CASSINI–HUYGENS

Titan's methane lakes

Sunglints, or specular reflections, are often seen on Earth when sunlight reflects off of the smooth surfaces of lakes and rivers. On 8 July 2009, the Visual and Infrared Mapping Spectrometer (VIMS) on Cassini captured the first sunglint from an extraterrestrial body of liquid, confirming the presence of lakes and seas near Titan's north pole. Titan's thick nitrogen (N_2) and methane (CH_4) atmosphere and photochemically generated haze layer prevent most visible light from reaching the surface, so this image was taken in the infrared at 5 μm. The sunlight reflected off of a lake, now called Jingpo Lacus, which is intermediate in size between Lake Ontario and Lake Superior (~8,000 square miles or 20,800 square kilometres).

Titan is the only other body in the Solar System besides Earth that currently has stable liquid on its surface. However, with a surface temperature of 94 K and pressure of 1.5 bar, water is solid and the surface conditions are close to the triple point of methane. Titan's lakes and seas are composed primarily of liquid methane and ethane (C_2H_6); ethane is one of the most abundant products of Titan's complex atmospheric chemistry, which produces numerous complex organic molecules. Titan's proximity to the triple point of methane allows for an active hydrological cycle and Cassini–Huygens observed extensive stream and river systems, large outbursts of clouds from convective methane storms, and evidence of rainfall. Titan's surface has been carved into a landscape that is irresistibly reminiscent of home. We now know that there is another world in the Solar System that has abundant liquids and organics and therefore harbours the potential for life. The sunglint captured by Cassini VIMS serves as a beacon for future explorers.

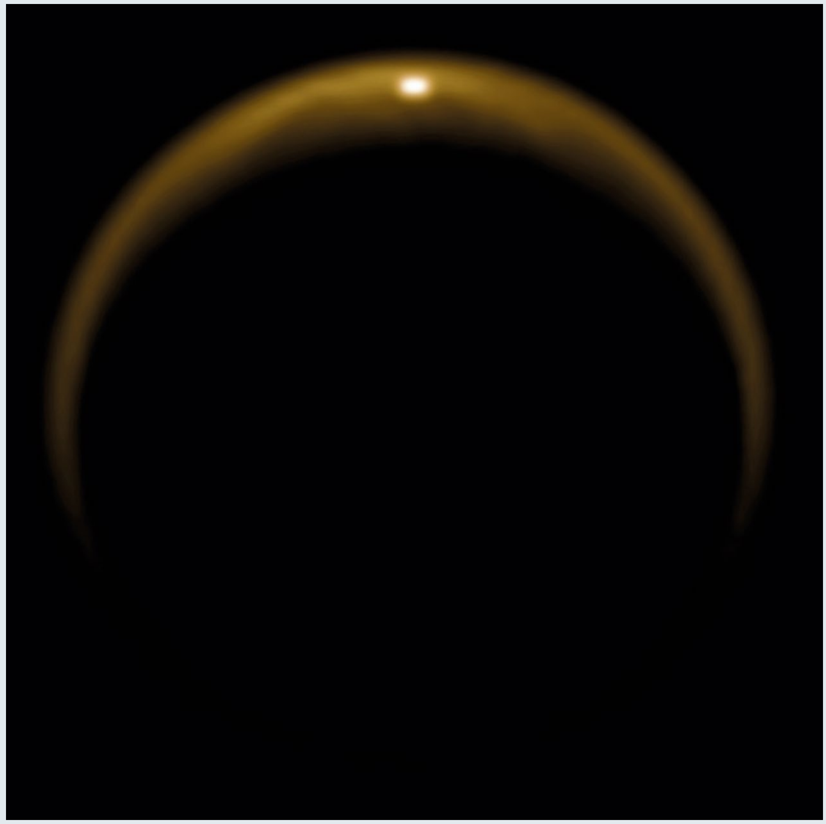

Image credit: NASA/JPL/University of Arizona/DLR

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Published online: 5 September 2017
DOI: 10.1038/s41550-017-0244-8

CASSINI-HUYGENS

Hyperion

Discovered orbiting about 1.5 million km from Saturn in 1848, Hyperion is one of the largest irregular moons in the Solar System. Spanning a distance of 360 km at its widest, but only 205 km at its narrowest, the moon suggested a violent past even before its close study by Cassini. Voyager 2 captured images of the moon from about 700,000 km that showed hints of a large crater. Ground-based observers tracked Hyperion over many nights to reveal that its rotation is chaotic: the moon isn't tidally locked to Saturn, but it doesn't have a regular rotation period either. Its irregular shape, elliptical orbit, and 3:4 orbital resonance with Titan are the causes of this unusual state. The New Horizons spacecraft discovered that two moons of Pluto — Nix and Hydra — are also in chaotic rotation.

During a flyby of Hyperion in 2005 that approached to within 500 km, Cassini captured the view shown here. A giant crater that is almost as wide as the moon dominates the sponge-like surface. The impactor causing this feature was sufficiently big to break Hyperion up, and maybe it did, as Hyperion's density is only 0.54 g cm^{-3}, about half that of the water ice that comprises most of the moon. This low density implies the moon's interior possesses void spaces; perhaps it is even a rubble pile.

Many small, dust-filled craters dot Hyperion's surface, and some of them have low-albedo floors. This dark material may be similar to the 'Phoebe dust' produced by Saturn's giant Phoebe ring that coats the dark side of Iapetus. This material, which is rich in organic molecules and carbon, is warmer than the water ice and 'drills down' into the craters to form deep pits similar to the Earth's suncups. Hyperion is a strange world, but it has a bit of the familiar.

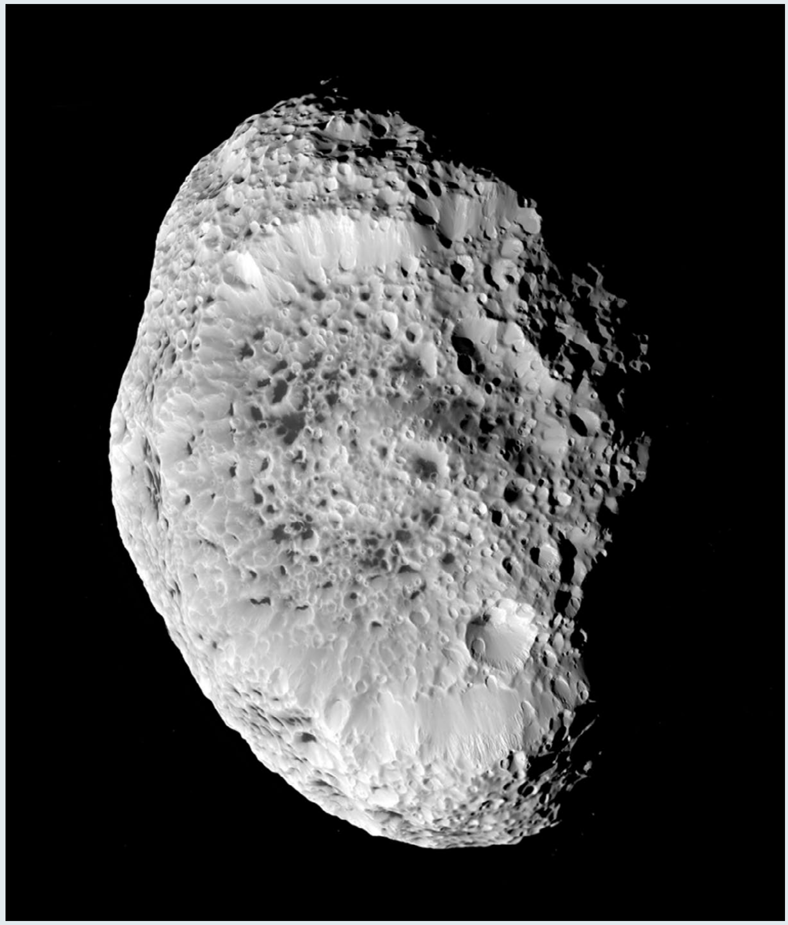

Image credit: NASA/JPL/Space Science Institute.

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Published online: 5 September 2017
DOI: 10.1038/s41550-017-0243-9

CASSINI-HUYGENS

Pan

Named after the Greek god of shepherds, the small Saturn moon Pan orbits in the middle of the prominent Encke Gap in Saturn's A ring, the outermost of the main rings of the planet. Its presence was predicted on the basis of Voyager observations of wavy patterns at the gap's edges, consistent with the gravitational effect of an unseen, embedded moon. Unresolved images of Pan were finally found in the Voyager 2 archive after a careful search by American planetary scientist Mark Showalter in 1990, almost a decade after the Saturn flyby.

These two images of Pan were taken on 7 March 2017, when the Cassini spacecraft passed within 25,000 km of the moon. With a mean radius of 14 km, Pan has a very peculiar shape, with a prominent equatorial ridge giving it the bizarre appearance of a giant 'ravioli' or 'flying saucer'. Nearby ring moons, particularly Atlas but also Daphnis, have somewhat similar shapes. Pan's density has been estimated to be 0.43 ± 0.15 g cm^{-3}, low for such an icy object, which means that the speed necessary to escape its surface will also be low. Therefore, when the moon has an impact from a ring particle, ejecta can escape Pan's gravitational field with relative ease.

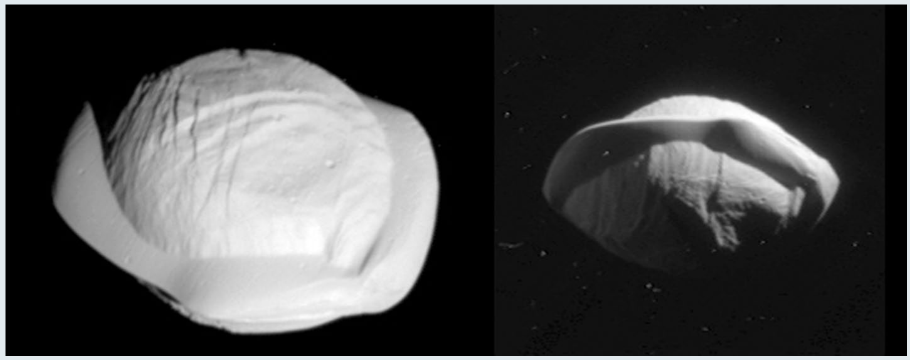

Image credit: NASA/JPL-Caltech/Space Science Institute

However, since the ring particles are nearly co-planar and the moon's spin axis is perpendicular to the ring plane, such material is then likely to be swept up by the moon and preferentially re-accreted in the orbital plane to form the distinctive equatorial ridge.

The existence of several rings or partial rings within the Encke Gap supports the idea that the process is ongoing. Current models suggest that Pan originally accreted into the more rounded central part visible in the images, created the gap for itself by shepherding the ring material on each side, and then grew its characteristic appendage.

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Published online: 5 September 2017
DOI: 10.1038/s41550-017-0252-8

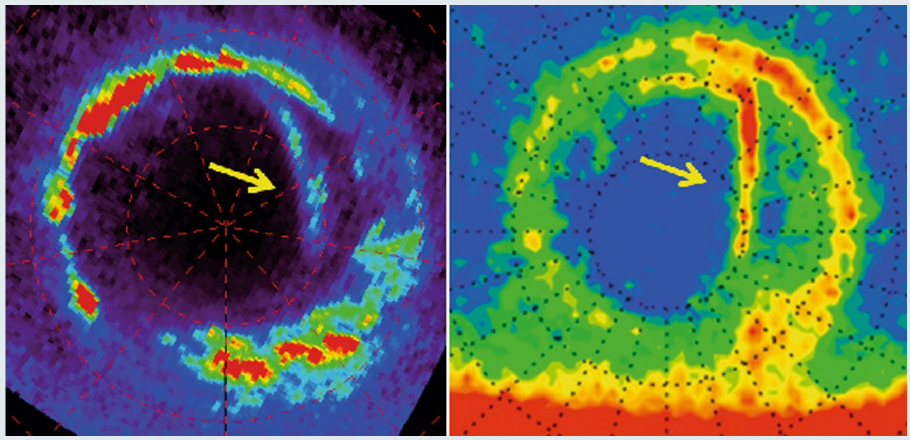
CASSINI-HUYGENS

Saturn's auroral arc

Auroral emissions, the natural light displays in the sky, are the optical manifestations of a chain of interactions involving the planetary atmosphere, its moons, interplanetary space and the Sun. The Ultraviolet Imaging Spectrograph (UVIS) instrument onboard Cassini allowed us to discover a striking auroral feature of Saturn: the 'nightside polar arc' (pictured left, indicated by the arrow), which strongly resembles a terrestrial transpolar arc (pictured right, indicated by the arrow).

Transpolar auroral arcs are some of the most spectacular and puzzling auroral emissions at Earth. They are also known as 'theta aurora' because when they are seen from above they look like the Greek letter theta (like an oval with a line crossing through the centre). They extend from the nightside auroral oval into the open magnetic field line region and often reach the dayside auroral oval. Nightside polar arcs, which are regularly observed at Earth, represent optical signatures of the interaction of the deep planetary magnetosphere with a stream of charged particles emitted by the Sun, through the process of magnetic reconnection.

Contrary to Earth, Saturn is a fast rotator. In addition, its magnetospheric plasma mainly originates from internal sources (such as Enceladus, neutral clouds and rings). These ingredients constitute a magnetosphere whose deepest region is not supposed to be vulnerable to the solar wind. The Cassini discovery shows that Earth-like polar arcs can exceptionally occur in a fast rotational and internally influenced magnetosphere such as Saturn's. One possible scenario could be that the polar auroral arc at Saturn is formed by solar-wind-driven magnetic reconnection in Saturn's magnetotail, like at Earth. This suggests that solar wind might have a stronger influence on Saturn's deep magnetotail region than we thought. This is the first and only observation that reveals the presence of such an arc at Saturn. The rarity of its appearance demonstrates that the conditions for its formation are rarely met at Saturn.



Credit: Image reproduced from A. Radioti et al. *Geophys. Res. Lett.* **41**, 6321–6328 (2014); AGU.

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Published online: 5 September 2017
DOI: 10.1038/s41550-017-0247-5

CASSINI-HUYGENS

Shadows of Saturn's B ring

As a ring scientist I've been studying Saturn's rings since the early 1980s, and the long shadows in this particular image fascinated me! By observing the rings at equinox, with the Sun edge-on, for the first time we could search for three-dimensional regions in the rings, and we found them. Equinoxes occur only once every 15 years at Saturn, so we were lucky to have had Cassini in orbit during this special time. This image from Cassini's narrow-angle camera was obtained on 26 July 2009, just two weeks before the equinox.

The bright outer edge of Saturn's B ring is at the top of the image, just below the Cassini division, the black area depleted in ring particles. The Sun is shining downward from the top. For the first time we saw the shadows of the largest ring particles towering 1–2 miles above the 10-metre-thick rings. Imagine yourself flying in the space station, looking down on the ancient pyramids in Egypt. If the Sun were overhead, the pyramids would be hard to pick out as they blend into the desert floor. Now imagine looking down again at the pyramids, but near sunset, the equivalent of equinox. Their large shadows stretch for miles across the desert, making them obvious. In the same way, Saturn's large ring particles cast their shadows on the rings, revealing themselves to Cassini's cameras for the first time. These large chunks — possibly agglomerations of smaller particles — at the outer edge of Saturn's B ring can tell us a great deal about how our Solar System's planets may have accreted. Saturn's ring disk is an excellent natural laboratory for studying processes that might have occurred in the early Solar System.

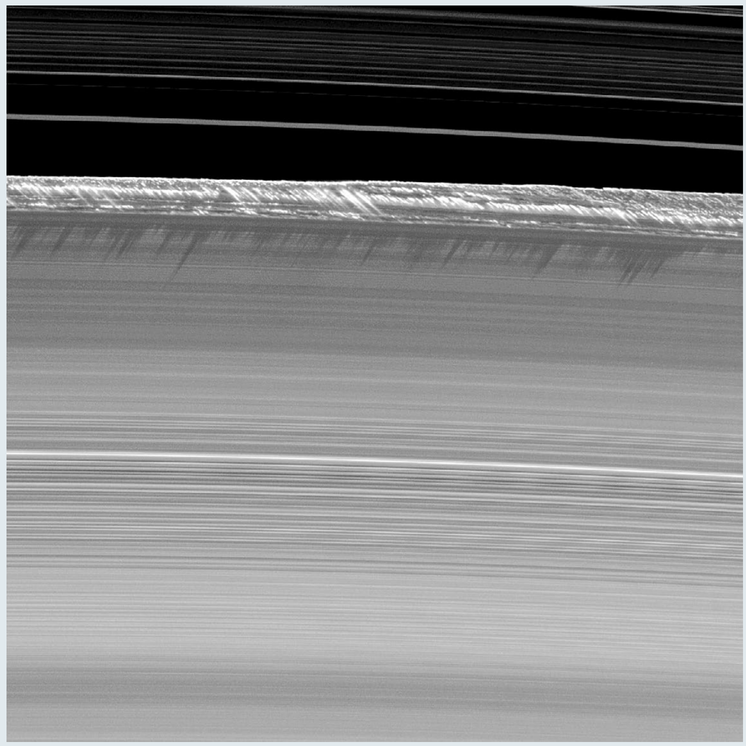

Image credit: NASA/JPL/Space Science Institute

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Published online: 5 September 2017
DOI: 10.1038/s41550-017-0254-6

CASSINI-HUYGENS

Titan's 'Mount Doom'

Cryovolcanoes, or ice volcanoes, erupt molten ices of different varieties (water, methane, ammonia and so on) instead of molten rocks, as happens on Earth. As such, they are present in the cold bodies of the outer Solar System such as icy moons. The existence of cryovolcanoes on Titan is still a matter of some debate. We have observed flow morphologies, but they can be difficult to interpret unambiguously as volcanic, as opposed to fluvial, and we know that Titan has fluvial activity. However, when the data for the Sotra Patera region of Titan were analysed, many of us concluded that this region, at least, was volcanic in origin.

This Cassini radar image of the area, obtained during the T25 and T28 Titan flybys at the beginning of 2007, is a perfect example of Cassini instruments working in synergy. It combines two Synthetic Aperture Radar images, which are used to reconstruct the topography with a digital elevation model (shown here with a vertical exaggeration of 10:1), with Visual and Infrared Mapping Spectrometer (VIMS) data, which show compositional differences in false colour (see a movie for the whole region at http://photojournal.jpl.nasa.gov/catalog/PIA13695).

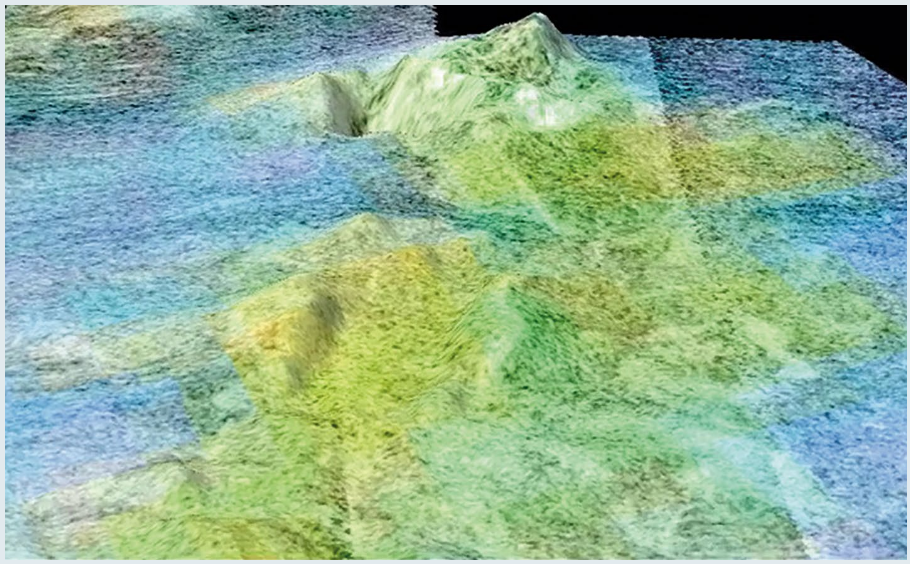

Image credit: NASA/JPL-Caltech/USGS/University of Arizona

The image shows one of the tallest peaks on Titan, Doom Mons, which is ~70 km in diameter and 1.45 ± 0.20 km high. Doom Mons is adjacent to the deepest depression so far found on Titan, Sotra Patera, an elongated pit ~30 km in diameter and 1.7 ± 0.2 km deep. These features, and the surrounding flow-like features around them (called Mohini Fluctus), have been interpreted as cryovolcanic. They are shown here in shades of green and yellow from VIMS data, whereas the dune fields are in blue. This colour difference indicates that the dunes have a different composition from the candidate cryovolcanic materials.

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Published online: 5 September 2017
DOI: 10.1038/s41550-017-0249-3

CASSINI-HUYGENS

Saturn in the infrared

The reason I am so partial to this image is that it shows a completely different view of Saturn than anything we ever saw before the Cassini spacecraft went into orbit. The Visual and Infrared Mapping Spectrometer (VIMS) observes at 352 different wavelengths between 0.3 and 5.1 μm, enabling different processes at different depths to all be viewed in the same false-colour image. At 2.3 μm (shown in blue), the icy ring particles are highly reflecting, while the methane gas in the atmosphere of Saturn strongly absorbs the sunlight, causing the planet to appear dark. At 3.0 μm (shown in green), the situation is reversed: water ice in the rings is strongly absorbing, whereas the planet's sunlit hemisphere is bright. As a result the rings appear blue, while the sunlit side of Saturn is greenish-yellow in colour.

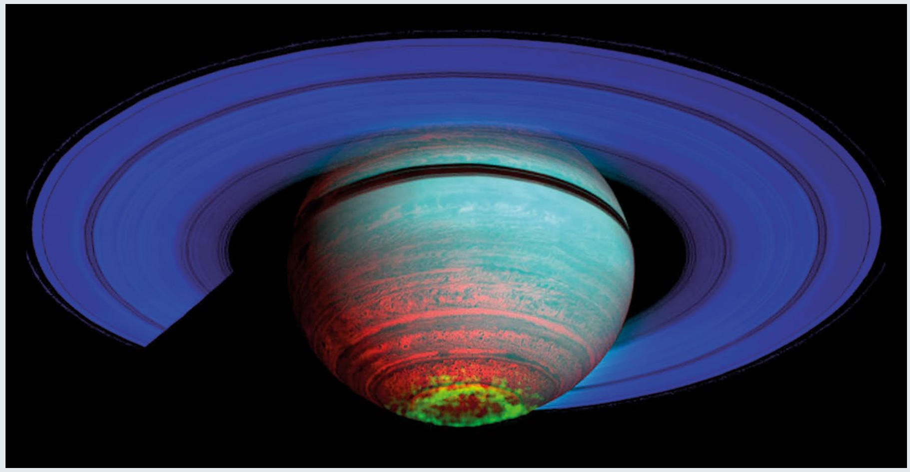

Image credit: NASA\JPL\University of Arizona\University of Leicester

Within the rings, the most opaque parts appear dark, while the more translucent regions are brighter. In particular, the opaque, normally bright B ring appears here as a broad, dark band separating the brighter A (outer) and C (inner) rings. At 5.1 μm (shown in red), reflected sunlight is weak and as a result the light from the planet is dominated by thermal radiation that wells up from the planet's deep atmosphere. Variable amounts of clouds in the planet's upper atmosphere block the thermal radiation, leading to a speckled and banded appearance, which is always changing due to the planet's strong winds. Last but not least, one can view the bright green emission of the southern aurora generated as a result of precipitating particles spiralling along Saturn's magnetic field lines near the south pole, which for me is the cherry on the cake since my instrument measures the magnetic field lines.

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Published online: 5 September 2017
DOI: 10.1038/s41550-017-0245-7

CASSINI-HUYGENS

Ring ripples

This mosaic of the inner part of Saturn's rings shows a variety of structures, including narrow gaps, sharp edges and a few ringlets that can be seen in many high-resolution images of the rings. However, unlike most of those images, this mosaic also shows fine-scale periodic variations in the ring's brightness that extend across this entire region. This pattern was only visible during a period of time around 2009 when the Sun was illuminating the ring from almost exactly edge-on. This unusual lighting geometry highlights vertical structures in the rings and so the periodic brightness variations seen here by Cassini likely represent a corrugation or 'ripple' extending across the rings.

Detailed studies of these ripples show that they are not static features, but slowly evolve over time. Extrapolating the observed trends in these structures backwards in time reveals that they were probably created in the early 1980s, when something, probably a cometary impact, disturbed a wide swathe of the rings. The rings therefore contain echoes of events that happened decades ago, and so preserve a record of the recent history of the outer Solar System.

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Published online: 5 September 2017
DOI: 10.1038/s41550-017-0248-4

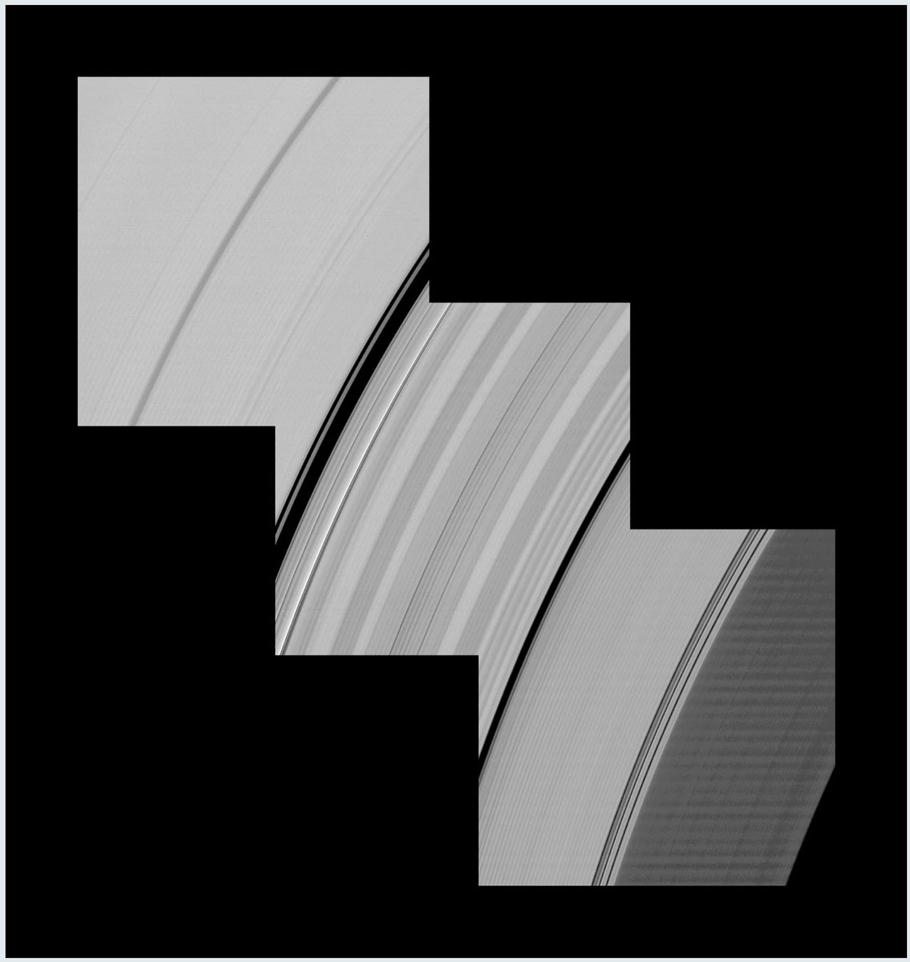

Image credit: NASA/JPL/Space Science Institute

CASSINI-HUYGENS

Enceladus and its plume

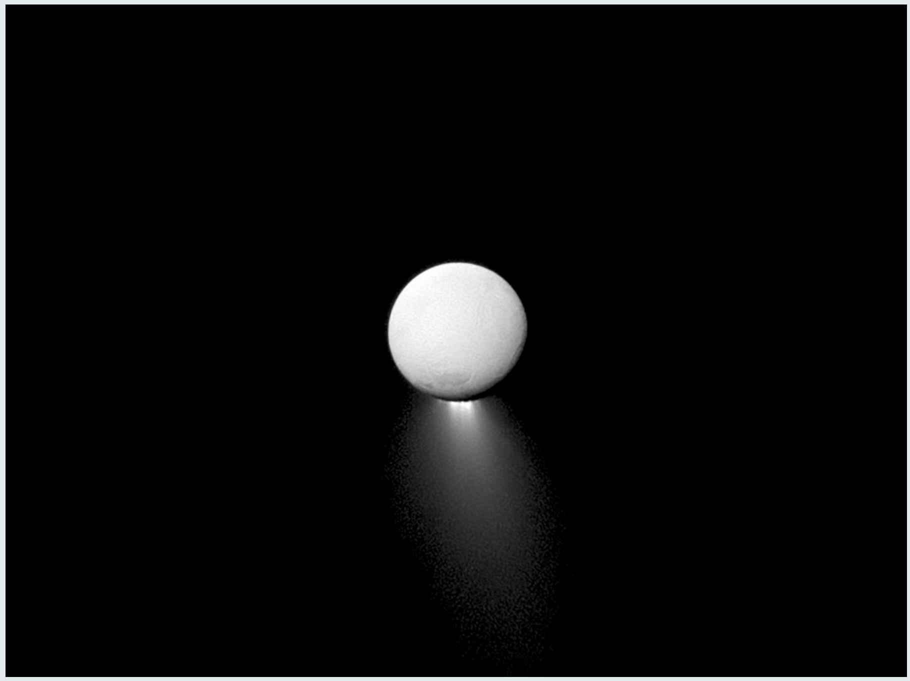

Image credit: NASA/JPL-Caltech/Space Science Institute

Enceladus is Saturn's most geologically active moon, spouting a plume of gas and grains discovered by Cassini. The low gravity of this tiny moon (just 500 km across) allows the material to escape into orbit around Saturn, where it forms the so-called E ring, discovered by astronomers just a half-century ago. The plume is fed by jets that escape from fractures in Enceladus's surface in and around the south pole, and the underlying source is thought to be an interior ocean of liquid water whose presence was also detected by the Cassini spacecraft. The plume is hard to see except when sunlight is shining through it and scattered by the grains, and therefore when the surface of Enceladus itself is not illuminated by the Sun. This unusual image, then, is not a composite of two images — it is a single image in which the surface of Enceladus is lit by reflected light from Saturn (Saturn-shine), while the plume (and its source jets close to the surface) are illuminated by the scattered light of the Sun, which is roughly in the direction of the camera (but out of the image).

The Cassini spacecraft flew through the plume seven times over its 13-year mission in Saturn orbit. During these penetrations instruments collected gas and both icy and dusty grains, finding frozen salt water, molecules including methane and also heavier organics (molecules containing carbon and hydrogen), hydrogen, and tiny silicon-bearing grains. Cassini also found large amounts of heat emanating from the south polar fractures, indicating that this tiny moon is being tugged and squeezed by tidal forces raised by Saturn — generating heat by friction. The Cassini results indicate that the ocean beneath Enceladus's icy crust can support microorganisms. Perhaps a future mission to Enceladus will snap an image similar to this one before plunging into the plume with instruments designed to search for the molecular signatures of life.

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Published online: 5 September 2017
DOI: 10.1038/s41550-017-0251-9

CASSINI-HUYGENS

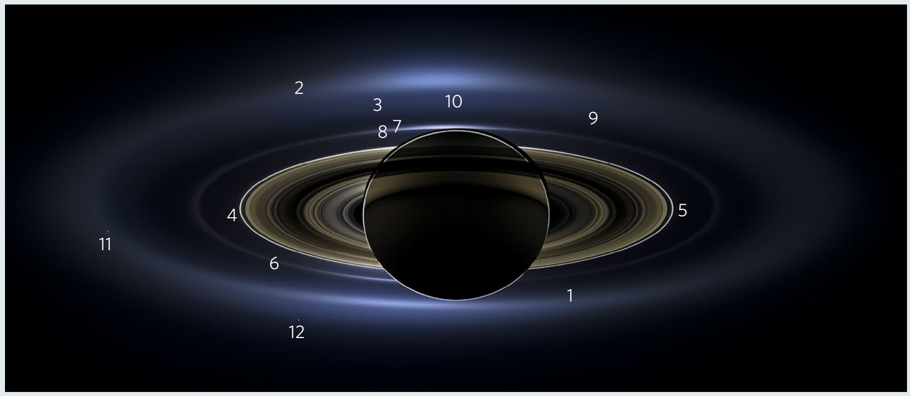
The day the Earth smiled

This mosaic, a 'family photo' of Saturn, its rings, seven of its moons and three inner planets (Earth, Mars and Venus), was shot on 19 July 2013, while Cassini was flying in the shadow of Saturn's disk, with the Sun shining behind the planet. This unique view, impossible for an observer on the Earth, allows us, among other things, to observe the sunlight scattered by icy particles within the tenuous E ring, continuously resupplied by Enceladus's plumes. Close to the rings appears a pale dot, our Earth, more than 1.4 billion kilometres away.

Looking at this remarkable image the prophetic words of Arthur C. Clarke, written well before Cassini arrived at Saturn in 2004, come to mind:

"However long you look at Saturn, and fly in and out among its moons, you can never quite believe it. Every so often you find yourself thinking: 'It's all a dream, a thing like that can't be real.' And you go to the nearest view-port — and there it is, taking your breath away. You must remember that, altogether apart from our nearness, we were able to look at the rings from angles and vantage points that are quite impossible from Earth, where you always see them turned towards the Sun. We could fly into their shadow, and then they no longer gleam like silver — they would be a faint blaze, a bridge of smoke across the stars. And most of the time we could see the shadow of Saturn lying across the full width of the rings, eclipsing them so completely that it seemed as if a great bite had taken out of them…"

Among the numerous images returned by Cassini, this is the one that for me best collects the richness of Saturn's system.



1 Earth/Moon
2 Mars
3 Venus
4 Prometheus
5 Pandora
6 Epimetheus
7 Janus
8 Janus's ring
9. Mimas
10. Pallene's ring
11. Enceladus
12. Tethys

Image credit: NASA/JPL-Caltech/SSI

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Published online: 5 September 2017
DOI: 10.1038/s41550-017-0255-5

CASSINI-HUYGENS

Saturn's big storm

In contrast to the dramatic meteorology of Jupiter, Saturn's golden-yellow hues provide an air of calmness, with slow seasonal changes from wintry blues to summertime yellows as the temperatures, chemistry and hazes evolve over Saturn's 29.5-year orbit. But, once every Saturnian year, a gigantic storm of billowing white cloud activity erupts from those serene cloud decks.

There were five recorded annual storms prior to Cassini's mission, all of which had erupted after the northern summer solstice (which just passed on 24 May 2017). It was incredibly fortuitous that a similar gargantuan storm occurred a decade earlier than expected, erupting from Saturn's northern mid-latitudes during early spring in December 2010. The plumes, thought to be powered by moist convection, lofted fresh volatiles upwards to condense to form bright white clouds. The fresh clouds and chemicals were redistributed by the prevailing winds, with the storm 'head' moving swiftly westward, and a turbulent tail of patchy clouds and newly formed anticyclones moving eastward. Eventually, the head of the storm encountered material from the tail, merging to form a new, white turbulent band on Saturn.

Cassini's multi-spectral capabilities provided a wealth of insights into the nature of the storm. Powerful lightning strikes, a signature of convective activity, were detected as both optical flashes and via their radio emissions. Fresh ices of water and ammonia were detected via the spectral signatures in reflected sunlight. Enormous stratospheric temperature perturbations, and the formation of a glowing, hot vortex known as 'the beacon', were discovered via their heat signatures and persisted for three years after the churning storm had abated. And radar observations after the storm had passed showed that the storm had completely cleared the atmosphere of ammonia gas, maybe by rain or snow. Combined, these Cassini data have allowed researchers to understand the convective phenomena and timescales for one of the most spectacular meteorological phenomena in our Solar System.

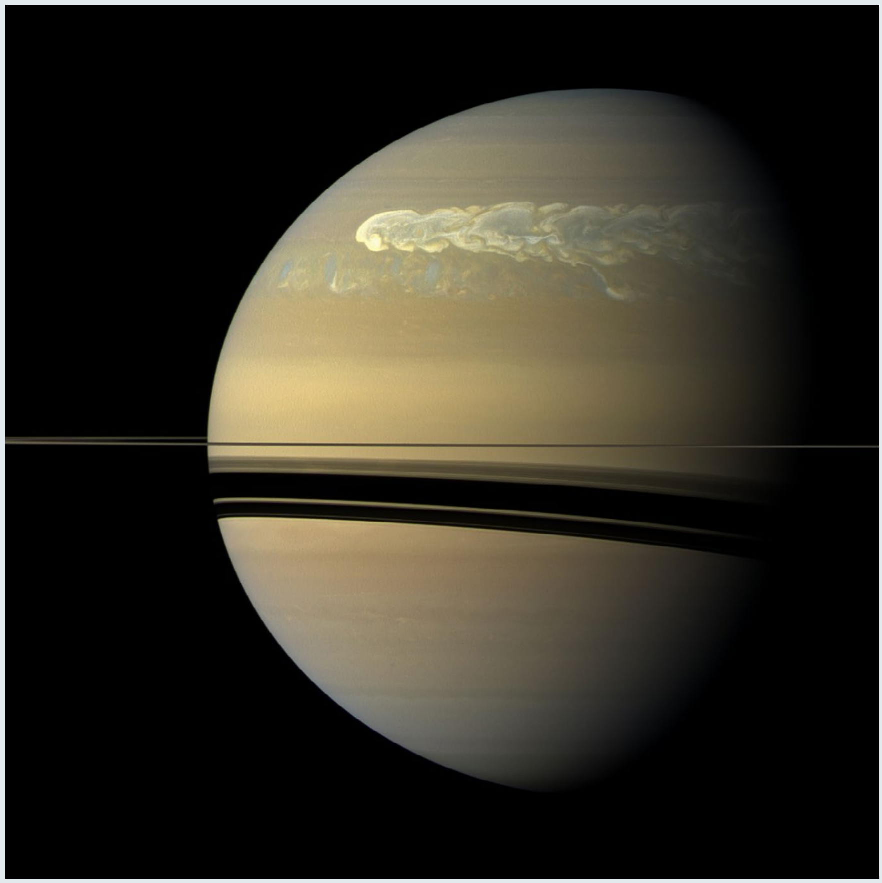

Image credit: NASA/JPL-Caltech/Space Science Institute

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Published online: 5 September 2017
DOI: 10.1038/s41550-017-0246-6

CASSINI-HUYGENS

Saturn's polar hexagon

The image shows a polar projection of Saturn's northern high latitudes in the 750-nm near-infrared filter of the Imaging Science Subsystem (ISS) camera onboard the Cassini orbiter. The image consists of a mosaic of eleven images captured on 6 January 2009. A hexagonal cloud feature stands out prominently; the feature has been known as the hexagon on Saturn, which was originally discovered in Voyager images captured during 1980–1981. Since then, the feature was seen in the 1990s using the Hubble Space Telescope after its launch in 1990 until the north pole went out of view after the equinox of 1995, and was not seen again until the Cassini spacecraft went into orbit around Saturn in 2004. When Cassini arrived at Saturn, the north polar region was still in winter polar night, and the hexagon could be detected only in thermal and mid-infrared emissions.

As Saturn approached the equinox of 2009, sunlight started illuminating the hexagon region; this mosaic is the first observation by Cassini of the hexagon illuminated by the Sun. The centre of the image appears dark because the north pole was not yet illuminated at the time. The hexagonal pattern is the meandering path of an atmospheric jet stream that blows at those latitudes. Multiple mechanisms have been proposed to explain its shape and near-perfect symmetry. Numerical as well as laboratory experiments have revealed that the vertical structure of the jet and the atmospheric stratification are important factors: when those physical effects are taken into account, a persistent wavenumber-6 pattern can be reproduced in numerical models as well as laboratory tanks. The vertical jet structure and atmospheric stratification are difficult to determine from observation, so these numerical experiments help our understanding of the atmosphere of Saturn at a depth that we cannot observe. Continued imaging from the Cassini orbiter has revealed that its colour changed gradually from bluish to golden as the north pole approached the summer solstice of May 2017.

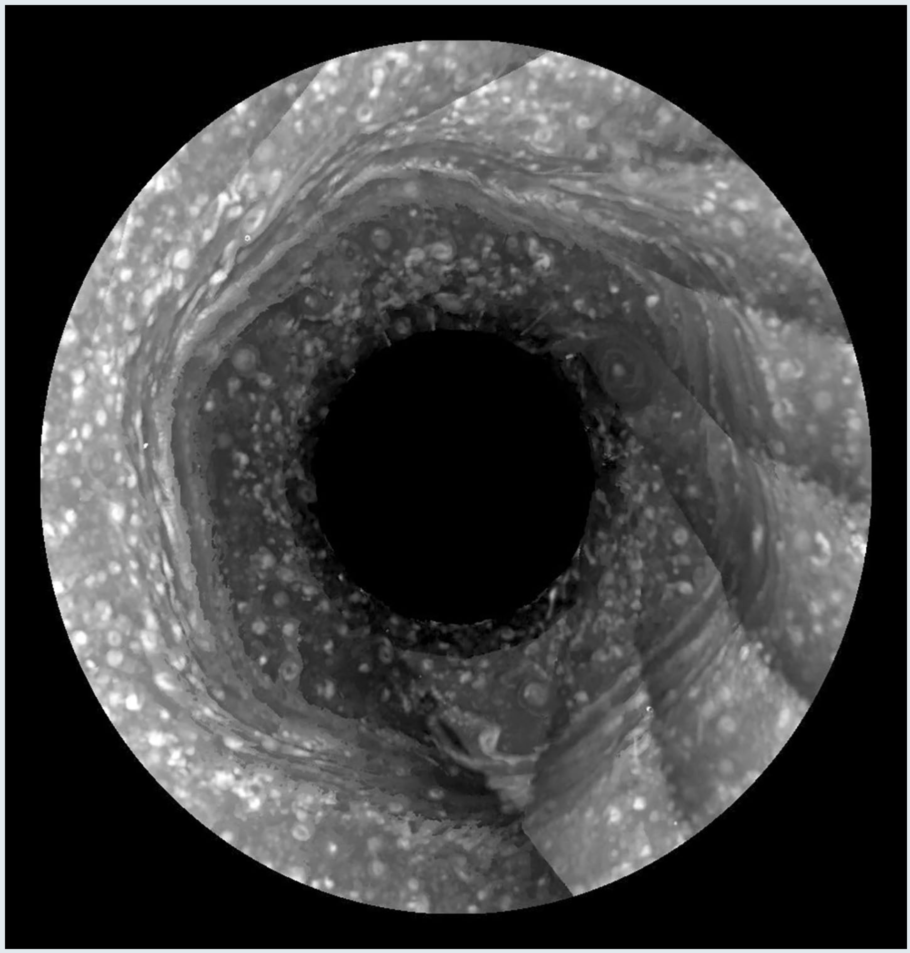

Image credit: NASA/JPL/Space Science Institute

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Published online: 5 September 2017
DOI: 10.1038/s41550-017-0253-7

CASSINI–HUYGENS

Huygens and Titan's methane cycle

The beginning of the Cassini mission was marked by the deployment of the Huygens probe on the surface of Titan. Detached on 25 December 2004 and landing a couple of weeks later, Huygens still holds the record of farthest man-made object to soft-land on a celestial body. Yet the most exciting thing about the images taken by its downward-looking camera (DISR) during the descent is not how alien this distant world looks, but instead how familiar it is, as this mosaic of three DISR images shows. It seems we are observing an Earth shoreline, with a fluvial channel flowing into the sea and a few bright water clouds floating around.

Of course, despite the visual similarities, Titan still has conditions very different from those on Earth. Due to Titan's cold temperatures (93 K at the surface), it is liquid methane that carved that fluvial basin, not water. In addition, what we are observing is the remnant of past events, as the whole area is now dry. Huygens landed on the sea-like region and did not float over some liquid surface, but rather touched down on an icy lakebed. The round pebbles scattered around, however, indicate that the area was indeed filled with liquid at some time. Subsequent climate modelling showed that Titan's global circulation disfavours the accumulation of liquid hydrocarbon at the equator, where the Huygens landing site is, but episodic flooding could happen.

Huygens images and data gave the definitive in situ evidence that Titan possesses a full hydrological cycle, parallel to Earth's water cycle but based on methane. This cycle, which couples the subsurface, surface and atmosphere through complex physical and chemical processes involving methane at all three states (gas, liquid and solid), clearly affected Titan's environment and may have impacted its potential for habitability. Few images exemplify the surprises and excitement of space exploration like this one.

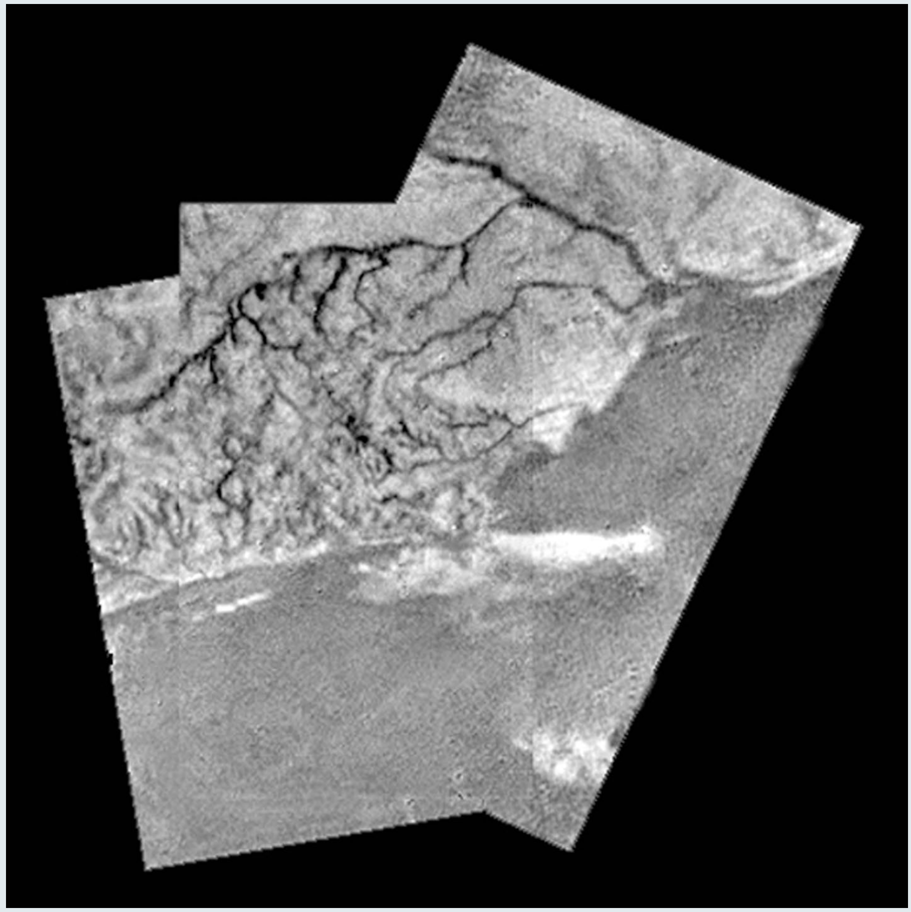

Image credit: NASA/JPL/ESA/University of Arizona

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Published online: 5 September 2017
DOI: 10.1038/s41550-017-0250-x