Modern Astronomy: Voyage to the Planets

Lecture 7

Saturn
Lord of the Rings

University of Sydney
Centre for Continuing Education
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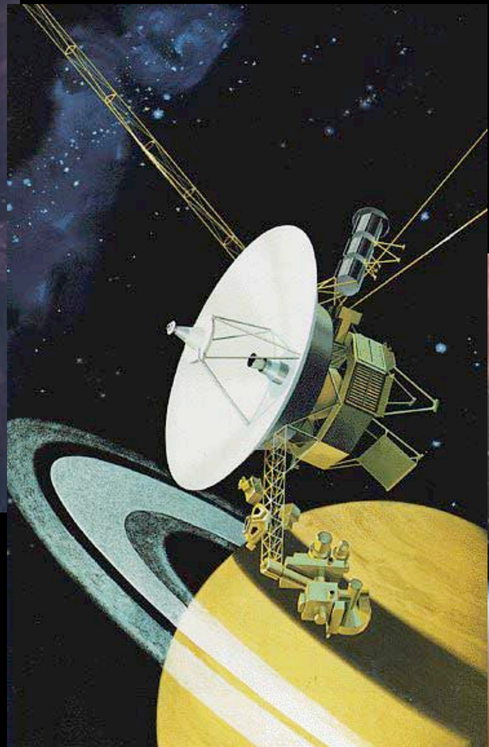
Three spacecraft have flown past Saturn, and one – *Cassini–Huygens* – has orbited the planet since July 2004.

Pioneer 11	1979	Flyby
Voyager 1	1980	Flyby
Voyager 2	1981	Flyby
Cassini–Huygens	2004	Orbiter and probe to Titan



Cassini has been touring the Saturn system since 2004, passing as close as possible to as many moons as possible. It uses close flybys of Titan to make gravity assists for course changes. Its official 4 year mission ended in June 2008; a two-year extension called the *Cassini Equinox Mission* will end in 2010.

Saturn

Basic facts

	Saturn	Saturn/Earth
Mass	568×10^{24} kg	95.159
Radius	60,268 km	9.449
Mean density	0.687 g/cm^3	0.125
Gravity (eq., 1 bar)	10.44 m/s^2	1.065
Semi-major axis	1433.53×10^6 km	9.582
Period	10,759.22 d	29.457
Orbital inclination	2.485°	-
Orbital eccentricity	0.0565	2.928
Axial tilt	26.73°	1.140
Rotation period	10.656 h	0.445
Length of day	10.656 h	0.444

Saturn is the second most massive planet in the solar system, and also the second largest in size (85% of Jupiter's radius). Like Jupiter, it is a gas giant, rotating every 10–11 hours (depending on latitude). Saturn has the lowest mean density of any planet: 0.7 g cm^{-3}, which is less dense than water.

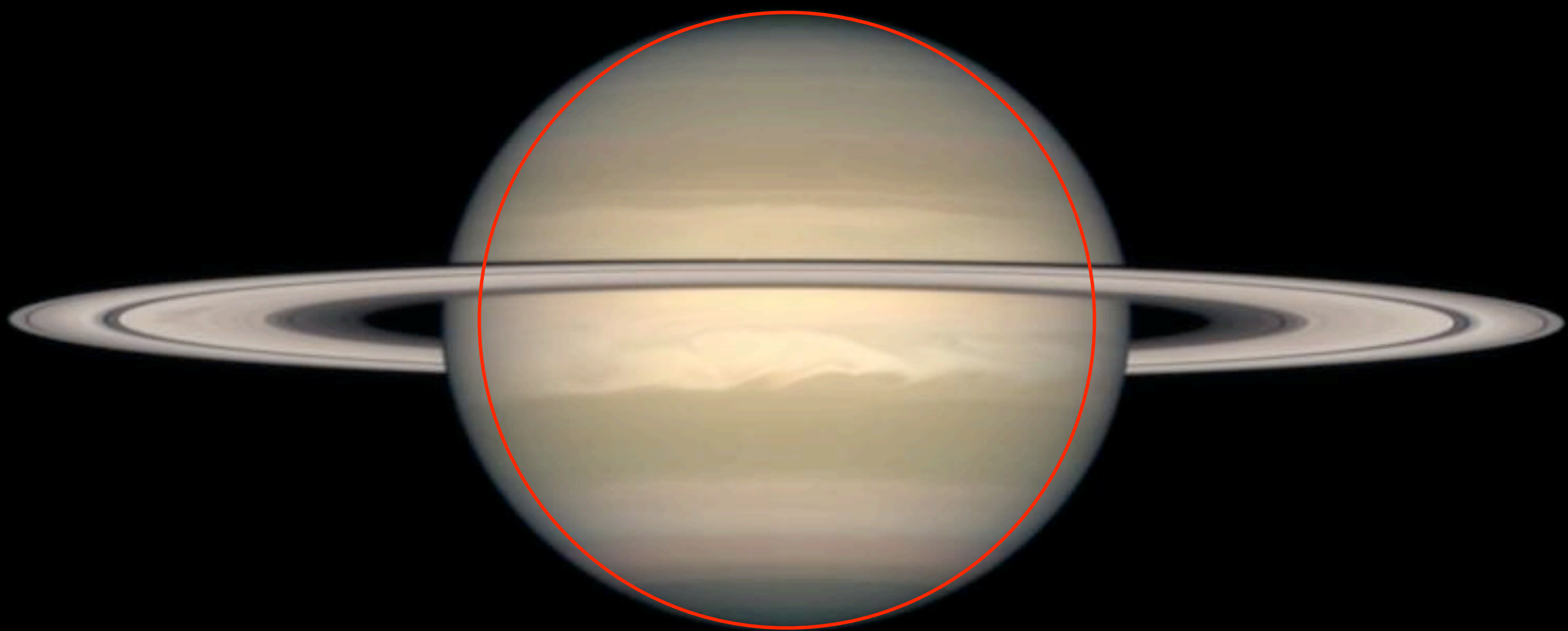
Cassini view of Saturn and its rings. The subtle northward gradation from gold to azure is a striking visual effect that scientists don't fully understand.

Strangely, *Cassini's* measurement of the length of Saturn's rotation is 6 minutes, or 1%, longer than that measured by Voyager!

This now appears to be due to the moon Enceladus: we'll discuss it a bit later.

Hubble animation of Saturn's rotation in 2003.

Saturn’s low density and rapid rotation make Saturn the most oblate planet: its equatorial and polar diameters vary by almost 10%.

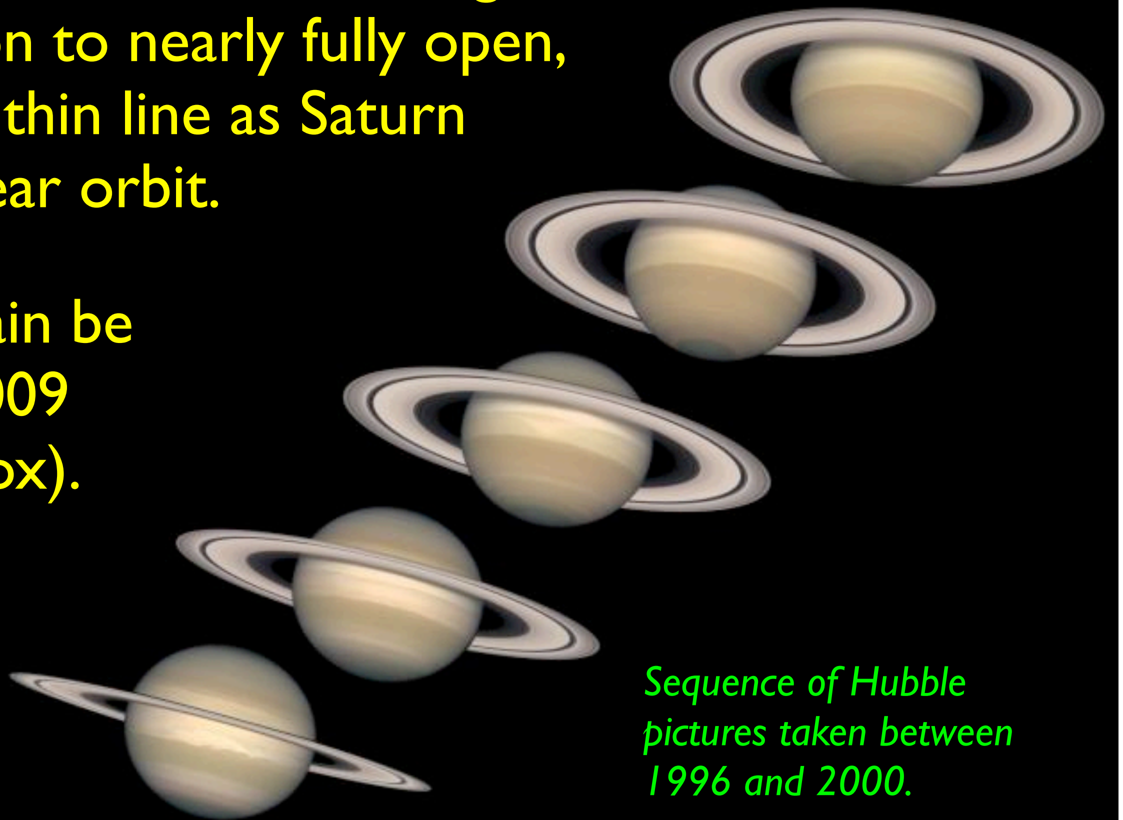


Hubble picture of Saturn taken in 1996

Saturn's equator is tilted relative to its orbit by 27°, very similar to the 23° tilt of the Earth. As Saturn moves along its orbit, first one hemisphere, then the other is tilted towards the Sun.

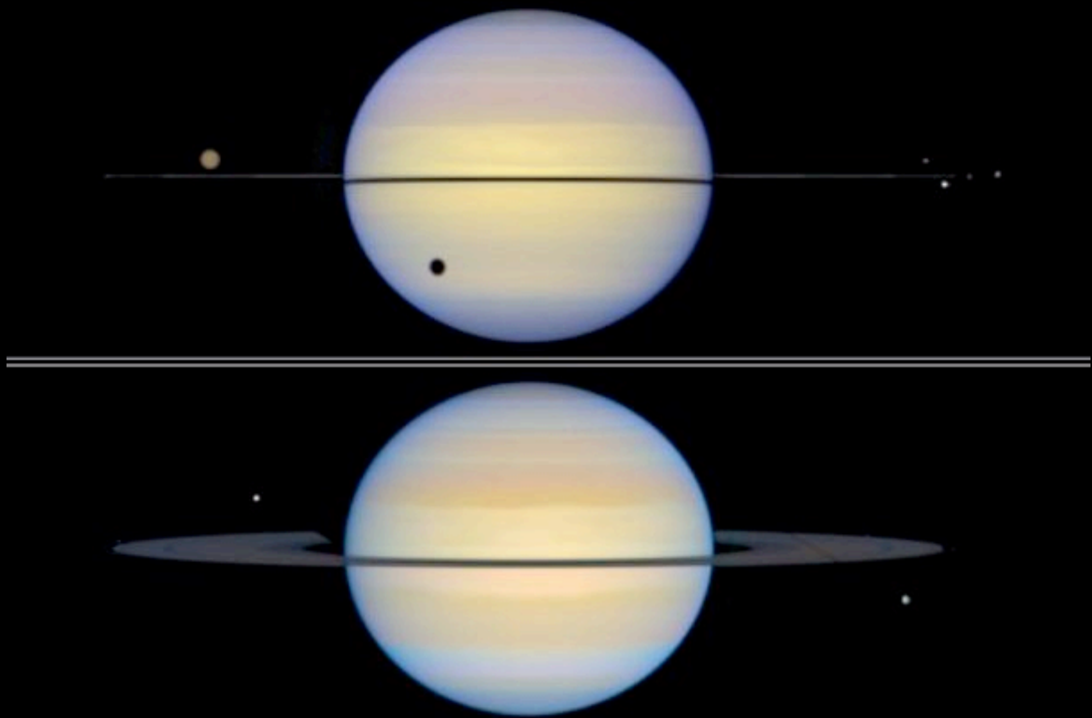
From the Earth, we can see Saturn's rings open up from edge-on to nearly fully open, then close again to a thin line as Saturn moves along its 29 year orbit.

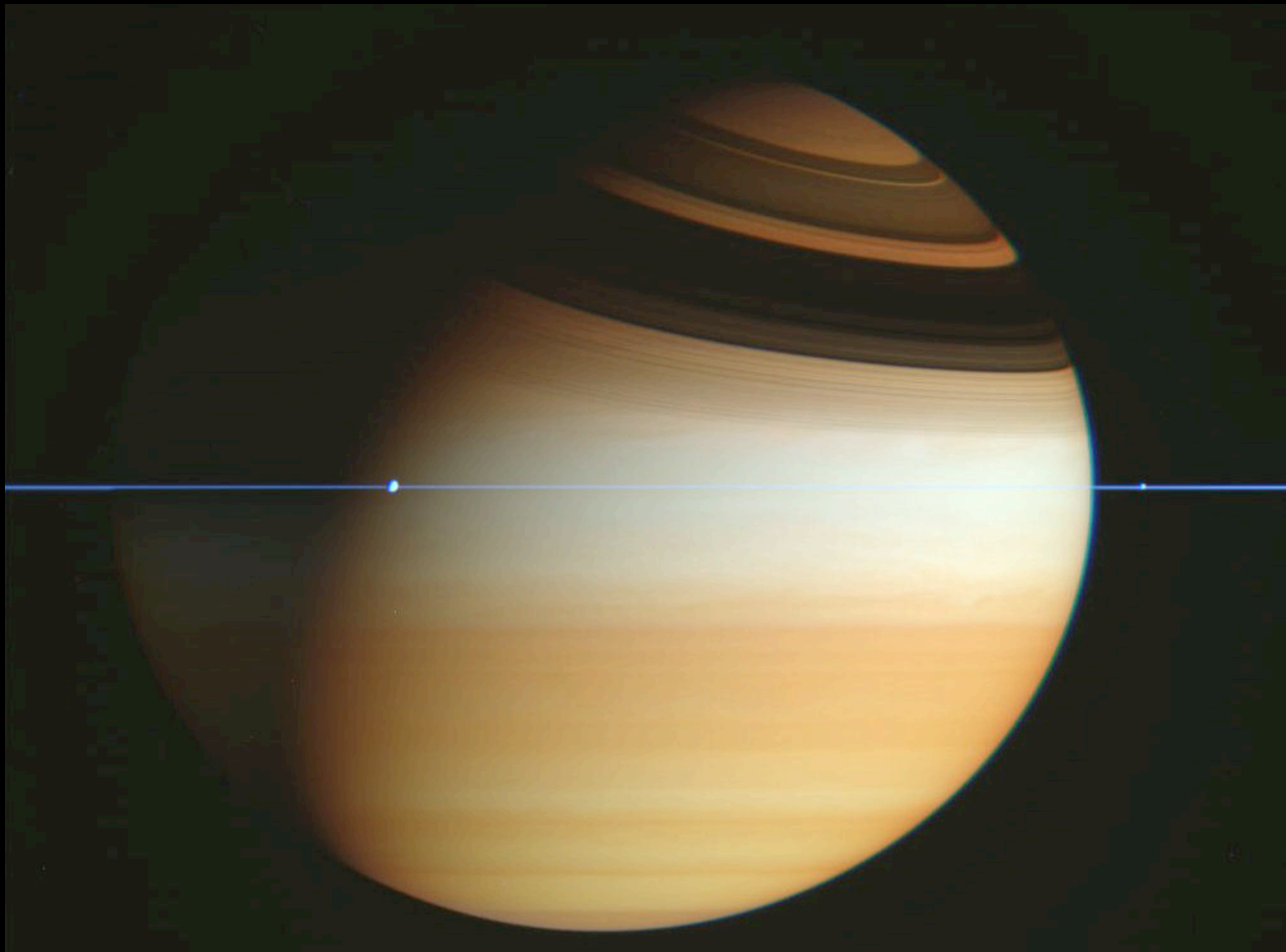
Saturn's rings will again be edge-on in August 2009 (the Saturnian equinox).



Sequence of Hubble pictures taken between 1996 and 2000.

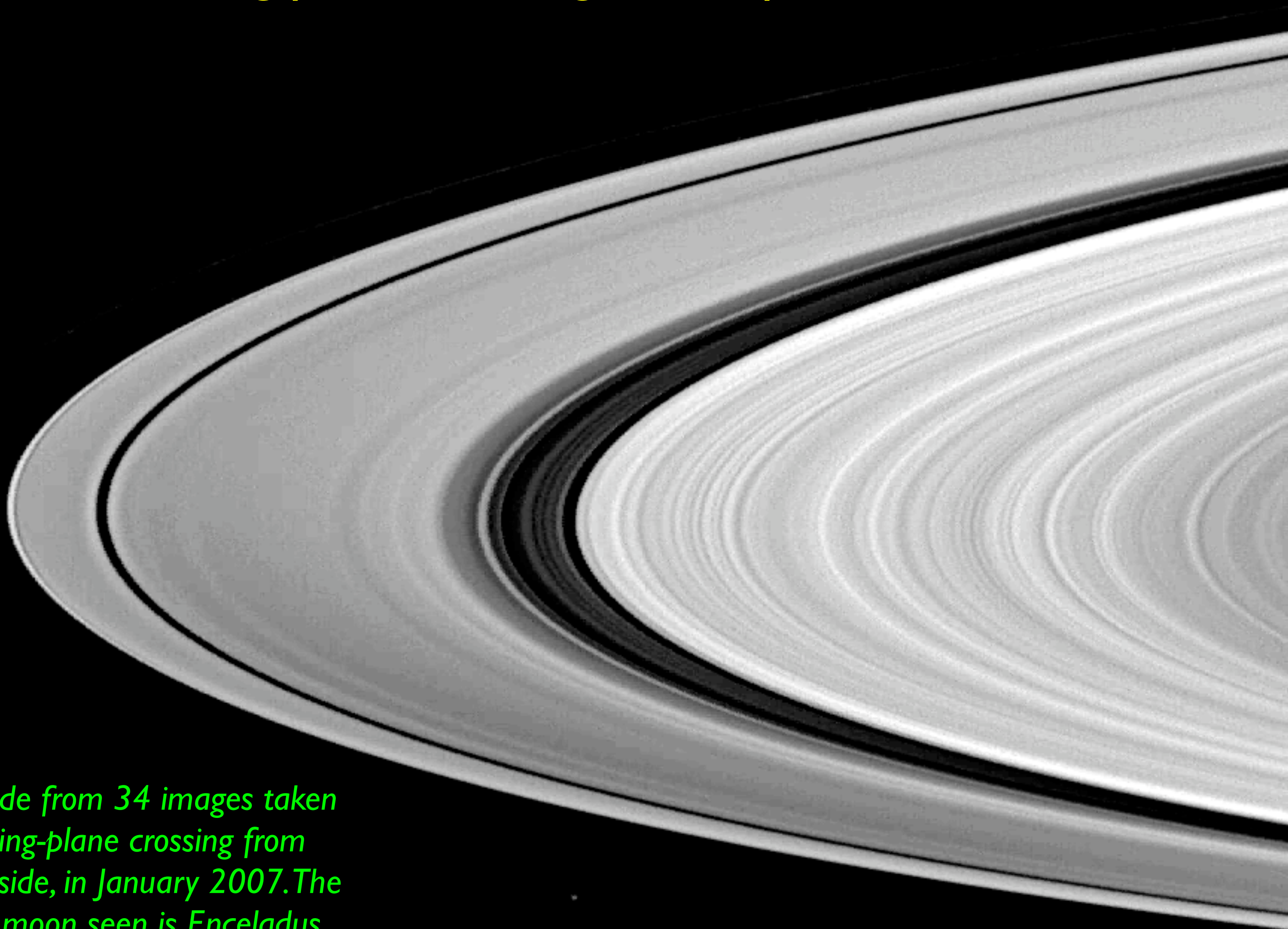
In 1995, Hubble took these pictures of the ring plane crossing, when Saturn's rings almost disappear to observers at Earth.





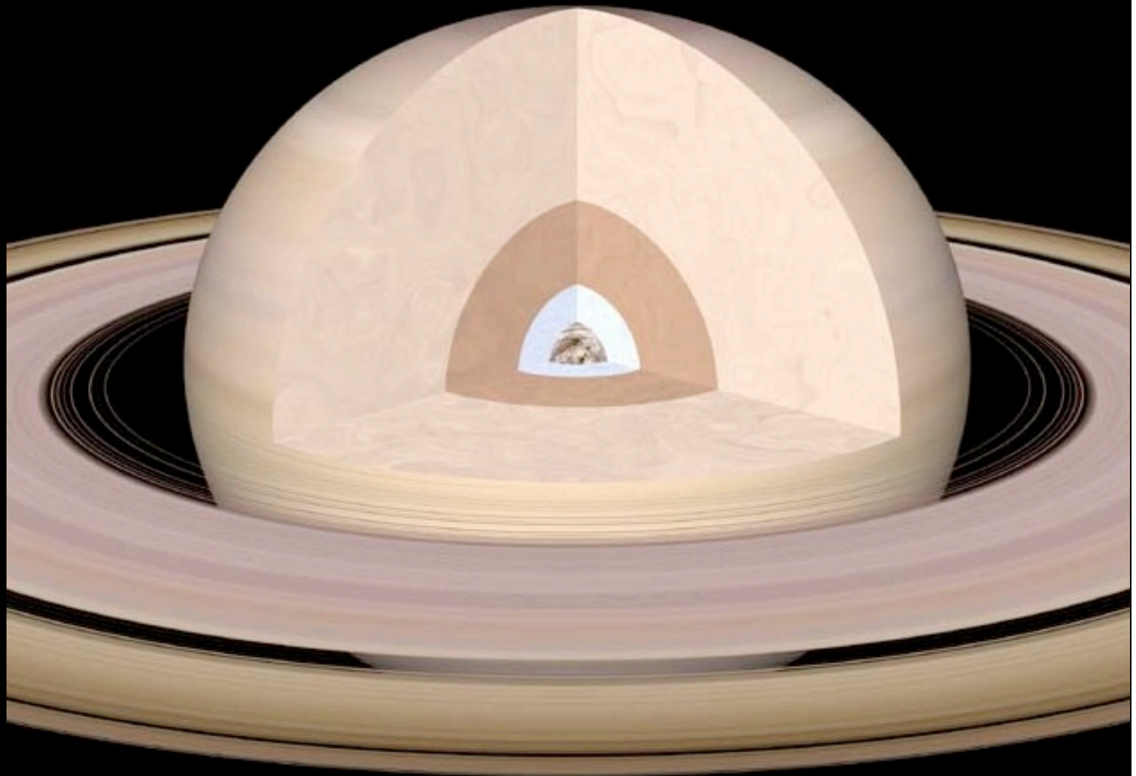
Cassini's ring plane crossing

Cassini sees ring plane crossings twice per orbit.

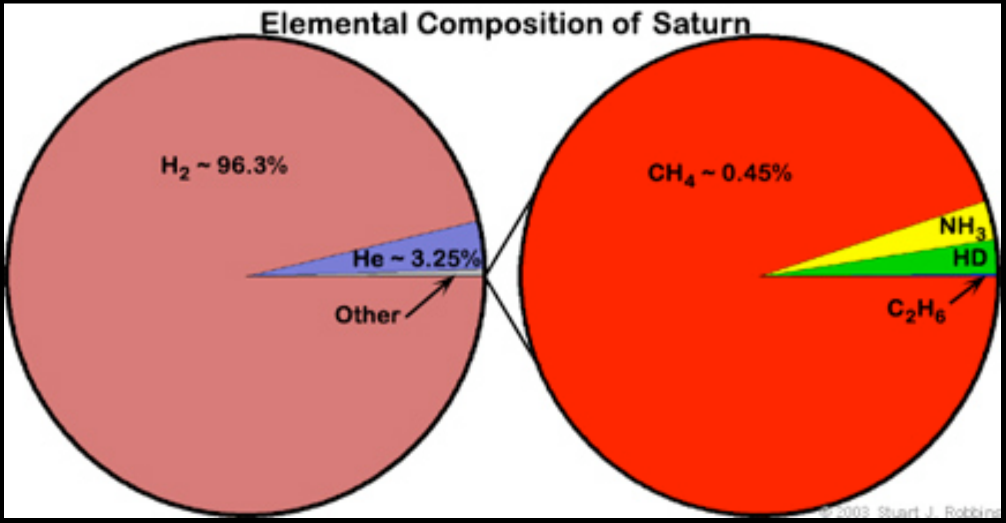


Movie made from 34 images taken during a ring-plane crossing from the sunlit side, in January 2007. The first large moon seen is Enceladus, showing its inclined orbit.

Saturn’s interior is similar to that of Jupiter, with a central rock core, surrounded by a layer of liquid metallic hydrogen, outside which is a layer of molecular hydrogen. Because Saturn is less massive than Jupiter, its interior pressure is lower, so the layer of liquid hydrogen is buried deeper inside the planet.

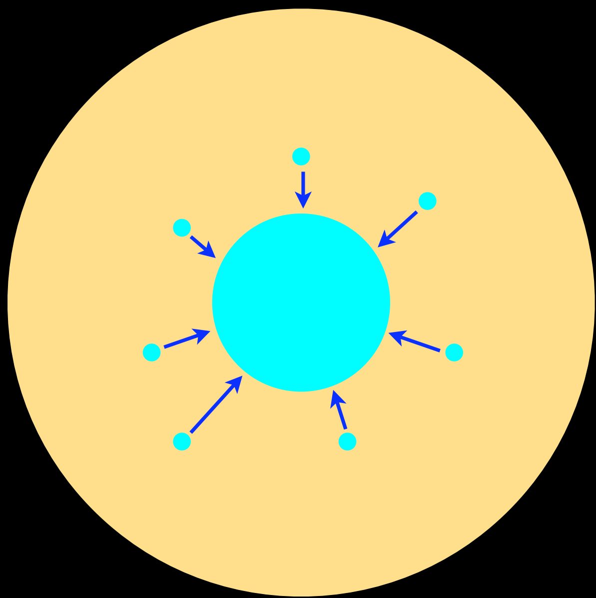


Saturn's atmosphere is similar to Jupiter's, consisting almost entirely of hydrogen and helium, with trace amounts of other gases. However, Saturn's atmosphere is deficient in helium compared to Jupiter's, which contains 10% helium.

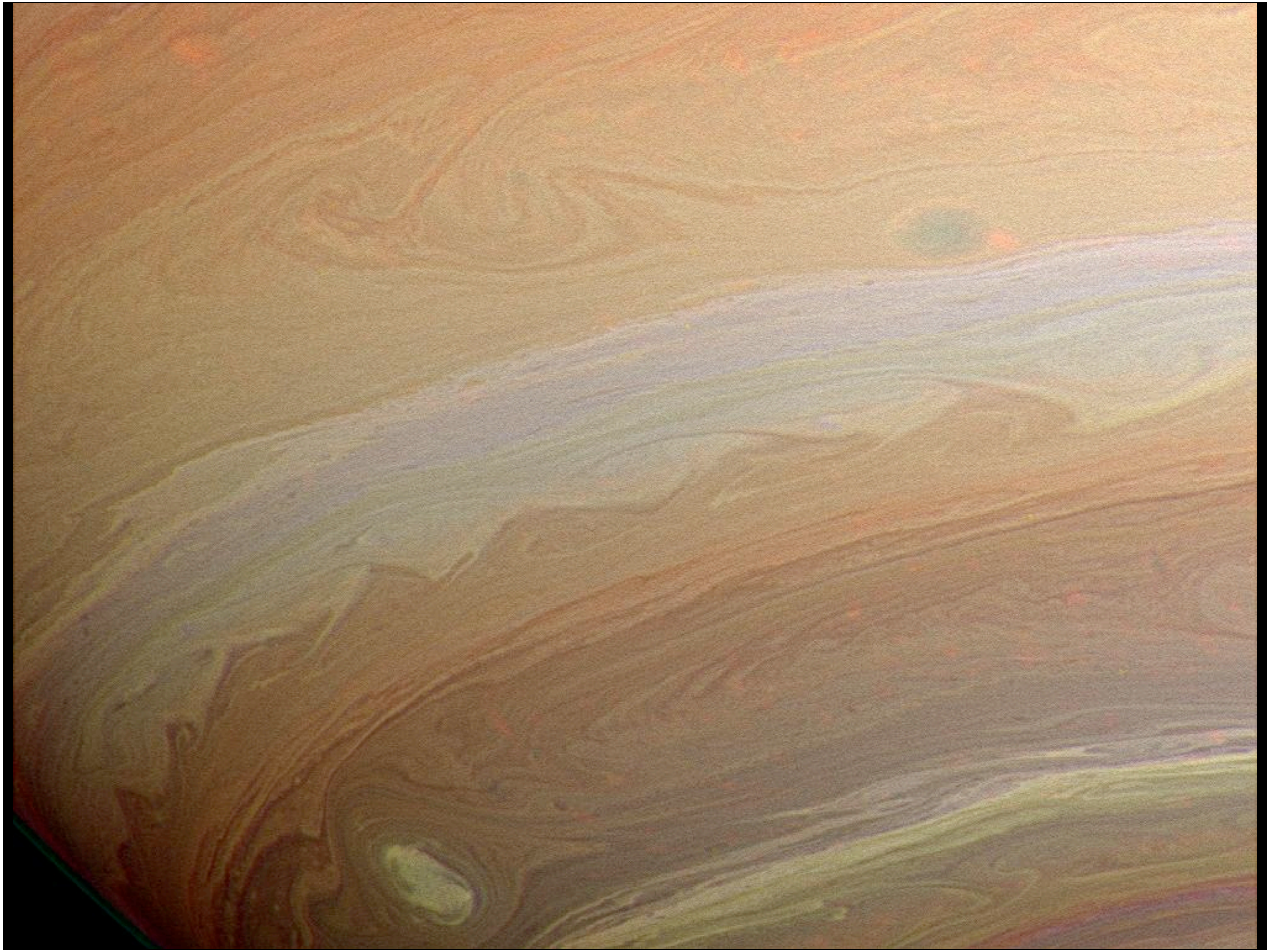


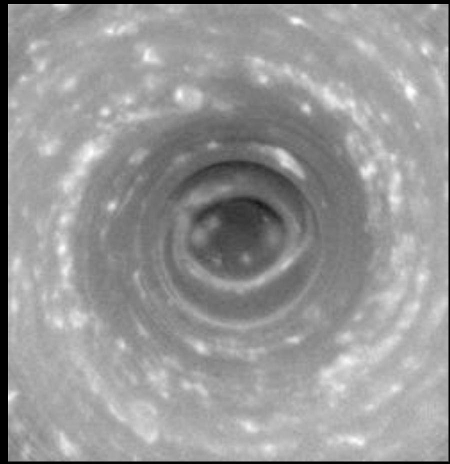
Like Jupiter, Saturn radiates more energy into space than it receives from the Sun: in fact, Saturn radiates more heat than Jupiter. Jupiter's remnant heat is leftover energy from the time of formation. But, since Saturn is less massive than Jupiter, it should have less leftover energy.

Instead, it is thought that Saturn’s atmosphere is separating out. Saturn’s atmosphere is colder than Jupiter’s, so helium forms droplets, which condense into *helium rain*. These sink towards the core, heating the atmosphere and depleting it of helium.



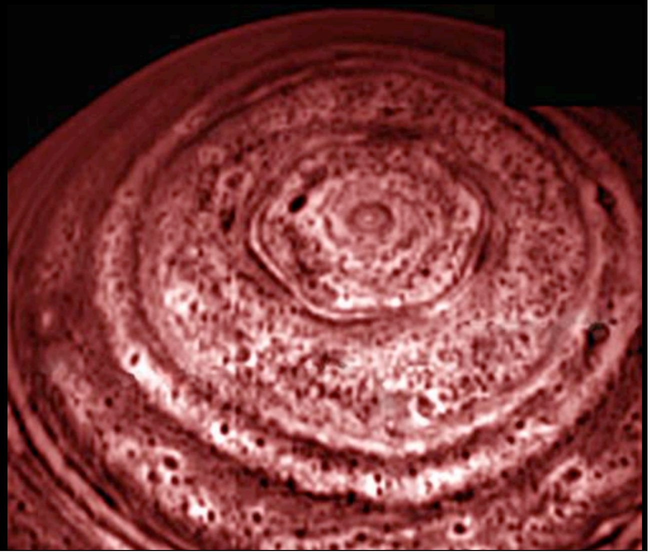
Saturn's atmosphere exhibits a banded pattern similar to Jupiter's, but Saturn's bands are much fainter.

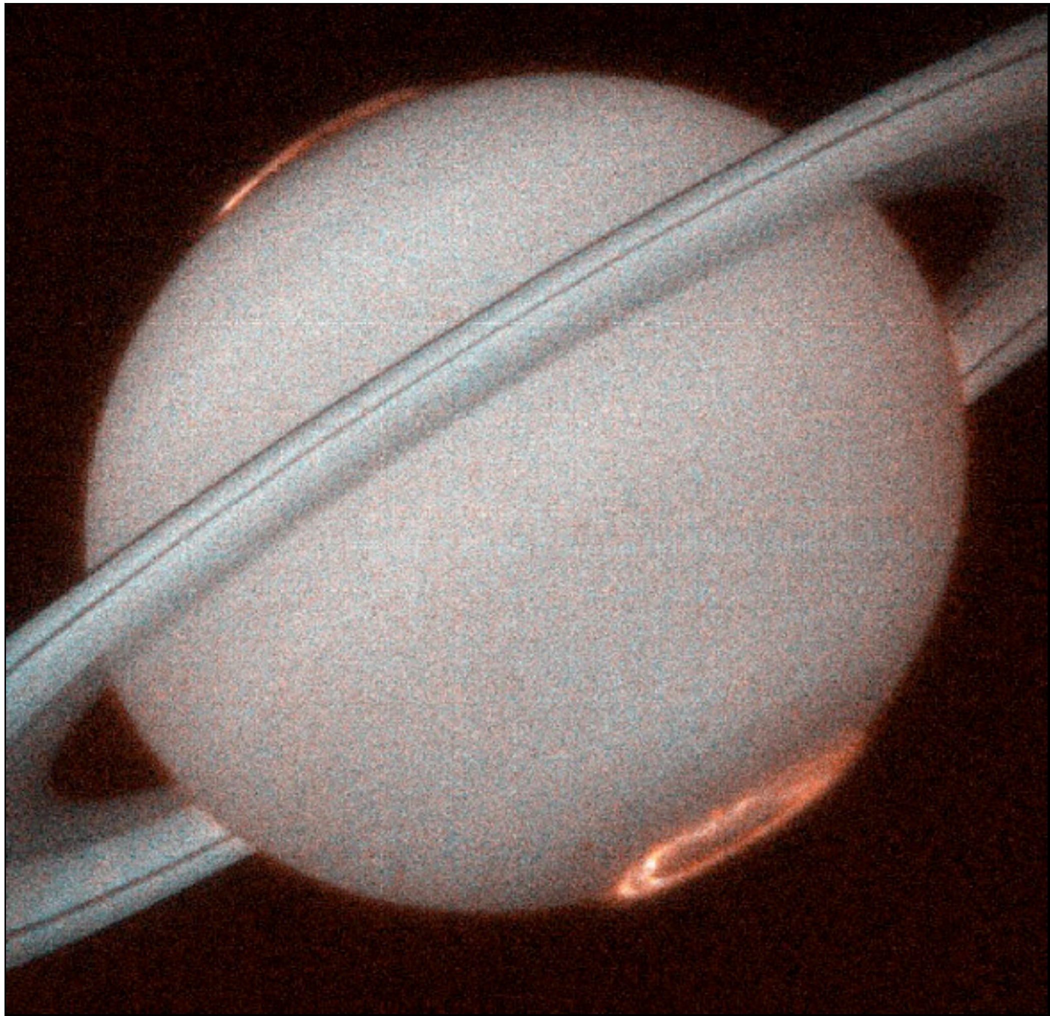




Polar vortex and hexagon

Like Earth and Venus, Saturn has a polar vortex: but around it is a bizarre hexagon 25,000 km across. It was originally spotted by Voyager, so the feature is long-lived. The feature extends deep into the atmosphere, about 75 km below the cloud tops.



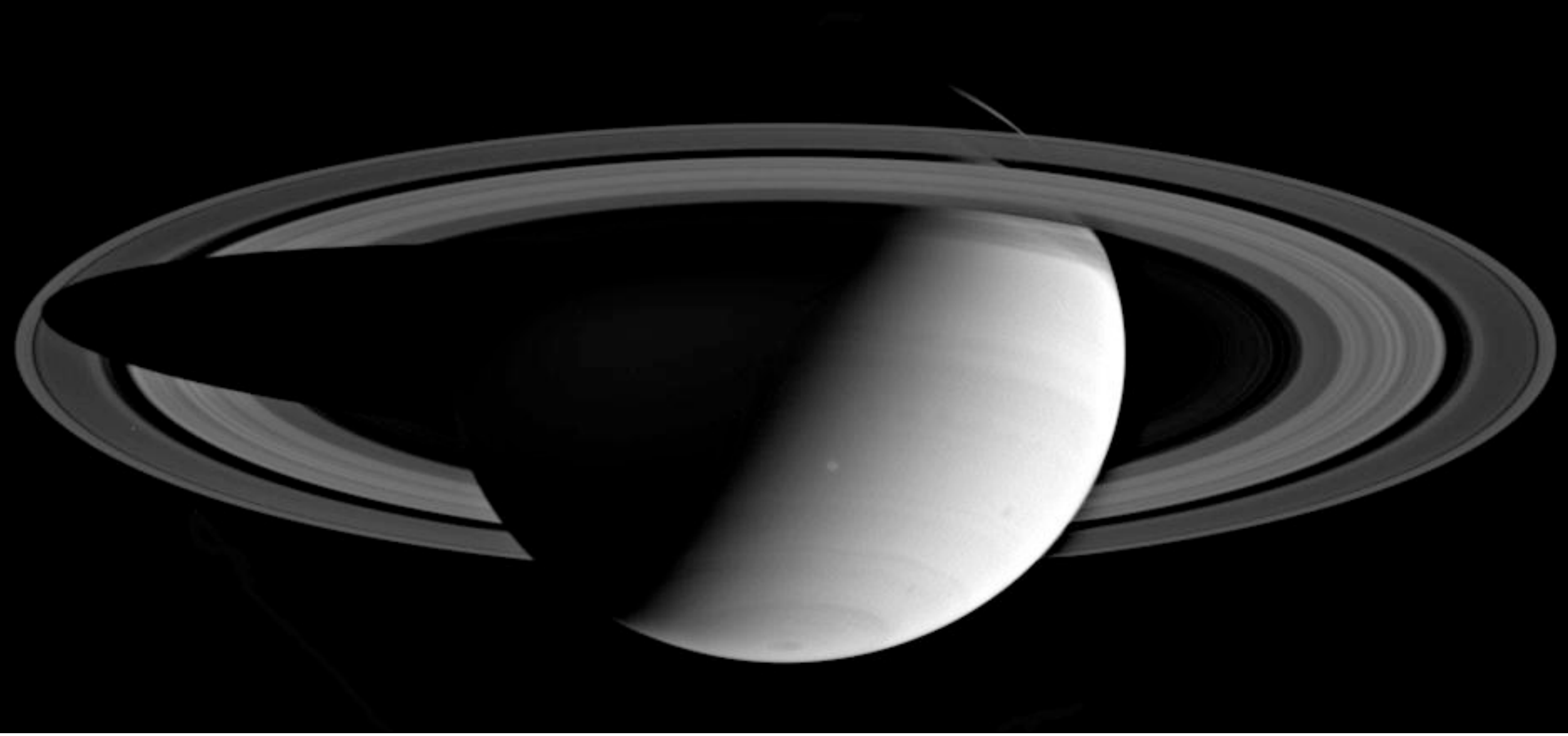


Hubble imaged powerful auroras at both poles.

Like Jupiter, Saturn has a magnetic field, though Saturn's field is less than half the strength of Jupiter's. Unlike Jupiter's (and Earth's), Saturn's magnetic field is aligned with its axis of rotation.

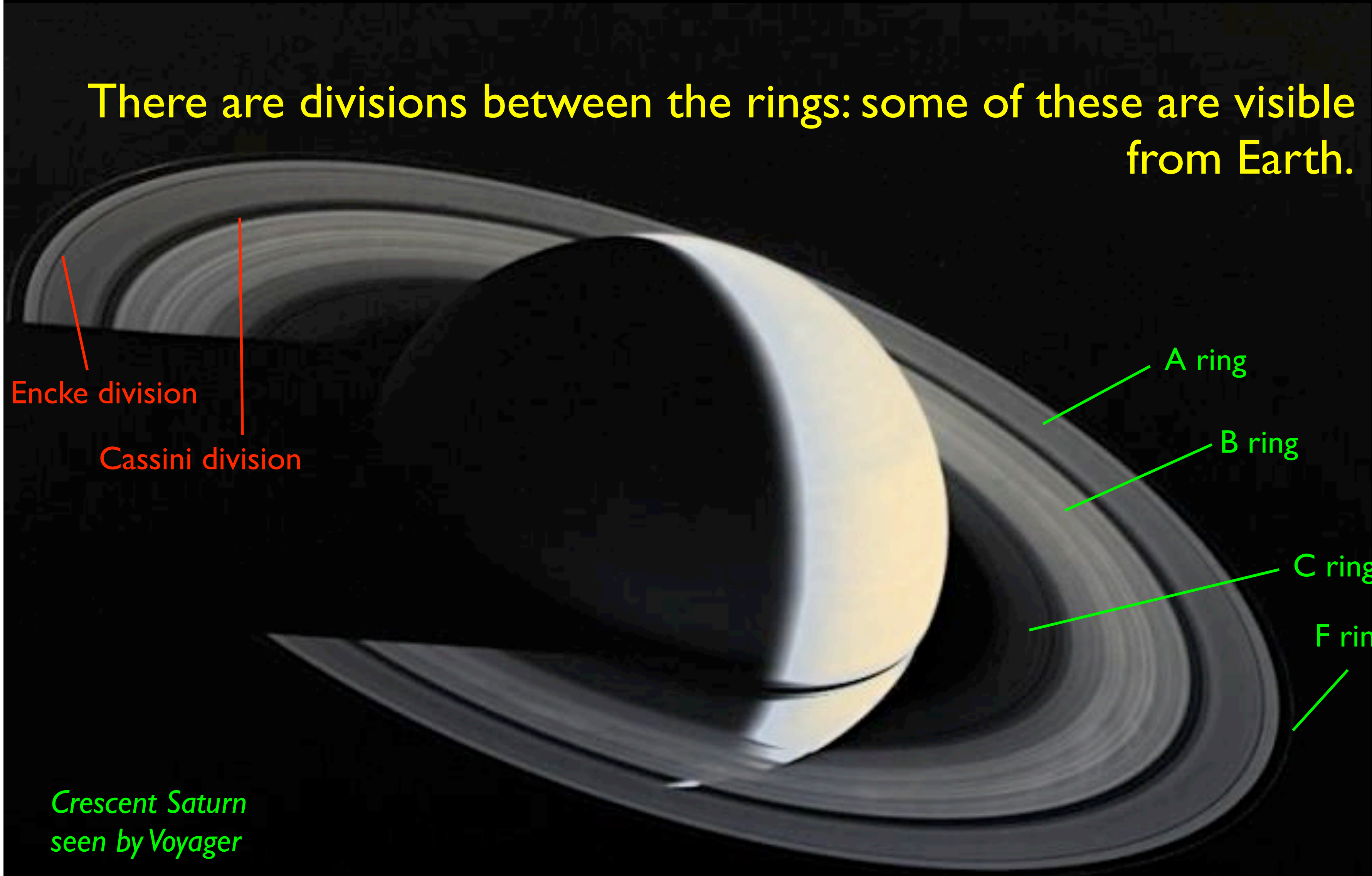
The most obvious feature of Saturn are the immense rings. The ring system is remarkably complex, and is still poorly understood.

It was Huygens who, around 1655, recognized that Saturn was "*girdled by a thin, flat ring, nowhere touching it.*"



The rings are less than 1 km thick and may be between 200m and 10m thick.

There are divisions between the rings: some of these are visible from Earth.

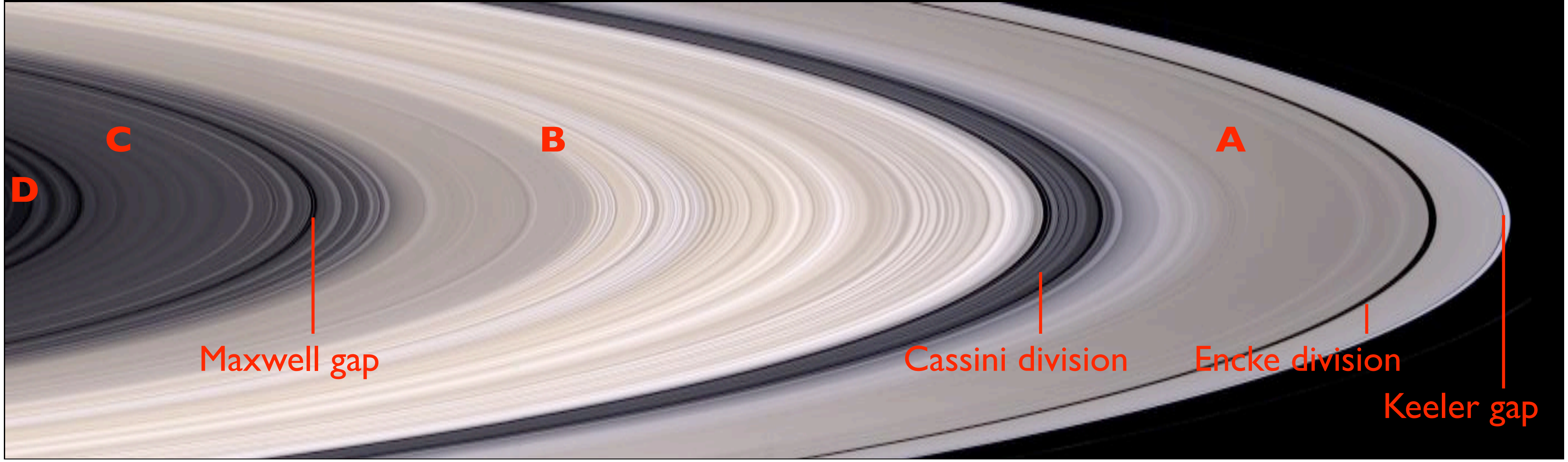


Crescent Saturn seen by Voyager

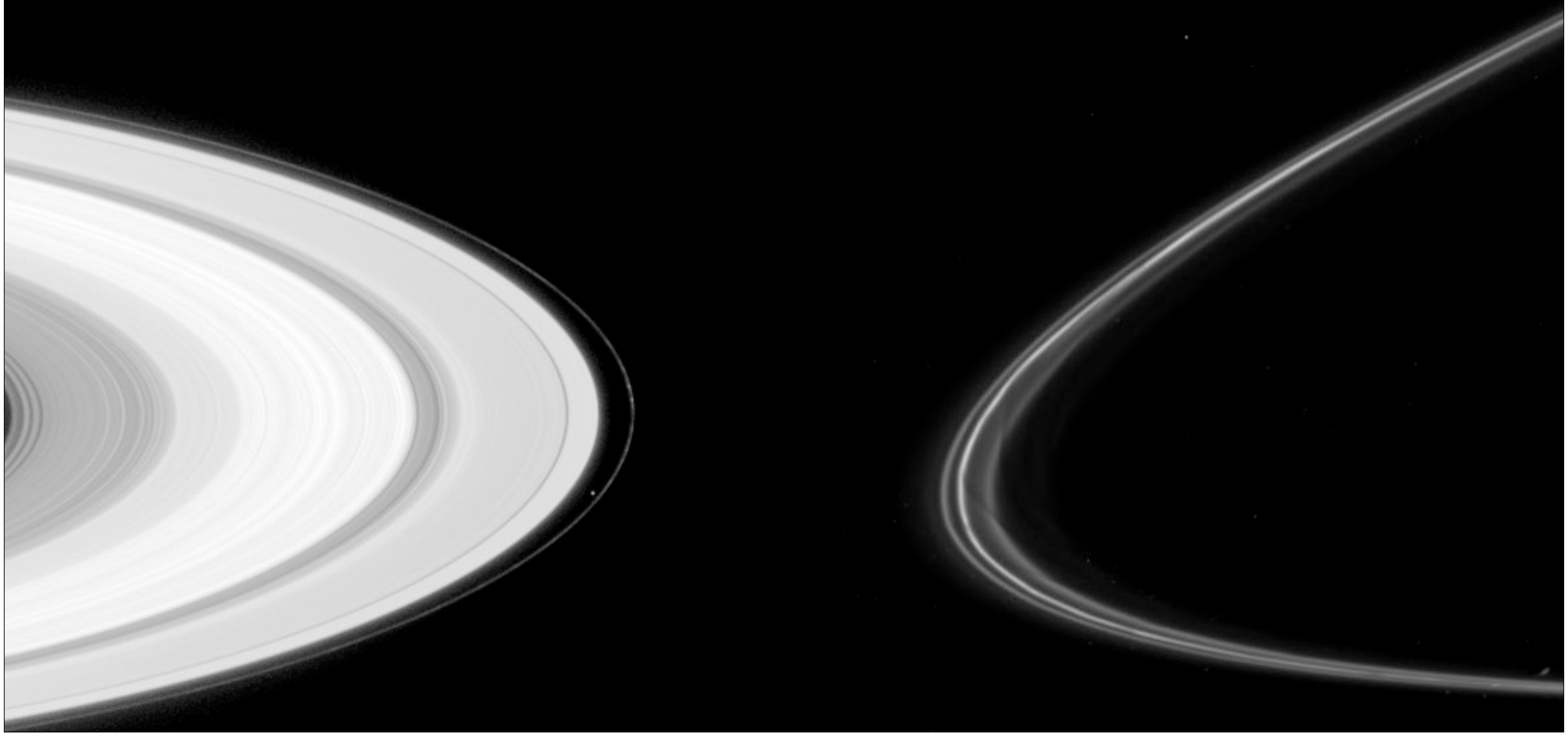
From closest to furthest from Saturn, there are seven sections to the ring system:

Name	Distance (10^3 km)	Width (10^3 km)	Thickness (km)	Albedo
D	67	7.5		
C	74.5	17.5		0.25
Maxwell gap	*87.5*	*0.27*		
B	92	25.5	0.1–1	0.65
Cassini division	*117.5*	*4.7*		*0.30*
A	122.2	14.6	0.1–1	0.60
Encke division	*133.6*	*0.325*		
Keeler gap	*136.5*	*0.035*		
F	140.2	0.03–0.5		
G	165.8	8	100–1000	
E	180	300	1000	

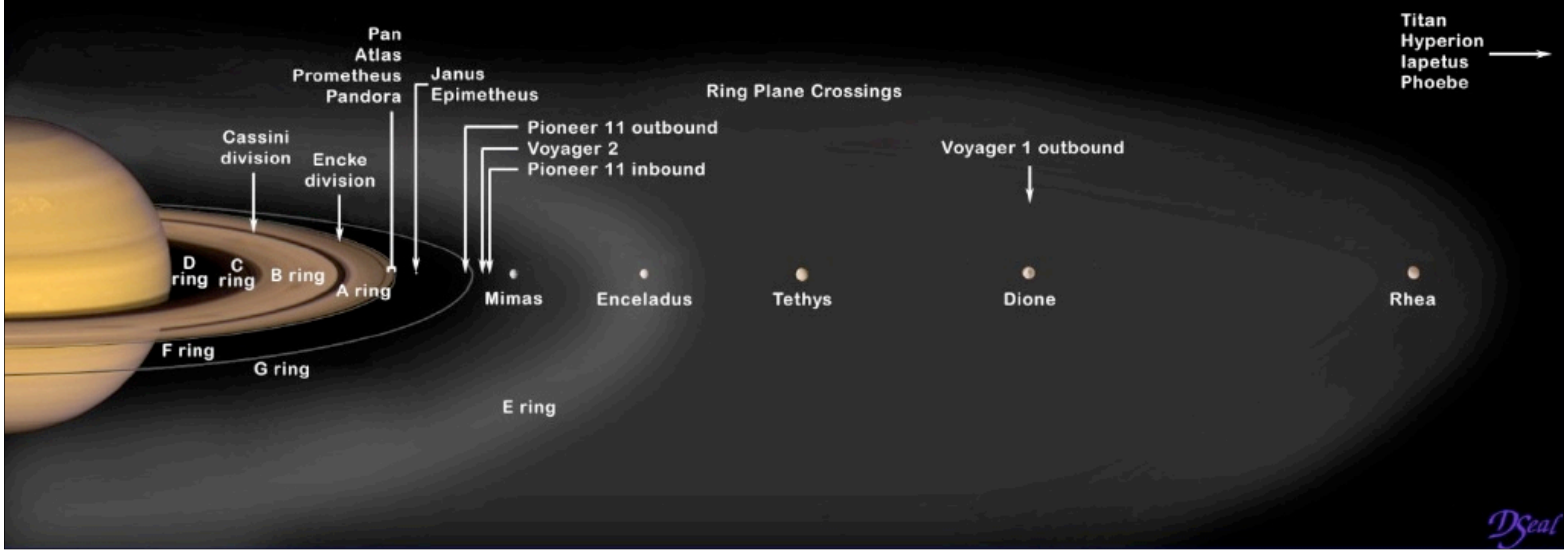
The D ring is the closest to Saturn and stretches down almost to the cloud tops. It contains few particles and is so dark and faint that it is invisible from Earth. Rings C, B and A are the three major rings of the ring system and can be seen from Earth. The C ring is the faintest of the three and is almost translucent. The B ring is the brightest of the three followed by the somewhat fainter A ring. Each major division is further subdivided into thousands of individual ringlets.



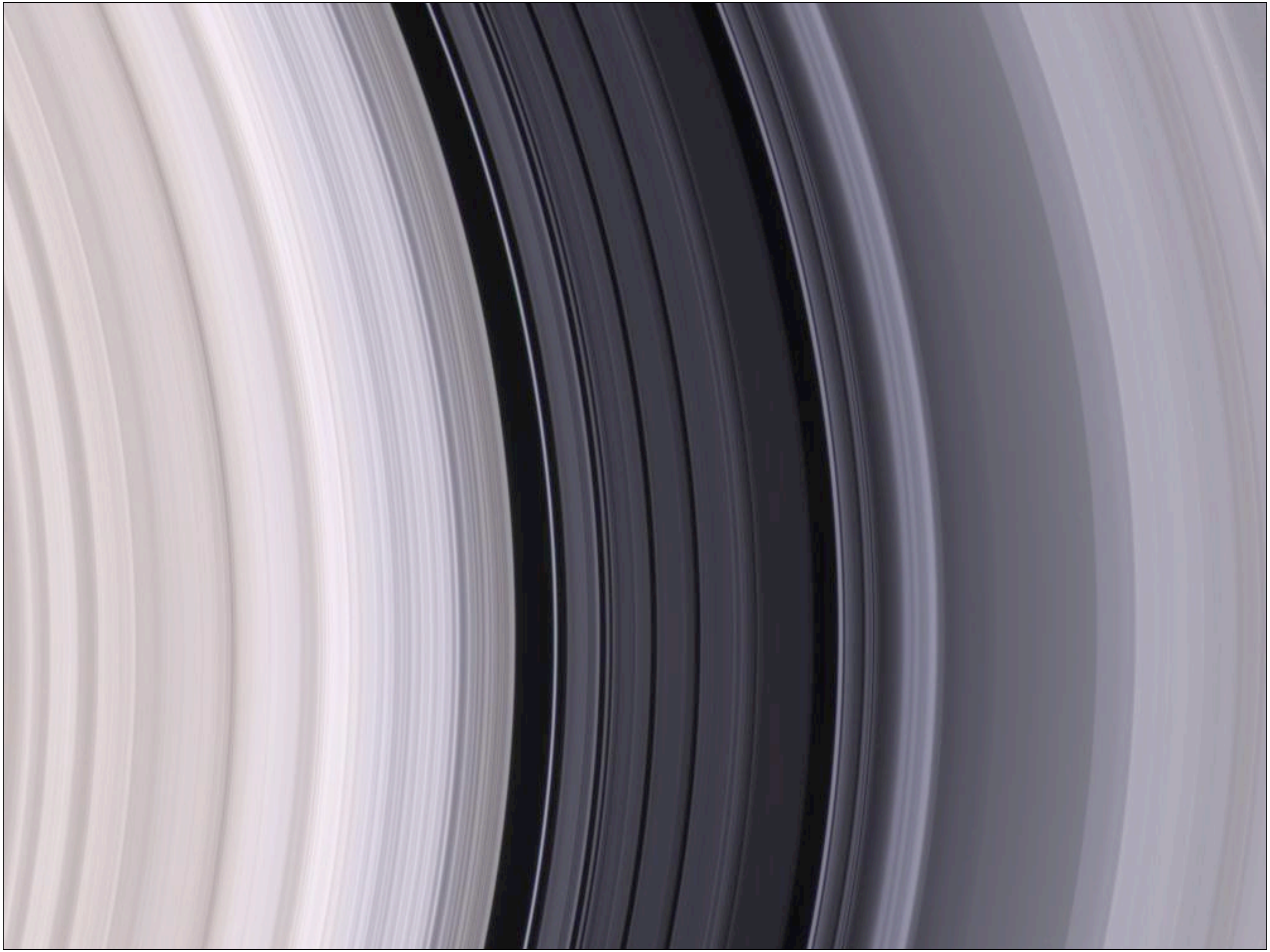
Just outside the A ring lies the F ring, the strangest ring of them all. It is faint, narrow and appears to contain bends and kinks. Close-up pictures show two narrow, braided, bright rings that trace distinct orbits.

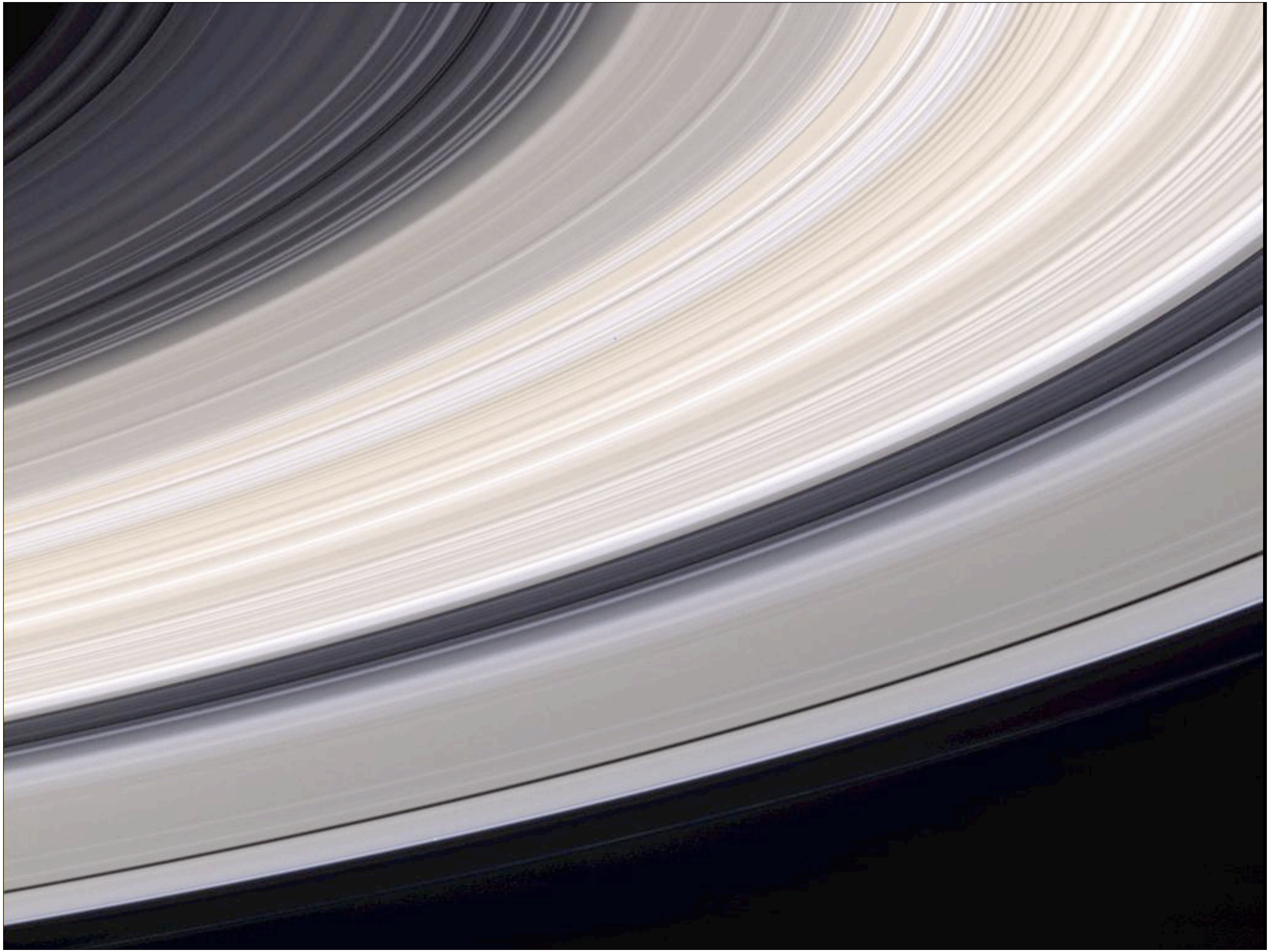


Following the F ring is the faint G ring and even farther out, well outside the main ring structure, lies the E ring. Unlike the main rings, the E ring has a vertical extent of several thousand kilometres, and is more like a cloud than a disk.



Panoramic view of Saturn, backlit by the Sun, showing an astonishing new view of the rings, including previously unknown faint rings.



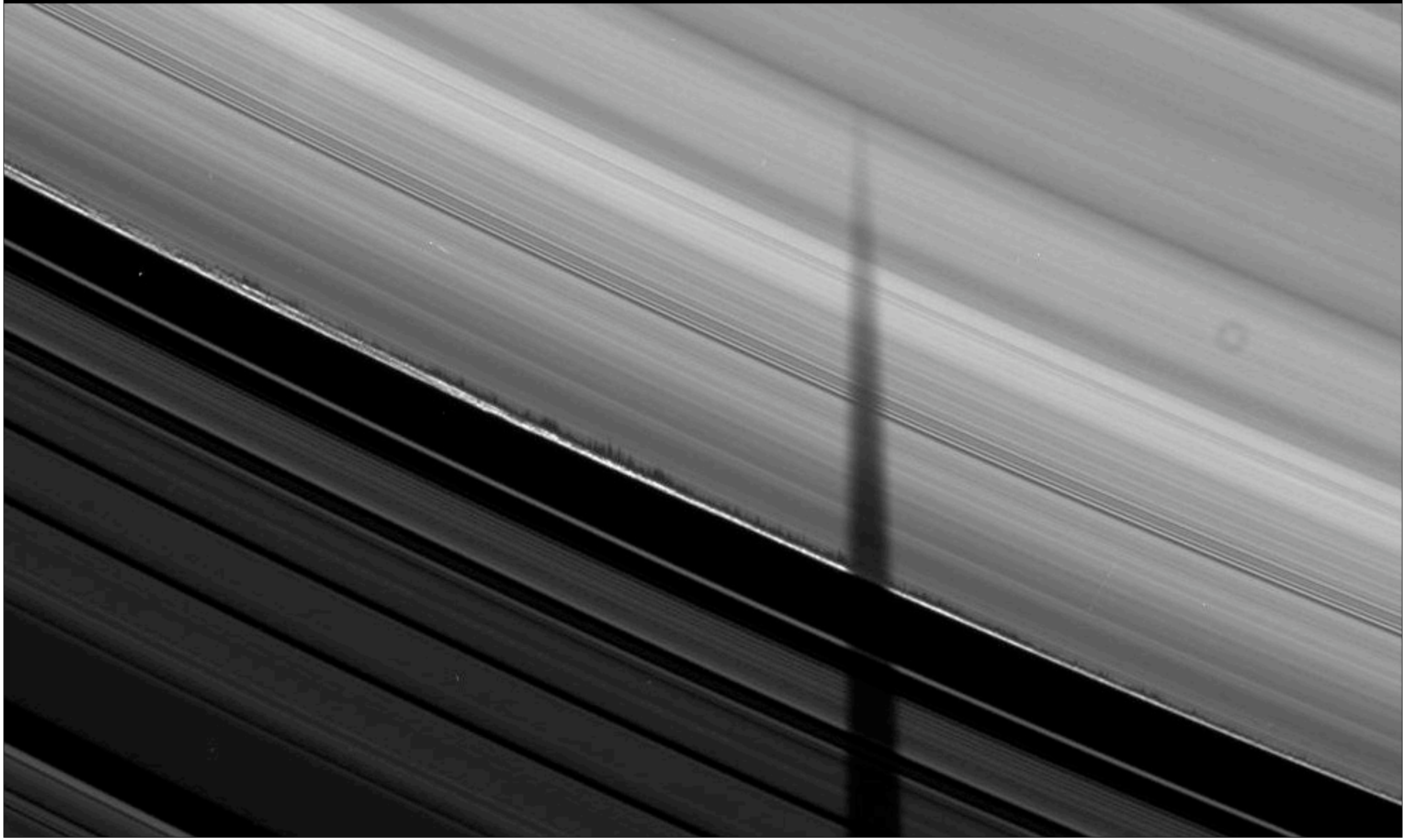


The divisions between the rings are caused by

- A satellite orbiting through the division and clearing it out (e.g. Pan and the Encke division); or
- A satellite pulling material from the area because of orbital resonance (e.g. Mimas and the Cassini division)

The inner and outer edges of the prominent B ring lie at distances corresponding to periods equal to one-half and one-third of Mimas' period.

The rings are extremely thin – possibly only 10 m thick – and composed almost entirely of water ice.

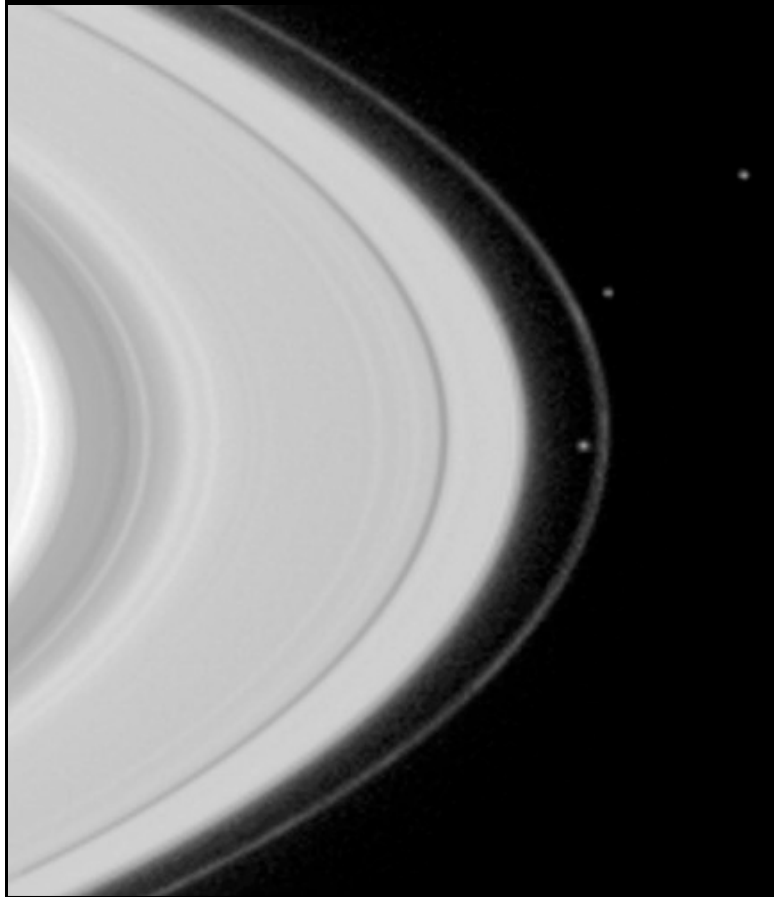


The brightness of the rings suggests they must be made primarily of ice, and the thinness of the rings implies the ring particles must be small, no more than a couple of meters across at most, and frequent collisions between ring particles would tend to break big chunks into smaller ones.

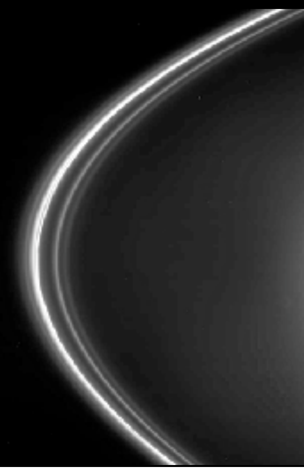
An artist's conception of the chunks and agglomerations of icy material making up the main rings of Saturn. (Painting by William Hartmann)

Several of Saturn's rings are maintained by "shepherd satellites". These are moons that keep the rings together and stabilised via gravitational attraction.

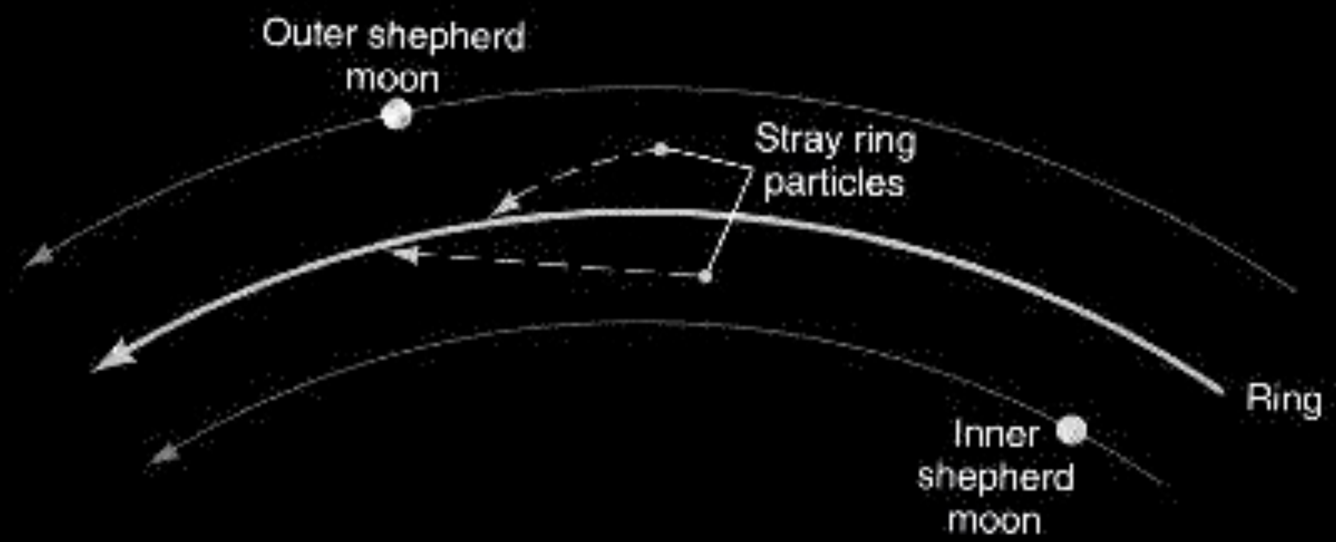
The F-ring has two shepherds – Prometheus and Pandora.



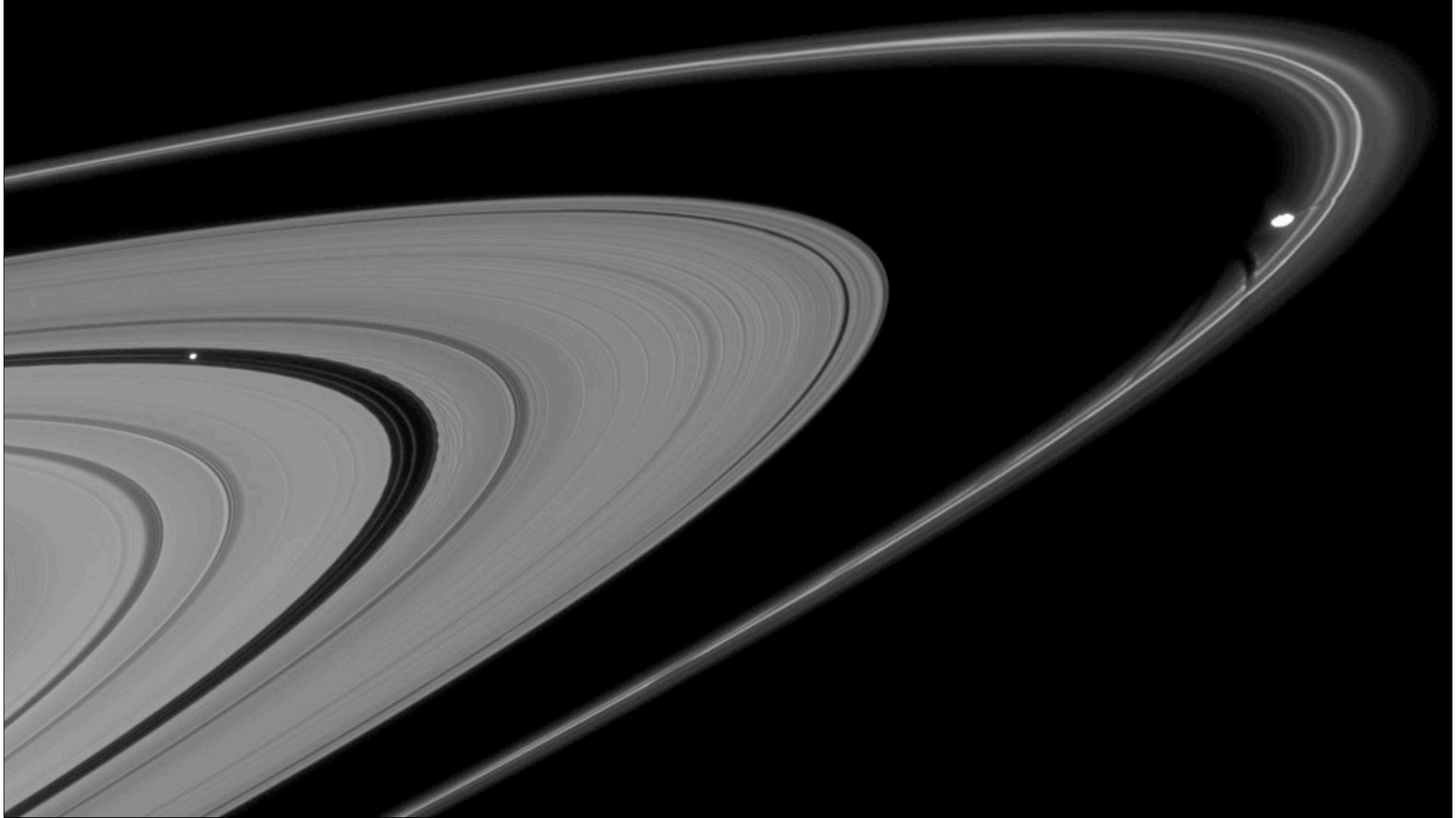
Prometheus orbits just inside the F ring, while Pandora orbits just outside.



The two small, irregularly shaped moons exert a gravitational influence on particles that make up the F ring, confining it and possibly leading to the formation of clumps, strands and other structures observed there. Pandora prevents the F ring from spreading outward and Prometheus prevents it from spreading inward.

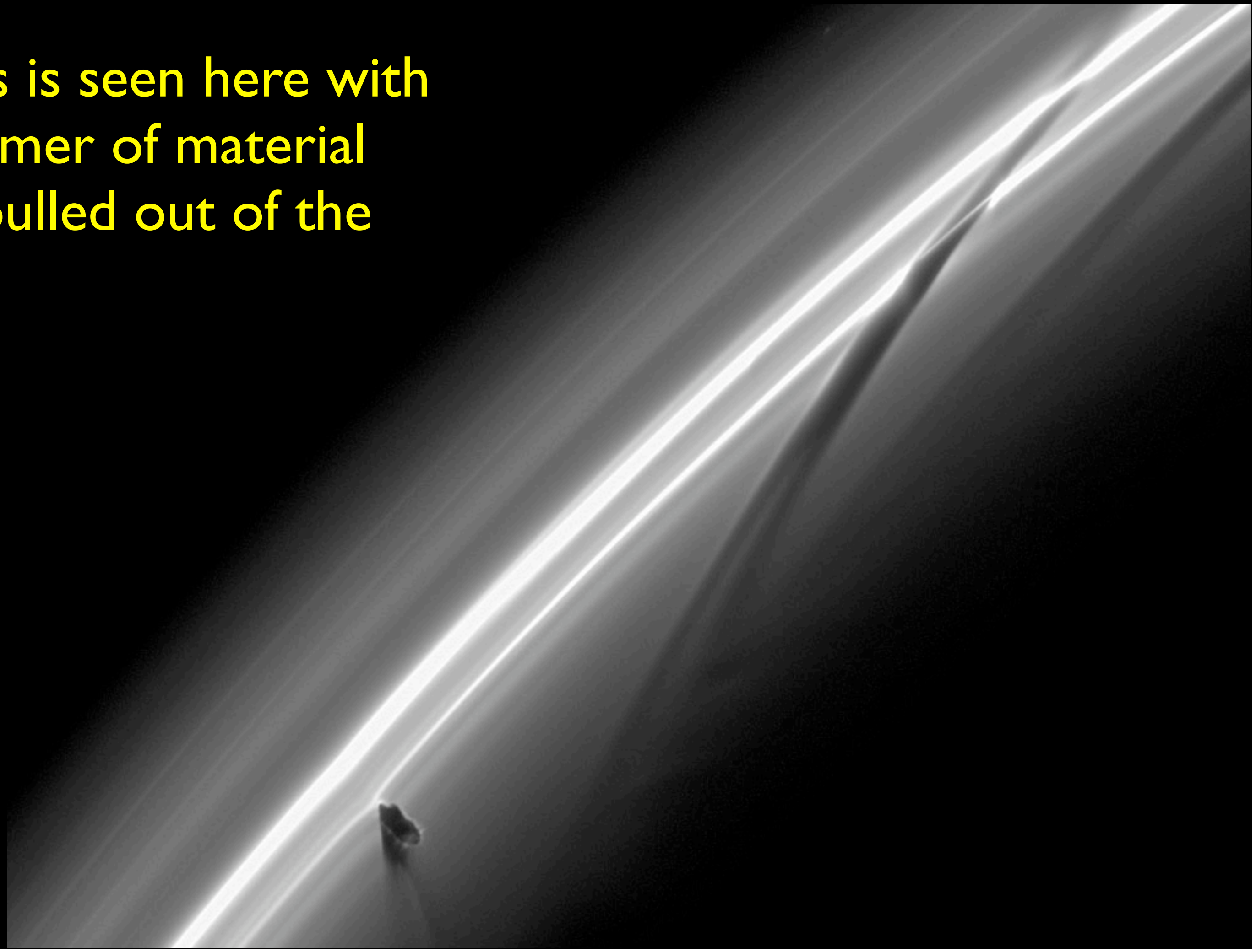


Pan and Prometheus creating waves in the rings

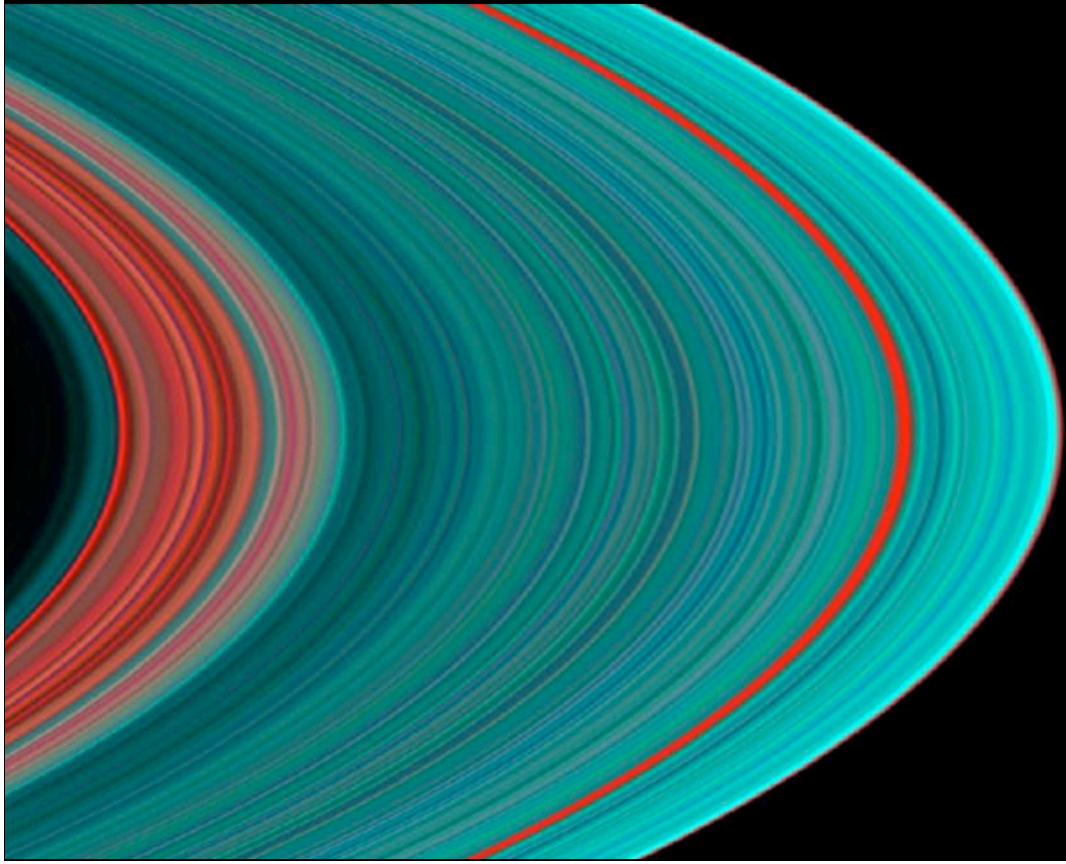


Cassini took this amazing picture of the shepherd moon Prometheus (102 kilometers across) working its influence on the multi-stranded and kinked F ring.

Prometheus is seen here with a long streamer of material that it has pulled out of the ring.



The colours of the ringlets and their variable opacity to radio waves suggest that they are sorted by particle size and possibly also by composition.

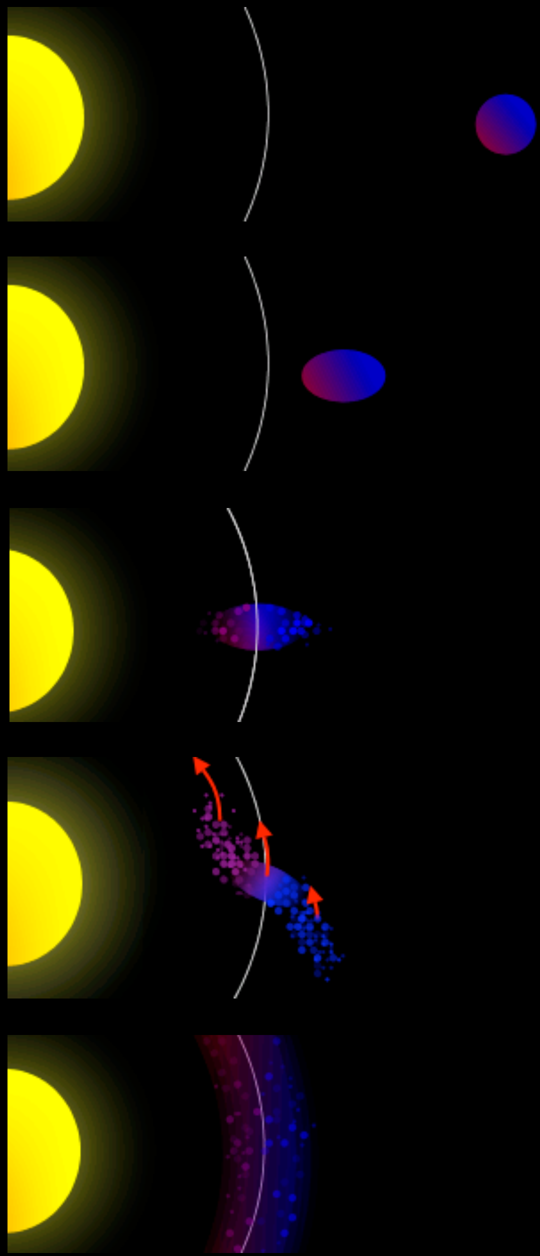


Cassini took this detailed image of the A ring in ultraviolet light. Blue represents areas rich in water ice, while red areas are rich in some sort of dirt. This and other images show that inner rings have more dirt than outer rings. The thin red band in the otherwise blue A ring is the Encke Gap. The exact composition of the dirt remains unknown.

Saturn’s rings are inside the *Roche limit*, which is the the minimum distance to which a an object can approach its primary body without being torn apart by tidal forces.

As a body moves towards the Roche limit, it is stretched by tidal forces; at the limit, the body disintegrates, and the varying orbital speed distributes the material in a ring.

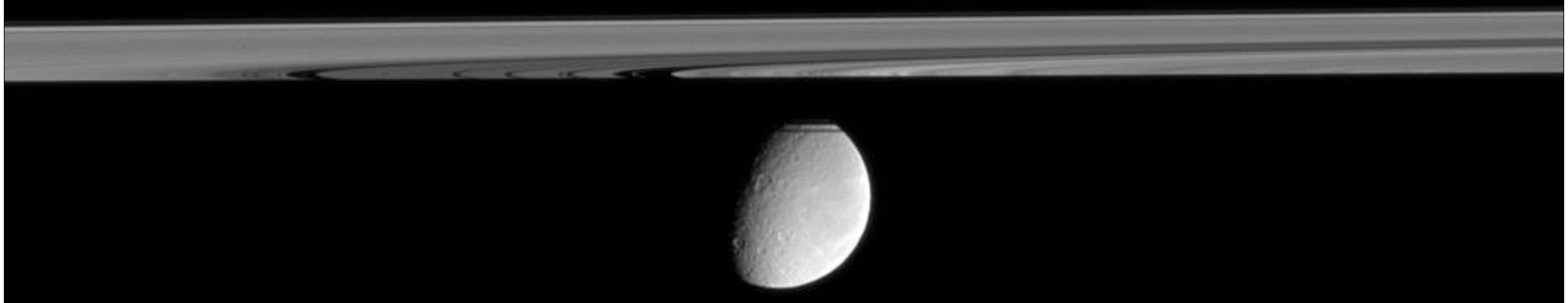
The above holds true for bodies held together solely by gravitational force. Solid bodies, which have tensile strength, can survive somewhat closer to the planet.



The origin of the rings is not clear. The total mass of material in the rings would make an icy moon one or two hundred kilometres wide, like Mimas. Until recently, it was thought that the rings were young: loss of angular momentum would destroy the rings in a few hundred million years. The brightness of the rings also suggests they are reasonably young.

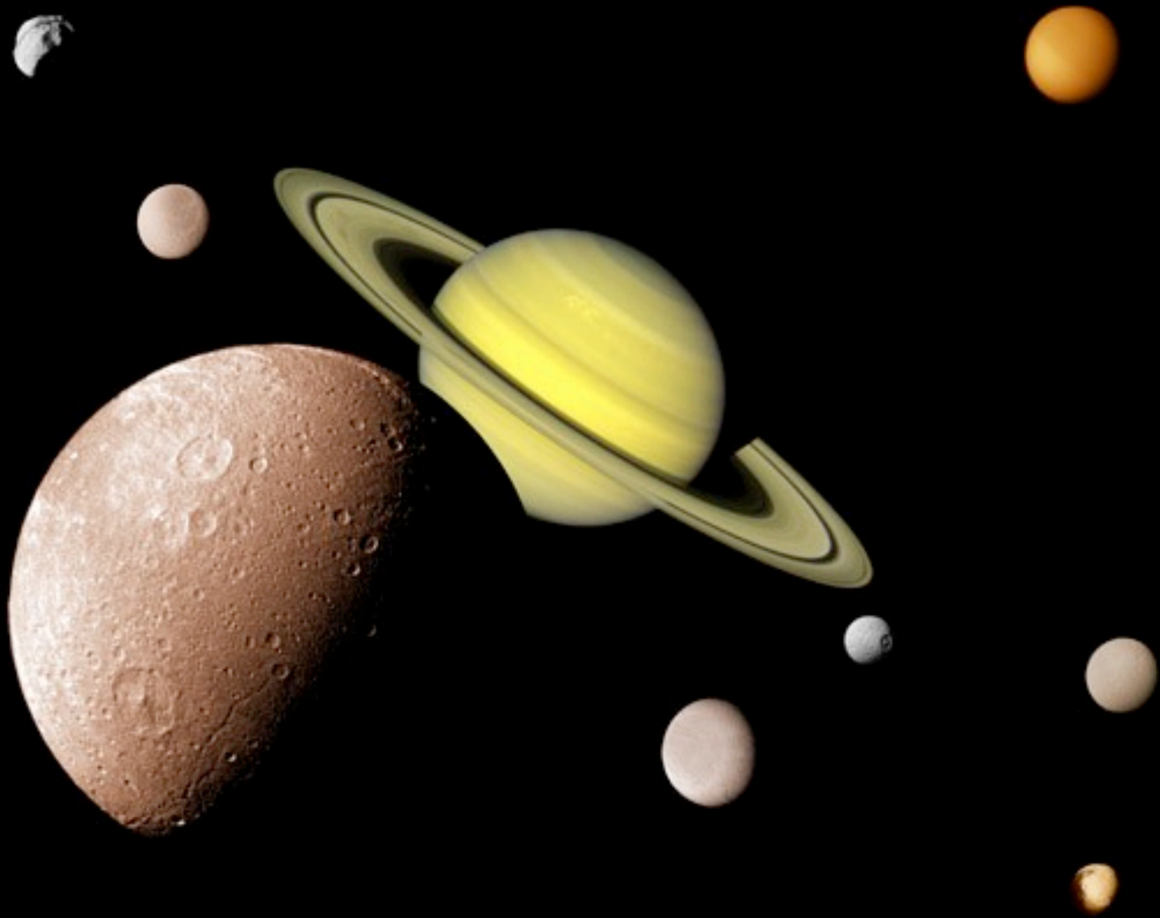
Possibly they were created by a comet that shattered a large moon, perhaps 100 million years ago.

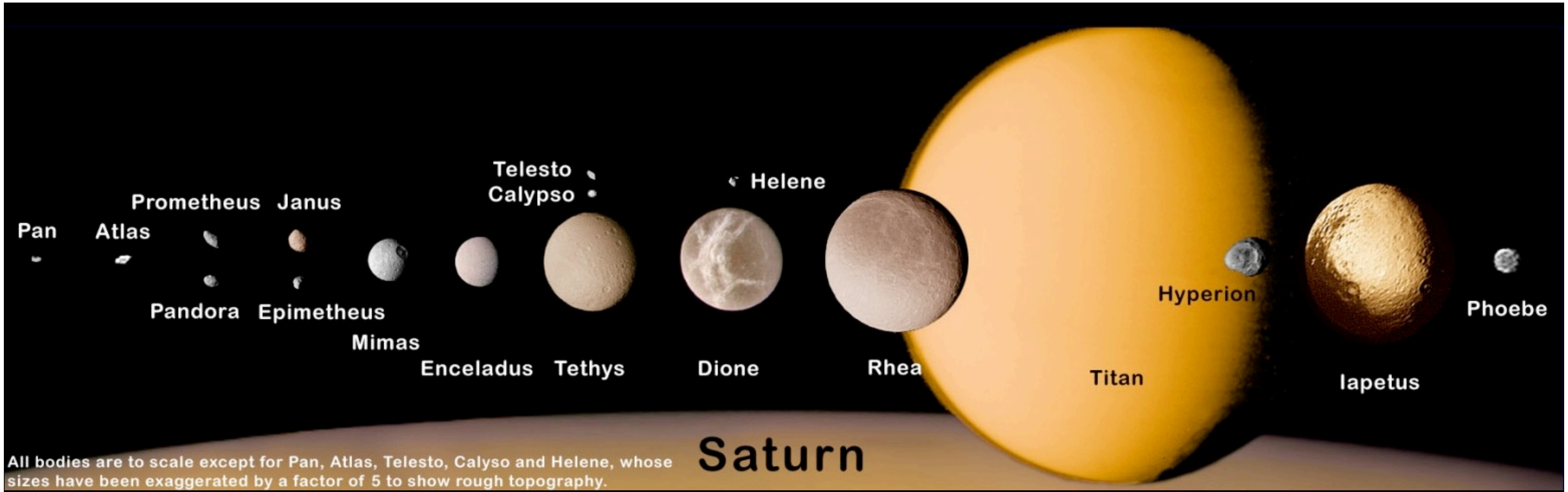
However, recent work suggests the ring might be much older, possibly dating back to the formation of the Solar System. The rings appear able to recycle material much more efficiently than had previously been supposed, explaining why they are still bright. Further, only in the early days of the Solar System were collisions frequent enough to make collisions likely.



Rhea hovers below the ring plane

Saturn's moons





Saturn has 61 known satellites. These make three groups: Titan by itself (the biggest), the six large icy moons: Mimas, Enceladus, Tethys, Dione, Rhea, and Iapetus, and the rest.

Of those moons for which rotation rates are known, all but Phoebe and Hyperion rotate synchronously. Several satellites are in resonant orbit: Mimas and Tethys are in a 1:2 resonance; Enceladus-Dione are also 1:2; Titan-Hyperion are in a 3:4 resonance.

Saturn's medium-sized moons:

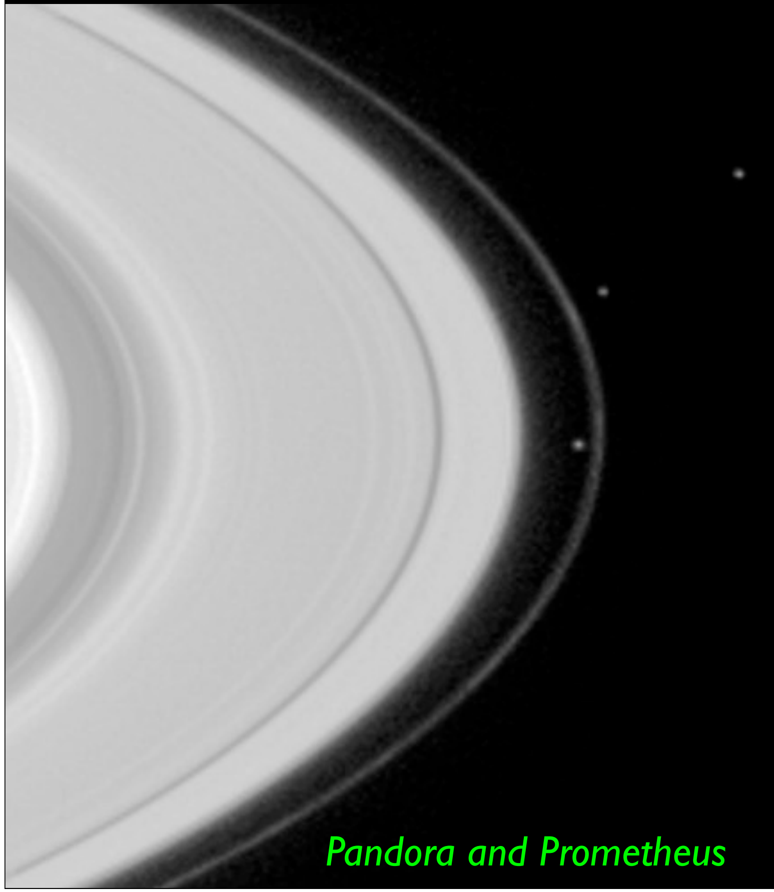
Name	Diameter (km)	Mass (10^{21} kg)	Density (g/cm^3)	Orbital distance (10^3 km)	Orbital period (d)
Prometheus	145x85x65	0.00027		139	0.613
Pandora	114x84x2	0.00022		142	0.629
Epimetheus	144x108x98	0.00056	0.7±0.2	151	0.694
Janus	196x192x150	0.002	0.7±0.2	151	0.694
Mimas	390	0.038	1.14±0.03	186	0.942
Enceladus	500	0.084	1.01±0.02	238	1.370
Tethys	1060	0.755	1.00±0.02	295	1.888
Dione	1120	1.05	1.44±0.07	377	2.737
Rhea	1530	2.49	1.33±0.10	527	4.518
Titan	5150	1350	1.88±0.01	1222	15.945
Hyperion	410x260x220	0.0177		1481	21.277
Iapetus	1460	1.88	1.21±0.12	3561	79.331
Phoebe	220	0.004		12952	–550.48

2:1 resonances (Mimas–Tethys, Enceladus–Dione)

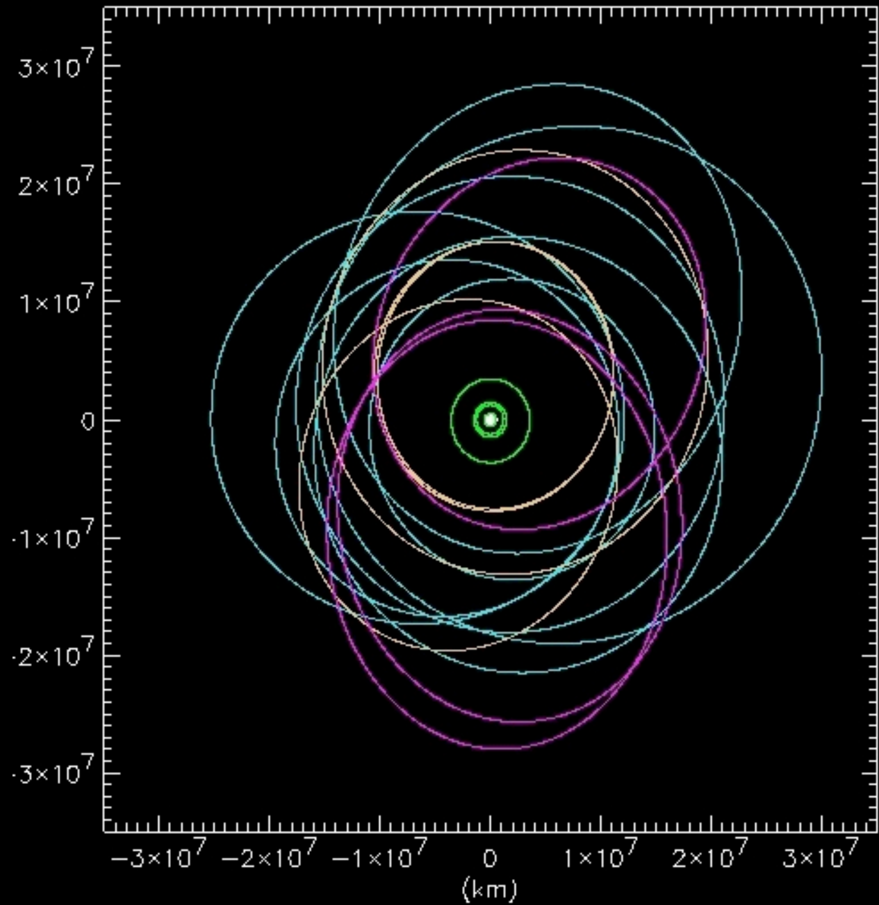
3:4 resonance (Titan–Hyperion)

Sixteen satellites orbit within the main rings themselves.

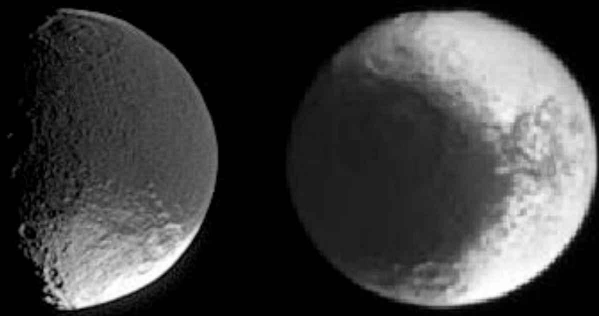
Outside the regular moons are a swarm of irregular moons, mostly captured asteroids.



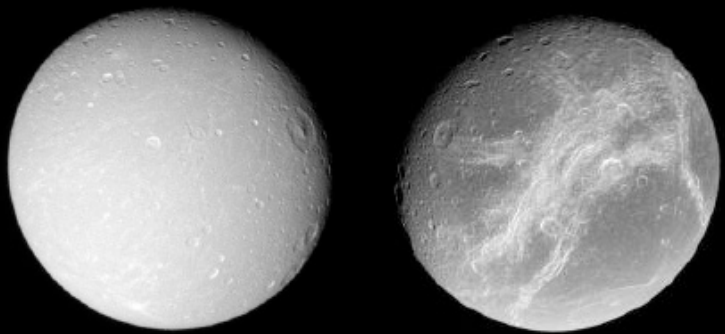
Pandora and Prometheus



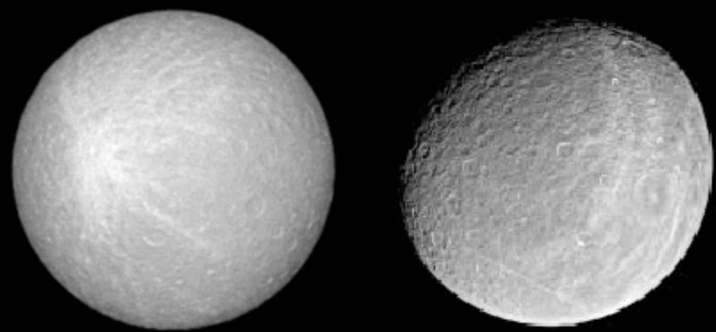
Most of Saturn's moons are tidally locked, keeping the same face towards the planet as they orbit. Many of them show a strong asymmetry between their leading and trailing hemispheres.



Iapetus



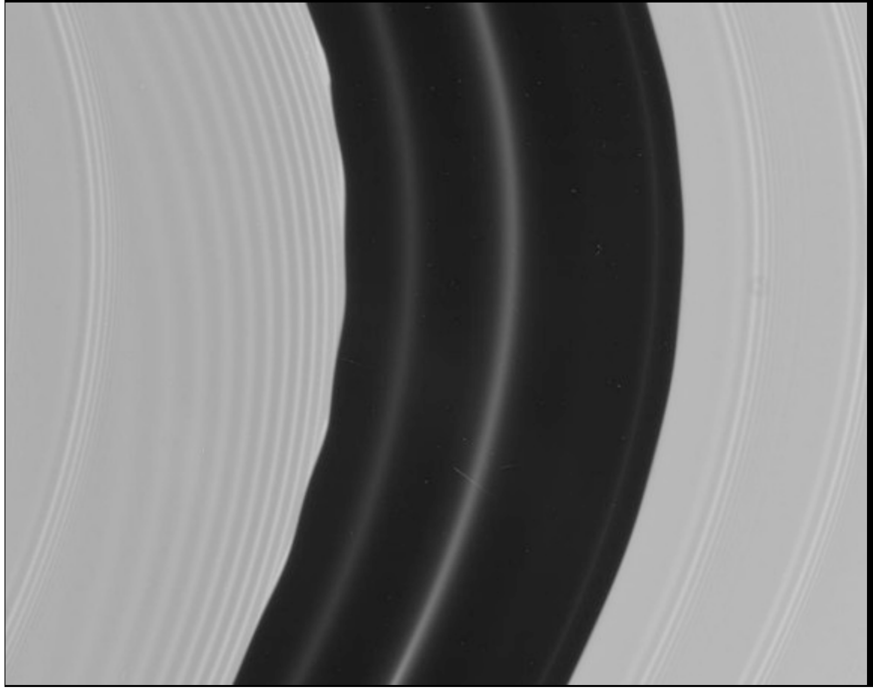
Dione

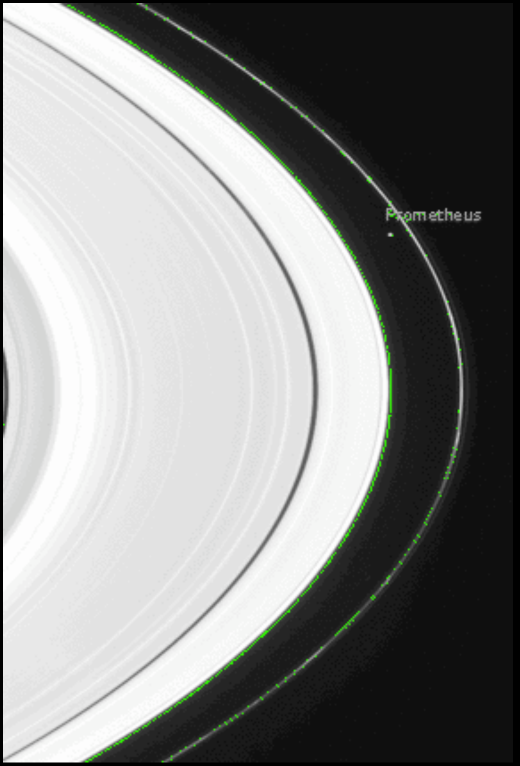


Rhea

Pan (radius 10 km) is located in the Encke gap. Its existence was predicted by "clumping" in the adjacent A-ring.

Atlas (radius 14 km) is a shepherd satellite of the A-ring.





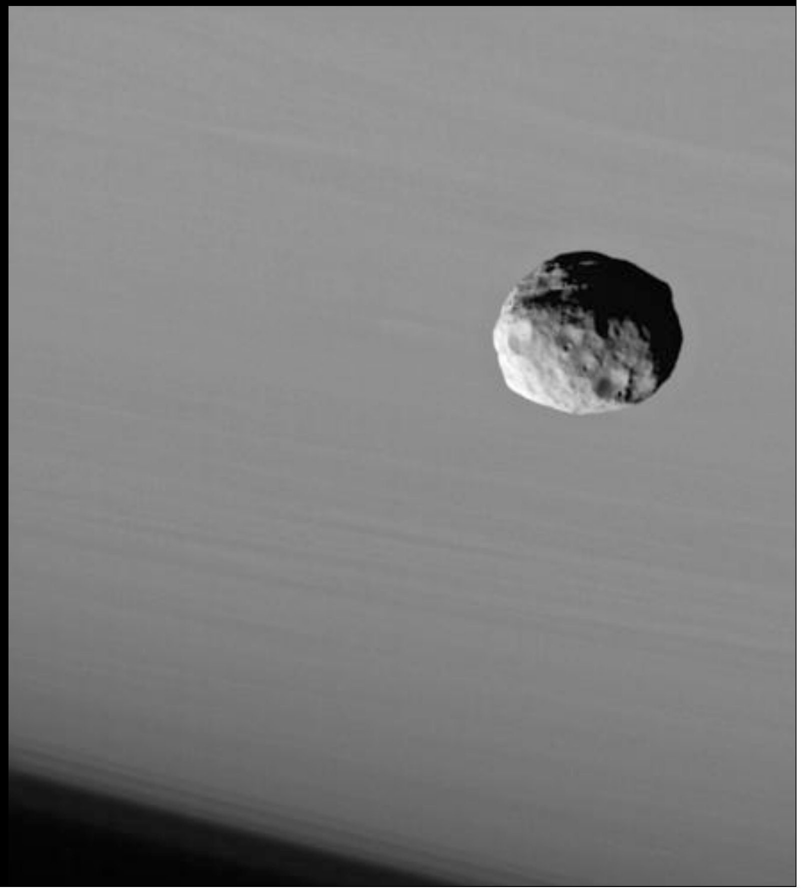
(left) Scalloping of the A-ring, caused by Pan. (above) Cassini images showing Pan orbiting in the Encke gap. Atlas, Prometheus, and Pandora are also visible in this animation.

Prometheus (radius 46 km) and Pandora (radius 46 km) are shepherds for the F-ring. They show craters up to 20 km across, and Prometheus also has small ridges and valleys. Their very low densities imply they are mostly composed of water ice.

Prometheus (above) and Pandora (right), taken by Cassini. Prometheus shows a 20 km crater on one side.

Janus (radius 89 km) and Epimetheus (radius 57 km) share the same orbit. Their orbits differ by less than 50 km, and when they approach each other, momentum is exchanged between them and the lower orbiting satellite is transferred to a higher orbit and vice versa. This occurs about every 4 years.

Janus (right) and Epimetheus. The two last swapped positions in January 2006, and Janus will remain the innermost of the pair until 2010, when they will switch positions again.

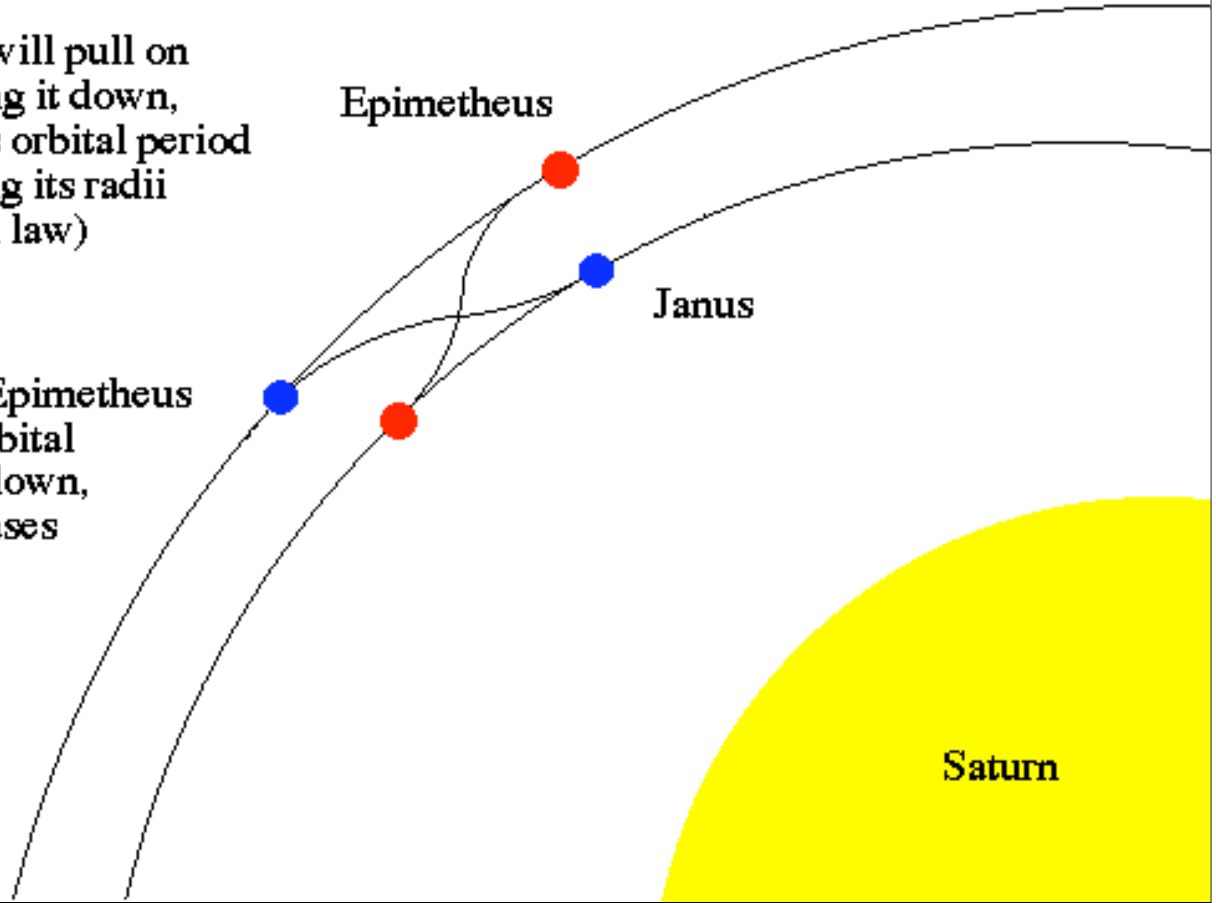


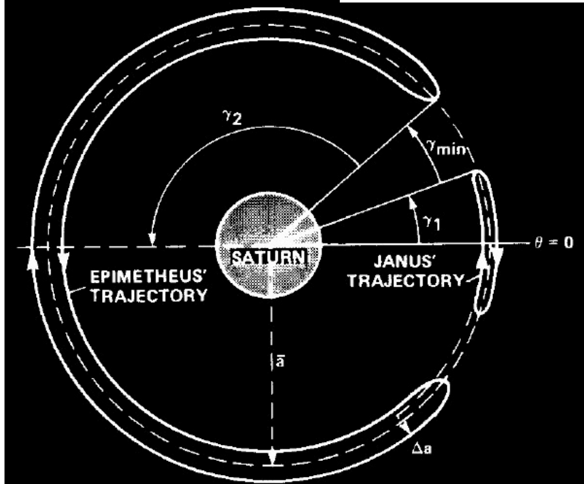
Janus in front of Saturn

Epimetheus and Janus travel in orbits separated by only 50km, and actually exchange places every few years.

Epimetheus will pull on Janus, slowing it down, increasing its orbital period and increasing its radii (Kepler's 3rd law)

meanwhile, Epimetheus speeds up, orbital period goes down, radius decreases

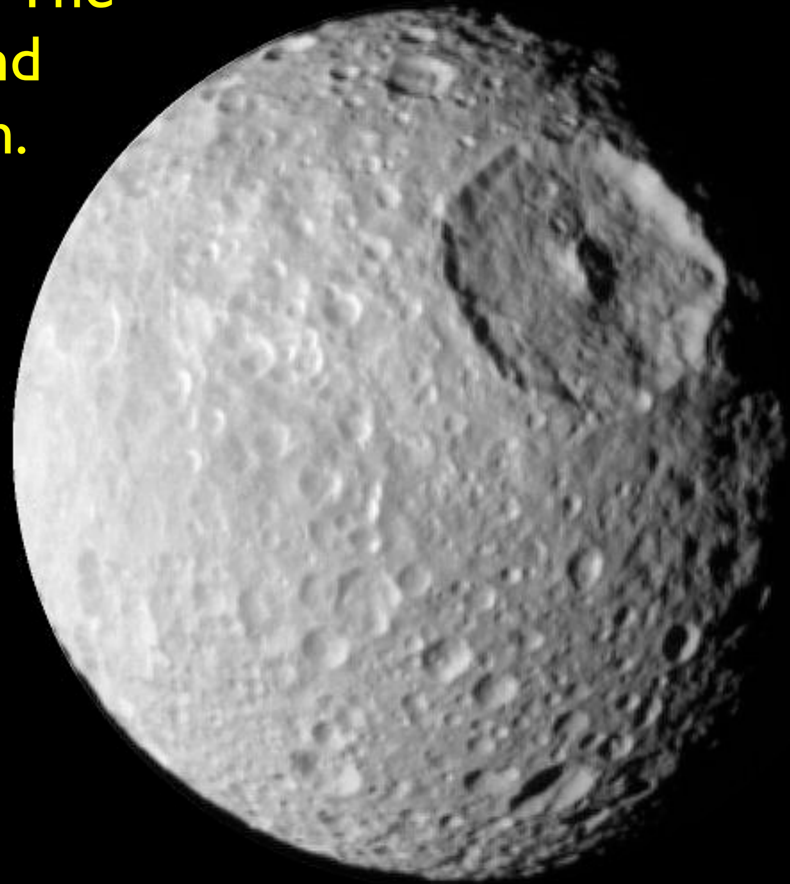


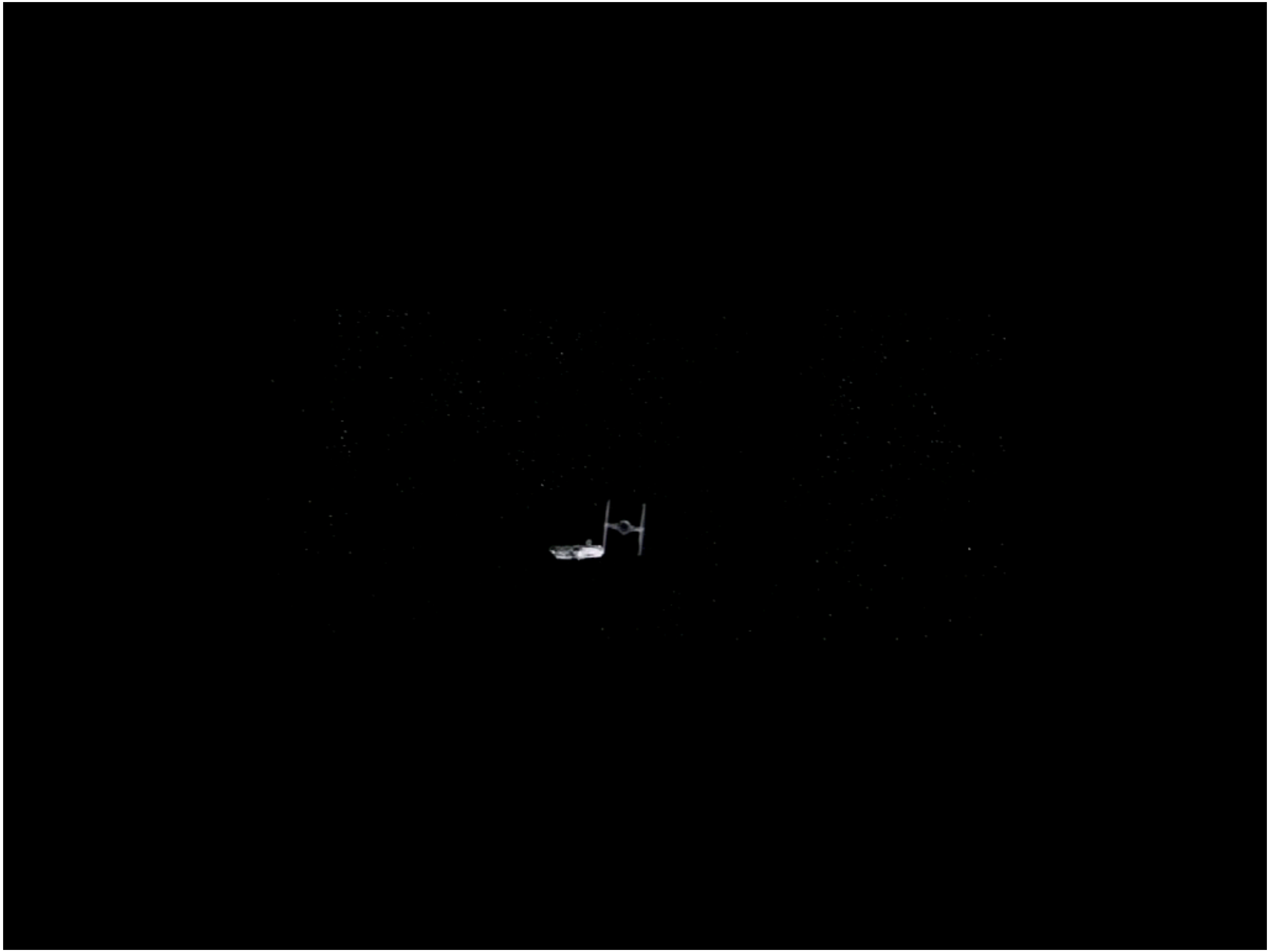


After the ring-shepherding satellites come the six medium-sized icy worlds. Unlike the relatively orderly Galilean satellites of Jupiter, Saturn's system of satellites shows few regularities.

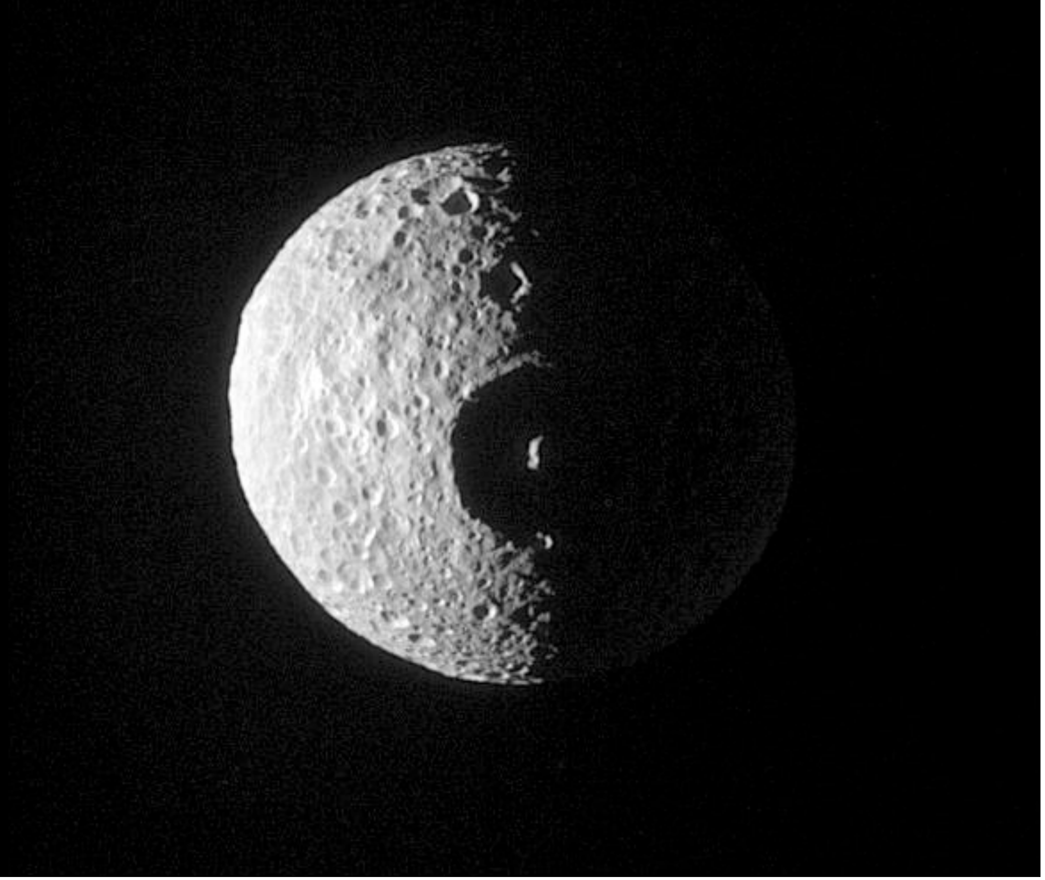
The medium sized Saturnian moons, with the Earth's moon for comparison.

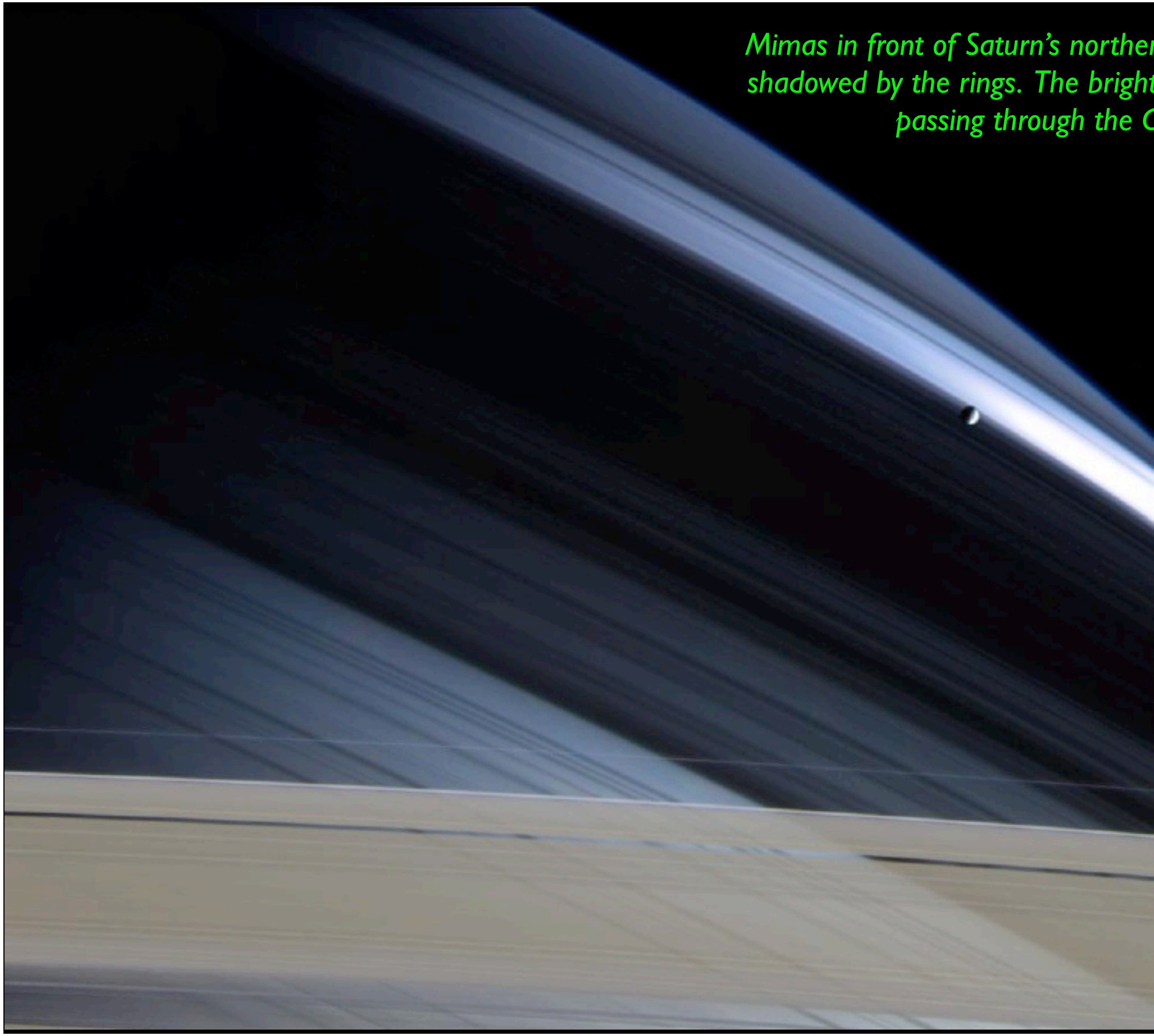
Mimas (radius 196 km) lies outside the main ring system but within the tenuous E ring. It has very low density, so it's mostly water ice. Its surface is saturated with impact craters. The largest crater is *Herschel* crater: 130 km across with walls 5 km high. The floor is up to 10 km deep and the central peak is 6 km high.





No other large impact craters are present on Mimas. This suggests that it has been re-surfaced, probably by large impacts. It later solidified and coalesced again, and was then cratered again.

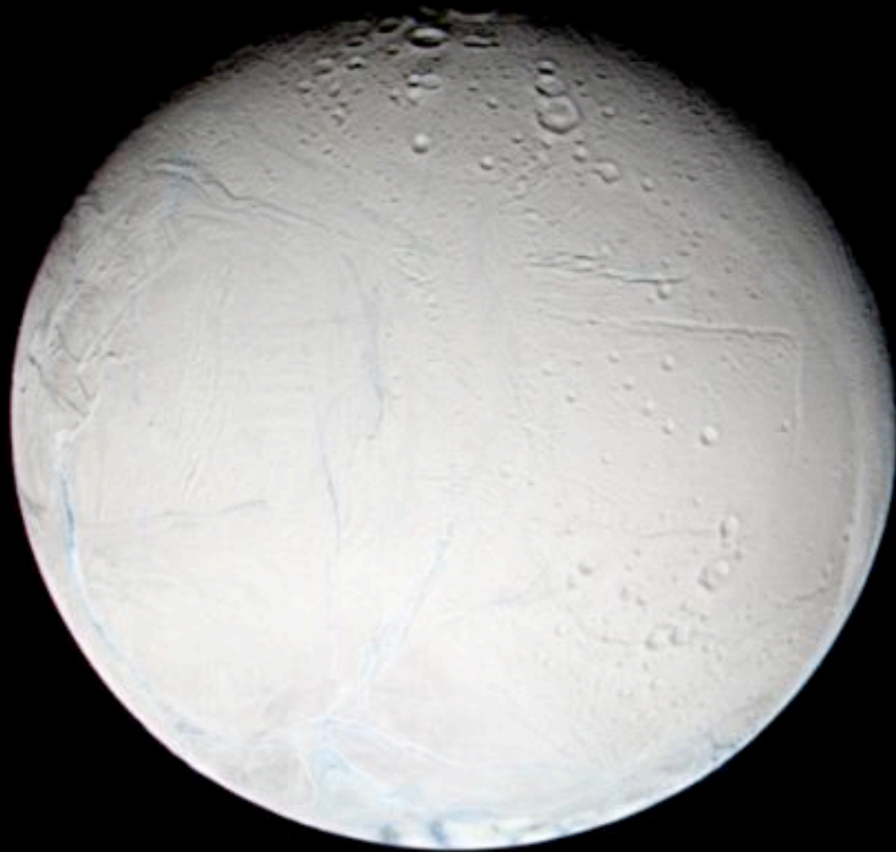




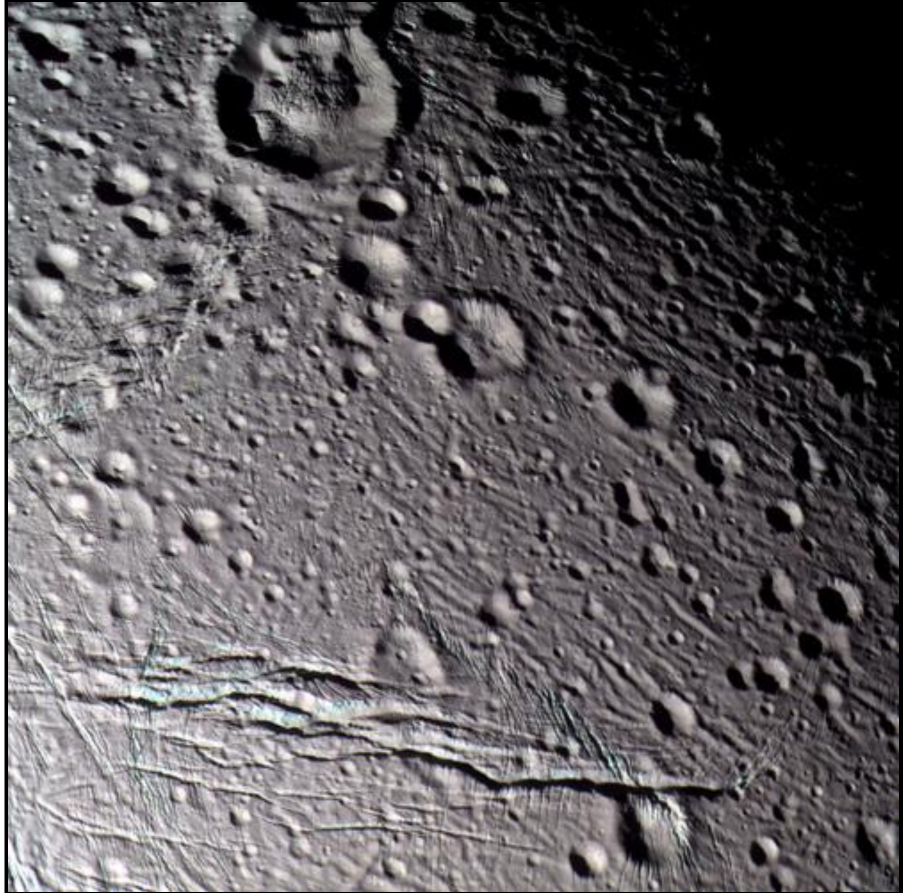
Mimas in front of Saturn's northern hemisphere, shadowed by the rings. The bright streak is light passing through the Cassini division.

Enceladus (radius 260 km) has the highest albedo in the Solar System (albedo 0.99). Its surface is dominated by fresh, clean ice.

Enceladus is in a 2:1 orbital resonance with Dione, which helps maintain Enceladus' orbital eccentricity (0.0047) and provides a heating source.



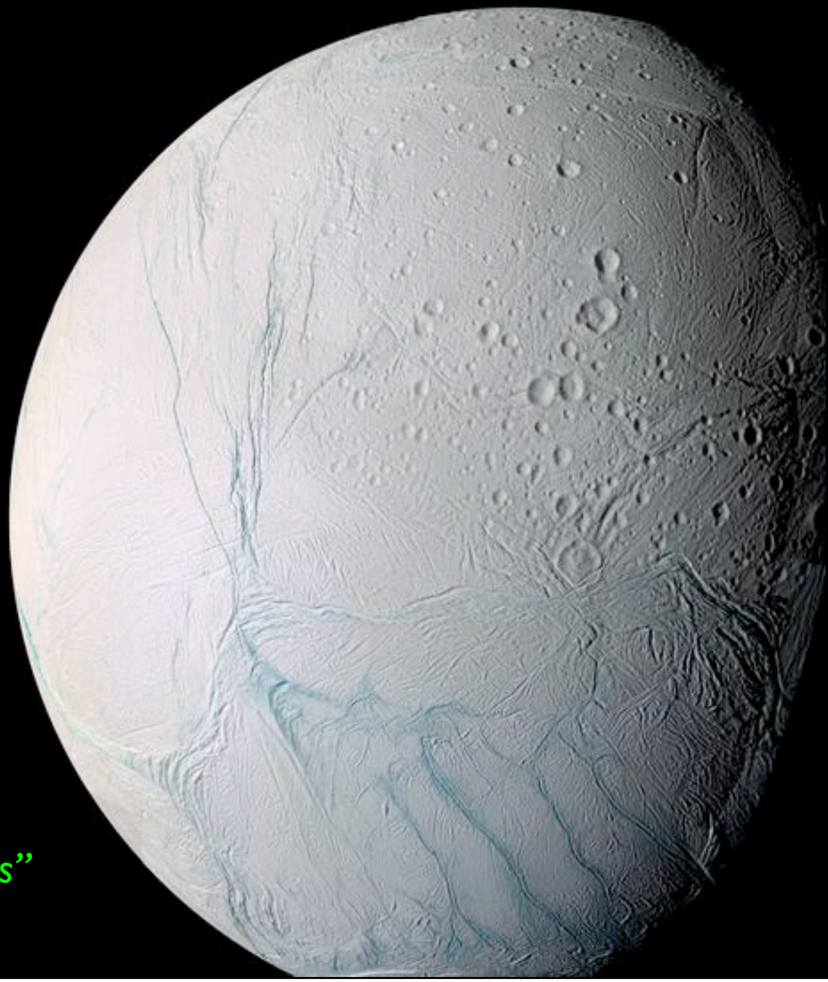
It shows many similarities with Europa. The surface has craters, which are overlain with extensive linear cracks and ridges. At least some of the surface is relatively young, probably less than 100 million years.



This means that Enceladus must have been resurfaced very recently, probably with some sort of "water volcanism".

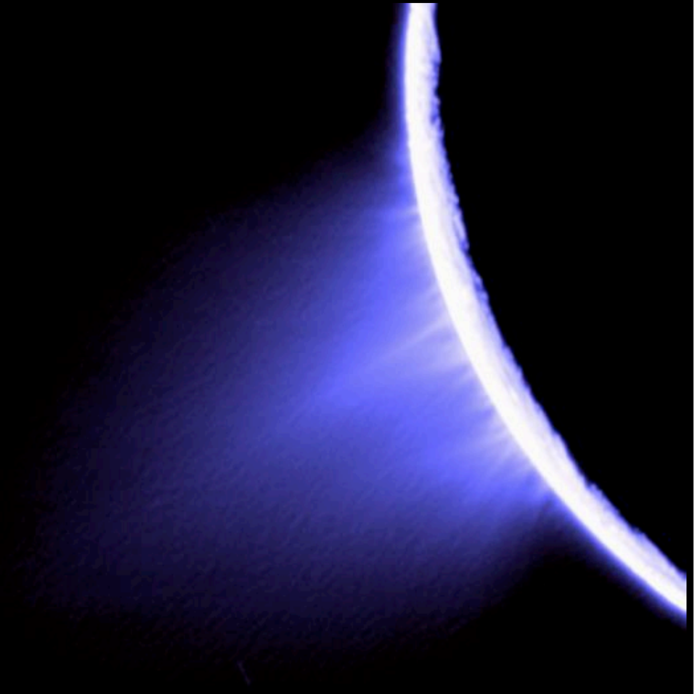
Cassini view of Enceladus, taking during its closest flyby. The surface is covered with craters of all sizes, and the entire scene is sliced by a complex network of fractures ranging in width from hundreds of meters in some places, to over three kilometers in others.

The south-polar region is smooth, and marked with a set of fractures, likely caused by a change in the moon's rate of rotation and the consequent flattening of the moon's shape.



Enhanced color view of Enceladus, largely of the southern hemisphere and including the south polar terrain at the bottom of the image. The blue regions are the "tiger stripes"

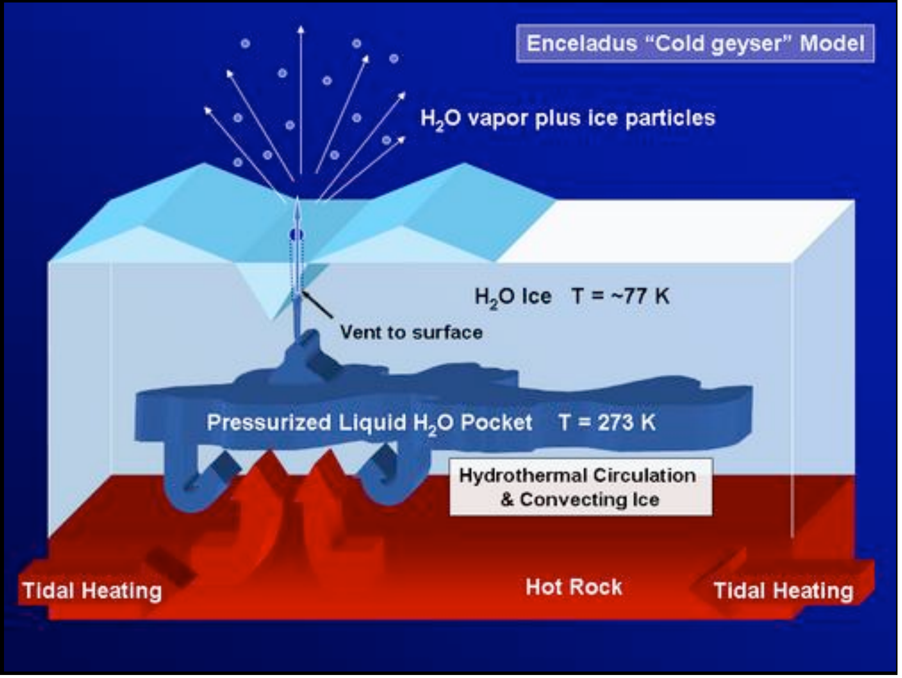
During flybys in 2005, Cassini imaged icy jets erupting off Enceladus, which thus joins Io at Jupiter and Triton at Neptune as an "active moon". The jets consist largely of water vapour and dust, but also contains carbon dioxide, methane, nitrogen and propane. There was no sign of ammonia, which had been suggested as a natural anti-freeze, so parts of Enceladus must be warmer than expected.



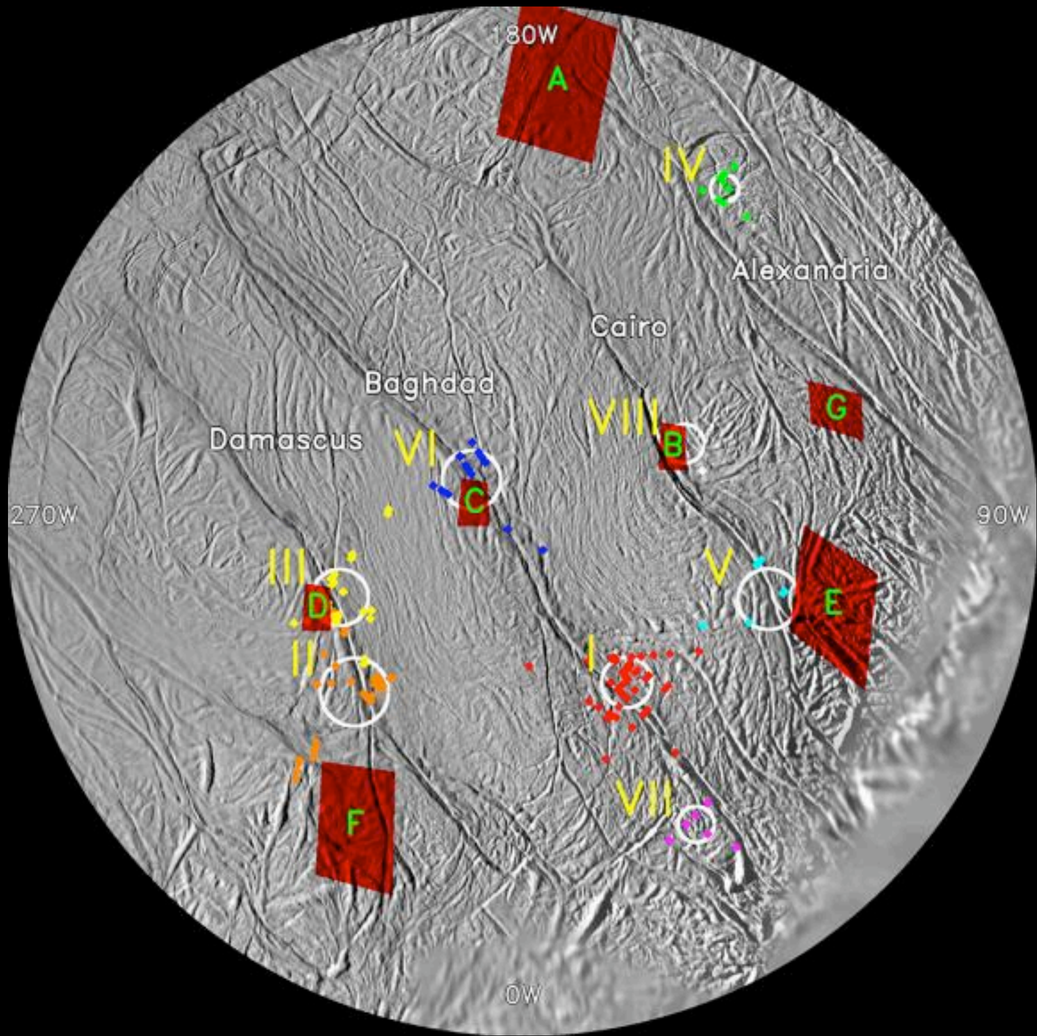
Cassini images of Saturn's moon Enceladus backlit by the sun, showing the fountain-like sources of the fine spray of material that towers over the south polar region. Several discrete sources are visible.

The eruptions produce about 150 kg of material per second, and are almost certainly the source of the E ring.

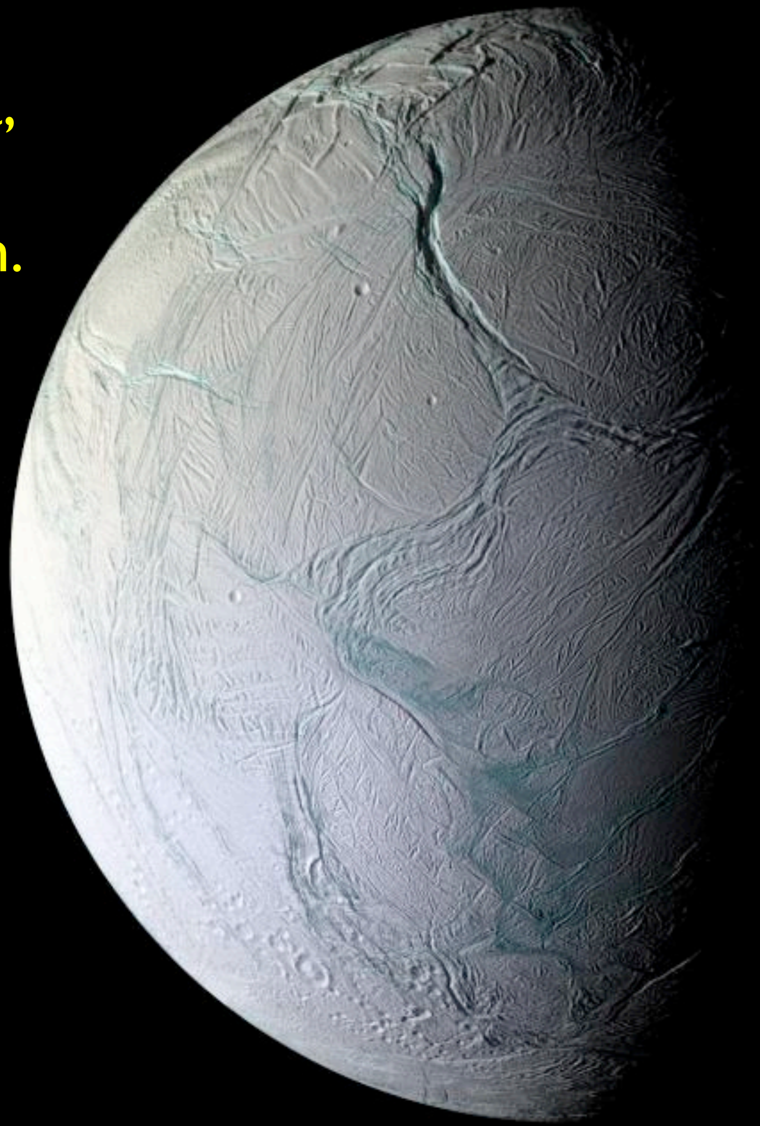
The most likely scenario is that the jets are erupting from near-surface pockets of liquid water above 0° Celsius, no more than tens of metres below the surface.



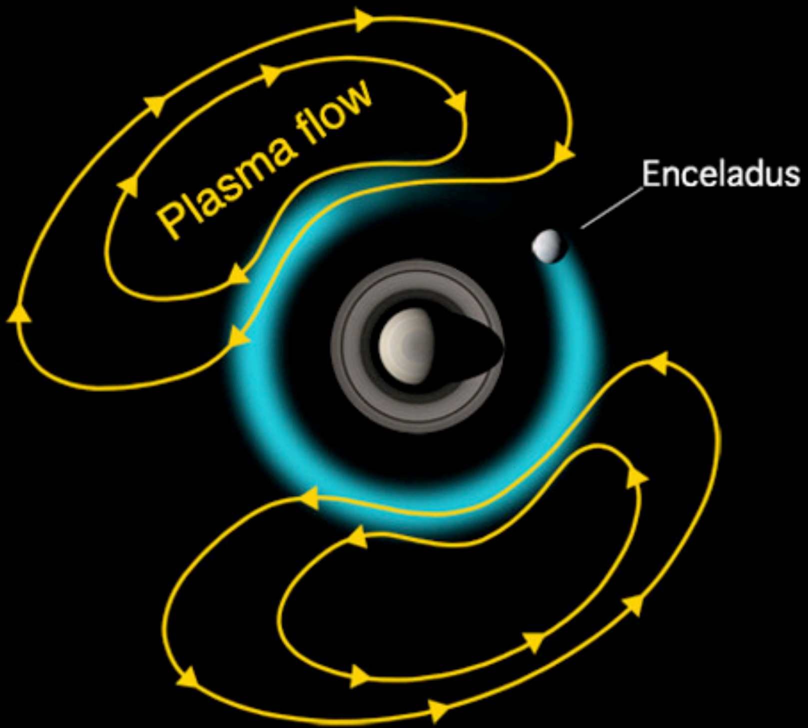
Cassini pinpointed the tiger stripe fractures in the south polar region as the source for the jets.



Enceladus shows a host of tectonic features: fractures, folds, and ridges. Like Europa, it appears to consist of floating ice on a global ocean.



The gas from Enceladus' geysers forms a torus around Saturn. As the particles become electrically charged, they are captured by Saturn's magnetic field, forming a disk of ionized gas, or plasma, which surrounds the planet near the equator. The particles weigh down the magnetic field so much that the rate of rotation of the plasma disk slows down slightly. This slippage causes the radio period, controlled by the plasma disk rotation, to be longer than the planet's actual rotation period. The period Cassini has been measuring from radio emission is not the length of the Saturn day, but rather the rotation period of the plasma disk.



The density of Tethys (radius 530 km) is 1.21 g/cm^3, indicating that it is composed almost entirely of water-ice. It is relatively lightly cratered, so its surface must have been liquid at some stage to smooth the crater out.

Ithaca Chasma is an enormous trough which extends at least three-quarters of the way around the globe. It is up to 100 km wide and reaches about 3 km in depth.

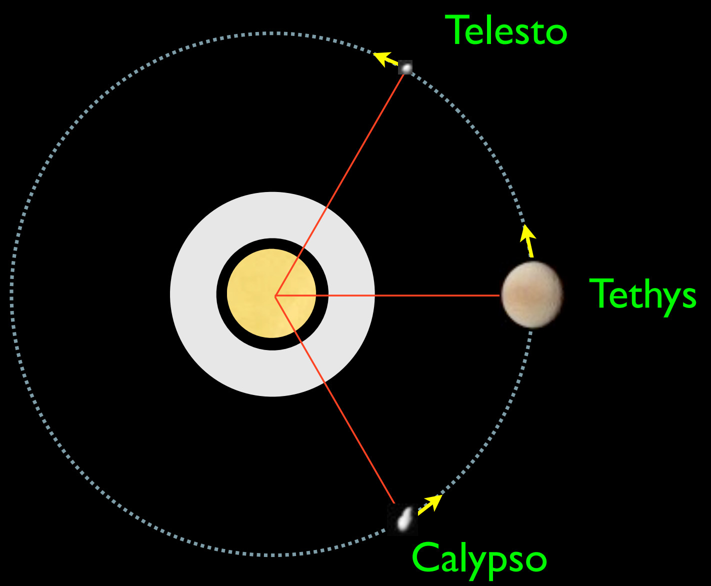
View of Tethys by Cassini, with Ithaca Chasma stretching across the surface.

Tethys is dominated by the *Odysseus* crater (400 km across). The flatness of the crater implies that Tethys must have been malleable at the time of impact.

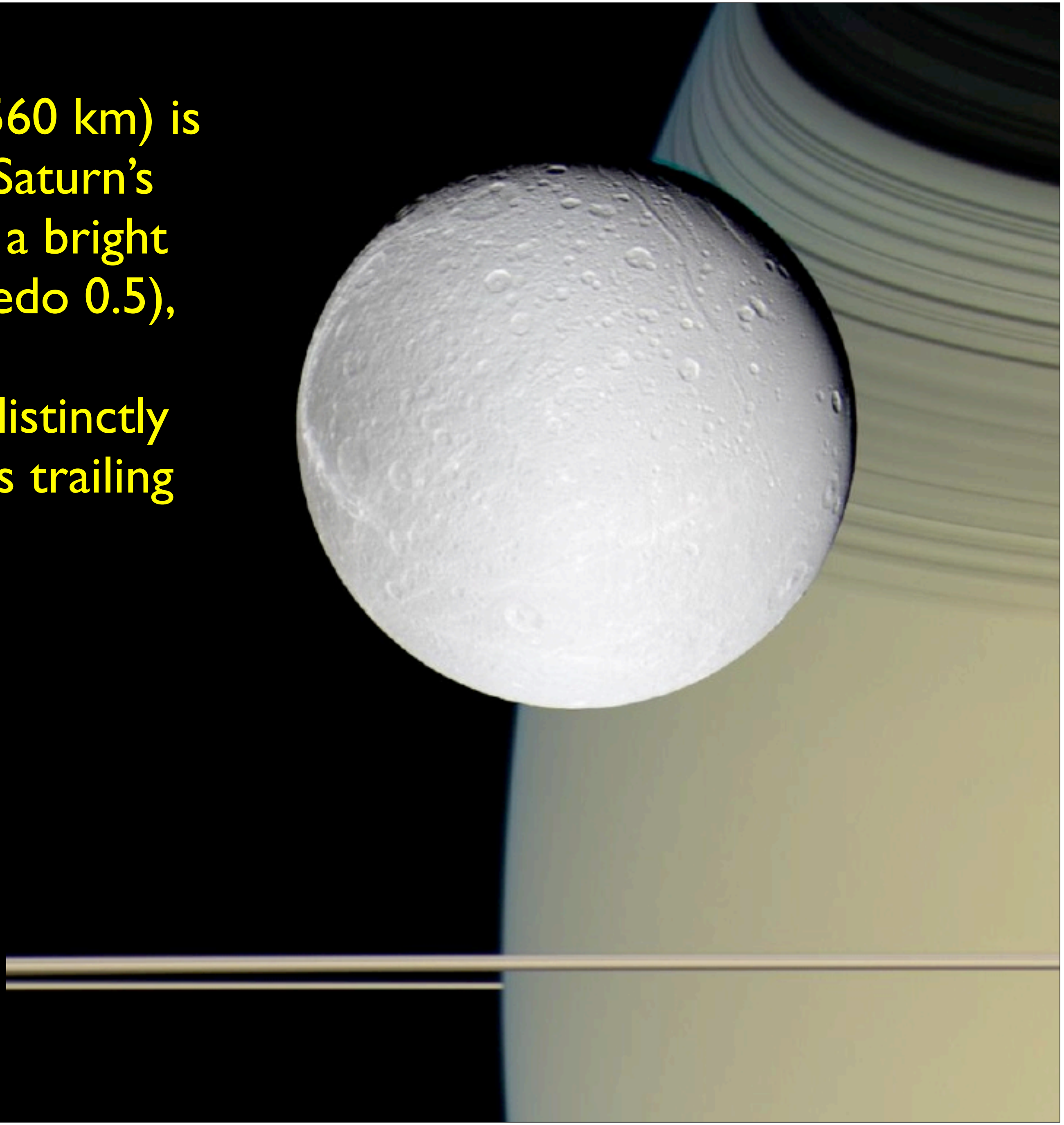
Odysseus is exactly opposite to the Ithaca Chasma, which suggests the impact may have been responsible for the formation of the chasma.

Odysseus Crater, on the leading hemisphere of Tethys.

Tethys has two trojan satellites, Telesto and Calypso. These orbit in the same orbit as Tethys but are 60° ahead and behind it.

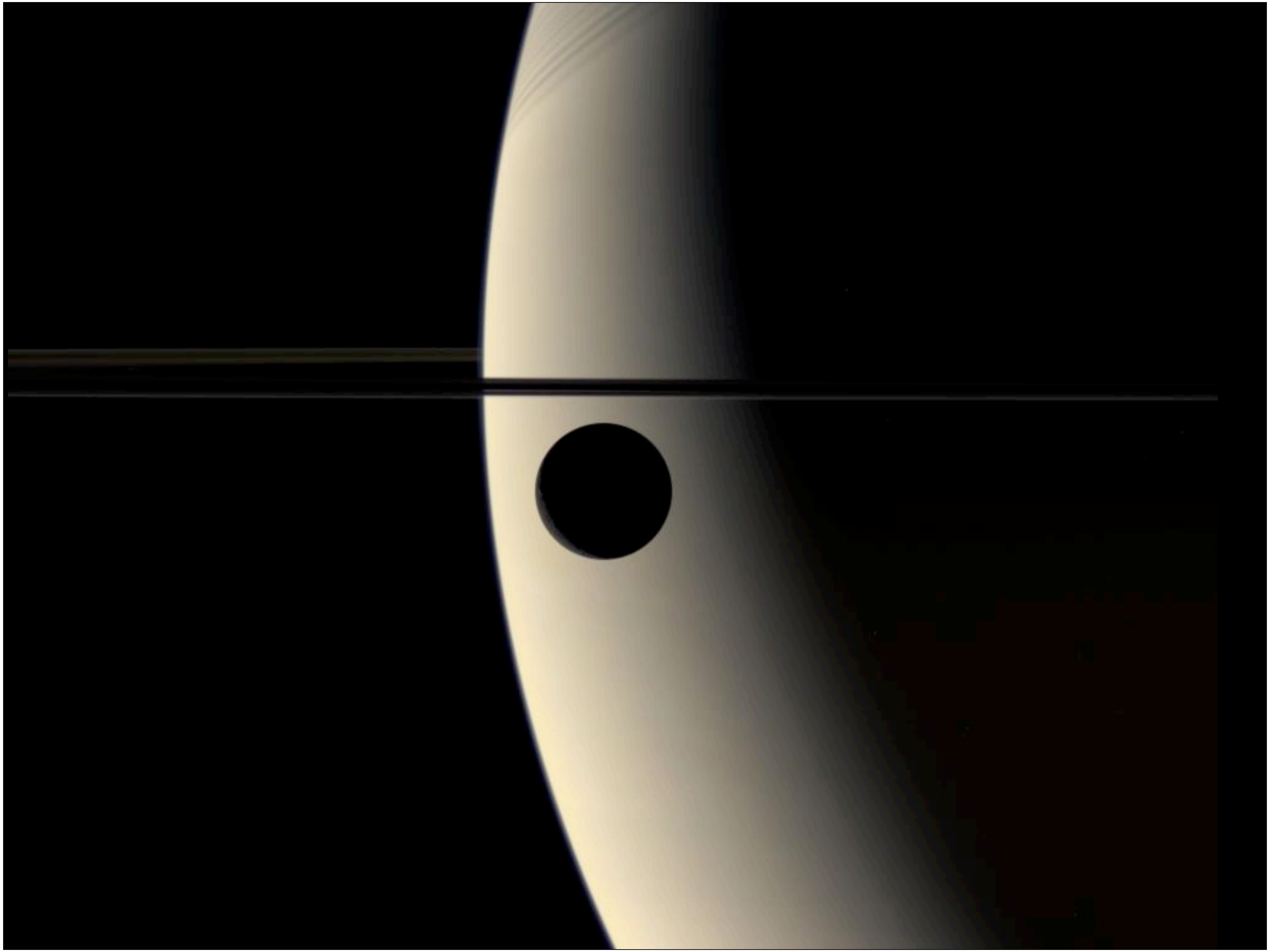


Dione (radius 560 km) is the densest of Saturn’s satellites. It has a bright icy surface (albedo 0.5), and its leading hemisphere is distinctly brighter than its trailing hemisphere.



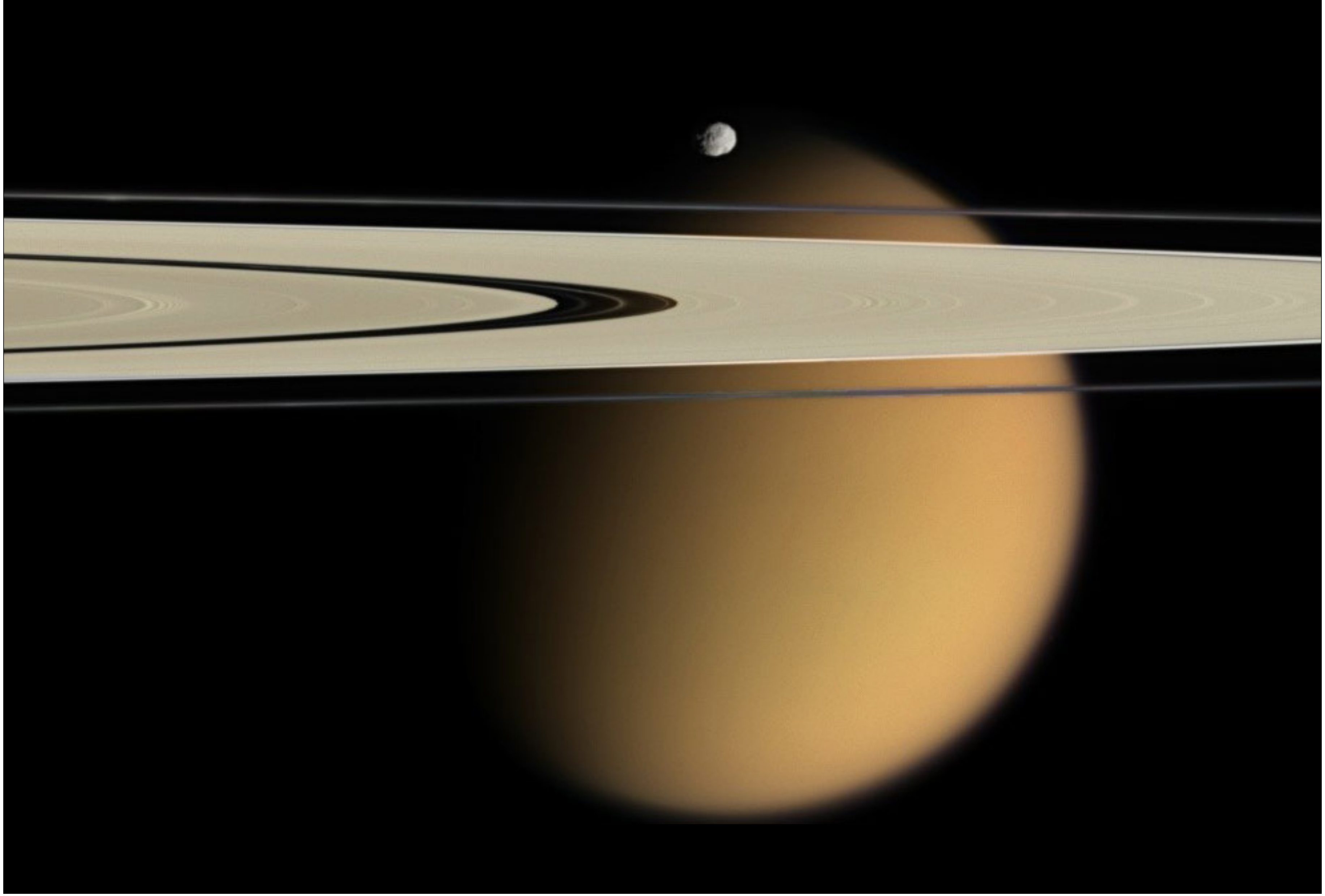
Rhea (radius 765 km) is the second largest of Saturn's moons. It is very similar to Dione: it also has vastly different leading and trailing hemispheres. The leading hemisphere is heavily cratered and uniformly bright. On the trailing hemisphere there is a network of bright swaths on a dark background and few visible craters.

Rhea's leading hemisphere, showing a large bright blotch.

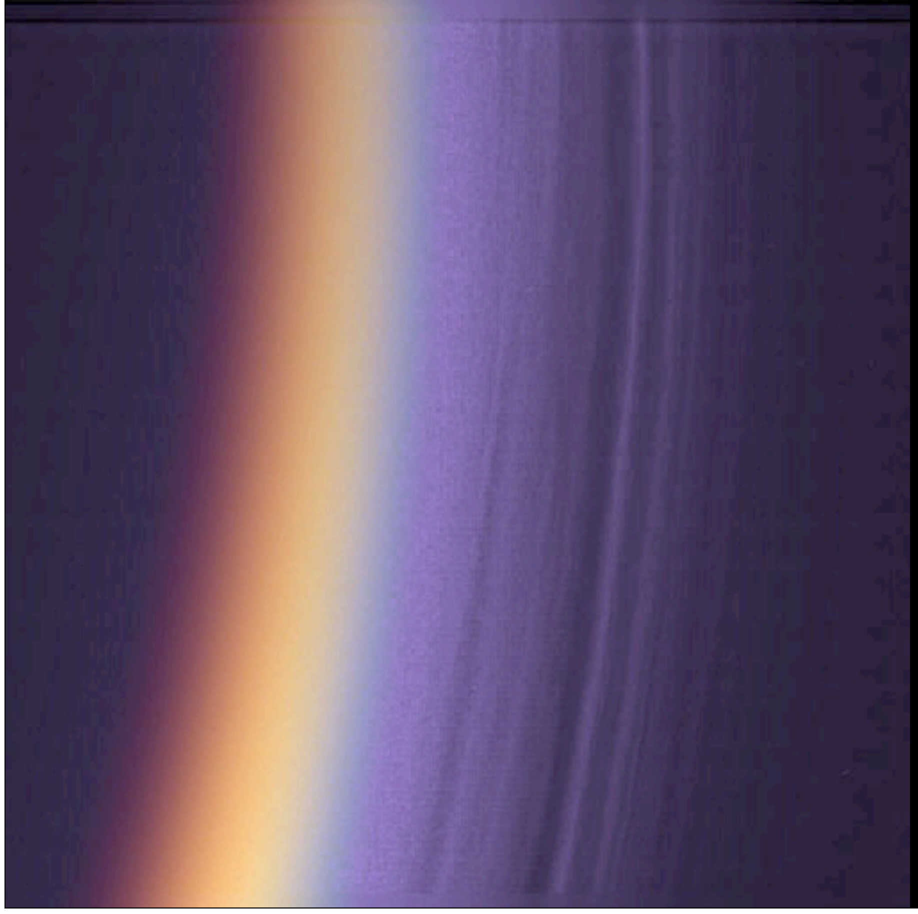


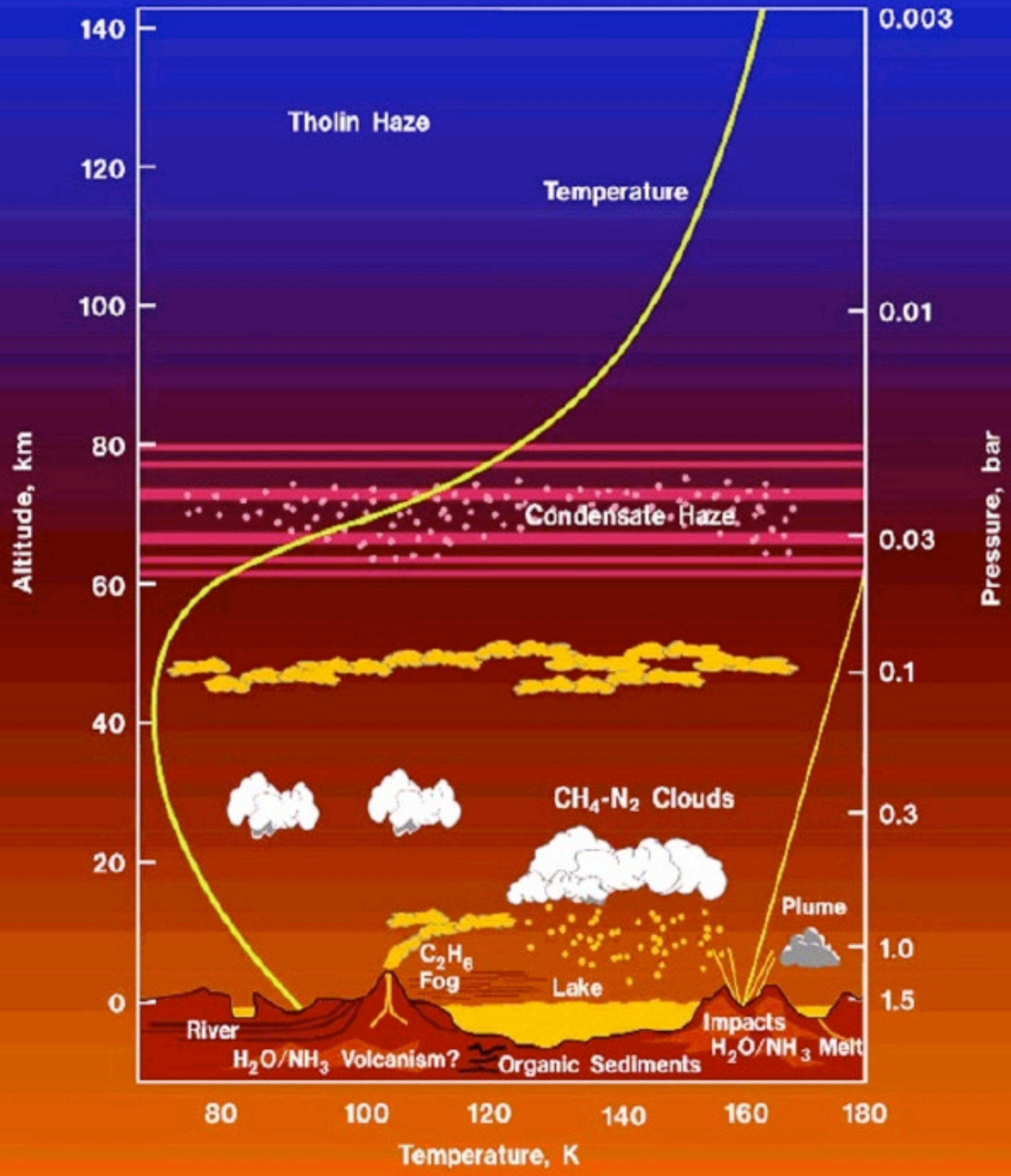
Titan (radius 2575 km) is Saturn's largest satellite and the second largest moon in the solar system (after Ganymede). It is the only satellite in the Solar System with an atmosphere. It is almost identical to Ganymede in mass and size, but is very different.

Small, battered Epimetheus before Saturn's A and F rings and smog-enshrouded Titan



Titan's surface pressure is more than 1.5 bar (50% higher than Earth's). The atmosphere is 94% nitrogen, with significant traces of various hydrocarbons making up much of the remainder. The organic compounds are formed when methane is destroyed by sunlight, so Titan's atmosphere is similar to the smog found over large cities, but much thicker.

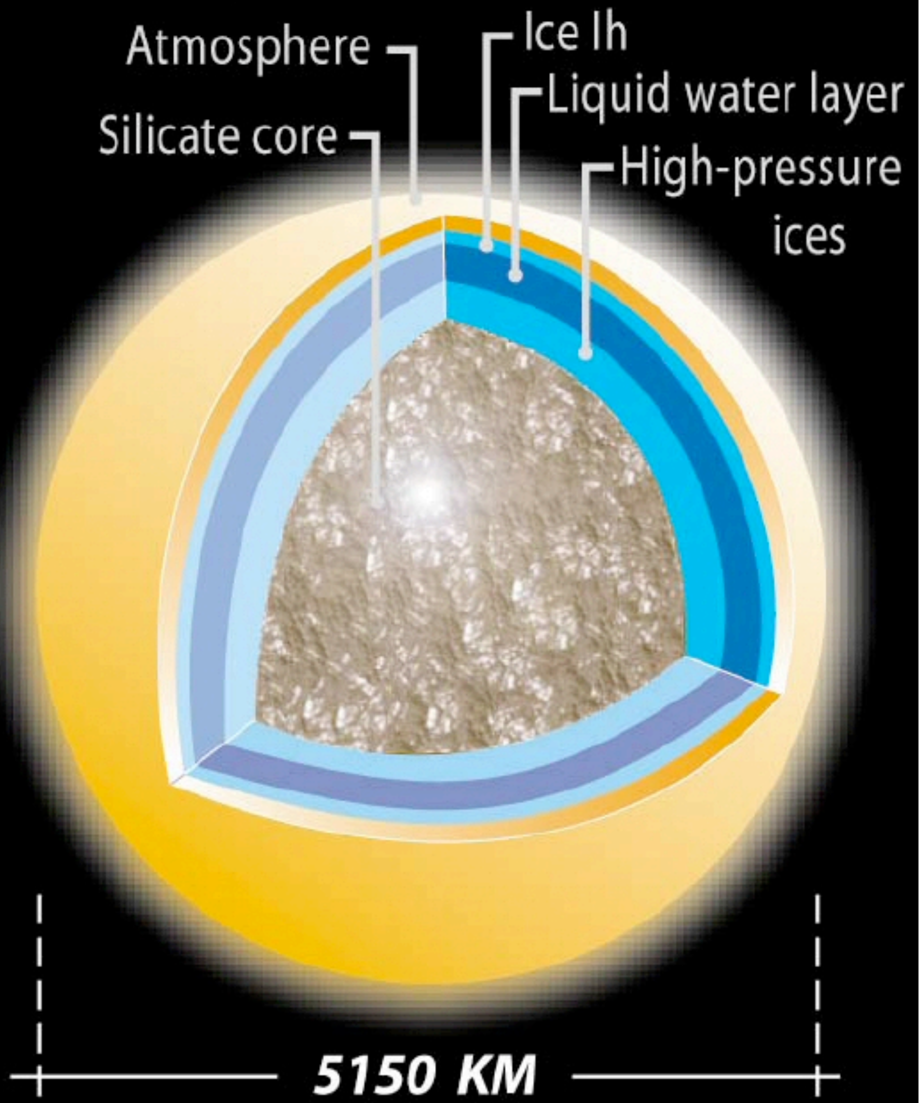




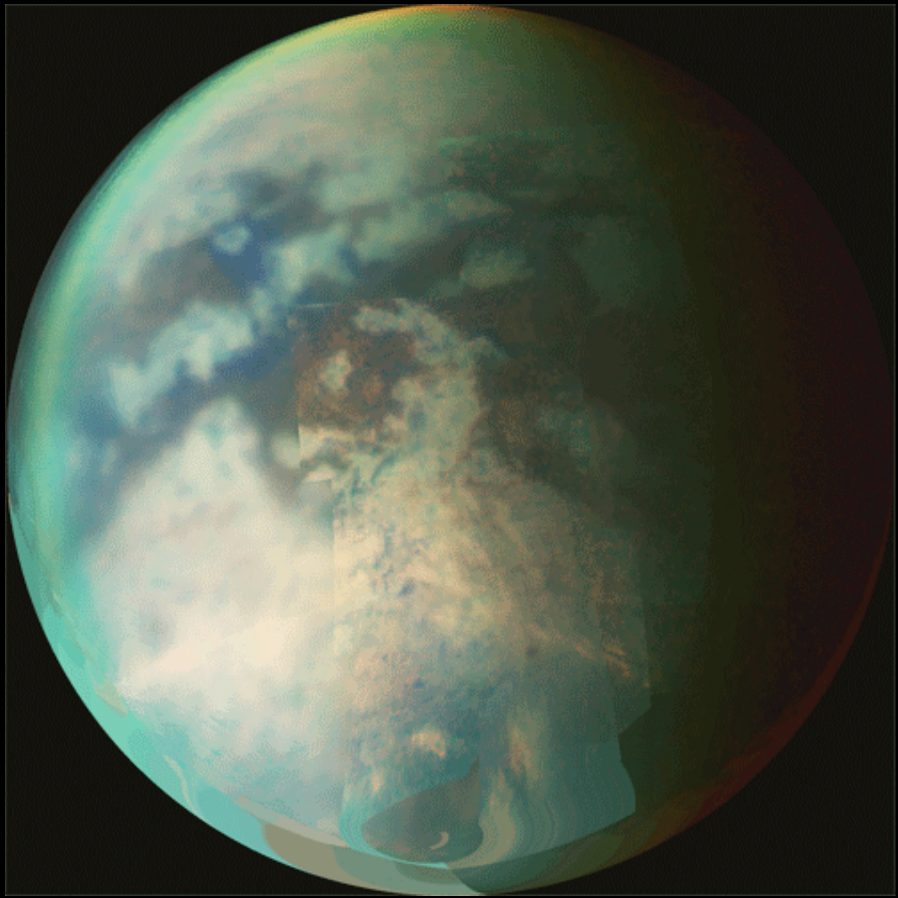
140
120
100
80
60
40
20
0
Altitude, km
0.003
0.01
0.03
0.1
0.3
1.0
1.5
Pressure, bar
Tholin Haze
Temperature
Condensate Haze
CH4-N2 Clouds
Plume
C2H6
Fog
Lake
River
H2O/NH3 Volcanism?
Organic Sediments
Impacts
H2O/NH3 Melt
80
100
120
140
160
180
Temperature, K

Titan's density is 1.88 g/cm^3, which means it must be half water ice and half rocky material. It is probably differentiated into several layers, with a rocky center surrounded by several layers of ice. Surface "rocks" on Titan are made of ice.

Titan's interior also includes a liquid water ocean, and probably large amounts of methane which can be outgassed to the surface.

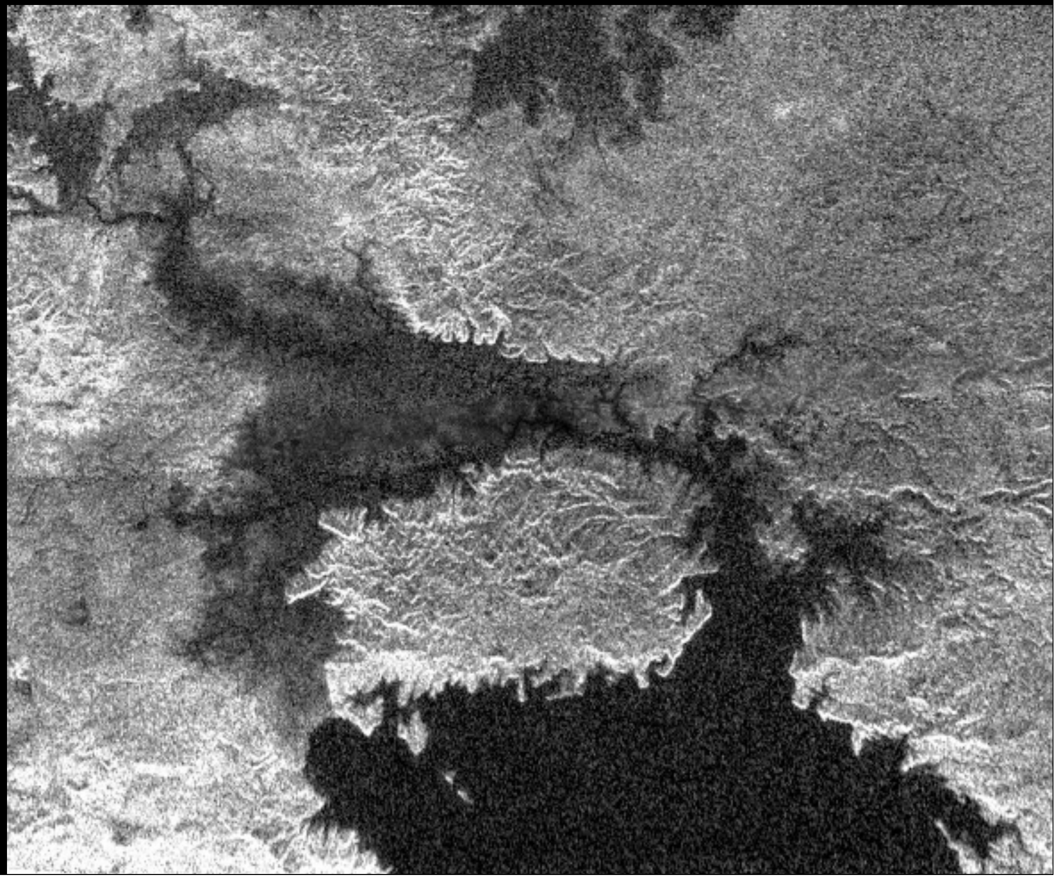


Titan's surface temperature is about –178°C. Infrared images allow us to see through the hazy atmosphere and down to the surface. We can see the remains of an old impact crater, as well as mountain ranges about 1.5 km high, covered by methane "snow".

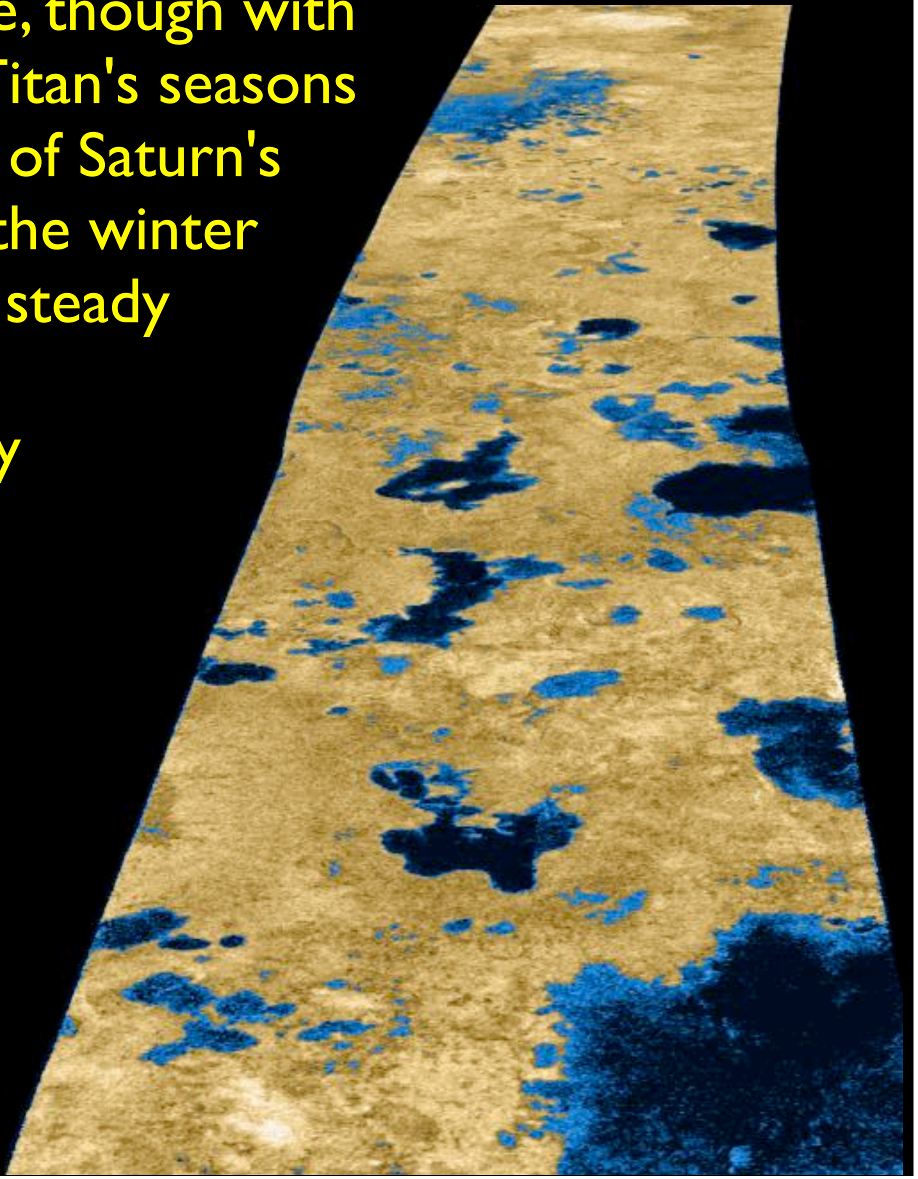


Composite of near-infrared images of Titan taken during two separate flybys.

Cassini took radar images during flybys of very smooth, dark features near Titan's north and south poles. These are almost certainly seas, probably filled with a combination of methane and ethane.

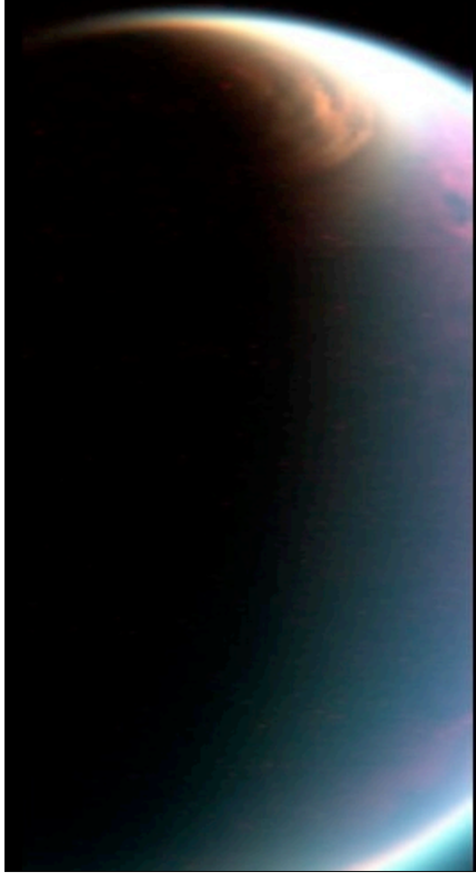


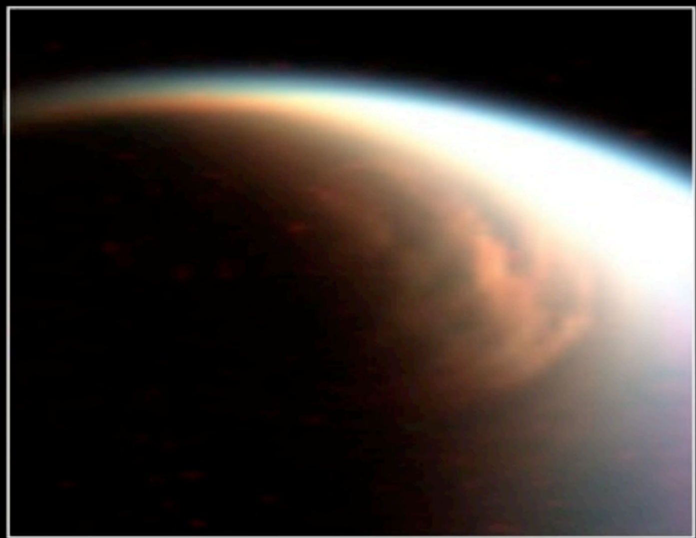
These lakes are the strongest evidence yet that Titan has an active hydrological cycle, though with a liquid other than water. As Titan's seasons change over the 29-year cycle of Saturn's orbit around the sun, lakes in the winter hemisphere should expand by steady methane rain, while summer hemisphere lakes shrink or dry up entirely.



False-colour perspective view of radar images of lakes; the image is 140 km across.

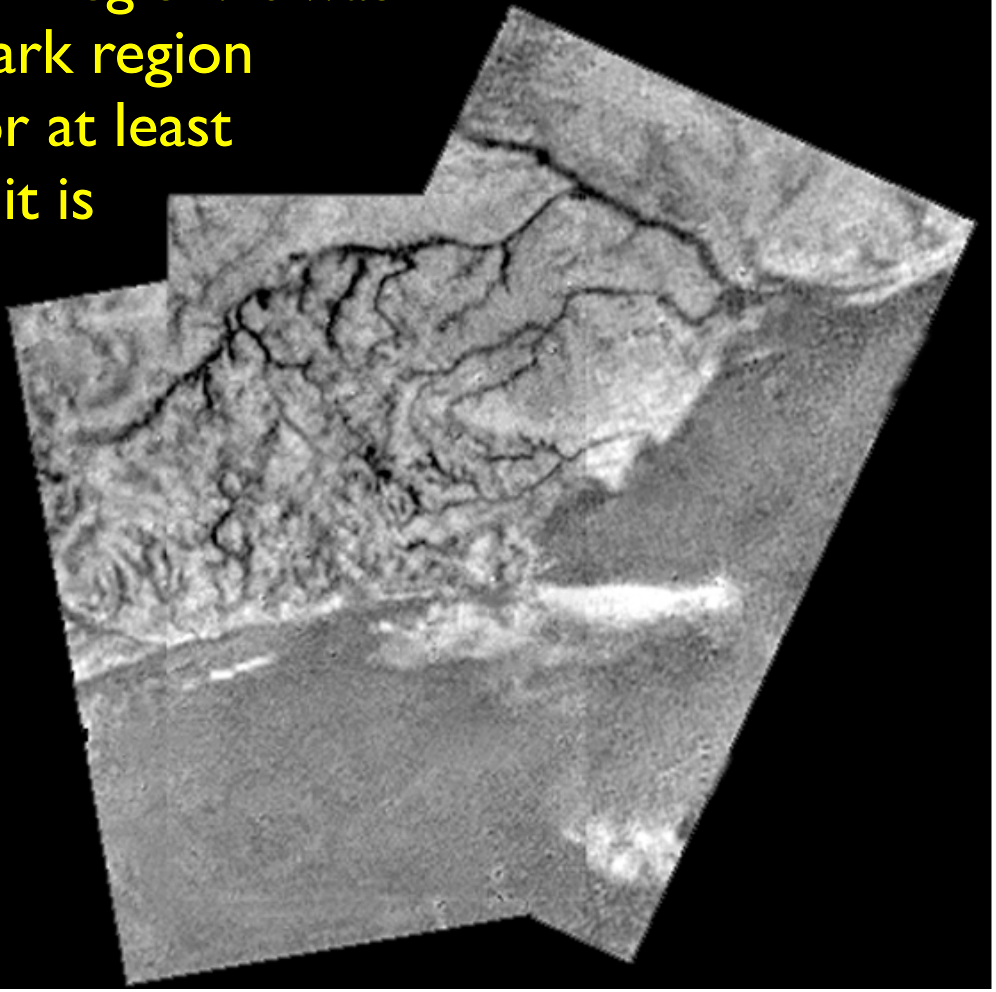
Cassini has imaged huge clouds over Titan. What they're made of is not clear, but they are presumably the source of the liquid recently seen on the surface. There is a fast-moving high-altitude wind, like a jet stream, moving at 720 km/h.



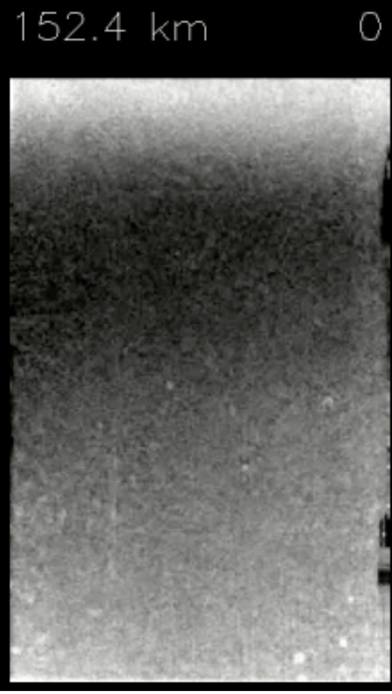


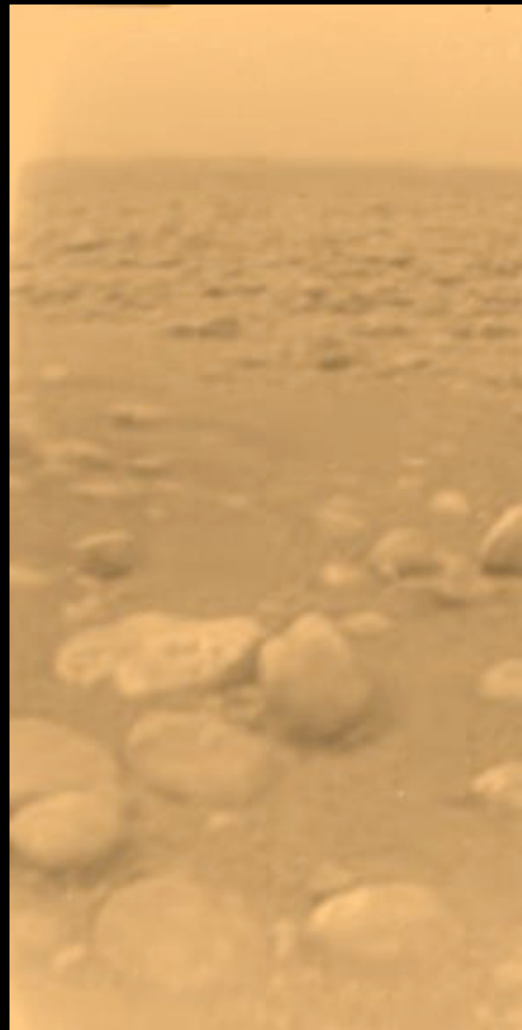
Giant cloud at the north pole, seen from a distance of 90,000 km

The Huygens probe descended to the surface of Titan on 14 January 2005. The Huygens images show pale hills crisscrossed with dark drainage channels. The channels lead into a wide, flat, darker region. It was initially thought that the dark region might be a lake of a fluid or at least tarry substance. However, it is now clear that Huygens landed on the dark region, and it is solid.



There is no immediate trace of liquid on the Huygens landing site. The images taken after the probe's landing show a flat plain covered in pebbles. The pebbles, which may be made of water ice, are somewhat rounded, which may indicate the action of fluids on them. It is possible that while Titan's rivers and lakes appear dry at the moment, rain may have occurred not long ago.



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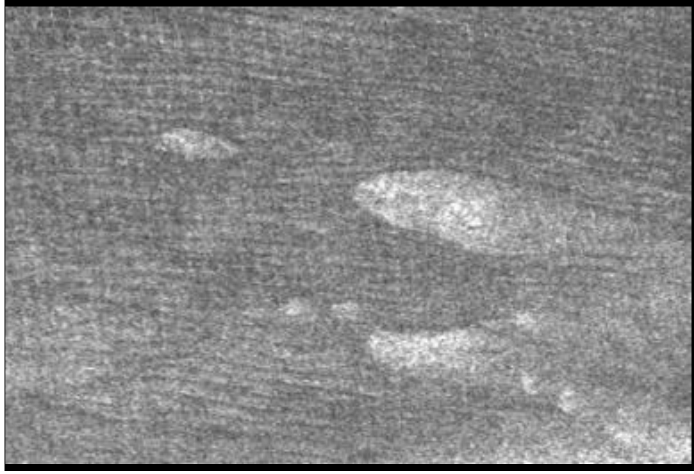
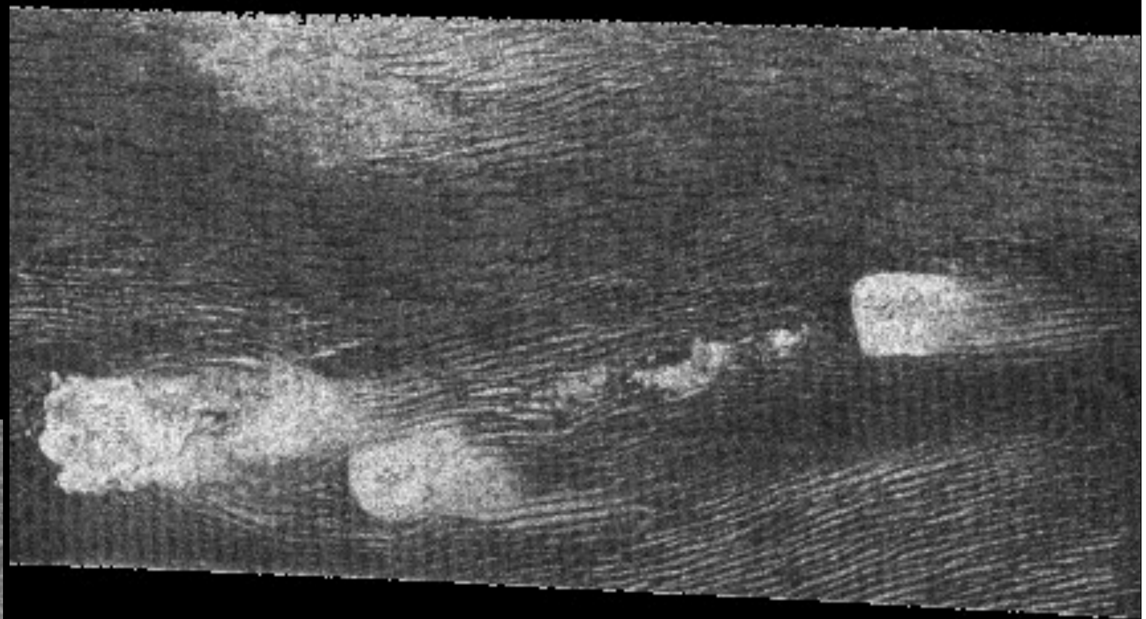
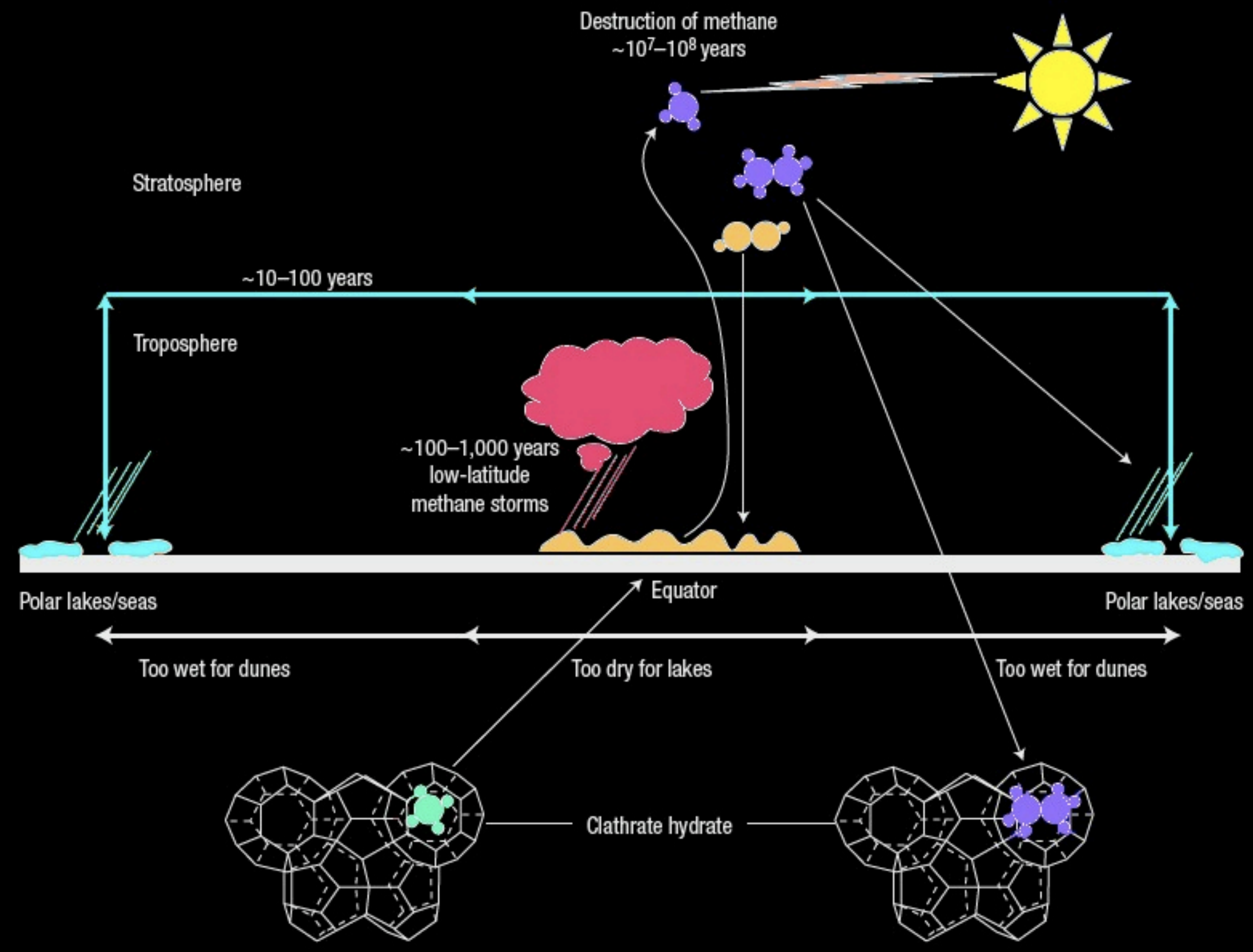
Cassini radar images near the equator saw long dark ridges that curve around the bright terrain. It is believed they are dunes that winds have blown across the surface of Titan from left to right.



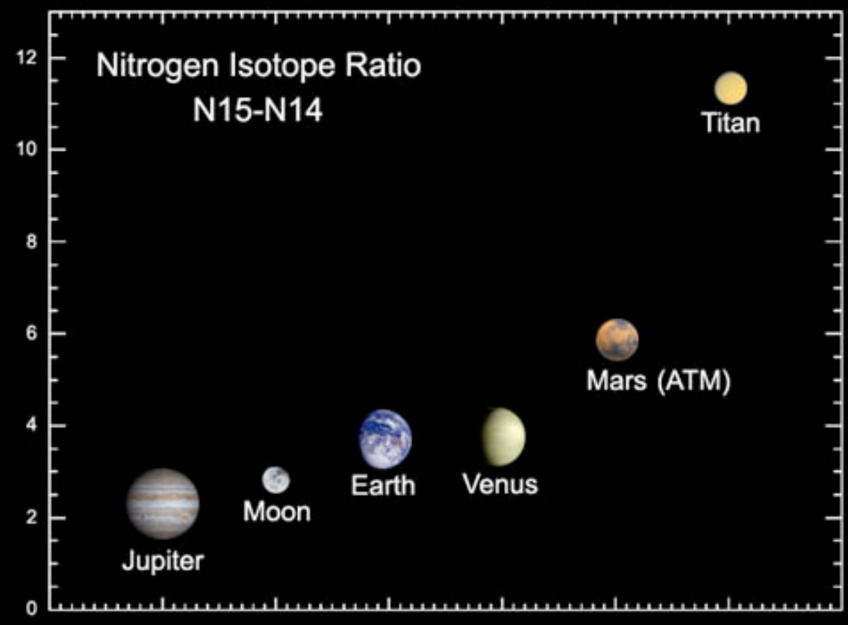




The methane cycle on Titan.

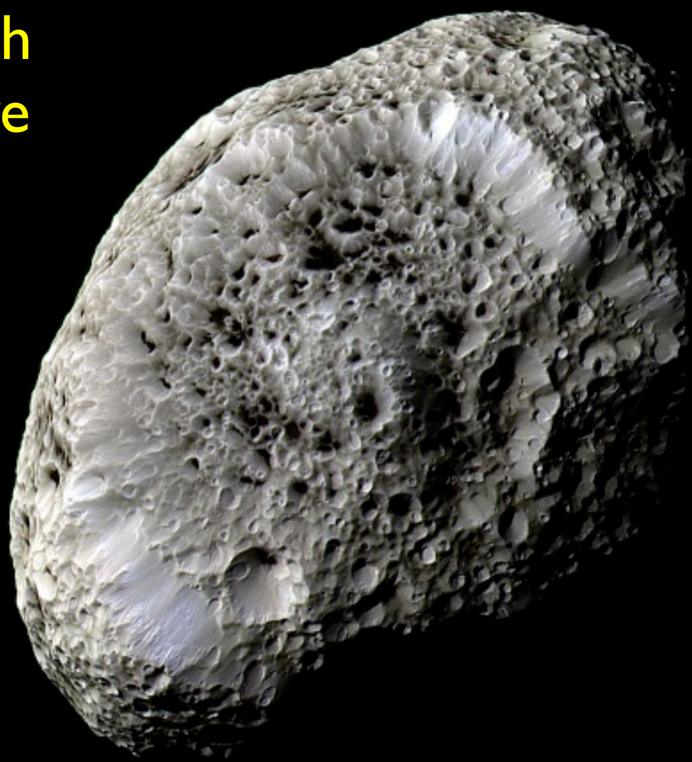
Measurements of the proportion of nitrogen-15 and nitrogen-14 in Titan’s atmosphere indicate that up to three-quarters of Titan's atmosphere may have been lost over geologic time.

Mars has a high ration of N^{15} to N^{14}, indicating that it has lost much of its atmosphere compared to other terrestrial planets. But Titan’s N^{15} to N^{14} ratio is even more extreme, indicating that it has lost even more. That makes the source of Titan's thick atmosphere more mysterious.

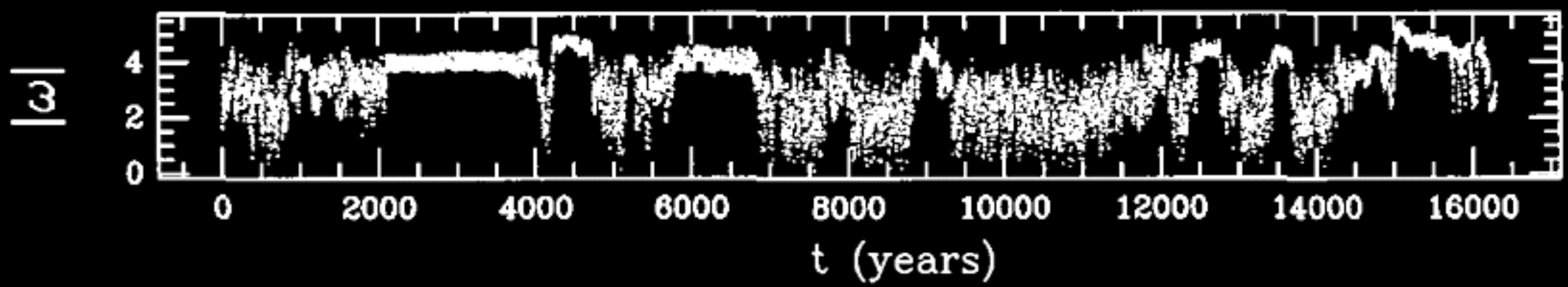


Hyperion (radius 143 km) is a highly irregular body. Its surface is uniform and very dark: it may be covered in material from Iapetus.

Cassini's flybys reveal that Hyperion is entirely saturated with deep, sharp-edged craters that give it the appearance of a giant sponge.



Hyperion is locked in a 3:4 orbital resonance with Titan. Its orbit is chaotic, that is, its axis of rotation wobbles so much that its orientation in space is unpredictable. It is possible that Hyperion is a fragment of a larger body that was broken by a large impact in the distant past, and was too close to Titan to have re-accreted. The same event has been linked to the enigmatic darkening of Iapetus.



Changes in Hyperion's spin frequency when integrated over 1,000,000 orbits. The motion varies from periods of complete chaotic tumbling to periods of regular looking behaviour (from Black et al. 1995)

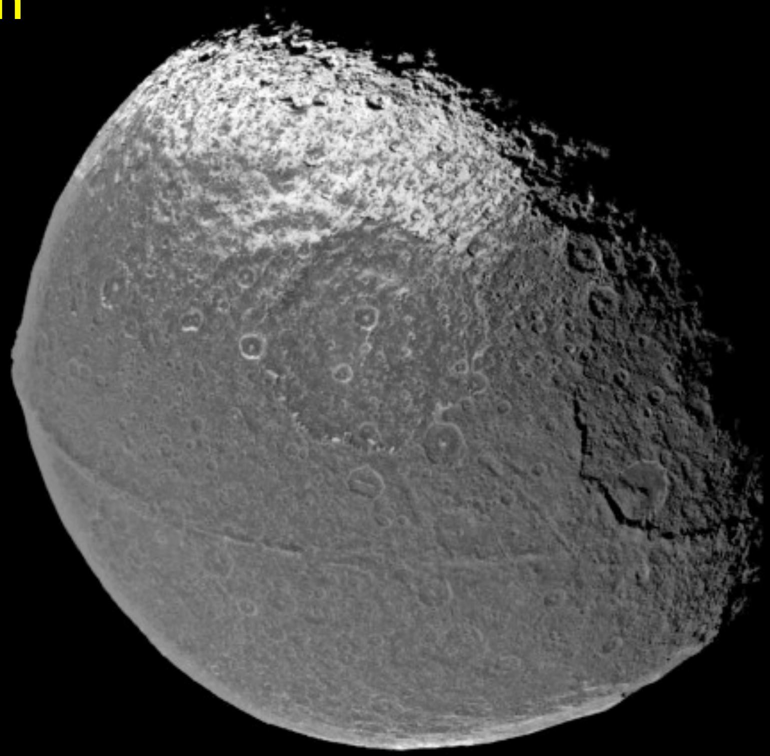
Iapetus (radius 730 km) is almost entirely water ice. Iapetus' leading and trailing hemispheres have very different albedos. The leading hemisphere has an albedo 0.03–0.05, while the trailing has albedo 0.5 – as bright as Europa.

Iapetus orbits much farther away from Saturn than any other large satellite, three times farther away than Titan. It is also the only one of Saturn's larger moons with an inclined orbit, 15° away from the ring plane.

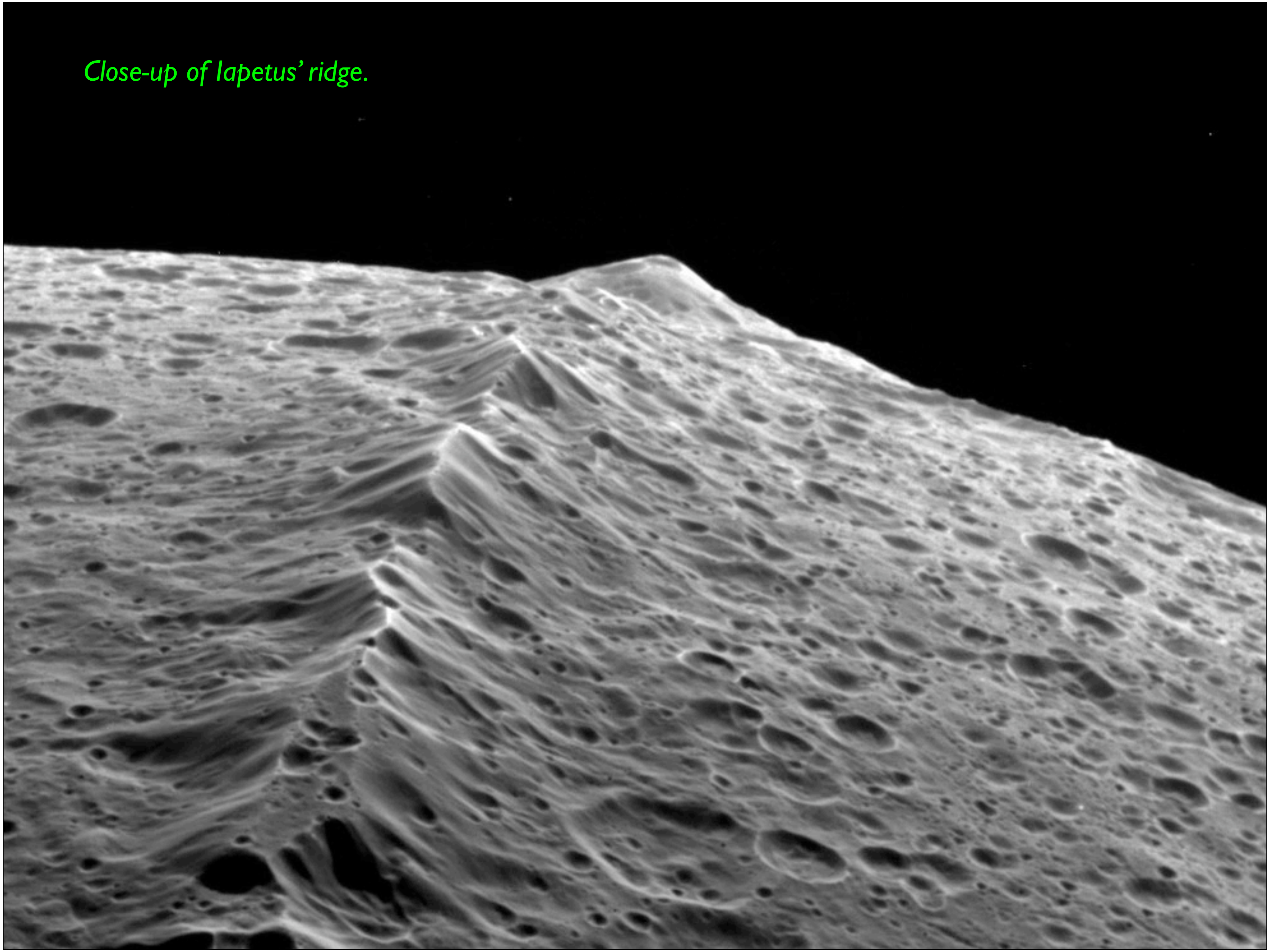
Voyager image of Iapetus, showing the dark and light terrains.

The most unique feature on Iapetus is a topographic ridge that coincides almost exactly with the equator, making Iapetus look like a walnut. The ridge is approximately 20 km wide and up to 20 km high. Along the roughly 1,300 kilometer (800 mile) length, it remains almost exactly parallel to the equator within a couple of degrees. The ridge appears only on the dark side.

The dark side appears to result from some dark material deposited on the icy surface. The origin and nature of this material is unclear. It may be dark debris from Phoebe, or it might consist of volcanic deposits.



Cassini view of the leading hemisphere of Iapetus.



Close-up of Iapetus' ridge.

Phoebe (radius 110 km) is almost 4 times more distant from Saturn than its nearest neighbour (Iapetus). Phoebe's eccentric, retrograde orbit and unusual albedo indicates that it may be a captured comet or Kuiper Belt object.

Its albedo is only 0.05, so it may be responsible for the dark surfaces of Hyperion and the leading hemisphere of Iapetus.

Cassini image of Phoebe taken in June 2004 from a distance of only 32,500 km.

So we can classify Saturn's moons into the same categories of activity we saw in Jupiter's moons:

	dead worlds	recently active worlds	active worlds
Jupiter	Callisto	Ganymede	Io Europa
Saturn	Mimas Iapetus Rhea	Tethys Dione	Enceladus Titan


Next week...
... we'll look at the outer planets:
Uranus, Neptune, and the minor planets beyond.

Further reading

There are no books containing results from *Cassini* yet: we're going to have to wait a few years before we get one of those. I have just one new book to recommend this week:

- **"Saturn: A New View"** by L. Lovett, J. Horvath and J. Cuzzi (Abrams 2006) contains 150 images from Cassini and Huygens. Not much text, unfortunately, but the images are truly astonishing.
- The book I mentioned last week, **"Satellites of the Outer Planets: Worlds in their own right"** by David Rothery (Oxford UP, 1999), has a good summary of Saturn's moons, at least up until Cassini.

As always, there are lots of good web-sites:

- The Cassini mission home page is at **"Cassini–Huygens: Mission to Saturn and Titan"**, http://saturn.jpl.nasa.gov/home/index.cfm
- Cassini has produced so many fantastic picures that it's hard to know where to start. One good place is the Cassini "Favourite Image" contest: http://ciclops.org/contest07.php?js=1
- Alan Taylor – the same chap who made the "All Solar System Bodies" image I recommended last week – has a selection of his favourite Cassini images at http://www.boston.com/bigpicture/2009/04/cassinis_continued_mission.html. He's very fond of the weird optical effects when the rings are refracted through the edge of Saturn's atmosphere, but they're certainly a gorgeous collection. If that's not enough, click on the "Previously" links to get more.

- A complete up-to-date list of all of Saturn's satellites can be found at Scott Sheppard's **"The Jupiter Satellite Page"**, http://www.ifa.hawaii.edu/~sheppard/satellites/ because it's subtitled "Now also the Giant Planet Satellite and Moon Page"
- **The Planetary Society** has excellent pages about Saturn's rings and moons, at http://www.planetary.org/saturn/rings.html and http://www.planetary.org/saturn/moons.html
- Two different views for the ages of Saturn's rings can be found at **"Science@NASA: The Real Lord of the Rings"**, http://science.nasa.gov/headlines/y2002/12feb_rings.htm and **"Saturn's rings may not be as young as they look"** http://www.sciencenews.org/view/generic/id/36716/title/Saturns_rings_not_as_young_as_they_look
- Great silliness: The Cassini CICLOPS team have written a game, so you can see what it's like playing golf in the differing gravity environments of Saturn's moons. It's surprisingly easy to lose your ball off the moon completely! http://ciclops.org/sector6/golf.php

Sources for images used:

All images of Saturn and its moons are from the NASA Planetary Photo Journal http://photojournal.jpl.nasa.gov/target/Saturn, unless otherwise indicated. I have given the Planetary Image Archive (PIA) number for each image

- Background image: NASA Planetary Photojournal PIA08934 http://photojournal.jpl.nasa.gov/catalog/PIA08934
- Spacecraft images: from NASA Solar System Exploration: Spacecraft images http://solarsystem.nasa.gov/multimedia/gallery.cfm?Category=Spacecraft
- Animation of Cassini's orbit: from Cassini-Huygens Operations http://saturn.jpl.nasa.gov/multimedia/videos/video-details.cfm?videoID=85
- Saturn portrait: PIA06193 http://photojournal.jpl.nasa.gov/catalog/PIA06193
- Ring shadows: PIA07772 http://photojournal.jpl.nasa.gov/catalog/PIA07772
- Saturn rotation: Hubblesite release 20 March 2007 http://hubblesite.org/newscenter/archive/releases/solar-system/2007/13/
- Oblate Saturn: Hubblesite gallery http://hubblesite.org/gallery/album/solar_system_collection/pr2001015c/
- Saturn tilting: Hubblesite gallery http://hubblesite.org/gallery/album/solar_system_collection/pr2001015a/
- Edge-on view of Saturn's rings: Hubblesite release 24 April 1996 http://hubblesite.org/newscenter/archive/releases/solar-system/1996/1996/16/results/50/
- Cassini ring plane crossing: from Astronomy Picture of the Day, 2005 May 4, compiled by Fernando Garcia Navarro, http://antwrp.gsfc.nasa.gov/apod/ap050504.html; movie PIA08356 http://photojournal.jpl.nasa.gov/catalog/PIA08356
- Saturn interior: from Courtney Seligman Online Astronomy Text http://cseligman.com/text/planets/saturn.htm
- Saturn's composition: from Journey through the Galaxy: Saturn, http://home.cwru.edu/~sjr16/advanced/saturn.html
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- Swirls in atmosphere: PIA08934 http://photojournal.jpl.nasa.gov/catalog/PIA08934
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- Aurorae: Hubblesite release 7 January 1998 http://hubblesite.org/newscenter/archive/releases/1998/05/image/a
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- Ring panorama: PIA06175 http://photojournal.jpl.nasa.gov/catalog/PIA06175
- Prometheus and F ring: PIA05402 http://photojournal.jpl.nasa.gov/catalog/PIA05402

- F ring: PIA06098 http://photojournal.jpl.nasa.gov/catalog/PIA06098
- Rings labelled: ESA Cassini-Huygens http://www.esa.int/SPECIALS/Cassini-Huygens/SEM7Q6HHZTD_1.html
- Backlit rings: PIA08329 http://photojournal.jpl.nasa.gov/catalog/PIA08329
- Ring views: PIA05421 http://photojournal.jpl.nasa.gov/catalog/PIA05421 and PIA07631 http://photojournal.jpl.nasa.gov/catalog/PIA07631
- Mimas' shadow on the rings: from http://www.boston.com/bigpicture/2009/04/cassinis_continued_mission.html
- Painting of Saturn's ring particles: by William Hartmann, http://www.psi.edu/hartmann/planets.html
- Prometheus and Pandora: PIA07712 http://photojournal.jpl.nasa.gov/catalog/PIA07712
- Ring shepherding satellites: from Astronomy 121: Saturn by Jim Schombert, http://abyss.uoregon.edu/~js/ast121/lectures/lec20.html
- Pan & Prometheus: PIA10468 http://photojournal.jpl.nasa.gov/catalog/PIA10468
- Prometheus strands: PIA10593 http://photojournal.jpl.nasa.gov/catalog/PIA10593
- Ring composition: PIA05075 http://photojournal.jpl.nasa.gov/catalog/PIA05075
- Roche limit: from Wikipedia: Roche Limit http://en.wikipedia.org/wiki/Roche_limit
- Voyager images of Saturn's moons: from Voyager – Images http://voyager.jpl.nasa.gov/image/images/saturn/1bg.jpg
- Saturn's moons: ESA Cassini-Huygens http://www.esa.int/SPECIALS/Cassini-Huygens/SEM7Q6HHZTD_1.html
- Pandora and Prometheus near F Ring: PIA05393 http://photojournal.jpl.nasa.gov/catalog/PIA05393
- Satellite orbits: from The Giant Planet Satellite and Moon Page http://www.ifa.hawaii.edu/~sheppard/satellites/satsatdata.html
- Leading/trailing hemispheres: Rhea: PIA07554 http://photojournal.jpl.nasa.gov/catalog/PIA07554 and PIA06575 http://photojournal.jpl.nasa.gov/catalog/PIA06575. Dione: PIA07687 http://photojournal.jpl.nasa.gov/catalog/PIA07687 and PIA08256 http://photojournal.jpl.nasa.gov/catalog/PIA08256. Iapetus: PIA08848 http://photojournal.jpl.nasa.gov/catalog/PIA08848 and PIA08177 http://photojournal.jpl.nasa.gov/catalog/PIA08177
- Janus and Epimetheus: PIA08170 http://photojournal.jpl.nasa.gov/catalog/PIA08170
  Janus in front of Saturn: PIA08296 http://photojournal.jpl.nasa.gov/catalog/PIA08296
- Orbits of Epimetheus and Janus: from Astronomy 121: Saturn by Jim Schombert , http://abyss.uoregon.edu/~js/ast121/lectures/epimetheus_and_janus.html and from Lissauer, Goldreich & Tremaine, "Evolution of the Janus-Epimetheus coorbital resonance due to torques from Saturn's rings", Icarus 64 425 (1985)

- Prometheus: PIA07549 http://photojournal.jpl.nasa.gov/catalog/PIA07549
  Pandora: PIA07632 http://photojournal.jpl.nasa.gov/catalog/PIA07632
- Mimas: PIA06258 http://photojournal.jpl.nasa.gov/catalog/PIA06258 and PIA06582 http://photojournal.jpl.nasa.gov/catalog/PIA06582
- Mimas in front of Saturn: PIA06142 http://photojournal.jpl.nasa.gov/catalog/PIA06142
- Enceladus: PIA07709 http://photojournal.jpl.nasa.gov/catalog/PIA07709
- Enceladus south pole: PIA07800 http://photojournal.jpl.nasa.gov/catalog/PIA07800
- Enceladus geysers: PIA08386 http://photojournal.jpl.nasa.gov/catalog/PIA08386
- Model for Enceladus geysers: Cassini-Huygens news release 9 March 2006 http://saturn.jpl.nasa.gov/news/press-release-details.cfm?newsID=639
- Sources of the jets: PIA08385 http://photojournal.jpl.nasa.gov/catalog/PIA08385
- Enceladus fractures: PIA11133 http://photojournal.jpl.nasa.gov/catalog/PIA11133
- Enceladus and Saturn's magnetic field: Cassini-Huygens news release 22 March 2007 http://saturn.jpl.nasa.gov/multimedia/images/image-details.cfm?imageID=2545
- Tethys: PIA07738 http://photojournal.jpl.nasa.gov/catalog/PIA07738
- Odysseus basin on Tethys: PIA07693 http://photojournal.jpl.nasa.gov/catalog/PIA07693
- Dione in front of Saturn: PIA07744 http://photojournal.jpl.nasa.gov/catalog/PIA07744
- Rhea: PIA08189 http://photojournal.jpl.nasa.gov/catalog/PIA08189
- Rhea occults Saturn: from Astronomy Picture of the Day 11 July 2006 http://antwrp.gsfc.nasa.gov/apod/ap060711.html
- Titan: PIA06230 http://photojournal.jpl.nasa.gov/catalog/PIA06230
- Titan, Epimetheus and ring: from http://www.boston.com/bigpicture/2009/04/cassinis_continued_mission.html
- Titan's atmosphere: PIA06160 http://photojournal.jpl.nasa.gov/catalog/PIA06160
- Titan atmosphere model: Cassini visuals http://www.jpl.nasa.gov/media/cassini-102504/visuals.html
- and interior: Mark Elowitz: Titan Exobiology http://www.markelowitz.com/titan.htm
- Images of Titan's surface: Cassini-Huygens release 12 December 2006 http://saturn.jpl.nasa.gov/news/press-release-details.cfm?newsID=709
- Clouds on Titan: PIA09171 http://photojournal.jpl.nasa.gov/catalog/PIA09171
- Radar images of seas: PIA09182 http://photojournal.jpl.nasa.gov/catalog/PIA09182 and PIA09102 http://photojournal.jpl.nasa.gov/catalog/PIA09102

- Huygens descent through Titan's atmosphere: from Cassini-Huygens Video, http://saturn.jpl.nasa.gov/multimedia/videos/video-details.cfm?videoID=79
- Rain on Titan: painting by Mark Garlick, from Astronomy Picture of the Day 2 August 2006 http://antwrp.gsfc.nasa.gov/apod/ap060802.html
- Dunes on Titan: PIA08738 http://photojournal.jpl.nasa.gov/catalog/PIA08738 and PIA03567 http://photojournal.jpl.nasa.gov/catalog/PIA03567
- Methane cycle: from Lunine & Atreya, "The methane cycle on Titan", Nature Geoscience 1, 159 (2008)
- Nitrogen ratios in Titan's atmosphere: from The Planetary Society, 28 October 2004, http://www.planetary.org/news/2004/cassini_titan00a_results1_1028.html
- Hyperion: PIA07740 http://photojournal.jpl.nasa.gov/catalog/PIA07740
- Hyperion chaos: from Black, Nicholson & Thomas 1995, "Hyperion: Rotational dynamics", Icarus 117, p. 149
- Hyperion flyby: PIA07742 http://photojournal.jpl.nasa.gov/catalog/PIA07742
- Voyager image of Iapetus: PIA00348 http://photojournal.jpl.nasa.gov/catalog/PIA00348
- Cassini images of Iapetus: PIA06166 http://photojournal.jpl.nasa.gov/catalog/PIA06166 and PIA08404 http://photojournal.jpl.nasa.gov/catalog/PIA08404
- Phoebe: PIA06064 http://photojournal.jpl.nasa.gov/catalog/PIA06064