

The Scientific Achievements of the Cassini-Huygens Mission

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Abstract. Discoveries from the Cassini-Huygens mission have revolutionized our understanding of Saturn, its complex ring system, the incredible assortment of moons and the planet's dynamic magnetic environment. The robotic spacecraft arrived at Saturn in 2004 after a 7-year flight from Earth, dropped a European Space Agency (ESA) parachuted probe named Huygens to study the atmosphere and surface of Saturn's big moon Titan, and commenced making astonishing discoveries. NASA's Cassini spacecraft explored the Saturn system for over 13 years, finally vaporizing in Saturn's atmosphere on 15 September 2017 to protect the ocean worlds, Enceladus and Titan, where it discovered potential habitats for life.

During those 13 years in orbit around Saturn, the Cassini-Huygens mission made some amazing discoveries and revealed the breathtaking beauty of the Saturn system. Some of Cassini's most surprising scientific discoveries came from encounters with Saturn's intriguing moons. Those discoveries include icy jets emanating from the south pole of tiny Enceladus, a moon that harbors a subsurface global ocean and hydrothermal activity. On giant Titan, methane rain carves river channels and fills lakes and seas with hydrocarbons, mixed with complex pre-biotic chemicals that form in its atmosphere and rain to the surface. These discoveries have fundamentally altered many of our concepts of where life might be found in our own solar system and beyond.

Some of Cassini's other amazing findings include a myriad of three-dimensional structures in the dynamic rings driven by interactions with Saturn's moons and interior; a giant Saturn storm that circled the entire planet for most of 2011, while a long-lived hexagonal jet stream discovered by Voyager in 1981 continues to encircle the north pole. Cassini solved the mystery of Iapetus' dual bright-dark surface, while uncovering another: the true rotation rate of Saturn's interior, thought to be precisely determined by Pioneer 11 and the Voyagers, remains unknown. Cassini's findings at Saturn have also fundamentally altered many of our concepts of how planets form around other stars.

This flagship mission was a cooperative undertaking by NASA, ESA, and the Italian space agency (Agenzia Spaziale Italiana (ASI)).

1. Introduction

Flybys of Saturn by Pioneer 11 in 1979, Voyager 1 in 1980 and Voyager 2 in 1981 provided brief visits and fleeting glimpses of the Saturn system, leaving to Cassini-Huygens to be the first spacecraft to orbit Saturn. Figure 1 is an overview of the mission and its key phases. Cassini provided the first in-depth, close up study of Saturn, its rings and moons, and its giant magnetosphere. Some of the key highlights of Cassini's ambitious inquiry at Saturn, including the unique final year of the mission, are described below.

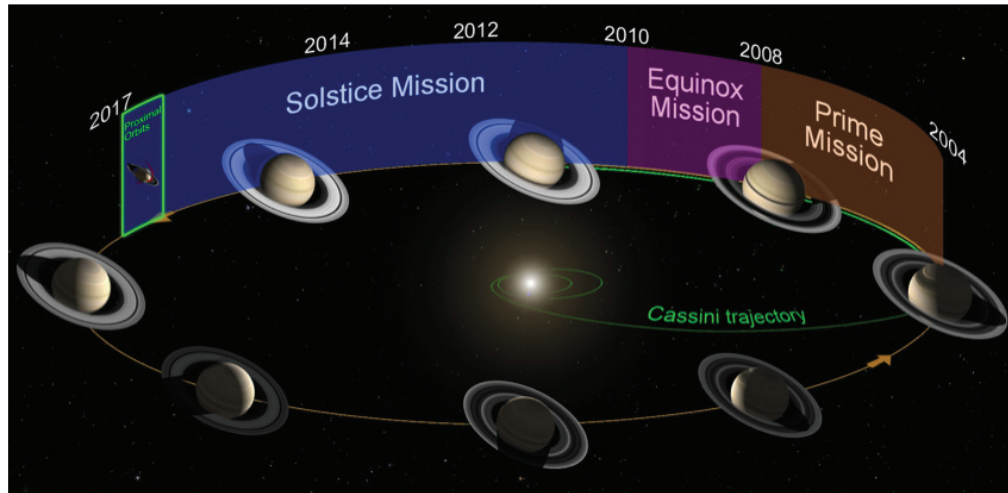


Figure 1. The Cassini mission phases (Prime, Equinox, Solstice and Grand Finale (green box)) shown against the 29.5 year Saturnian orbit. Cassini arrived in July, 2004, two years after northern winter solstice, and spent 13 years in orbit around Saturn before plunging into Saturn's atmosphere on 15 September 2017. (Credit: NASA/JPL).

2. Ocean Worlds Enceladus and Titan

Cassini discovered two ocean worlds circling Saturn. One, tiny Enceladus, has a liquid water ocean beneath its icy crust that provides a subsurface source for a plume of material spewing from the south pole. The other moon, Titan, has lakes and seas of liquid hydrocarbons on its surface, primarily near its north pole, as well as an internal liquid water ocean.

2.1. Enceladus

Enceladus, a small moon only about 500 km across, was an unusual puzzle prior to Cassini because of its very bright surface. As the brightest moon in our solar system it reflects almost 90% of the sunlight it receives. During Cassini's early flybys, images of the moon (Figure 2) revealed a system of extensive cracks and large regions completely devoid of craters. The south polar region contains large tectonic features, is devoid of craters, and is the youngest surface on Enceladus. It includes a system of four nearly parallel fractures, nicknamed "tiger stripes", that are centered near the pole (Helfenstein 2010). Each "tiger stripe" is about 130 km long and two to four km wide. They are separated from each other by approximately 35 km.

Activity on Enceladus was first detected by Cassini's magnetometer as a deflection in Saturn's magnetic field (Dougherty et al. 2006). During a close targeted flyby in 2005, Cassini's thermal infrared spectrometer discovered a hot spot centered on the south pole (Spencer et al. 2006). The four tiger stripe fractures were the warmest regions – more than 100 degrees Celsius warmer than the surrounding areas (Howett et al. 2011) - and were the source of an immense ice plume imaged by Cassini's camera (Porco et al. 2006). The giant plume of water vapor and ice grains is fed by both discrete jets (Porco et al. 2014) and curtains of material (Spitale et al. 2015) originating

inside each tiger stripe. The localized jets in the tiger stripes are the warmest regions on the moon (Spencer & Nimmo 2013; Goguen et al. 2013).

The lack of impact craters in the tiger stripe region demonstrates that it is a geologically fresh surface that is constantly renewing itself. A fair fraction of the plume material eventually re-impacts Enceladus but some of the smallest grains are the source of the tenuous, distended E ring (Spencer et al. 2006; Kempf et al. 2010; Mitchell et al. 2015), which is densest at the orbit of Enceladus and spreads throughout the system. The E ring interacts with the inner moons, coating one side with bright, fresh material. Cassini discovered that the source of the plume is a global liquid water ocean beneath Enceladus' crust (Iess et al. 2014; Thomas et al. 2016). The ocean is about 10 km deep beneath an ice shell that is about 26 – 31 km thick, and perhaps considerably thinner, as thin as 5 km, in the south polar region.

In addition to water vapor (Hansen et al. 2006), Cassini's ion and neutral mass spectrometer (INMS) discovered that the plume gasses contain carbon dioxide and simple hydrocarbons such as methane, propane, and acetylene (Waite et al. 2009, 2017). During Cassini's closest dive through the plume in 2015, INMS discovered molecular hydrogen (H_2) (Waite et al. 2017). Cassini's cosmic dust analyzer (CDA) found icy particles as well as salt-rich ice grains containing sodium and potassium that are probably frozen droplets from an underground salty ocean (Postberg et al. 2009, 2011; Glein et al. 2015). CDA also discovered tiny grains of silica, less than 10 nanometers in size, originating from Enceladus' ocean (Hsu et al. 2015). These tiny silica grains most likely condensed from hot water spewing from hydrothermal vents on Enceladus' seafloor. The excess hydrogen discovered by INMS could also be coming from the hydrothermal vents. The source of energy for the activity on Enceladus is tidal interactions among Enceladus, Dione, and Saturn (Tobie et al. 2008). With liquid water, an energy source, and carbon-bearing organic molecules, the subsurface ocean of Enceladus could harbor the ingredients for primitive life. Unfortunately, the Cassini orbiter did not carry the instruments needed to detect life.

2.2. Titan

Titan is the largest moon in the Saturn system, slightly larger than the planet Mercury, and the only moon in our solar system with a dense atmosphere. Titan is also the only body other than Earth that displays clear evidence for surface liquids: liquid hydrocarbons. Titan's atmosphere is mostly nitrogen with some methane and a haze layer of organics that give Titan its orange appearance. Key Titan results can be found in the books "Titan: Interior, surface, atmosphere, and space environment" (Müller-Wodarg et al. 2014) and "Titan from Cassini-Huygens" (Brown et al. 2010).

2.2.1. Huygens probe landing on Titan's surface

The Huygens probe became the first human-made object to land on an outer solar system moon, Titan, and the farthest landing from Earth ever made. Huygens was built and operated by the European Space Agency (ESA) and was carried as a passenger on the Cassini spacecraft. Huygens separated from Cassini in December 2004 and landed on Titan three weeks later, on 14 January 2005. The probe's 2-hour and 27-minute parachute descent provided the first in situ measurements of atmospheric temperature, pressure and composition, and provided the first detailed images of the surface. The Cassini spacecraft flew overhead and collected the Huygens data, including about 30 minutes on Titan's surface, before Cassini turned to Earth to relay the data. Huygens

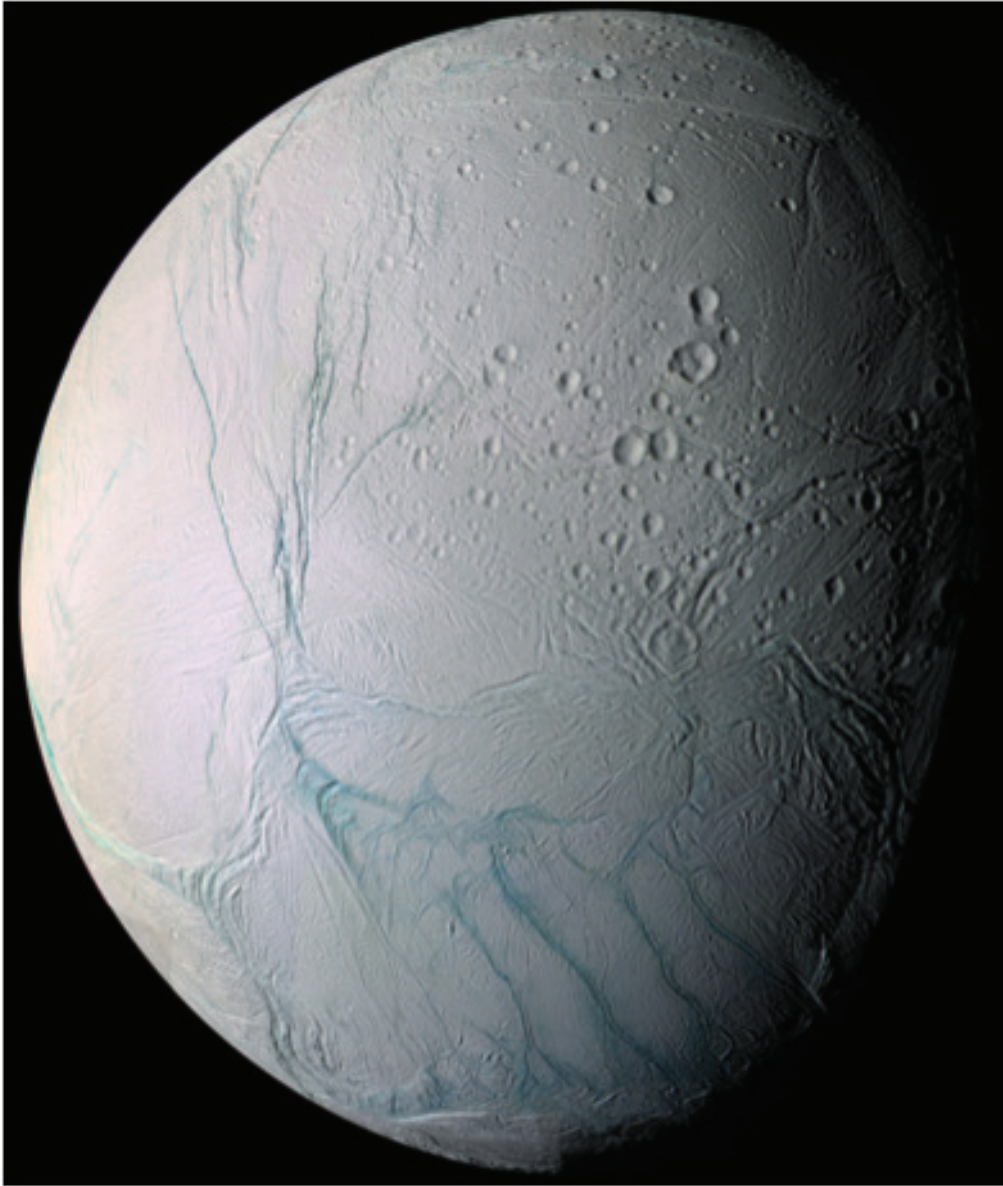


Figure 2. A high-resolution, 21-frame Enceladus mosaic, taken by the Cassini cameras on July 14, 2005, provide a full-disk view of the four tiger stripes and the anti-Saturn hemisphere on Enceladus. This false-color view includes images taken at wavelengths from the ultraviolet to the infrared portion of the spectrum. In this false-color, many long fractures on Enceladus exhibit a pronounced difference in color (represented here in blue) from the surrounding terrain (Credit: NASA/JPL/Space Science Institute).

landed in a dry lakebed filled with rounded pebbles (Figure 3), near the Xanadu region, an equatorial area about the size of Australia. Images taken at about 10 km altitude

captured dendritic erosional patterns on a hillside with very steep slopes. The rounded, smoothed pebbles at the landing site are evidence of flowing liquid.

Huygens revealed Titan to be a world remarkably like Earth before life evolved. An array of complex hydrocarbons was found in Titan's atmosphere, created by the break-up of methane high in the atmosphere. An overview of Huygens science can be found in Lebreton et al. (2009).

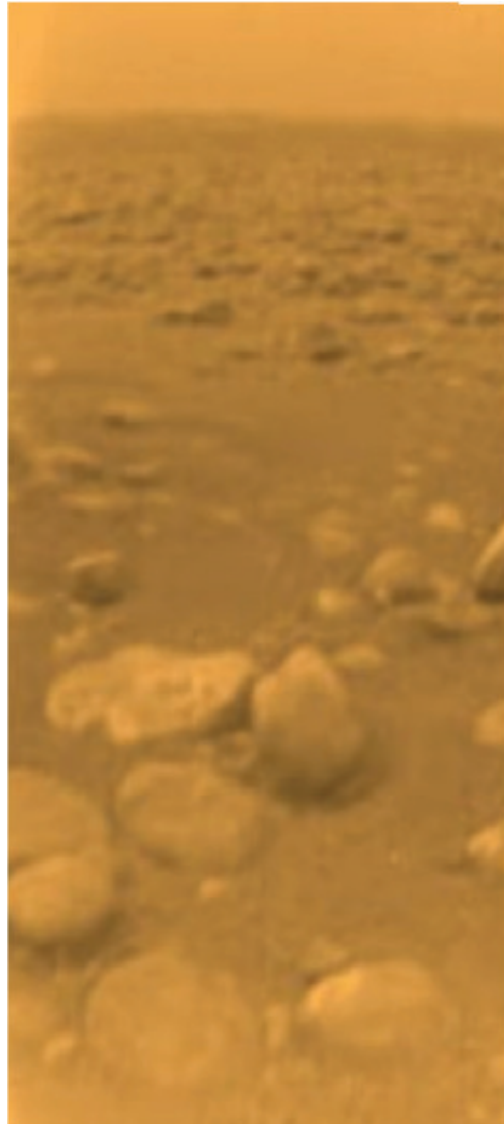


Figure 3. Huygens returned this small image from the surface of Titan. This colored view was processed to add reflection spectra data, and gives a better indication of the actual color of the surface. (Credit: ESA)

2.2.2. Titan as an Earth-like analogy

The surface of Titan was examined from orbit using radar and imaging at both visible and infrared wavelengths, which showed that Titan has many geologic processes reminiscent of those on Earth. These processes generate methane clouds and rain, build river channels, form lakes and seas containing liquid methane and ethane, form complex atmospheric hydrocarbons, and generate dunes of hydrocarbon particles. Cassini's studies revealed Titan to be remarkably like a pre-biotic Earth. On Titan, methane plays the role of water on Earth, and water ice is a key ingredient of the rocky soil. Titan's methane cycle is analogous to Earth's hydrologic cycle, but at temperatures about 200 K lower.

Titan's surface consists of broad regions of light and dark terrain. Some of the dark, equatorial regions generally consist of long, linear dunes (Radebaugh et al. 2008). Titan's lakes and seas are confined primarily to the polar regions. In the south polar region, one lake, Ontario Lacus, was seen by Cassini while the north polar region small lakes, and large seas about the size of the Great Lakes, abound (Stofan et al. 2007). A specular reflection observed by the visual and infrared mapping spectrometer (VIMS) definitively verified that the dark lake regions contain liquid (Stephan et al. 2010).

3. Other Icy Moons

Cassini's highlights from some of the other icy moons are described below. Cassini's findings revealed each moon as an individual world, complete with its own unique features and puzzles. For more details on Saturn's icy moons, see chapters in the book "Enceladus and the Icy Moons of Saturn" (Schenk et al. 2018).

3.1. Mimas thermal anomaly

Mimas is the innermost and smallest of the intermediate-sized satellites with a diameter of 394 km. During a close flyby in February 2010 the infrared spectrometer discovered that leading side of Mimas – the hemisphere that faces forward in the moon's orbit about Saturn – is about 15 degrees K colder than the other side (Howett et al. 2011). The cold side contains the crater Herschel, an impact structure that spans a third of the moon's diameter. This thermal anomaly is a result of a contrast in thermal inertia between the leading and trailing sides of Mimas. The leading face is altered by bombardment of highly energetic electrons. This bombardment increases the contact between regolith grains, decreases their porosity and increases thermal inertia (Schenk et al. 2011). Models of Saturn's E ring suggest that the side of Mimas that faces away from the direction of motion should be preferentially coated by particles from the E ring. Mimas's exceptionally high reflectivity (it is the second most reflective moon in the solar system) support this hypothesis. Water ice is the primary compound detected on its surface. Its heavily cratered appearance argues against current activity on the moon.

3.2. Iapetus light and dark sides

One hemisphere of Iapetus is as dark as charcoal while the other half is nearly as bright as snow. The reason for this light-dark dichotomy was not known prior to Cassini's arrival at Saturn. An Earth-orbiting infrared telescope discovered a very tenuous ring at the orbit of Phoebe (Verbiscer et al. 2009), probably dust thrown off the moon by tiny meteor impacts. This dust is swept up by Iapetus as it orbits Saturn. The darkest side

of the moon is centered exactly in the direction of motion of the satellite. A handful of small impact craters on the dark side punch through to bright material below, suggesting that the dark material is not very deep.

Cassini discovered a 20-km high ridge that circles most of the equator (Porco et al. 2005). The ridge breaks up into mountains (Figure 4) in some of the lowest albedo regions. The ridge must have been formed early in the history of Iapetus because it is heavily cratered and eroded. The surface of Iapetus is mainly water ice with small amounts of carbon dioxide, carbon, and complex organic molecules present.

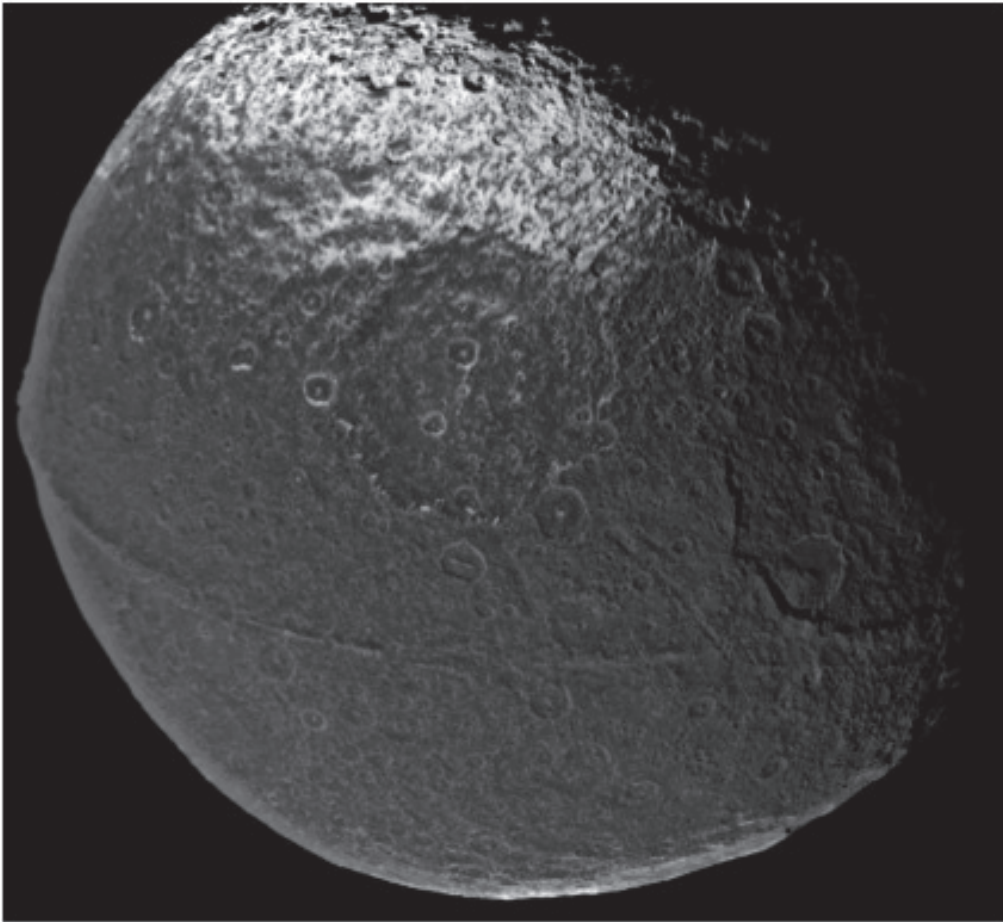


Figure 4. Cassini image of Iapetus taken during the December 2004 close flyby. The bright/dark terrain and equatorial ridge are visible. (Credit: NASA/JPL/Space Science Institute).

3.3. Phoebe, a captured world

Two weeks before Saturn orbit insertion, Cassini-Huygens flew close to Phoebe, the largest outer irregular moon of Saturn. Phoebe moves in an inclined, retrograde orbit that is 13 million kilometers from Saturn. It is covered with impact craters that were probably created by collisions with smaller outer moons. Some of the craters contain icy patches and layered structures; others have unusual conical shapes. Phoebe reflects

about 10% of the sunlight that falls on it, about the same as that reflected by the Earth's moon. In addition to water ice its surface is composed of carbon and carbon dioxide (Clark et al. 2005). The presence of carbon and the fact that its density is higher than that of the other medium-sized moons of Saturn suggest that Phoebe was formed near the edge of the Solar System and migrated inward to be captured by Saturn (Johnson & Lunine 2005). Phoebe may come from the Kuiper Belt, the reservoir of icy/rock bodies that dwell beyond the orbit of Neptune and that may provide clues to the architecture of the early Solar System and its subsequent evolution.

3.4. Discovery of seven small moons

Cassini discovered seven small moons in the inner Saturn system (Thomas et al. 2016). Pallene and Aegaeon are associated with diffuse, dusty rings, and Anthe and Methone are associated with ring arcs. A tiny moon, Daphnis, orbits in the Keeler gap and may help to keep it clear. An even smaller moon causes propeller-like structures in a ring of Saturn (S/2009 S). Another Cassini discovery is the moon Polydeuces, which moves in a gravitationally stable zone in Dione's orbit known as the Lagrangian point. It joins another Dione Lagrangian and two Tethys Lagrangians. Prior to Cassini, Saturn already had a unique family of small satellites, including the co-orbitals Janus and Epimetheus, which switch orbits every four years and appear to have been one body until their violent separation. Other previously known moons include the F ring shepherds, Prometheus and Pandora, as well as Atlas, orbiting just outside the A ring edge, and Pan, which clears the Encke gap (Figure 5).

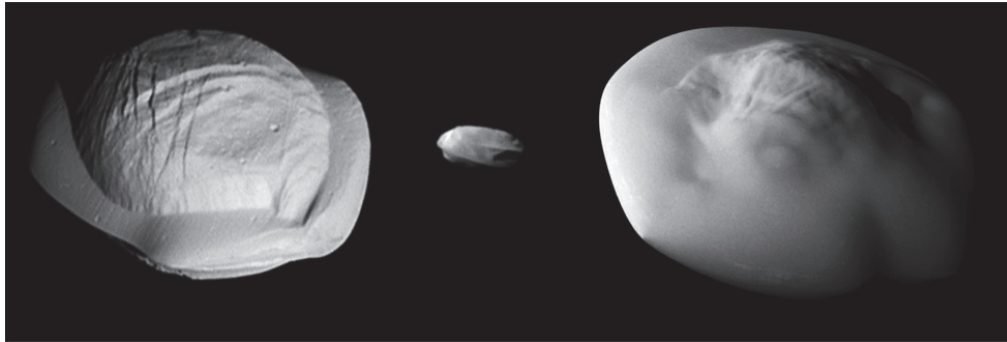


Figure 5. Cassini images of Pan (left), Daphnis (center) and Atlas (right) as observed in 2017 during the closest flybys ever of these moons.

4. Saturn's rings

Saturn's rings are both beautiful and complex, and the processes observed there provide a laboratory for how planets might form. Some of the highest resolution data on the rings were obtained at Saturn orbit insertion (SOI) in 2004. Tiny propellers and straw-like clumping in the strongest density wave peaks were first detected in the images from the SOI unlit ring scan. For more detailed summaries, see ring chapters in the books "Saturn from Cassini-Huygens" (Dougherty et al. 2009) and *Planetary Ring Systems: Properties, Structure, and Evolution* (Tiscareno & Murray 2018).

4.1. Active and dynamic rings

Cassini's 13 years in orbit made it possible to observe temporal changes in Saturn's dynamic ring system. The spacecraft discovered migrating propeller-shaped structures and unexpected ring particle clumping, imaged the possible birth of a new moon at the edge of the A ring, and observed one of the most active, chaotic rings in our solar system, Saturn's F ring.

Some places in Saturn's rings were changing on very short timescales of weeks or months. Dozens of objects, 0.1-1 km in size, orbiting in the A ring, changed their locations as they interacted with neighboring material. These unseen objects opened up tiny propeller-shaped gaps that were captured in the Cassini cameras and in stellar occultations of the rings (Tiscareno et al. 2010). Cassini observed channels opening and closing in the F ring, in response to close approaches by the tiny moon Prometheus (Murray et al. 2005). Clumps and dusty jets appeared and disappeared in the F ring core, excited by embedded moonlets and disturbed by objects with orbits eccentric enough to dive through the ring (Murray et al. 2008; Beurle et al. 2010). A new moon, Aegaeon, was discovered inside Saturn's G ring (Hedman et al. 2010). Several new ringlets appeared during Cassini's 13 years in orbit (Hedman et al. 2009). They were composed mostly of fine dust grains; one in the outer Cassini Division was barely visible when Cassini arrived but was among the dustiest features in the rings by the end of the mission.

4.2. Vertical ring structures seen at equinox

Many new discoveries were made during equinox in August 2009, the time when the sun was edge-on to the rings, so vertically extended objects cast long shadows on the rings. Once every half Saturn year the ring plane aligns with the center of the Sun, and for a brief time the northern and southern sides of the rings receive essentially no sunlight. During this unique time, Cassini observed long shadows up to 2.5 km high (Figure 6) created by objects larger than the 5-meter vertical thickness of the rings to determine the heights of structures within the rings. They included towering shadows from km-sized objects near the outer edge of the B ring, and the vertical extent of edge waves in the Keeler gap created by the tiny moon Daphnis (Tiscareno & Murray 2018). The rings also cooled to their lowest temperatures, heated for a few days only by Saturnshine (Spilker et al. 2013).

4.3. Ring Composition

The ring particles in Saturn's main A and B rings are nearly pure water ice but show a strong ultraviolet absorption that varies in strength from place to place. The reddish color of varying intensity in the rings is deeper where the ice signature is strongest. The rings probably darken with time as they are polluted by meteoroid bombardment. The less massive C ring and Cassini Division look more polluted (redder) than the more massive A and B rings (Cuzzi et al. 2010).

4.4. Ring microstructure on sub-km scales

Hundreds of stellar and radio occultations of the rings were obtained throughout the mission at a large variety of ring geometries, including some of the best-ever radio occultations during the Grand Finale as the radio signal was beamed through the rings while Cassini flew close to Saturn. Detailed horizontal and vertical structure in the

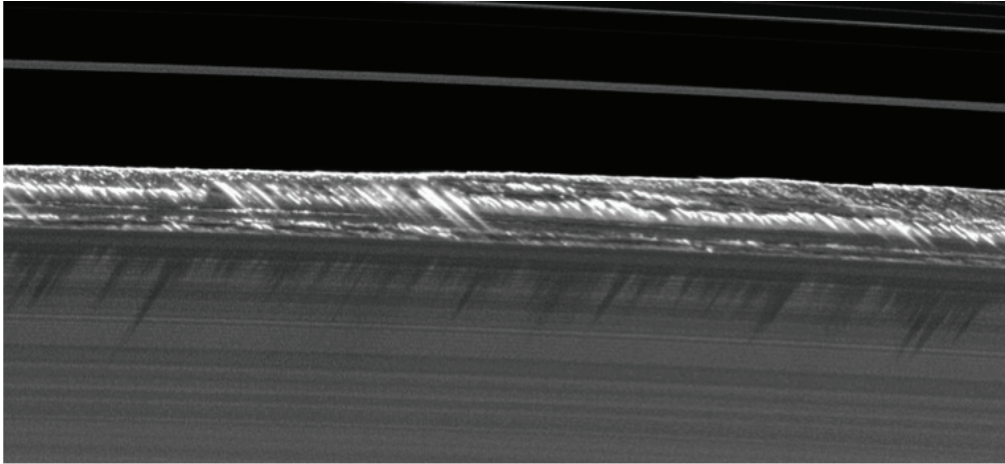


Figure 6. Vertical structures, among the tallest seen in Saturn's main rings, rise abruptly from the edge of Saturn's B ring to cast long shadows on the ring in this image taken by NASA's Cassini spacecraft two weeks before the planet's August 2009 equinox. (Credit: NASA/JPL/Space Science Institute).

rings was revealed at multiple wavelengths. They provided a detailed map of Saturn's rings, including three-dimensional measurements of tendril-like, ephemeral structures in the rings called self-gravity wakes (Colwell et al. 2006). These transient gravitational instabilities form but are torn apart by Saturn's tides. Similar behavior in a protoplanetary disk might play a role in formation of planets in our own solar system and beyond. A different kind of microstructure, which behaves like self-gravity but is due more to viscous forces in the rings than self-gravity, can also be seen throughout the densest parts of the rings (Colwell et al. 2007).

Modeling of the damping behavior of dozens of spiral density and bending waves constrained the mass of most of Saturn's main rings (Tiscareno et al. 2007). However, occultations were not able to directly probe the densest parts of the B ring so its mass remains uncertain. Cassini directly measured the total ring mass late in the mission and the analysis of those data is under way.

5. Saturn

Cassini's long-lived mission has provided an opportunity to observe a giant storm and seasonal change at Saturn. Cassini arrived just two years after northern winter solstice and the mission ended right after northern summer solstice providing almost two complete Saturn seasons of observations. The ring shadows, originally covering the northern hemisphere, moved through the equator at equinox and covered the southern hemisphere by the end of the mission. Cassini watched as the northern winter hemisphere changed from blue to golden as sunlight once again fell on Saturn's atmosphere. Aurora and lightning were also observed on Saturn. Curtains of aurora tower over 1,200 km above the limb. Lightning is generally associated with Saturn storms. For more detailed summaries, see Saturn chapters in the book "Saturn in the 21st Century" (Baines et al. 2018).

5.1. Saturn's giant northern storm

Late in 2010, a giant storm quickly erupted in Saturn's relatively bland atmosphere. This type of storm typically occurs only once every 30 years, but this one arrived 10 years early, providing a unique observing opportunity for Cassini (Baines et al. 2018). Within months, this storm completely encircled the planet with a swirling band of clouds and vortices (Sayanagi et al. 2013). The largest temperature increases ever recorded for any planet were measured in the stratosphere and molecules never before seen in Saturn's upper atmosphere were detected. The storm began to fade away shortly after the vortex in its "head" collided with one in its "tail", about nine months after it began (Fletcher et al. 2011).

5.2. Saturn's north polar hexagon

Saturn's alternating eastward and westward jet streams define the cloud bands that circle the planet on lines of constant latitude to within about one degree of each pole. One of the jet streams, near 75 degrees north latitude, forms a hexagonal pattern that is two Earth diameters across (Baines et al. 2009). Voyager first discovered the hexagon, and it is still there after 35 years. Small clouds move eastward around the corners of the pattern. This hexagonal-shaped jet stream (Figure 7) is remarkable for its stability and longevity. Its source remains a mystery.

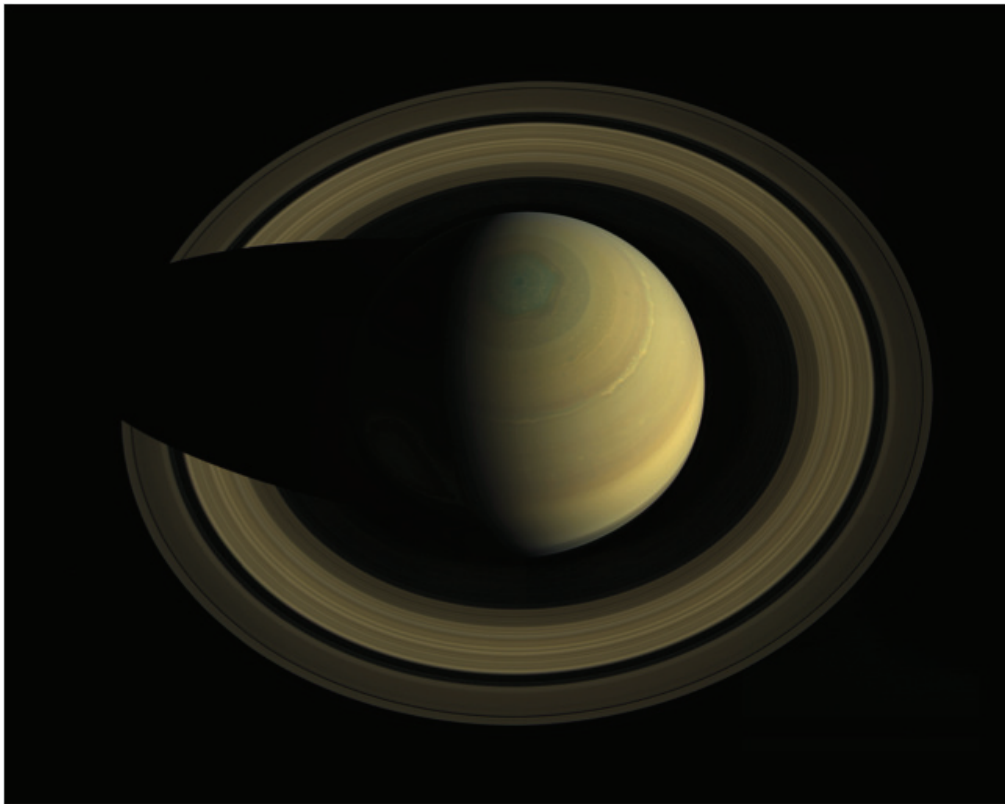


Figure 7. The greenish hexagon, about two Earth diameters across, is clearly seen at Saturn's north pole. (Credit: NASA/JPL/Space Science Institute).

5.3. Discovery of hurricanes at Saturn's poles

Cassini discovered hurricane-like storms at both of Saturn's pole. The hurricanes are about 50 times larger than a typical Earth hurricane and are centered exactly at the poles (Fletcher et al. 2008; Sayanagi et al. 2017). In the south, Cassini discovered the clear eye of a hurricane-like vortex, with eyewall clouds towering 70 kilometers above the clouds in the center. There is a warm vortex at Saturn's north pole as well. Each vortex shows well-developed eye walls (Dyudina et al. 2008).

6. Magnetosphere

Detailed Cassini measurements have completely changed our understanding of Saturn's magnetosphere. The magnetosphere is a giant cavity in the solar wind that is created as the flow of the solar wind interacts with Saturn's magnetic field. Cassini mapped the magnetosphere and corresponding magnetic field at a variety of geometries and local times. Material from the Enceladus plume is a major source of water products that feed Saturn's magnetosphere. Cassini's fields and particles instruments measured currents, plasma and neutrals in the magnetosphere.

6.1. Radio waves not linked to Saturn's internal rotation period

Saturn emits radio waves known as Saturn Kilometric Radiation (SKR) that were first observed by Voyager in the early 1980's and were interpreted as an indicator of Saturn's internal rotation period. Cassini results showed that the SKR signals were not coming from the interior of Saturn as originally assumed. The SKR period changed from year to year, an impossibility if the SKR is tied to the interior. When Cassini first arrived at Saturn and measured the SKR period, data from the radio and plasma wave instrument also showed that the radio waves' frequencies were different in the northern and southern hemispheres (Gurnett et al. 2009). In addition, planetary period oscillations observed in magnetic field data reveal a similar story: the period of these oscillations (although close to the expected planetary period of about 10.7 hours) changed over time, particularly with season, and were different in the northern and southern hemispheres (Provan et al. 2009). Clearly the observations to date of SKR and its associated magnetic field are not coming from the interior but seem to be an atmospheric signal.

Finally, the SKR period is closely related to periodic signals in the magnetosphere. Those periods depend on which physical quantity is being measured, including charged particles, neutral atoms, and magnetic field – and they don't always agree. The origin of the multiple periodicities is not well understood, and hence Saturn's internal rotation rate, and the length of a Saturn day, are still unknown. Data from Cassini's Grand Finale are still being analyzed but to date no reliable indicator of the internal rotation rate has been detected.

7. Cassini's Final Year: The Grand Finale

After 13 years in orbit, the Cassini-Huygens Mission to Saturn ended in a science-rich blaze of glory. Cassini sent back its final bits of unique science data on September 15, 2017, as it plunged into Saturn's atmosphere, vaporizing to satisfy planetary protection requirements. Cassini's final phase covered roughly ten months and ended after the first-time exploration of the region between the planet and its rings.

In late 2016 Cassini transitioned to a series of 20 Ring Grazing orbits (Figure 8, red orbits) with periapses just outside Saturn's F ring, providing close flybys of tiny ring moons, including Pan, Daphnis and Atlas, and high-resolution views of Saturn's A and F rings. A final Titan flyby in late April 2017 propelled Cassini's periapsis across Saturn's main rings to initiate the Grand Finale orbits. Comprised of 22 orbits, Cassini repeatedly dove between Saturn's innermost rings and upper atmosphere to answer fundamental questions unaddressed earlier in the mission. The last orbit turned the spacecraft into the first Saturn atmospheric entry probe.

The Grand Finale orbits (Figure 8, blue orbits) provided the highest resolution observations of the C and D rings and Saturn, and in-situ sampling of the ring particle composition, Saturn's atmosphere, plasma, and innermost radiation belts. The gravitational field was measured to unprecedented accuracy, providing information on the interior structure of the planet, winds in the deeper atmosphere, and mass of the rings. The magnetic field provided insight into the physical nature of the magnetic dynamo and structure of the internal magnetic field. The ion and neutral mass spectrometer sampled the upper atmosphere for molecules that escape the atmosphere as well as molecules originating from the rings. The cosmic dust analyzer directly sampled the composition from different parts of the main rings for the first time. Fields and particles instruments directly measured the plasma environment between the rings and planet.

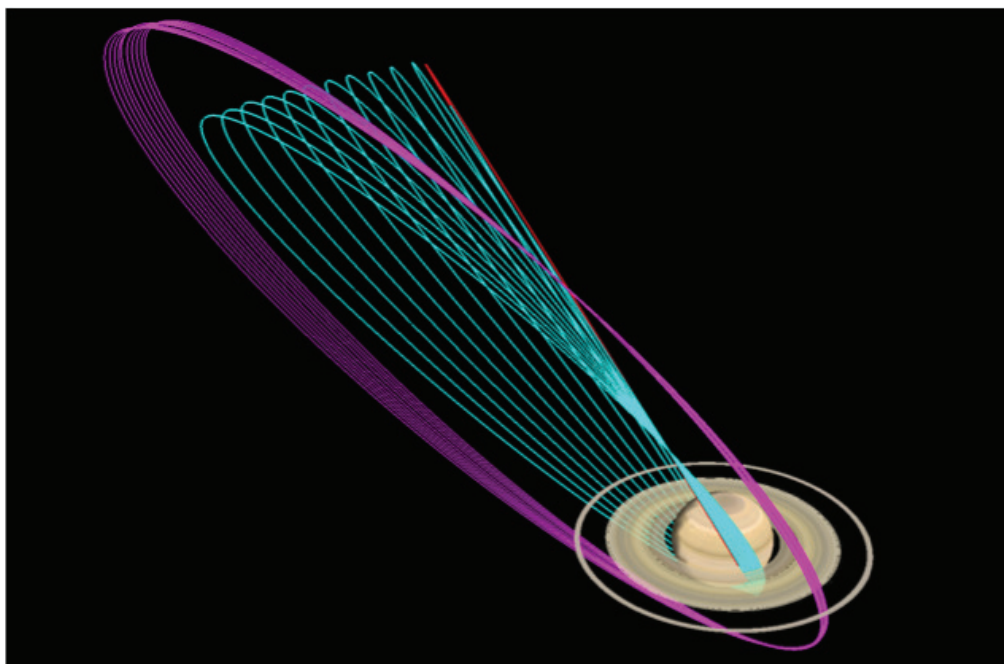


Figure 8. Cassini's final year included 20 Ring-Grazing orbits (pink) and 22 Grand Finale orbits (blue), each about 7 days long. The mission ended on 15 September 2017 as Cassini plunged into the atmosphere of Saturn. (Credit: NASA/JPL).

Cassini's final year was like a brand-new mission as she explored a region of the Saturn system unexplored by any previous outer planet spacecraft. Cassini's final Earth-bound transmission occurred on September 15, 2017, as she plunged into the planet, sending her last bits about the directly sampled atmosphere to Earth, then vapor-

izing in Saturn's atmosphere. This protective measure ensured that any hardy, Earthly microbes that might have survived onboard Cassini did not inadvertently contaminate either Enceladus or Titan.

8. Conclusion

Building upon past achievements and observations, Cassini has set the stage for future missions to explore this amazing system, leaving an incredibly rich legacy of discoveries that have changed our views of the Saturn system, of how solar systems form, and the potential for life elsewhere in our universe.

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Dr. Linda Spilker presenting a bag of Cassini Grand Finale badges to Prof. Ip to celebrate his 70th birthday and 35 more years!