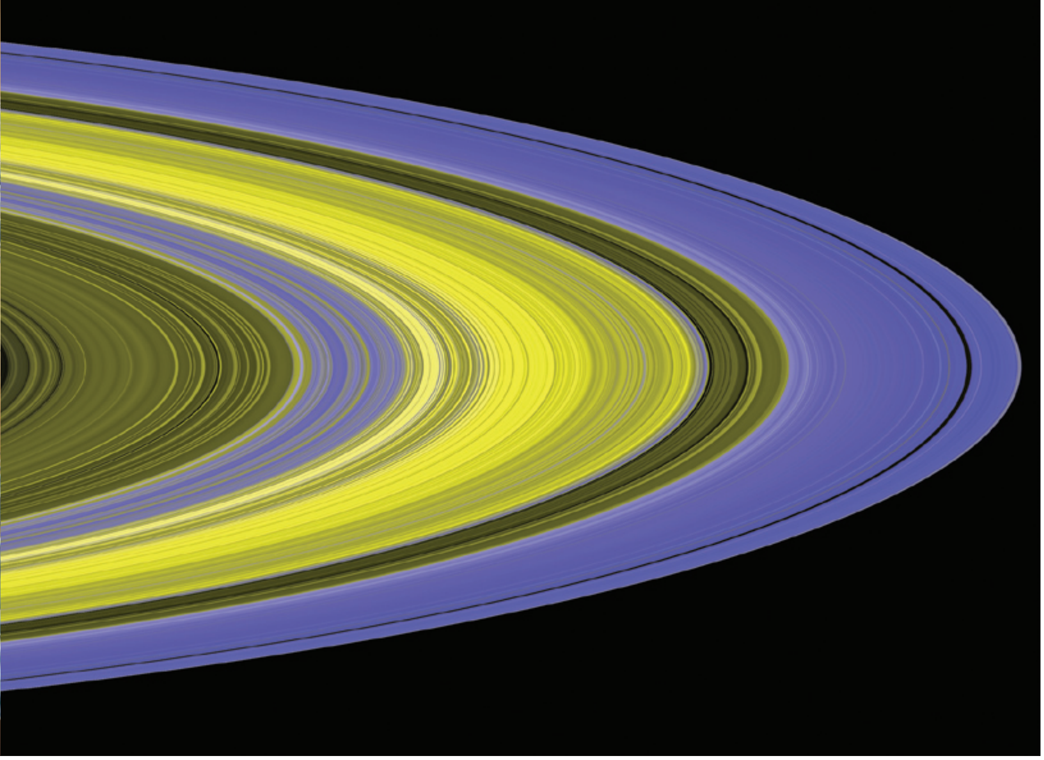
Cassini confirmed the presence of the taffylike clumps of material by sending radio signals through the rings to Earth. These signals—with a strength of less than a billionth of a watt by the time they arrived here!—were picked up by the ultrasensitive receivers of JPL's Deep Space Network, which has stations in California, Spain, and Australia in order to ensure that one set of ears is above the horizon at all times. Besides communicating with NASA's robotic explorers (and spacecraft of other nations as well), the 70- and 34-meter dishes are also used for radio-science experiments. In this case, the ring particles absorbed and scattered the radio waves in a manner that revealed their size and distribution.

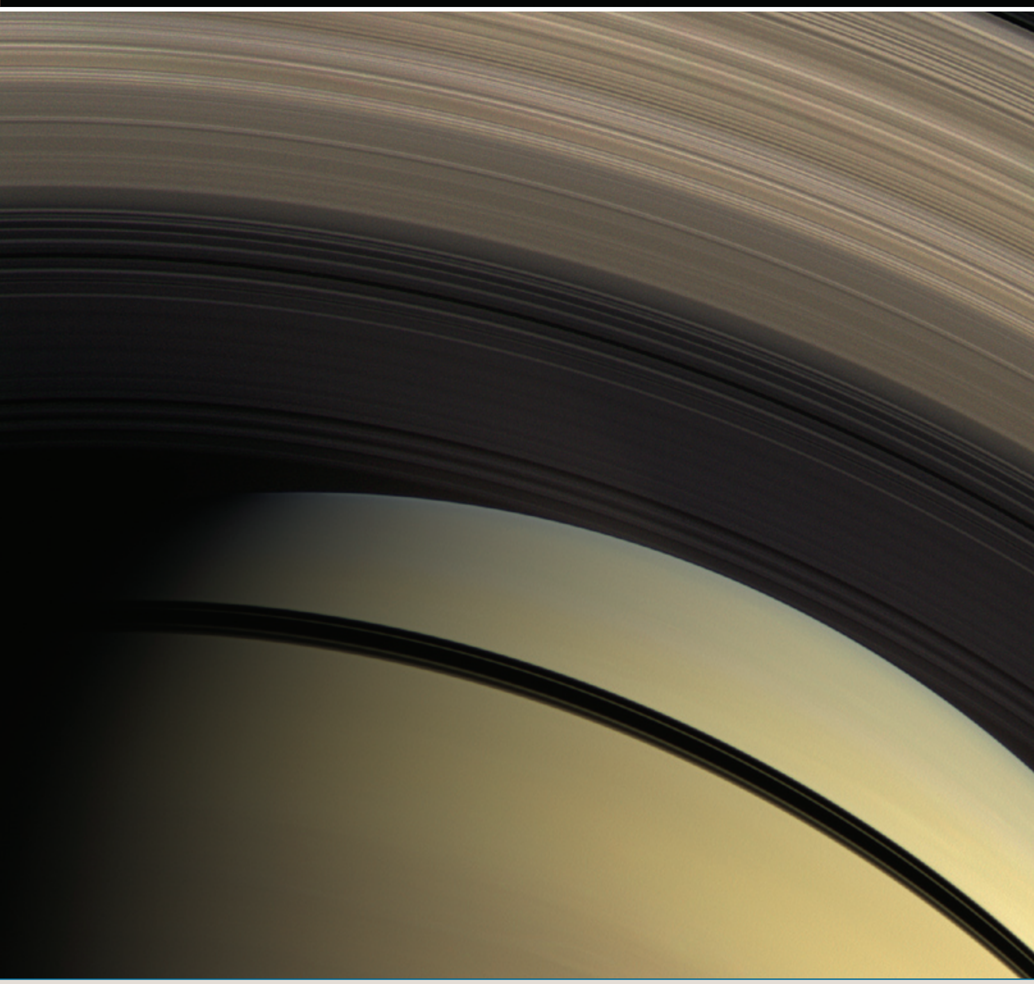
The clumps, called self-gravity wakes, are a special case of the spiral density waves mentioned earlier, which Cassini has now shown to exist all over Saturn's rings. "We first saw self-gravity wakes in the A ring, which is less dense, so they are farther apart and easier to see. They just leaped out at us," says Spilker. "They are harder to tease out in











the B ring, because it is so optically thick."

All the particles in all the rings are constantly colliding, but the dense B ring affords the most chances for the particles to adhere to one another afterward, held together by gravity and their own stickiness. The resulting flat sheets of material grow by accretion until they are 30 to 50 meters wide, at which point Saturn's gravity pulls them apart. Under different circumstances, if they were farther from the planet, the wakes might have been the seeds of moons.

And what of those ring particles? What are they made of? Though we know that water ice is 99 percent of the ring material, the other 1 percent remains a puzzle. Cassini has returned spectacular images showing that the rings when bathed in sunlight appear golden, golden-brown, or even slightly pinkish. If the rings were made only of water ice, they would be frosty white or bluish-white, like glacial ice on Earth. Something else is creating the subtle hues seen by Cassini, which has cameras with much greater color sensitivity than those on earlier spacecraft, notes Spilker.

"Originally, after Voyager 2 flew past Saturn, we thought the fact that the rings were so bright and clean must have meant that they were young. Now we're starting to think that maybe they're a mix of young and old. There may be some processes that periodically break the ring particles open and recycle the contents. You can imagine breaking open a snowball and releasing fresh material into the system, making the rings appear cleaner and brighter. We'd really like to get an idea of the rate at which the rings are accumulating additional, non-icy material and then figure out what kind of processing is going on within the rings."

Spilker thinks that soon we'll be able to tease out the subtle signals associated with ring contaminants from the very large signal that corresponds to water ice. One of the instruments working overtime on identifying the chemical makeup of the rings is Cassini's Visual and Infrared Mapping Spectrometer, or VIMS, which maps colors at

Clockwise, from top left: 1. An artist's rendition of the ring particles. They continually clump and disperse again, forming thin, curved transitory aggregates with nearly empty space in between.

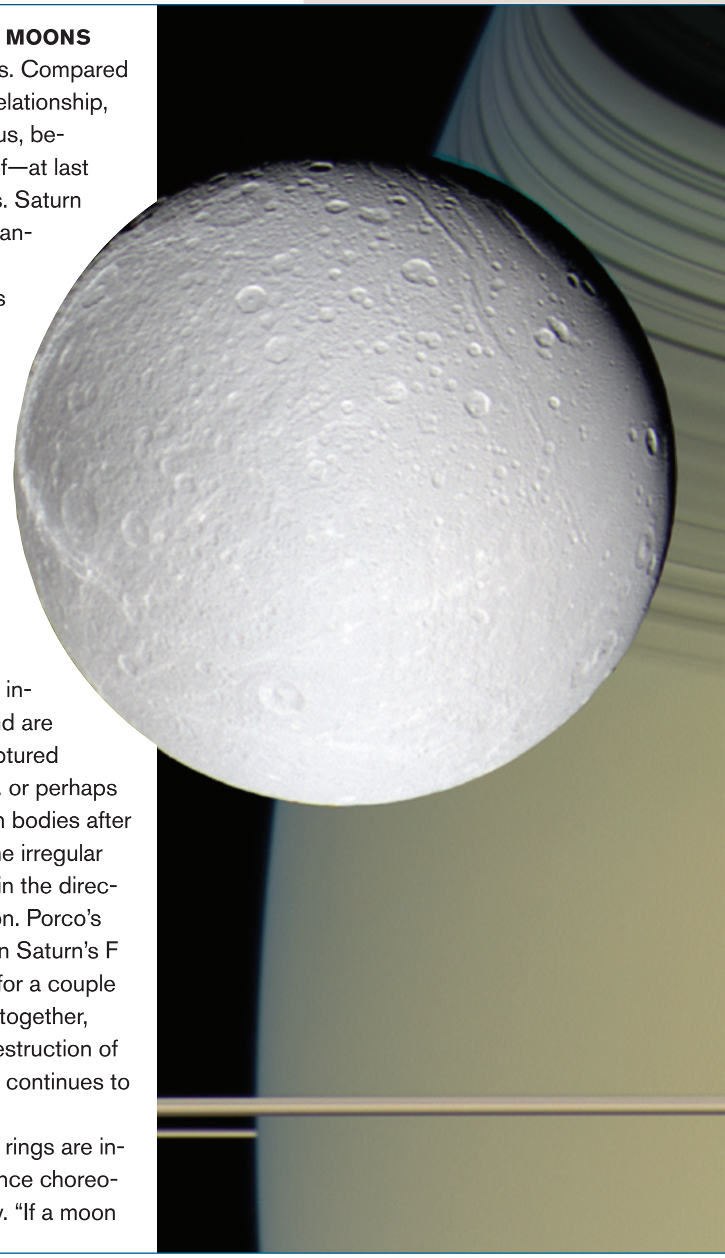
2. This false-color image from UVIS shows the density and orientation of the clumps. The brightest regions are the densest—in fact, the middle of the B ring was too dense for Alpha Arae's light to penetrate. The clumps are tilted into oblique wakes in the blue regions, and are oriented along concentric circles in the yellow ones.

3. A natural-color view of the sunlit rings, as seen from below. The translucent C ring runs through the center of the frame, while the denser B ring arcs across the top.

4. As Saturn neared equinox in November 2008, the "spokes" (seen here as dark smudges) first seen by the Voyagers one Saturn year earlier returned to prominence.

5. In September 2009, a month after equinox, the spokes stand out much more clearly. Janus, a small moon 179 kilometers in diameter, can be seen at upper left.

Below: A natural-color shot of icy Dione, snapped when Cassini was very nearly in the ring plane. The rings form a razor-thin horizontal stripe across the bottom of the picture, while the set of narrow, curving shadows cast on Saturn by the C ring is visible behind Dione. A portion of the B ring's shadow adorns the upper right corner.



different wavelengths than does CIRS. Like CIRS, the VIMS spectrometer breaks light into its component wavelengths. Because every molecule reflects a specific set of wavelengths and absorbs the rest, scientists can identify molecules by their spectral "fingerprints." Shortly after Cassini arrived at Saturn, VIMS data hinted at the presence of some kind of iron-bearing compound—perhaps not too surprising, as many scientists think the rings are the remnants of icy comets and iron-bearing meteoroids torn apart by Saturn's gravity.

The composition of the rings has a direct bearing on their age. Water ice is easily eroded, and ring particles are pulverized by micrometeoroids and ground up by collisions with each other. Saturn itself plays a role in breaking down the ice grains—UVIS has detected an immense cloud of oxygen atoms liberated from ring ice by bombardment from Saturn's own internal radiation. The cloud surrounds Saturn and extends for millions of kilometers beyond Saturn itself, says Esposito. The rings also have their own atmosphere of oxygen gas, produced when ultraviolet light from the sun interacts with the water ice. Other kinds of debris, such as tiny pieces of rock or minerals from micrometeorites, are harder to erode and have greater longevity. "It could very well be that different parts of the ring system have different ages," says Porco. "The massive middle B ring might be a lot older than the A ring. One might be billions of years old and the other only a few tens of millions or hundreds of millions of years. We don't know."

MOONS, MOONS, AND MORE MOONS

And then there are the moons. Compared to Earth and its monogamous relationship, Saturn is downright promiscuous, being accompanied by a retinue of—at last count—62 orbiting companions. Saturn is surrounded by real moons, wannabe moons, pieces of moons, and fleeting moons. Cassini has discovered seven moons—not to mention hints of numerous suspected but unconfirmed moons that we infer from their effects on the structure of the rings—and during roughly the same interval, other observers have found 24 more. These moons are all tiny—less than 18 kilometers wide—and irregularly shaped. They travel in eccentric, steeply inclined orbits far from Saturn, and are thought to be minor planets captured by Saturn's gravitational pull . . . or perhaps debris from the breakup of such bodies after they were captured. Some of the irregular moons are retrograde, orbiting in the direction opposite to Saturn's rotation. Porco's team even discovered objects in Saturn's F ring that could only be tracked for a couple of orbits before disappearing altogether, suggesting that creation and destruction of moonlike bodies around Saturn continues to this day.

Saturn's moons and Saturn's rings are inextricably linked in a cosmic dance choreographed by the forces of gravity. "If a moon

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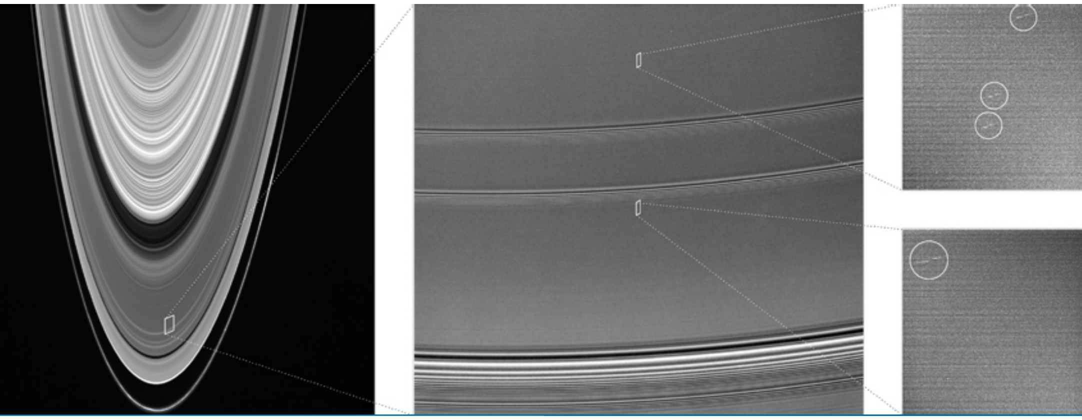


The propellers in context. The leftmost photo shows the F, A, and B rings. Zooming in on the box in the middle of the A ring (center), we see a large density wave caused by Janus and Epimetheus at the bottom of the frame and two smaller density waves in the middle. Zooming in on the featureless regions between the waves, we find four propellers (circled), each about five kilometers from tip to tip and caused by an unseen moonlet about 100 meters in diameter. The leading blade is about 300 meters closer to Saturn than the trailing one; the resolution is 52 meters per pixel.

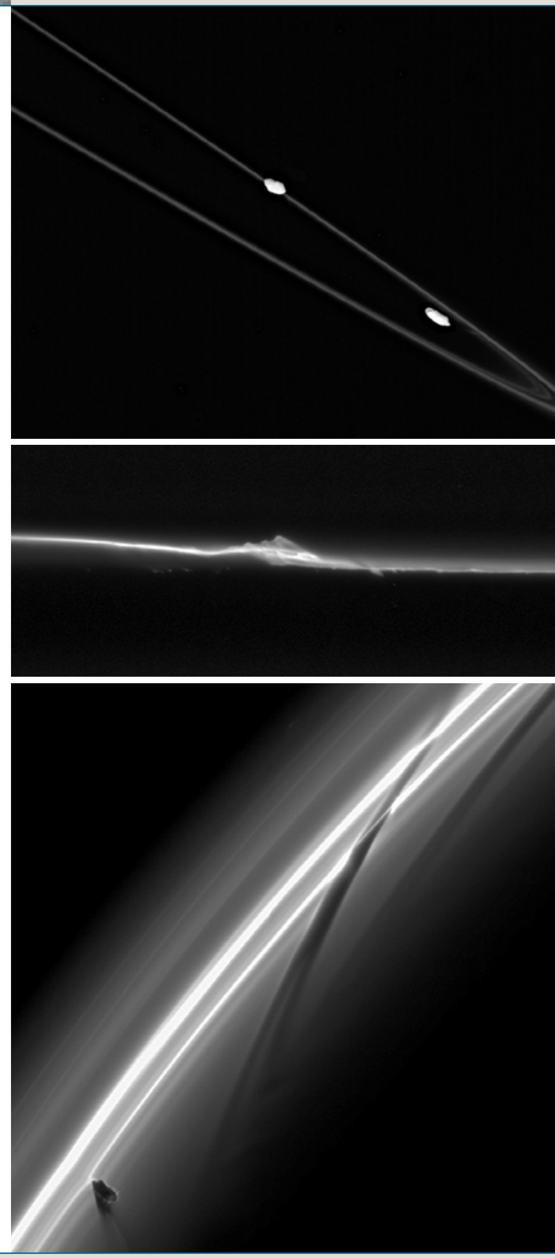
is large enough," explains Spilker, "it can clear a gap in Saturn's rings by exerting a gravitational pull on the ring particles within a certain distance of itself. Good examples of that are two of Saturn's 'ring moons,' Pan and Daphnis. Pan orbits in the center of the Encke gap, and it keeps that gap open and pretty much free of ring particles, except for a few dusty ringlets in the gap. Daphnis, a much smaller moon, keeps the Keeler gap open. It's a much narrower gap because the moon is smaller."

In a way, Saturn's rings are a laboratory for determining how small an orbiting object can be and still be considered a moon. "Cassini found still smaller objects that would like to open a gap but don't have enough gravity to succeed," says Spilker. Instead, like speedboats, they create "wakes" that travel with them. But rather than being V-shaped, these wakes resemble two-bladed airplane propellers. One blade sticks out ahead of the moonlet, pulled forward by gravitational attraction to faster-moving ring material nearer to Saturn. The other blade stretches out behind, tugging on slower-moving material farther from the planet. The propellers can be as long as five kilometers from tip to tip. A propeller's span depends on the size of its moonlet, but even the biggest moonlets are still too small to be seen. Cassini has so far discovered more than 150 such moonlets.

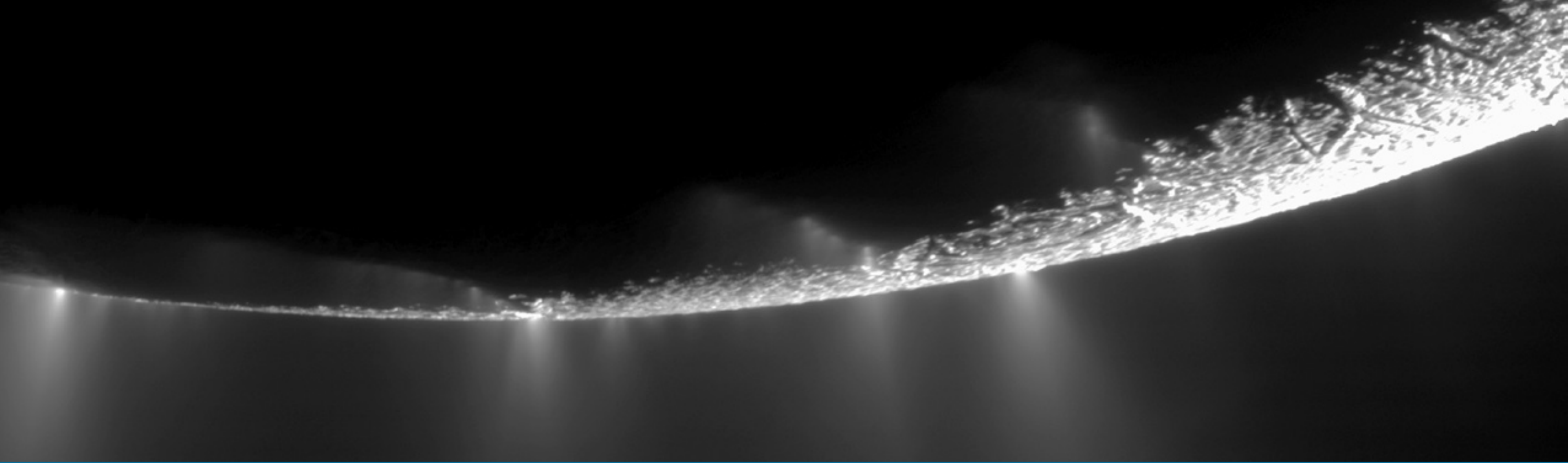
Out at the edge of the main ring system lies the narrow, quirky F ring, held in place by the shepherd moons Prometheus and Pandora. Cassini has photographed the F ring in exquisite detail. We can now see that it clumps in places where aggregates of ring material or hidden moonlets lie, and kinks where the gravitational pull of Prometheus tugs on material in the ring. In fact, Prometheus literally collides with the F ring at the point in its orbit most distant from Saturn. As it moves back toward the planet and away from the ring, the moon pulls material out of the F ring, leaving dark channels behind.

In a way, Galileo was not that far off when he mistook Saturn's rings for companion moons. Sometimes Saturn's rings are a source of material for the moons, and sometimes Saturn's moons are a source of material for the rings. Cassini has confirmed that at least three of Saturn's moons are gaining girth from the rings. Pan, Daphnis, and Atlas started out as "football-shaped bodies," says Porco. "But as they sweep their paths clean, some material accretes on their surfaces, forming waistline bulges that make them look a bit like flying saucers."

Several of Saturn's moons produce rings or partial rings. The most celebrated of these is Enceladus, which spews geysers of water ice and vapor laced with organic material. (See *E&S* No. 1, 2006.) The icy particles are pulled into orbit around Saturn to form the diffuse E ring. "The geysers of Enceladus," says Porco, "are perhaps our most stupendous and significant discovery, because they very likely erupt from pockets of organic-rich liquid water. Not only does this suggest a potentially habitable environment below the south pole of the moon, but



Top: Potato-shaped Pandora (left), Prometheus (right), and the F ring.
Middle: A hidden moonlet's gravity disturbs the F ring, swirling it like a wisp of smoke.
Bottom: Cassini snapped this shot half an hour after Prometheus (in the bottom left corner) burst up through the F ring—in fact, its shadow on the ring shows that it's not quite all the way out yet. It's beginning to pull a streamer of material after itself, which will eventually leave a dark channel in the ring. On its previous pass about 15 hours earlier, it tore open the channel that stretches downward across the center of the image; an even earlier channel that has started to fill back in extends into the upper right corner and out of frame.



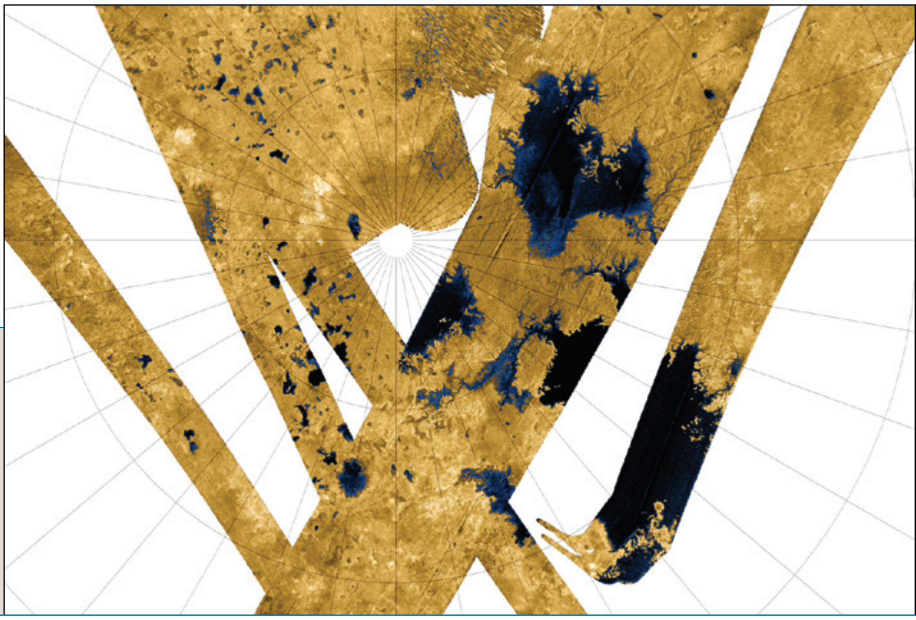
the way in which Enceladus is generating heat—and it is generating a lot of heat—is a fascinating problem in the study of planetary moons." Several other rings and ring arcs discovered by Cassini are believed to be made of dust ejected from the surfaces of various moons by meteoroid impacts. These include the Janus/Epimetheus ring, the Methone ring arc, the Anthe ring arc, and the Pallene ring.

Janus and Epimetheus, by the way, are unique in the solar system, as far as we know. The two moons essentially share the same orbit, with Janus until recently being some 50 kilometers "inside" Epimetheus. The inside moon travels slightly faster because it is slightly closer to Saturn, and since Janus is 181 kilometers across and Epimetheus is 116 kilometers wide, you'd think they'd plow into each other. Not so—when the inner moon overtakes the outer one once every four years, gravity steps in. The outer moon pulls on the inner moon, giving it extra momentum and flinging it into a higher orbit in which it, paradoxically, moves more slowly. At the same time, the inner moon tugs on the outer moon, siphoning off some of its momentum and dropping it into a lower, faster orbit. The moons trade orbits as they retreat back the way they came. The chase begins again, but now with a new pursuer. This cosmic game of tag was most recently played out this past January, putting Janus on the outside track until 2014, says Cornell's Matthew Tiscareno (BS '98), an associate on the Cassini Imaging Team. Like the grooves on a vinyl LP (remember those?), it turns out that some of the spiral density waves in Saturn's rings carry a record of the duo's past orbital swaps, as he discovered after the 2006 exchange. There is undoubtedly other information encoded in the rings as well, he says, adding that we are just starting to figure out how to extract it.

What's next for Cassini? The mission extension to 2017 will allow us to follow a complete change of seasons on Saturn, as the south pole goes into darkness and summer arrives in the north. Spilker points out that Cassini arrived at Saturn just a couple of years after the northern winter solstice. Scientists noticed at the time that the atmosphere in the north looked much bluer than in the south, so they will be watching to see if a similar bluish-colored haze starts to form down under as the southern hemisphere receives less sunlight.

Cassini will also keep an eye on Saturn's largest moon, Titan. The spacecraft's radar mapper has peered through Titan's smoggy skies to identify about 400 lakes, some quite large, of a liquid methane-ethane mixture. Porco describes them as being like "Lake Michigan, filled with paint thinner." The lakes are found in the polar regions, but there are more in the north than the south—including all the really big ones that might properly be called seas. Planetary scientists are curious to see if the coming of spring to the north will cause the lakes to evaporate and their contents to turn into rain in the southern hemisphere, creating fresh lakes there.

But the changing seasons alone may not be sufficient to explain the asymmetric distribution of Titan's lakes. A team led by Associate Professor of Planetary Science Oded Aharonson and including grad student Alexander Hayes (MS '08), Jonathan Lunine (MS '83, PhD '85) of the Lunar and Planetary Lab at the University of Arizona, Ralph Lorenz of the Applied Physics Lab at Johns Hopkins, Michael Allison of the NASA Goddard Institute for Space Studies, and JPL Director Charles Elachi (MS '69, PhD '71) has proposed that Titan may have a much longer cycle of climate change. Just as our ice ages are widely believed to be driven by regular, predictable variations in the tilt of Earth's axis and the eccentricity and precession of its orbit around the



Above: The fountains of Enceladus. More than 30 jets of all sizes can be seen here, over 20 of which were previously unidentified. Cassini took this shot just before barreling through the spray on November 21, 2009, in order to sample its composition.

Right: The oily seas of Titan, tinted blue and black in this radar mosaic of the north polar region. The large one at upper-right whose coastline we can completely see is bigger than Lake Superior.

“The geysers of Enceladus,” says Porco, “are perhaps our most stupendous and significant discovery.”

sun—collectively called the Milankovitch cycles—similar changes in Saturn’s (and therefore Titan’s) tilt and orbit may be at work on Titan. If the lakes don’t fly south for the winter, it could bolster this theory.

When the time comes to end the mission, NASA may decide to send Cassini into the depths of Saturn, much as Galileo (the spacecraft, not the scientist) was incinerated in Jupiter’s atmosphere. Such a fiery demise would preclude any chance of Cassini one day crashing into—and perhaps contaminating—one of Saturn’s moons. If a later mission does discover microbes on Enceladus, for example, we’d like ironclad assurance that they’re not stowaways from Earth. First, however, Cassini would complete a final set of experiments—orbiting near Saturn’s cloud tops, perhaps sampling the dusty D ring, measuring the mass of the B ring for the first time, and acquiring precise measurements of Saturn’s gravitational and magnetic fields. In that way, Cassini will end its mission as it began, providing views of Saturn in greater detail than ever before.

By studying Saturn, says Spilker, we can put ourselves into context. Titan’s primordial chemistry—a nitrogen atmosphere, no free oxygen, and small amounts of organic materials—may show us what Earth was like a very long time ago. And Saturn’s bling may give us hints about how and where to look for planets around other stars. Notes Porco, “The processes occurring at Saturn today are similar to those that occurred in the very early days of the solar system, when the material now contained in the planets was spread out into a flattened disk. We stand to learn a great deal about the early stages of solar systems throughout the galaxy, and the cosmos, by studying Saturn’s rings.” e&s

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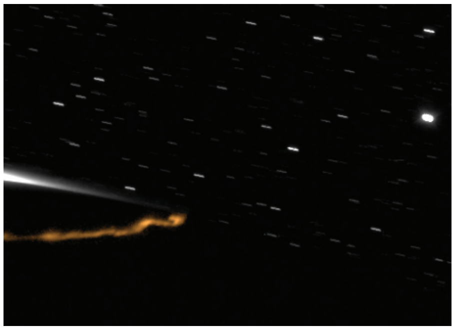

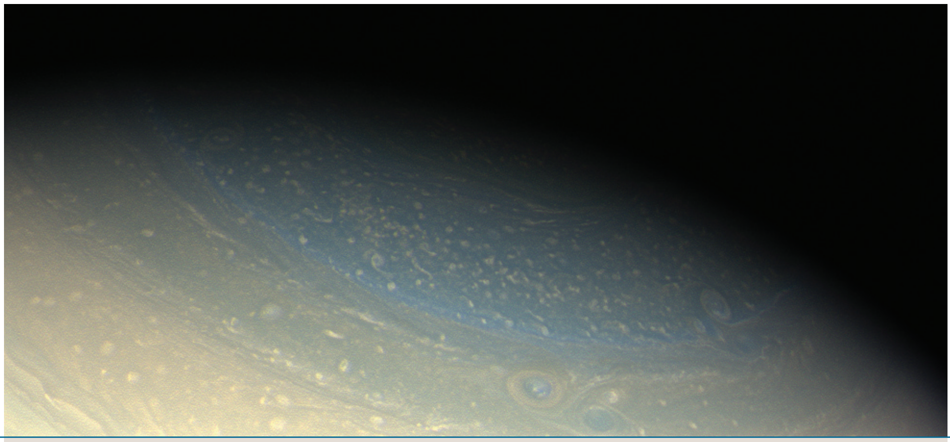

Top: A frame from the first-ever visible-light movie of Saturn’s auroras. (The aurora has been colored orange to make it easier to see.) The movie was shot over 81 hours spanning October 5–8, 2009. Bottom: Saturn’s atmosphere is not as showy as Jupiter’s, with its baroque, swirling bands of clouds in vivid colors and long-lived, eye-catching storms like the Great Red Spot. But in its own pastel way, Saturn’s atmosphere is just as complex and intriguing. This true-color image of the north pole was taken in November 2008, as the northern winter was drawing to a close. We can see hundreds of bright storm systems, and a blue that has since faded to other colors with spring’s return.