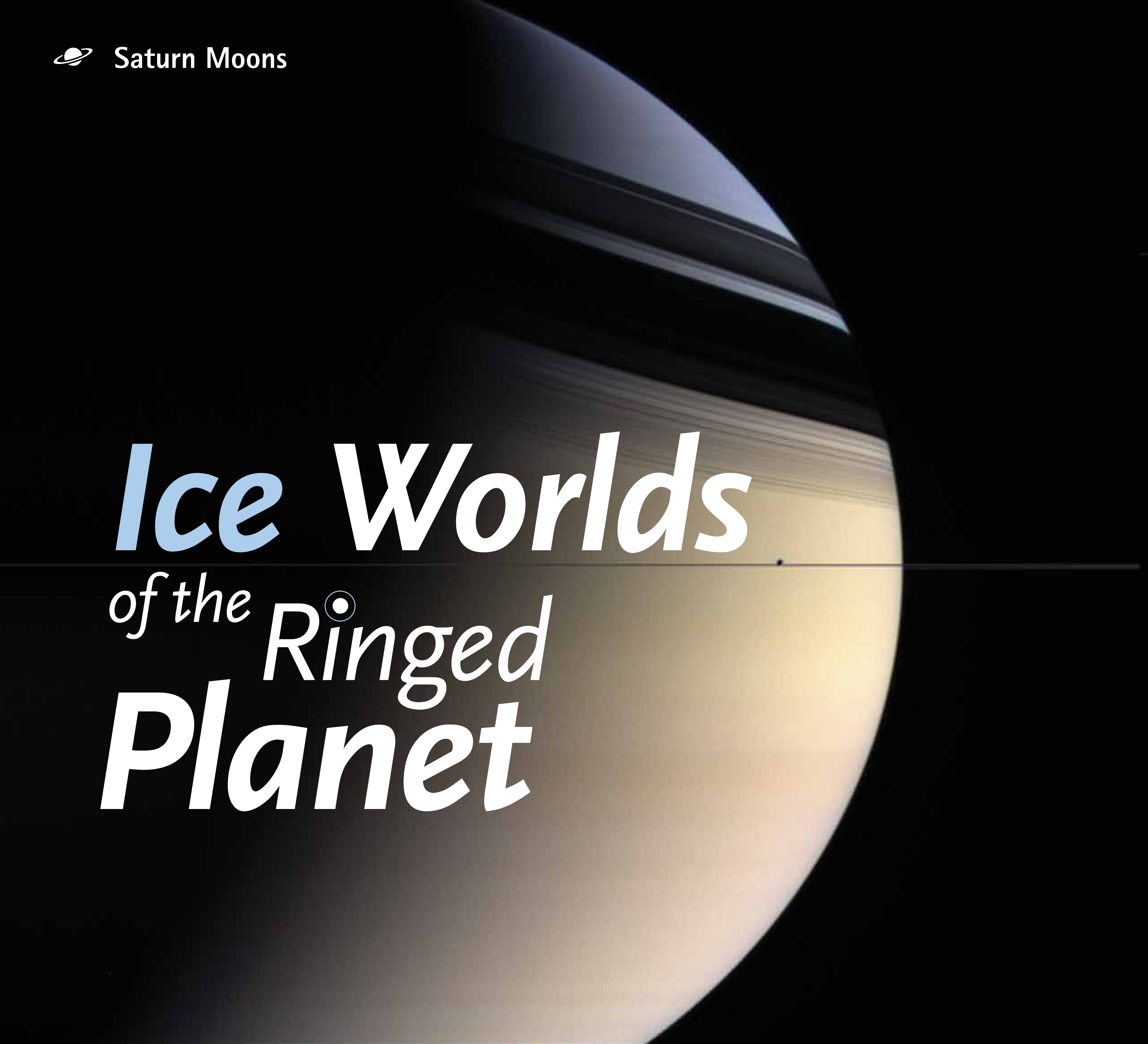
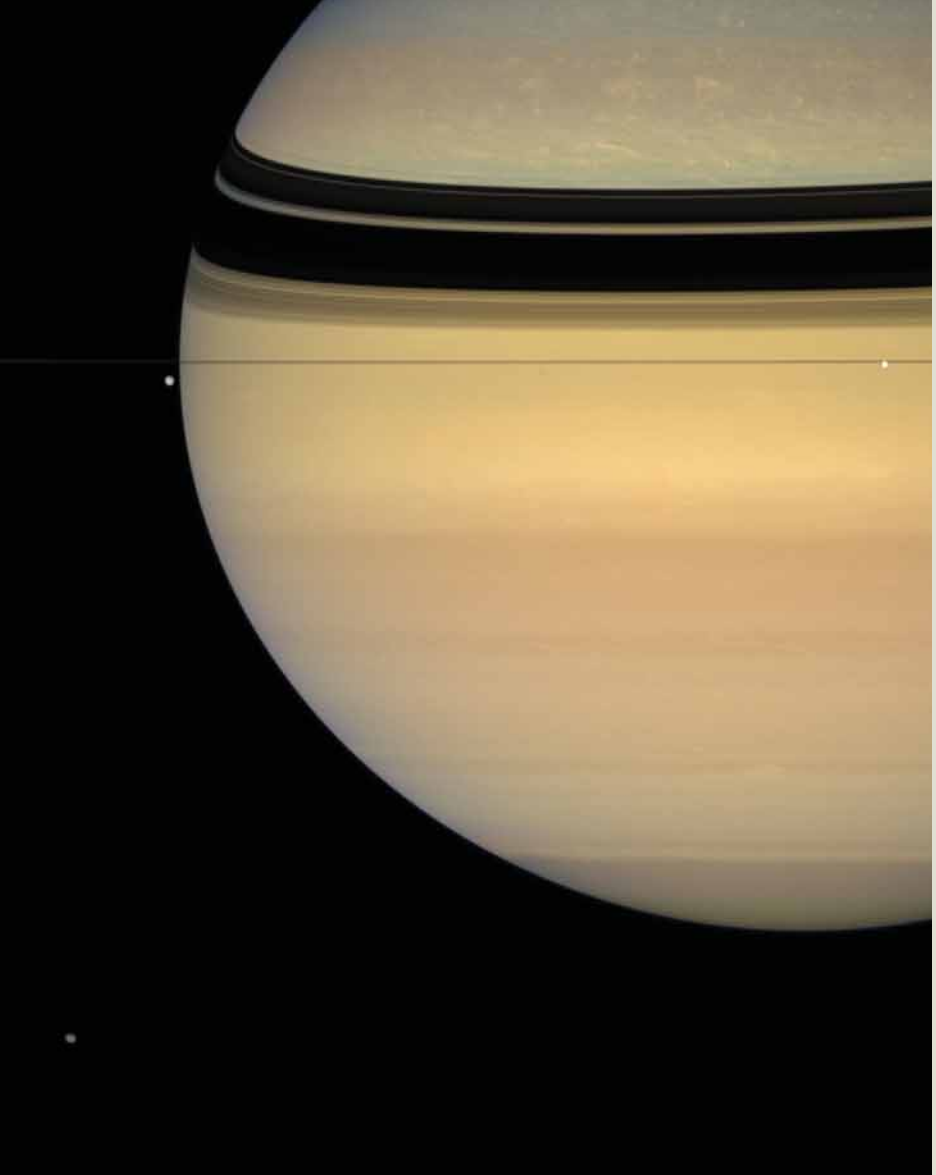


Ice Worlds of the Ringed Planet



NASA's Cassini mission has solved long-standing mysteries about Saturn's icy moons, but raised new ones in their place.

EMILY LAKDAWALLA

Cassini-Huygens was billed as a mission to Saturn and Titan. But it has also thrilled us with unexpected discoveries and amazing images from Saturn's mid-size moons: Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion, Iapetus, and Phoebe. Though far smaller than Titan, each iceball is a unique world with interesting geology.

One of the greatest surprises has been Enceladus. Only Saturn's sixth-largest moon, it has proven to be astonishingly active. Water-rich geysers rocket hundreds of kilometers into space. Its potential for liquid water and perhaps even life provokes discussion of a dedicated mission, ranking tiny Enceladus among such tantalizing worlds as Titan and Europa. Meanwhile, Cassini has resolved the nearly 340-year-old mystery of why Iapetus, Saturn's outermost mid-size moon, is black as coal on one face and icy on the other.

Touring Saturn

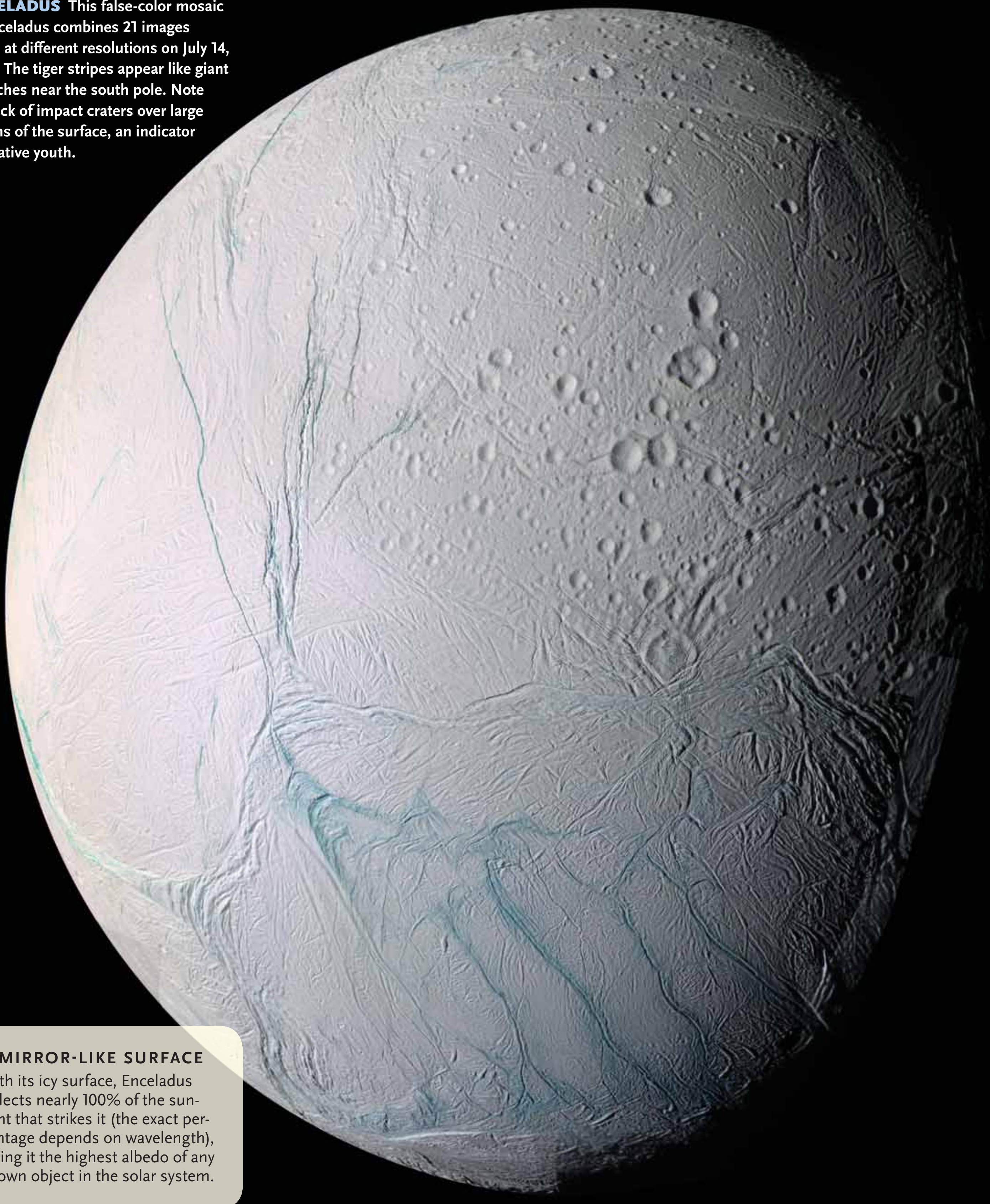
Cassini is bound by gravity to travel in ellipses around Saturn. The moons orbit the giant planet on near-circular paths with speeds, sizes, and inclinations often quite different from Cassini's. Mission navigators shift the spacecraft's orbit to tour the Saturnian system using frequent flybys of Titan, the only moon massive enough to provide a gravity assist.

To study the other moons, Cassini must burn precious fuel to position itself in the right place at the right time to meet one in its orbit. These targeted flybys usually involve an approach to within 2,000 kilometers (1,200 miles), and sometimes as low as 25 km. Other non-targeted opportunities present themselves through chance orbital juxtapositions, but generally Cassini must approach nearer than 200,000 km to conduct useful science.

Cassini's moon observations thus come in rare, concentrated bursts of data. Before Cassini arrived, Enceladus had already been marked for

SATURN'S SWARM OF BEES The Ringed Planet has 61 known moons, most of which are only a few kilometers across. In these images from NASA's Cassini orbiter, we see several of the planet's 8 mid-sized satellites, objects a few hundred to 1,500 km across. The icy moon Enceladus, a prime target for future exploration because of its potential habitability for life, appears in all three of these images. In the far left image, it appears to the right of center just above the ring plane. In the image above, the moon appears at the far right, in the ring plane. And in the image below, Enceladus appears just above and to the left of the rings.

UNLESS OTHERWISE INDICATED, ALL IMAGES: NASA / JPL / SPACE SCIENCE INSTITUTE; AUTHOR PHOTO: ERIK NELDER

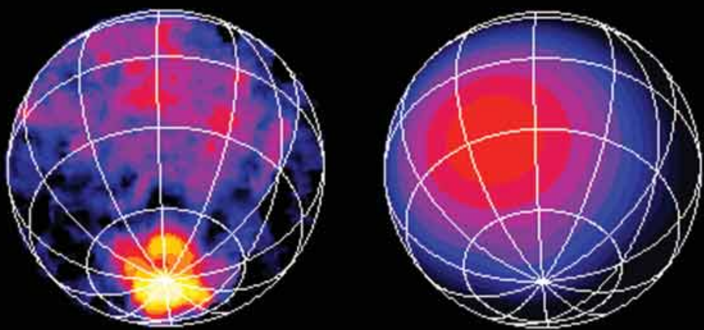


ENCELADUS This false-color mosaic of Enceladus combines 21 images taken at different resolutions on July 14, 2005. The tiger stripes appear like giant scratches near the south pole. Note the lack of impact craters over large swaths of the surface, an indicator of relative youth.

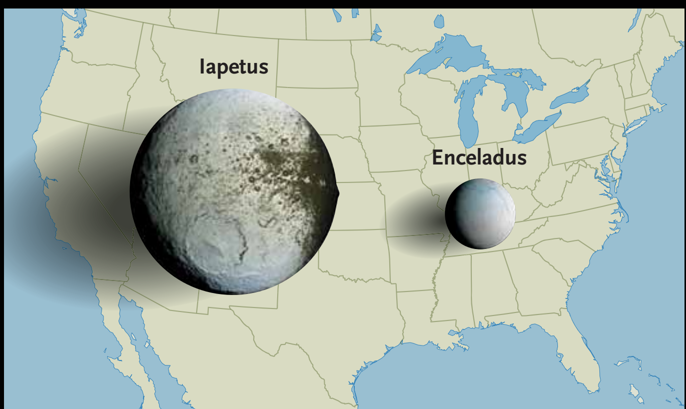
MIRROR-LIKE SURFACE

With its icy surface, Enceladus reflects nearly 100% of the sunlight that strikes it (the exact percentage depends on wavelength), giving it the highest albedo of any known object in the solar system.

E RING Saturn's broad, diffuse E ring is densest near the orbit of Enceladus. The ring's ice particles originate from geysers shooting from the moon's south pole. In this Cassini image, taken on September 15, 2006, Enceladus is the spot inside the ring, and the slightly larger moon Tethys appears as a crescent at the far left.



TEMPERATURE MAP *Left:* Cassini's Composite Infrared Spectrometer (CIRS) found a surprisingly warm region near Enceladus's south pole, a spot more recently linked to geysers. *Right:* Without this escaping heat, the pole would be colder than the rest of the surface.



MOONS COMPARED Enceladus and Iapetus are both considered medium-sized satellites. They are much smaller than Earth's Moon, Jupiter's Galilean satellites, and Titan, but are big enough for their self-gravity to pull them into a nearly spherical shape.

CENTER: NASA / JPL / GSFC; BOTTOM: S&T: CASEY REED

special attention, with four targeted flybys; the rest of the mid-sized moons received only one (and Mimas, none). Cassini's mission was extended starting in mid-2008, in part, to include more Enceladus encounters. There have since been three targeted incredibly close Enceladus flybys, and four more are scheduled.

Intriguing Enceladus

With its anomalous brightness, scientists have long suspected that something odd was going on at Enceladus. In 1966 astronomers discovered Saturn's E ring. Unlike the A through D rings, the E ring is incredibly diffuse, made of tiny water-ice particles. It extends vertically, covering a huge volume that encompasses the orbits of Mimas to Rhea. Yet it's densest near Enceladus's orbit. It seemed that Enceladus and the E ring were linked. But how?

Voyager 2 images showed us the northern and equatorial regions of Enceladus, revealing that internal geologic activity has wiped part of Enceladus's surface clean of craters. Just as Jupiter's volcanic moon Io is heated by tidal flexure from 2:1 and 4:1 orbital resonances with Europa and Ganymede, so too does Enceladus receive regular internal heat inputs from a 2:1 resonance with Dione.

But the E ring's water-ice particles need continuous resupply. It seemed ridiculous that a body as small as Enceladus — only 500 km across — could be geologically active today, and could provide the necessary input of particles to sustain the E ring.

This conundrum was solved by the Cassini discovery of Enceladus's plumes. By mid-2005, observations from the magnetometer, the Ultraviolet Imaging Spectrograph (UVIS), the Ion and Neutral Mass Spectrometer (INMS), the Cosmic Dust Analyzer (CDA), and the Composite Infrared Spectrometer (CIRS) showed that a watery atmosphere was originating from parallel troughs, called *sulci*, discovered by Cassini's cameras near the south pole. CIRS found the vents to be at least 60 kelvins warmer than the frigid 70 kelvins expected for the south pole.

The emblematic photos of Enceladus's plumes came in November 2005, when the vagaries of orbital mechanics finally permitted Cassini's main cameras, the Imaging Science Subsystem (ISS), to acquire moderate-resolution, high-phase views at an angle where the plumes' dust particles could scatter sunlight in a forward direction. Triangulation of the jets seen in ISS images pointed back to many of the south pole's hottest spots measured by CIRS.

Staring Down the Throat

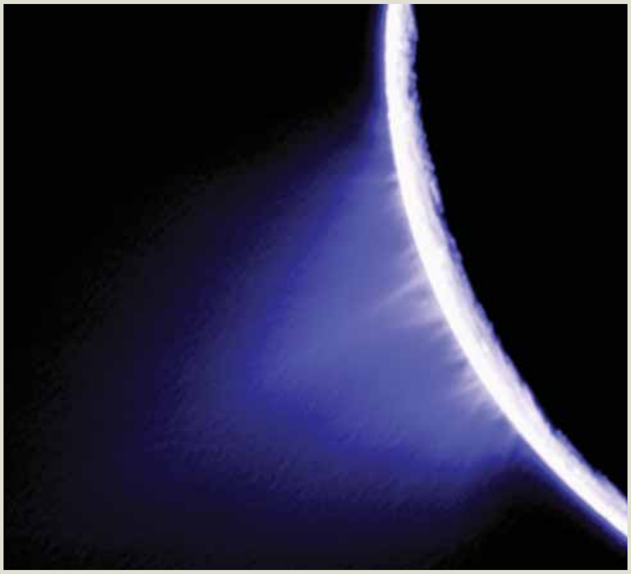
The close flybys in 2008 have all occurred at very high inclination, so Cassini could swoop in from above the north pole, shoot just above the surface somewhere in the southern hemisphere, and catch outbound views staring straight down onto the enigmatic south-polar terrain, flying more or less through the plume itself. The plume particles were considered too small to threaten the spacecraft despite the inevitability of high-speed collisions.

The fly-throughs have firmly established the connection between the Enceladus plumes and the E ring. The plumes are made of two components: gas and particles. The INMS found the gas to be primarily water vapor (92%), mixed with smaller amounts of carbon dioxide, nitrogen, methane, ammonia, hydrocarbons including acetylene and propane, and possibly even argon. The gas shoots out at a speed of many hundreds of meters per second. Since that is much higher than Enceladus's escape velocity, it goes into Saturn orbit, populating the E ring. A large fraction of the particles, primarily ice, come out at much lower speed, so most re-impact Enceladus, giving it its fresh, snowy countenance.

If Enceladus has been venting at its current rate over the age of the solar system, it would have lost 20% of its mass. Enceladus is much denser than either of its neighbors, Mimas or Tethys, another possible indication that it has lost a substantial quantity of lower-density water ice to the E ring.

Using a novel technique to compensate for the spacecraft's high relative velocity (17.7 km per second), the imaging team was able to take sharp pictures of the south-polar terrain during the August 11 and October 31, 2008 encounters. The resulting panoramic views revealed a rumpled and fractured terrain, seamed with deep fissures, and covered everywhere with house-sized boulders of ice. Many of the images were targeted to cover areas where CIRS had found the hottest temperatures, and where triangulation had identified plume sources.

Although the sulci are fresher than the surrounding terrain, they were not obviously different near the mapped plumes; the sulci appear uniform along their length. The imaging team has concluded that there is nothing special about the location of a given plume source. Plumes may emanate from any point along a sulcus, and they may move with time. The sulci could be sites of crustal spreading, like Earth's mid-Atlantic ridge. Such tectonic activity would explain the apparent youth of Enceladus's south-polar terrain.



THE PLUMES OF ENCELADUS Cassini scientists use false-color images such as this to identify individual plumes with source regions on the tiger stripes *(sulci)*. The plumes shoot hundreds of kilometers into space and include water-ice particles, water vapor, carbon dioxide, nitrogen, methane, ammonia and other gases. In other words, they contain the ingredients for life.

ENCELADUS IN SILHOUETTE Cassini captured this dramatic view of Enceladus against Saturn's night side on May 4, 2006. The moon's geysers are clearly visible against Saturn's southern hemisphere, which is illuminated by sunlight reflecting off the rings.

Is There Liquid Water?

CIRS observations show that the vents are relatively hot, at least 145 kelvins (–200°F). This is intriguingly close to the lowest temperature at which water could melt in the Saturn system — 170 kelvins — but only if there is a lot of ammonia present, which would depress the water's melting point. Yet INMS observed ammonia only during the very closest of the 2008 flybys, and not in great abundance. And the Visual and Infrared Mapping Spectrometer (VIMS) has found none on the surface.

Since temperatures tend to increase with depth on any body, there could be liquid water very close to Enceladus's surface, perhaps even just 40 meters (130 feet) down. It's mechanically possible for the boiling of that water to drive the high-speed plumes.

But there's another possibility that would leave Enceladus without near-surface liquid water. The plumes could be driven by the explosive decomposition of a form of ice called clathrate, which has many gaps in its crystal lattice that could allow it to hold up to 10%, by weight, of other gases. This is the same percentage that was observed in the gas component of the plumes.

If tidal flexure causes Enceladus's sulci to open and close over the course of an orbit, new cracks could expose clathrates to the vacuum of space, whereupon they would explode, driving the gas and entrained particles outward at very high speed.

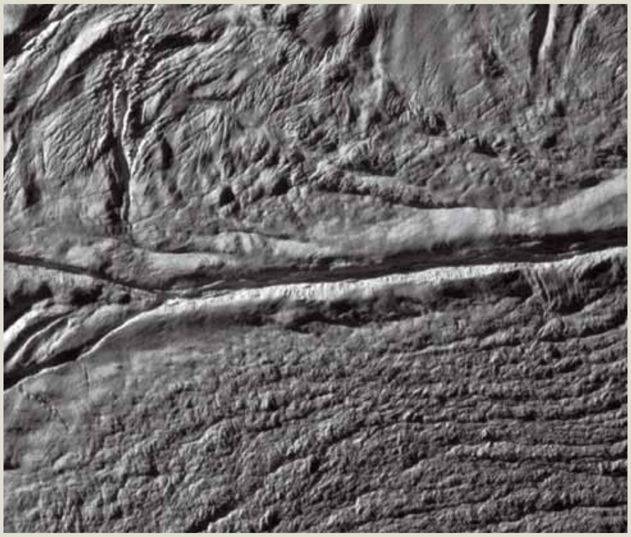
The tidal forces that squeeze Enceladus could generate heat just by rubbing the two sides of the sulci against each other. Again, this would be a dry process, not requiring near-surface liquid water; it could help to expose and heat clathrates, or could operate without any clathrates being present. Cassini's future Enceladus flybys will be directed in part at trying to distinguish among these competing ideas.

Whether or not pockets of liquid water are driving the geysers, there could still be liquid water much deeper down, well below the source of the plume activity. Many of the solar system's round icy moons (and also the dwarf planets of the Kuiper Belt, and the main-belt asteroid Ceres) are theorized to have layers of liquid water at some depth below their frozen surfaces. Enceladus is small, but it has a lot of heat. So it's very likely that Enceladus has either a global ocean or a localized south polar layer between its icy crust and its rocky core.

To learn more about the Cassini mission and Saturn's icy moons, visit http://saturn.jpl.nasa.gov.

The composition of Enceladus's plumes — particularly the presence of molecular nitrogen and hydrocarbons such as methane, acetylene, and propane — hint that complex catalytic chemistry may have taken place inside the moon. Mineral-rich liquid water may have circulated among warm rocks below an insulating cap of ice, producing nitrogen from ammonia, and hydrocarbons from carbon dioxide.

This chemistry could be taking place now, or could have happened long ago. Either way, there was probably liquid water, heat, organic chemicals, and active chemistry — the stuff of life. As a possible abode for past or present life, Enceladus has catapulted from being moderately interesting to brief consideration as the prime target of NASA's next flagship mission to the outer solar system. NASA and ESA recently decided on a mission to visit Jupiter's moons, but the fact that diminutive Enceladus was included among such exalted company is amazing.



TIGER STRIPES UP CLOSE **In August *(left)* and October *(right)* 2008, Cassini swooped under Enceladus's south pole at close range, giving scientists high-resolution views of the tiger stripes, which might behave much like spreading ridges on Earth's ocean floors.**

Yin-Yang Iapetus

Unlike Enceladus and Titan, Iapetus is about as geologically dead as moons come. Iapetus intrigues scientists because of the utter weirdness of its two-toned color — blacker than coal over much of its leading hemisphere, and gray, dirty ice across the trailing hemisphere. What created this hemispheric dichotomy? Was it *endogenic,* arising from internal geologic activity, or *exogenic,* imposed from the outside?

Both hemispheres are thickly scarred with impact craters, but Iapetus's topography is more than just craters. One of the oddest things discovered in Cassini images is a long ridge of mountains lying exactly on the equator, like the seam on a walnut. Some of the ridge's mountains had been spotted in Voyager images, but no one expected it to stretch halfway around the moon. In places it rises nearly 20 km high, and measures 70 km across at the base. It disappears in a place where the earlier topography is obliterated by a huge impact basin. Across the transition to the bright terrain the ridge breaks up into seven or so isolated mountains seen by Voyager, and then vanishes.

Analysis of the ridge's shape suggests that it's very old, perhaps forming as a result of a slowing in Iapetus's rotation rate. But later impacts have battered the ridge so severely that it's difficult to tease out its original shape and, therefore, its origin. Overall, Iapetus's markedly lumpy shape indicates that it has been frozen rigid for most of its history.

If Iapetus has been frozen that long, there can't be any internal geologic activity maintaining the separation between the dark and bright terrain. Something must maintain it; the many impacts that have reshaped Iapetus's surface should have exposed bright ice in dark regions and distributed dark material to formerly bright regions. So scientists have sought an external origin for the yin-yang pattern.

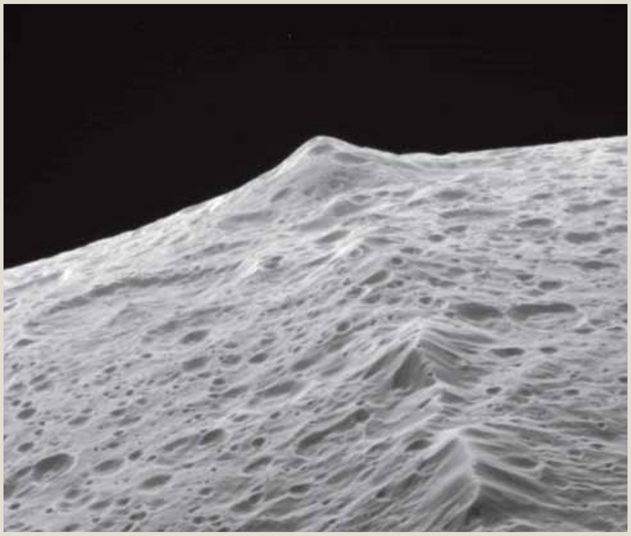
Cassini's imaging team has discovered telling facts about the patterns of bright and dark material. First, the story wasn't as simple as "leading side black/trailing side white." The dark material snakes around the equator onto the trailing side, while both the north and south poles are bright on both leading and trailing hemispheres.

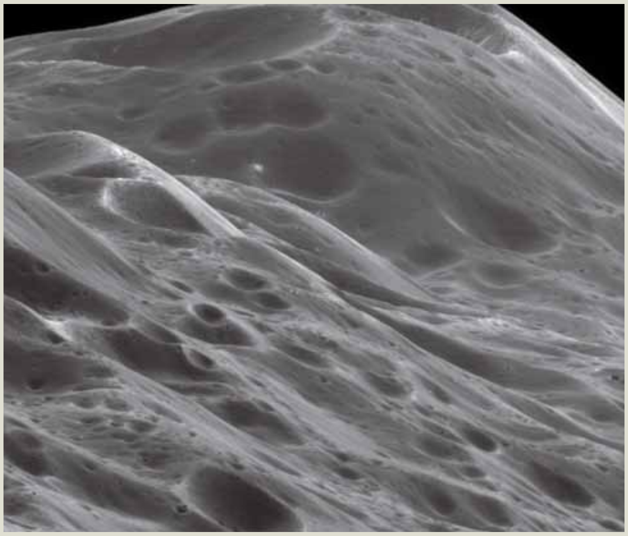
Yet there is a color difference that closely follows the leading-trailing boundary. The leading side is redder than the trailing side, a statement that holds true across both dark and bright terrains. Dark material is concentrated

IAPETUS THE TRICKSTER

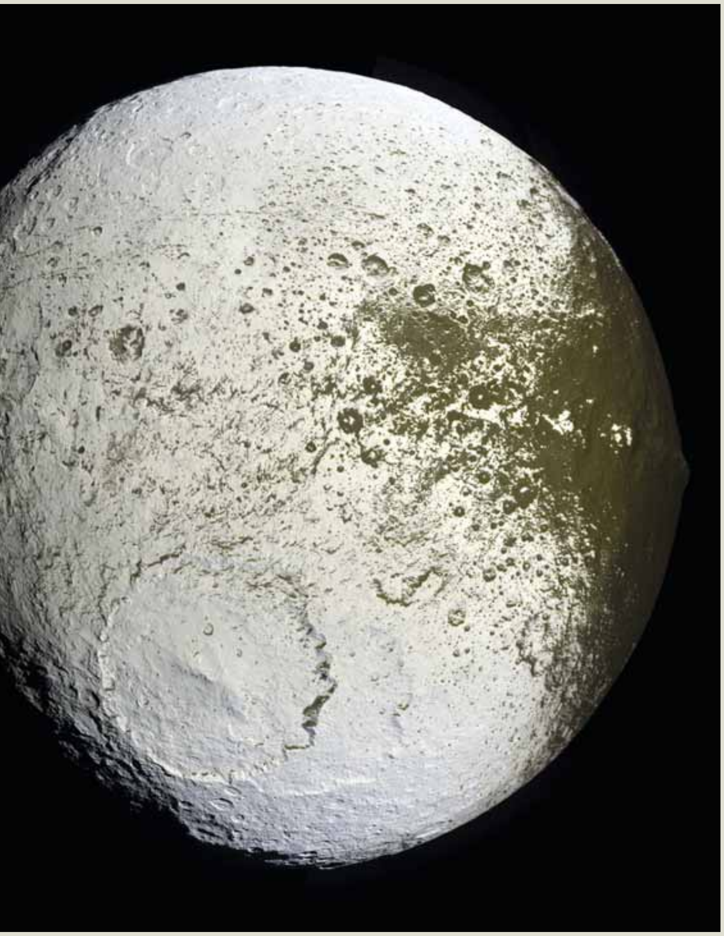
Soon after Giovanni Domenico Cassini discovered Iapetus in 1671 on the western side of Saturn at magnitude 10, he noticed that the moon disappeared on the eastern side. With an improved telescope, he finally found it on the eastern side in 1705, at magnitude 12. He brilliantly and correctly inferred that Iapetus has a dark and light hemisphere, and that it's tidally locked to Saturn.

YIN-YANG SATELLITE
Iapetus's leading hemisphere *(left)* is as dark as coal, while the trailing hemisphere *(right)* is considerably lighter in tone. The image on the left shows the equatorial ridge, which stretches halfway around the moon. If the ridge formed off the equator, tidal interactions with Saturn would have forced it to straddle the equator.





IAPETUS'S HIMALAYAS These high-resolution Cassini images, taken during its September 10, 2007 Iapetus flyby, show small sections of the equatorial ridge. In places, the mountains rise nearly 20 kilometers above the average elevation, meaning they would dwarf the highest mountains on Earth. Only Mars's giant volcanoes outrank these peaks in our solar system.



LEFT: NASA / JPL / SPACE SCIENCE INSTITUTE / GORDAN UGARKOVIC, RIGHT: NASA / JPL / SPACE SCIENCE INSTITUTE

on the equator-facing rims of craters in the bright region, whereas bright material is concentrated on pole-facing rims of craters in the dark region. A model originally developed to explain weird terrain on Jupiter's moon Callisto suggested itself: thermal segregation.

When dark material lands on Iapetan ice, the darker ice heats more rapidly, and to higher temperatures, than brighter ice. When exposed to sunlight, the ice within the warm dark regions vaporizes more rapidly than ice within the bright regions does. Thermal segregation gets a leg up on Iapetus because, on its very distant orbit, it rotates very slowly, only once every 80 days. So its daytime temperatures, as confirmed by CIRS, rise much higher than those on other moons', facilitating vaporization.

The water vapor eventually freezes back to the ground. It is more likely to freeze onto colder surfaces, including bright areas and also shadowed areas like pole-facing crater walls. Losing ice, the dark regions get even darker. It's a runaway process that rapidly blackens dusted regions in a matter of a few to a few tens of million years — just a blink of an eye in geologic terms.

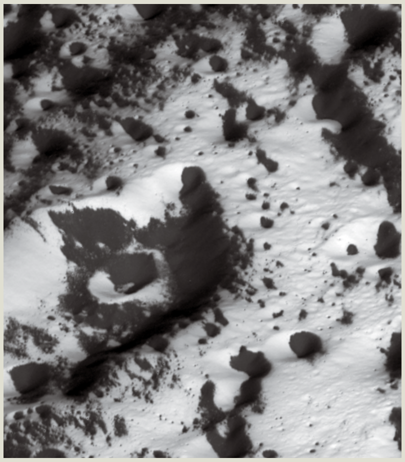
BOUND FOR IAPETUS

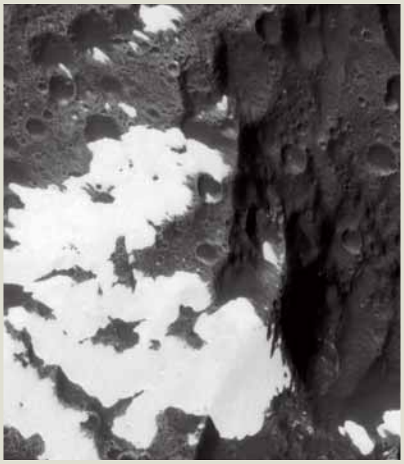
In Arthur C. Clarke's novel *2001: A Space Odyssey*, the spaceship *Discovery* travels to Iapetus, not Jupiter (as depicted in the movie)

When Cassini flew past Iapetus during its September 10, 2007 targeted flyby, it captured detailed maps of the transition zone between the bright and dark regions. At every scale, there was no gray, only black and white, confirming the thermal segregation model. The initial source of the leading hemisphere's darkening remains a mystery.

Sunset on the South Poles

Cassini's four-year primary mission was highly productive. It solved the mystery of the origin of the E ring and Iapetus's hemispheric dichotomy. It has added Enceladus





IAPETUS UP CLOSE During its September 10, 2007 flyby, Cassini obtained the first high-resolution images of Iapetus. The images partially solved the mystery of Iapetus's two-toned surface. The image taken in a bright region *(left)* shows that equator-facing crater rims remain dark. This pattern, along with areas where light material is found in dark regions *(right)*, suggests runaway thermal segregation. Ice more quickly vaporizes on the warmer, dark surfaces, so they remain dark, and water vapor freezes on bright, colder terrain.

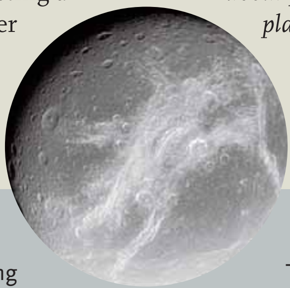
to two prestigious lists: places where we have observed active geology, and potentially habitable worlds.

With all 12 instruments still healthy and with plenty of remaining fuel, Cassini recently began a two-year extended Equinox Mission. The orbiter will carry on with its studies while watching the Saturnian system go through its northern vernal equinox in August 2009. The team is proposing a second extension lasting a further 7 years, so it can watch full winter descend upon the southern poles.

With the arrival of autumn and winter to Saturn's southern hemisphere and moons, the Sun will set from Enceladus's south pole. But Cassini and its team of scientists will continue to monitor the warm glow of Enceladus's vents on into the polar night. ✦

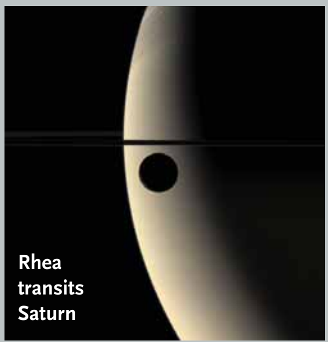
Planetary Society web editor ***Emily Lakdawalla*** *blogs daily about past and present planetary exploration missions at planetary.org/blog. She lives in Los Angeles with her husband and a daughter, soon to be joined by another.*

Rings Around Rhea?



Dione

On a November 26, 2005 flyby of Rhea — Saturn's second-largest moon — Cassini's Magnetospheric Imaging Instrument (MIMI) detected what may be a system of three or more rings surrounding the satellite. MIMI found that something unseen blocks the flow of electrons through the magnetosphere in Rhea's neighborhood. MIMI detected three sharp drops in its electron counts on each side of Rhea.



Rhea transits Saturn

If the rings exist, they're made of particles too large to be seen in the forward-scattering geometry that made Enceladus's plumes visible. And they're too sparse to be noticed by regular reflected light. So it might not be possible for Cassini to perform follow-up observations that could confirm a Rhea ring system.

The Cassini magnetometer has seen hints of a source of plasma at Dione, and the VIMS team has also reported the possibility of a tenuous atmosphere of methane and water ice surrounding this moon. The ISS team has searched for plumes from Dione like the ones seen at Enceladus, but has so far come up empty.

Meanwhile, a mysterious dark band on Tethys first observed in Voyager images has failed to yield to explanation. The band is obvious in Cassini images, darkening a patch of territory on the leading side, centered almost perfectly on the equator, and apparently disregarding local topography. Its relatively dark color might mean its surface ice contains different-size ice crystals than other areas of Tethys. The equatorial location might suggest that the E ring has something to do with its formation, but no one has yet proposed a mechanism to relate the two.

Tethys