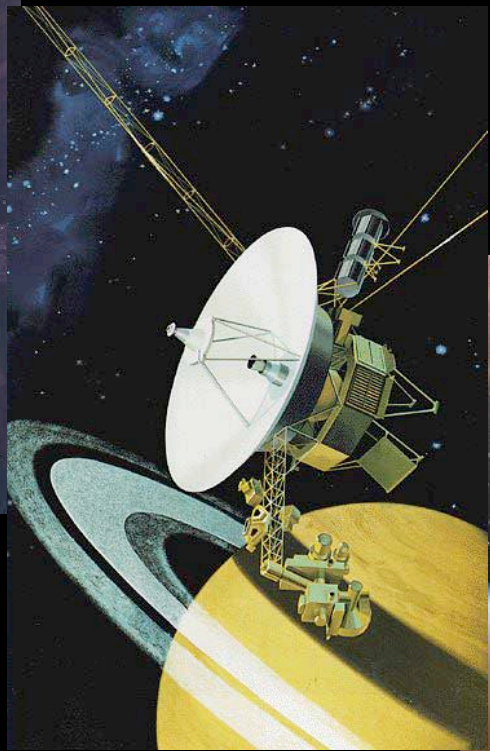

Modern Astronomy:
Voyage to the Planets
Lecture 7
Saturn
Lord of the Rings
University of Sydney
Centre for Continuing Education
Autumn 2005

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



Saturn

Basic facts

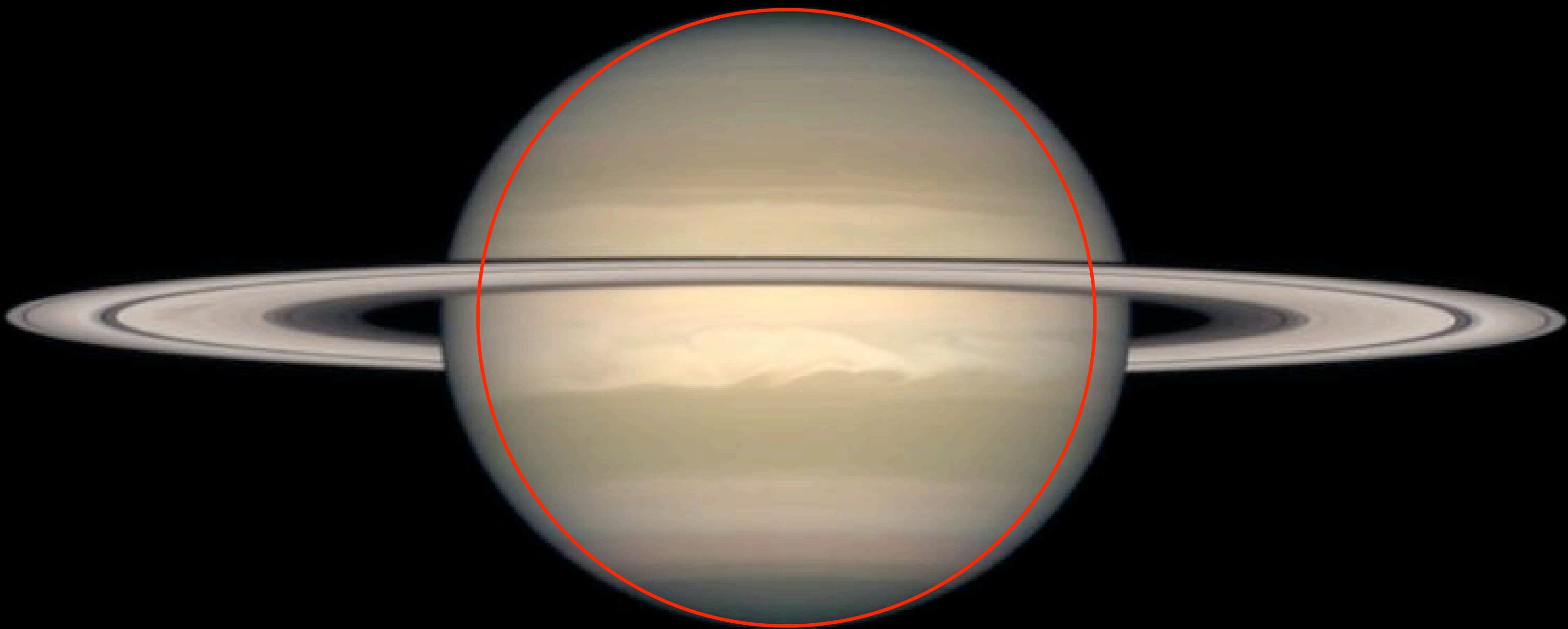
	Saturn	Saturn/Earth
Mass	568×10^{24} kg	95.159
Radius	60,268 km	9.449
Mean density	0.687 g/cm^3	0.125
Gravity (eq., 1 bar)	10.44 m/s^2	1.065
Semi-major axis	1433.53×10^6 km	9.582
Period	10,759.22 d	29.457
Orbital inclination	2.485^o	-
Orbital eccentricity	0.0565	2.928
Axial tilt	26.73^o	1.140
Rotation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

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

Hubble animation of Saturn's rotation in 1990.

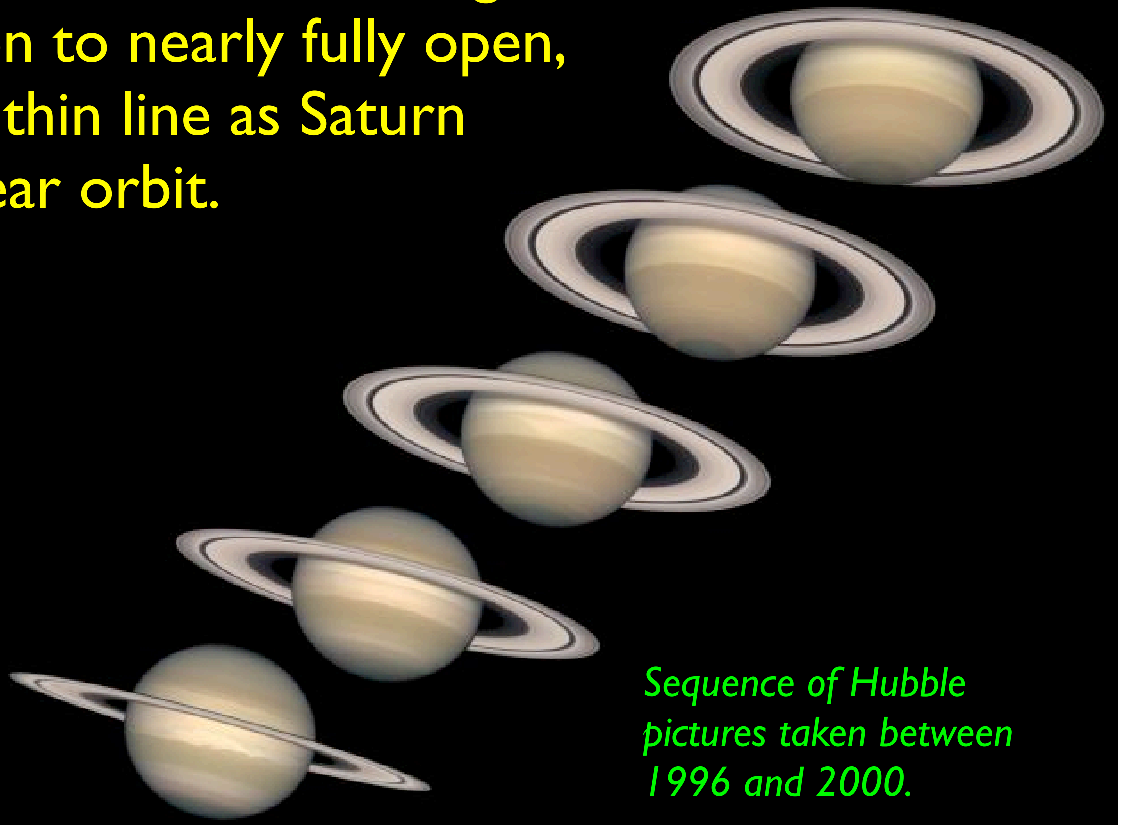
Saturn's low density and rapid rotation make Saturn the most oblate planet: its equatorial and polar diameters vary by almost 10%.



Hubble picture of Saturn taken in 1996

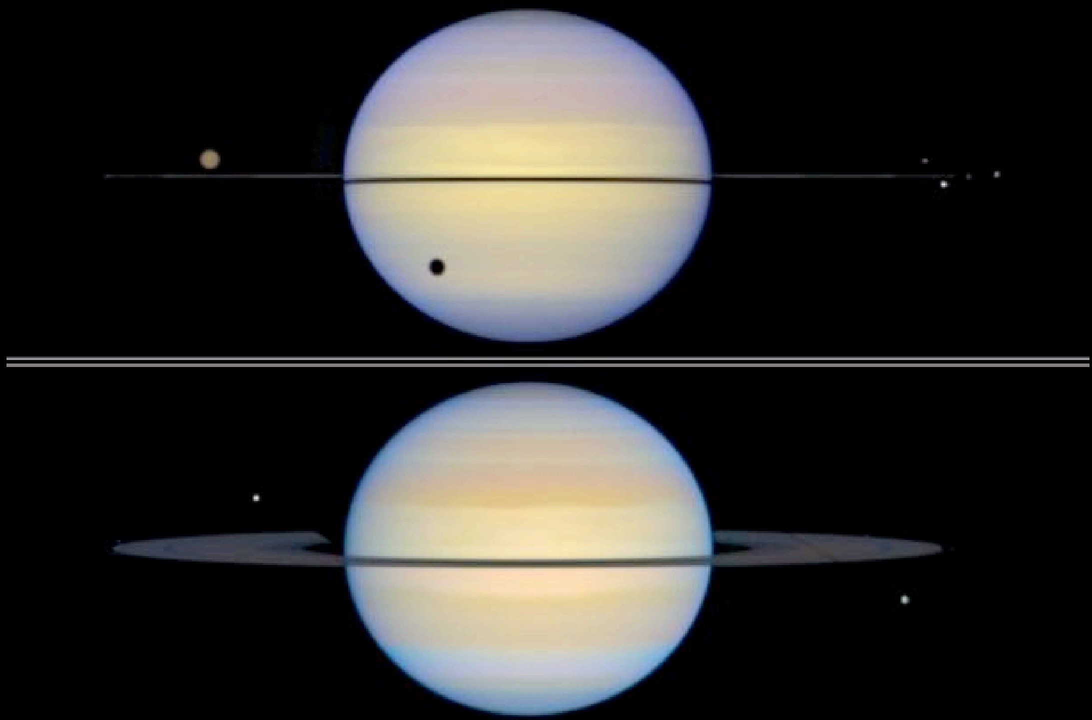
Saturn's equator is tilted relative to its orbit by 27°, very similar to the 23° tilt of the Earth. As Saturn moves along its orbit, first one hemisphere, then the other is tilted towards the Sun.

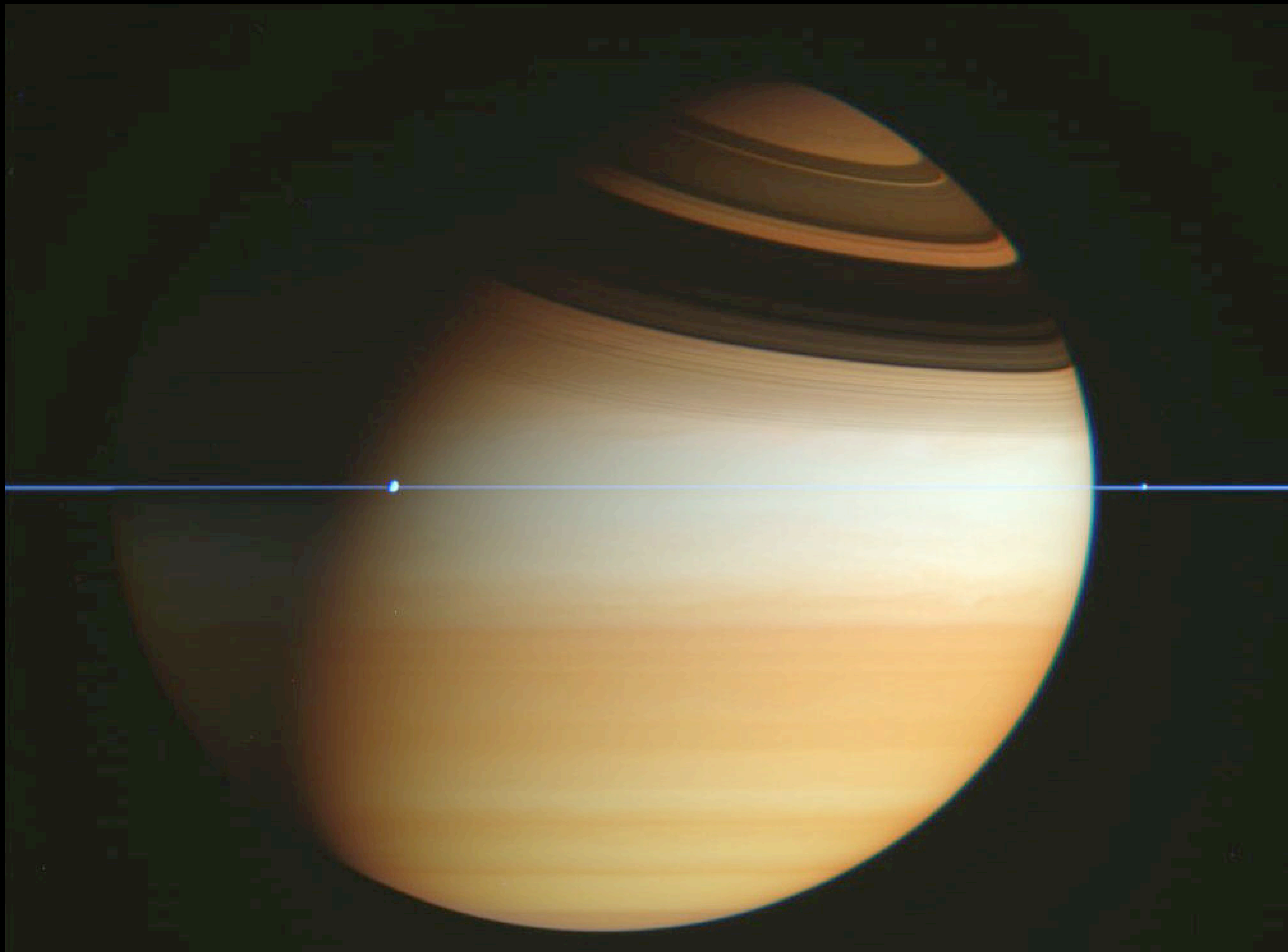
From the Earth, we can see Saturn's rings open up from edge-on to nearly fully open, then close again to a thin line as Saturn moves along its 29 year orbit.



Sequence of Hubble pictures taken between 1996 and 2000.

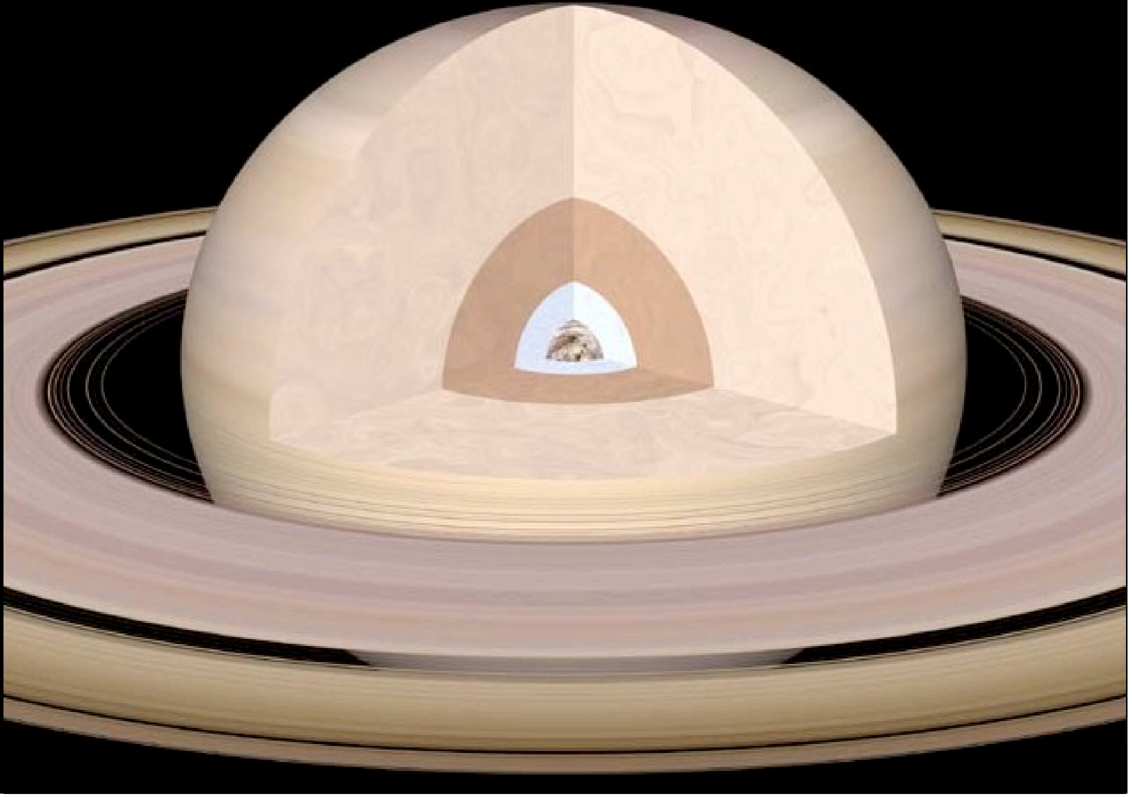
In 1995, Hubble took these pictures of the ring plane crossing, when Saturn's rings almost disappear to observers at Earth.



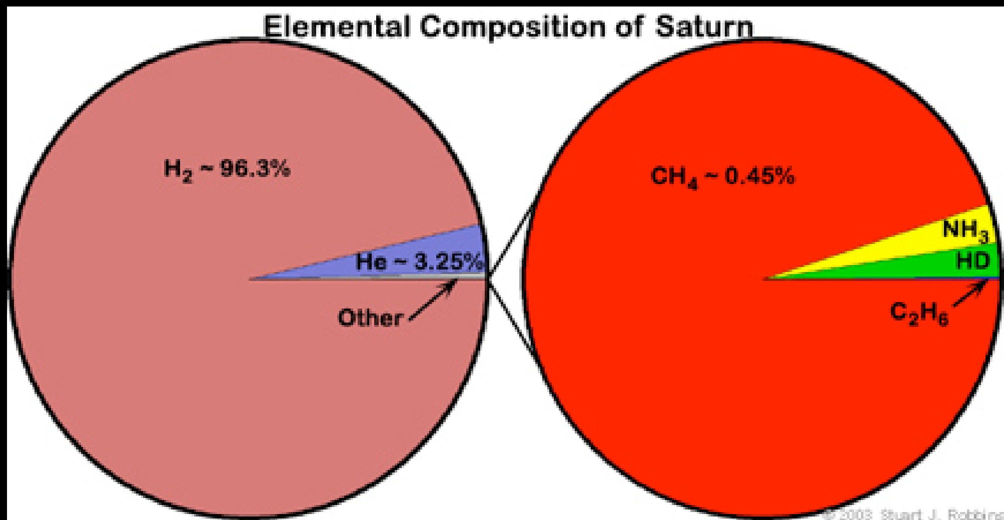


Cassini's ring plane crossing

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.

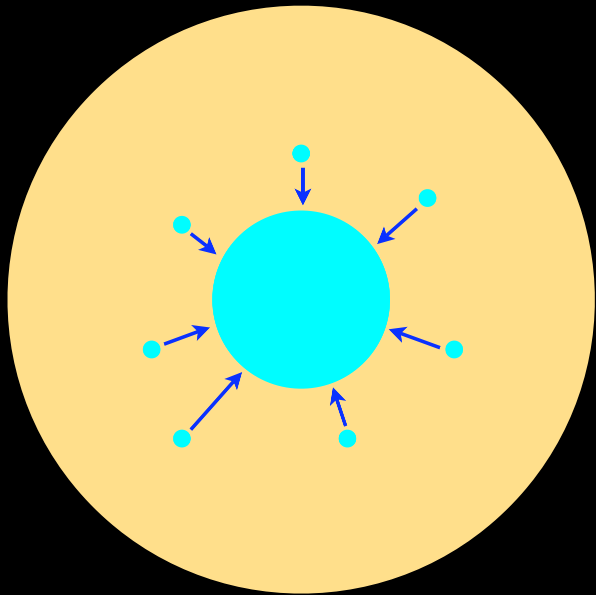


Saturn’s atmosphere is similar to Jupiter’s, consisting almost entirely of hydrogen and helium, with trace amounts of other gases. However, Saturn’s atmosphere is deficient in helium compared to Jupiter’s, which contains 10% helium.

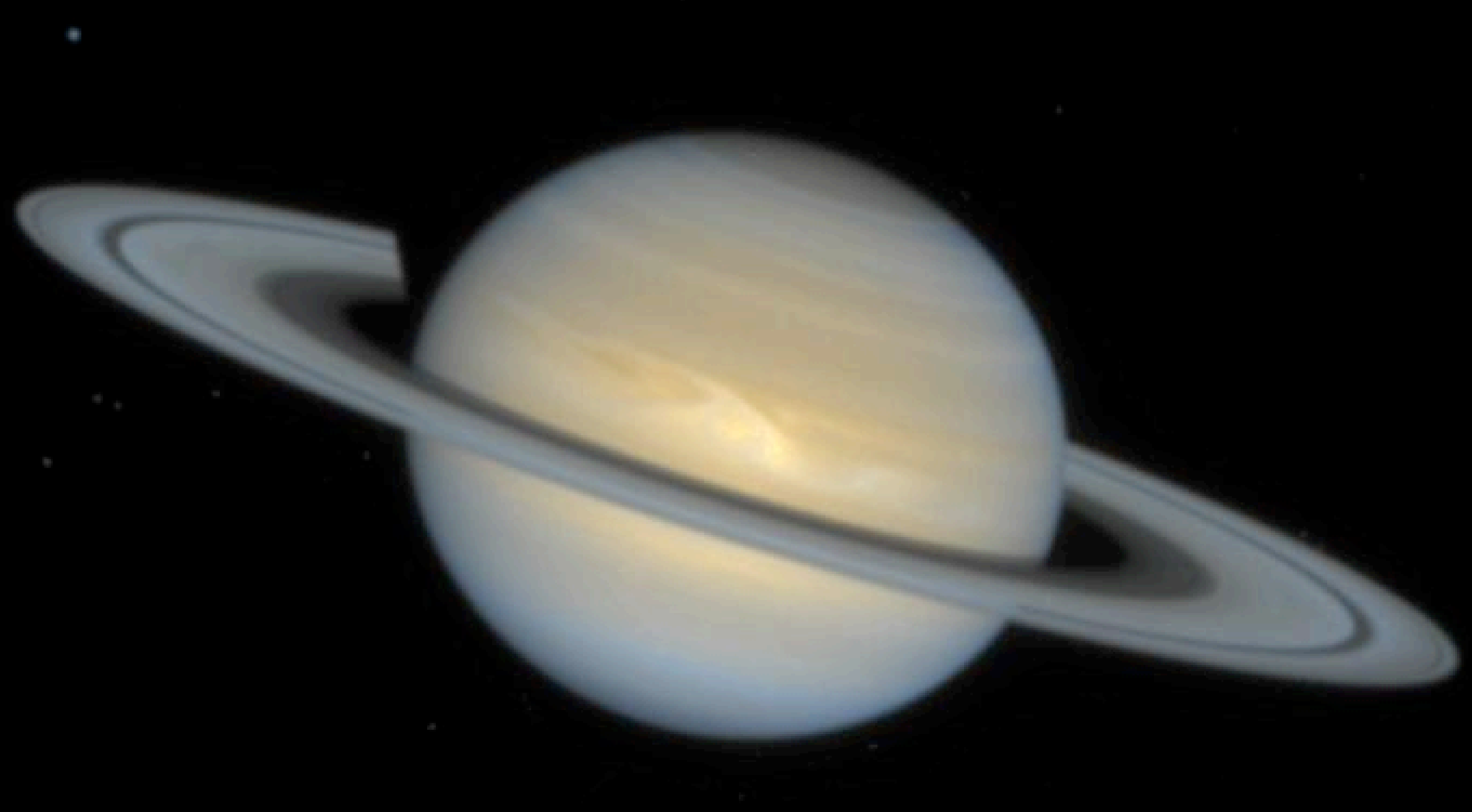


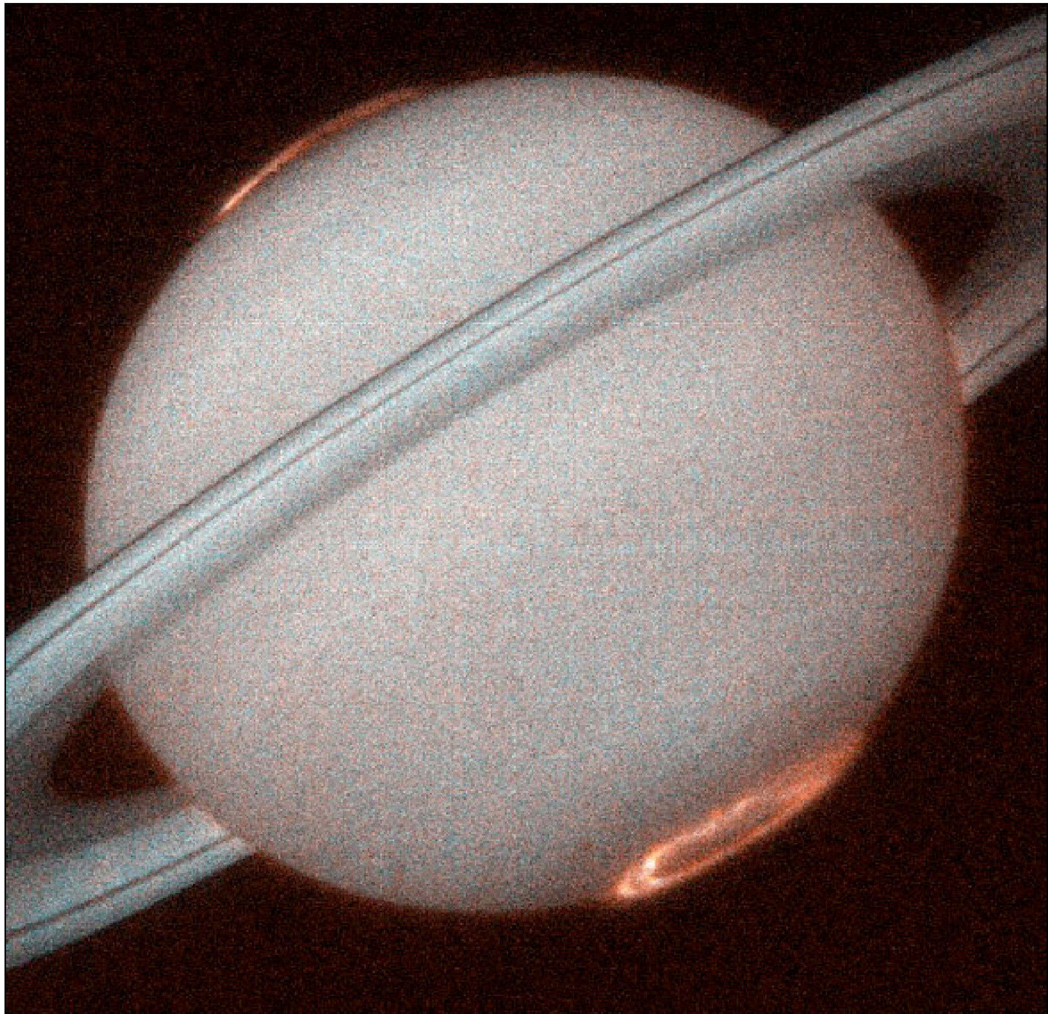
Like Jupiter, Saturn radiates more energy into space than it receives from the Sun: in fact, Saturn radiates more heat than Jupiter. Jupiter's remnant heat is leftover energy from the time of formation. But, since Saturn is less massive than Jupiter, it should have less leftover energy.

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.



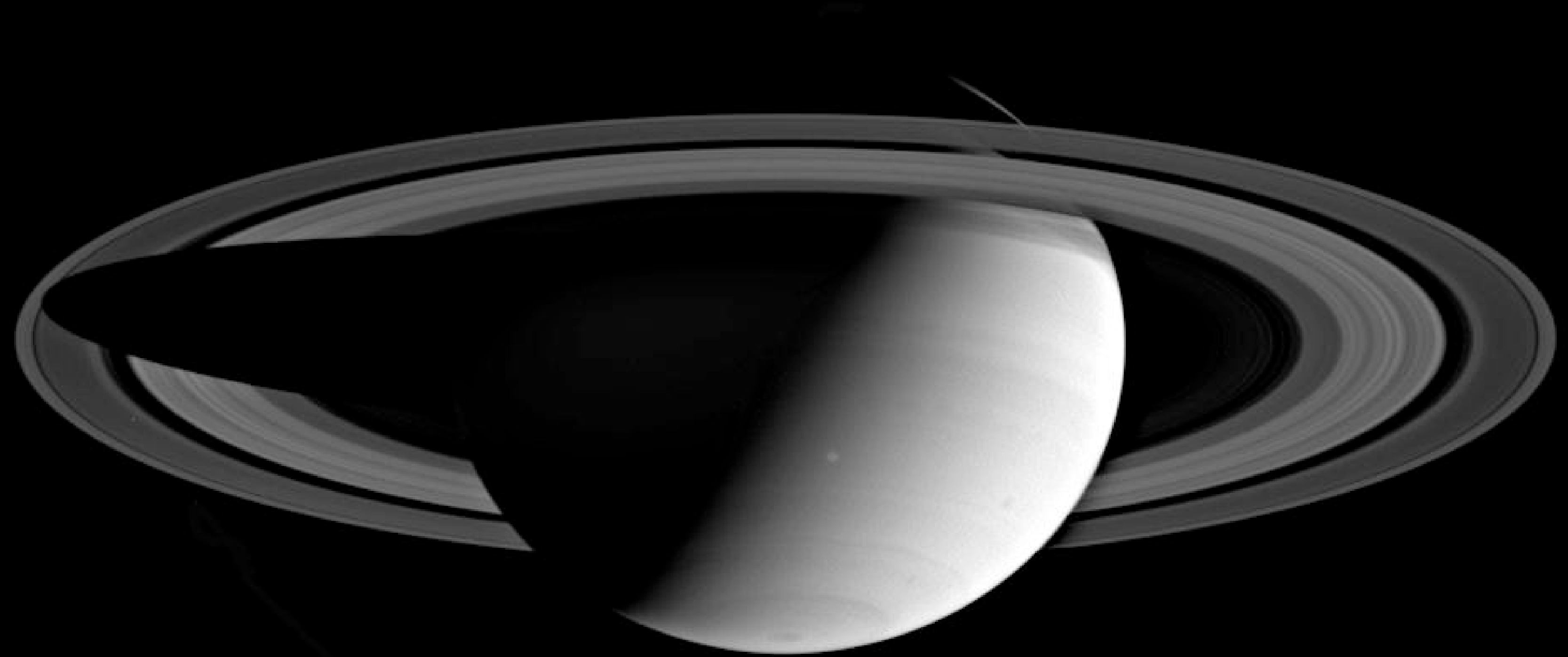


Hubble imaged powerful auroras at both poles.

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.

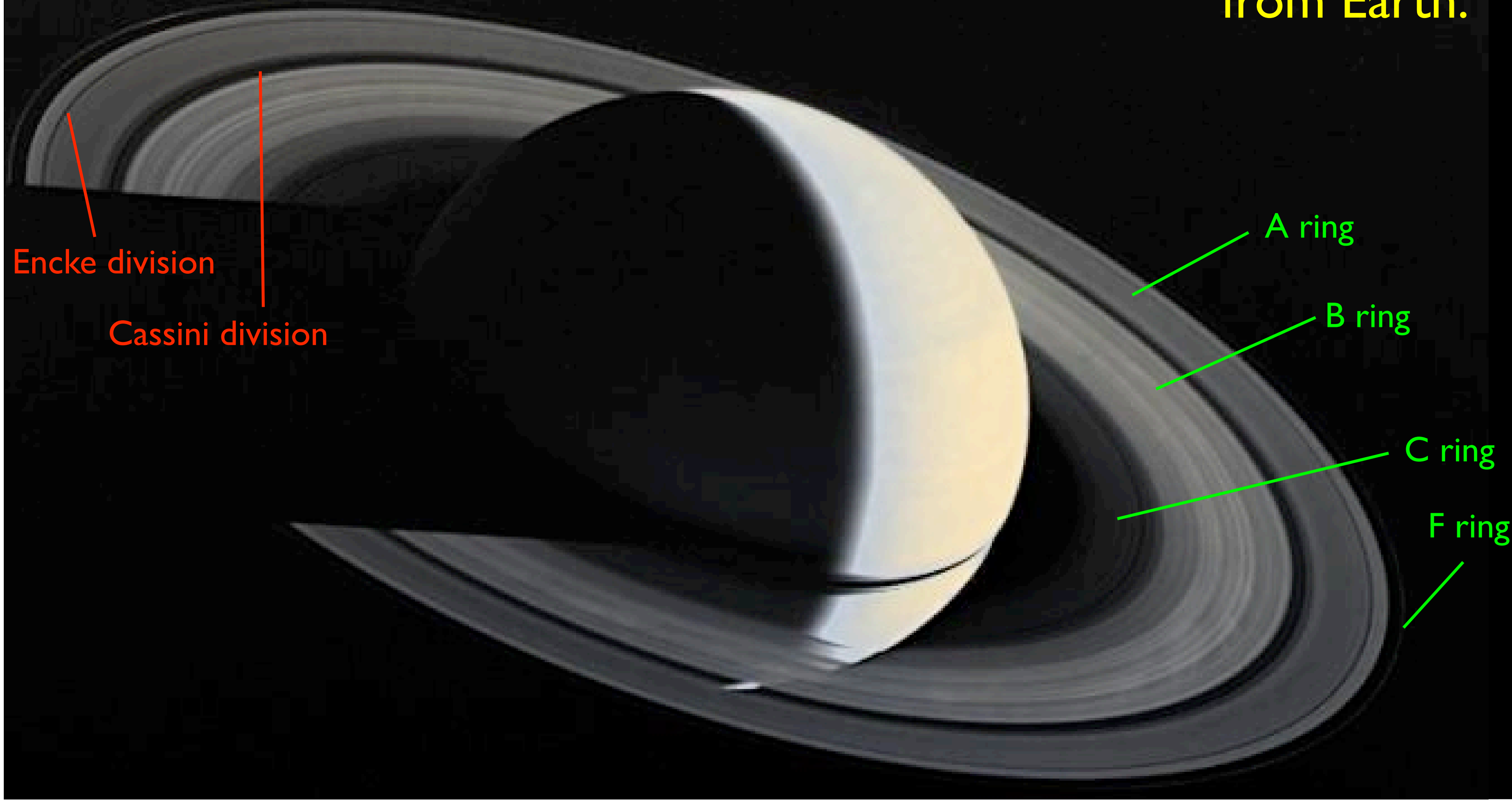
The most obvious feature of Saturn are the immense rings. The ring system is remarkably complex, and is still poorly understood.

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.

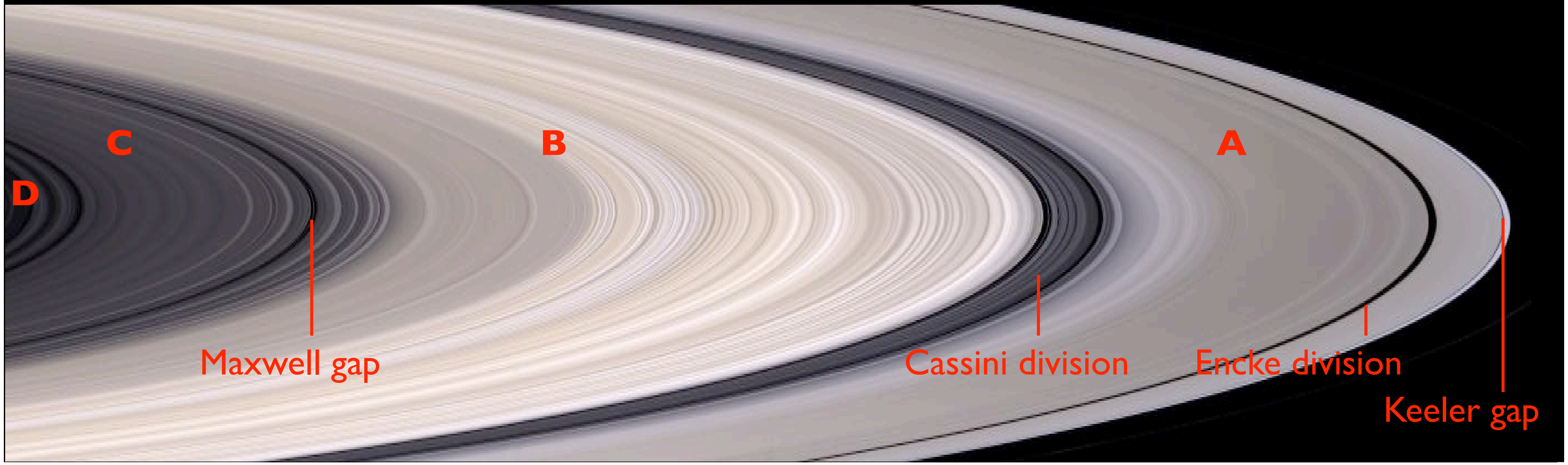
There are divisions between the rings: some of these are visible from Earth.



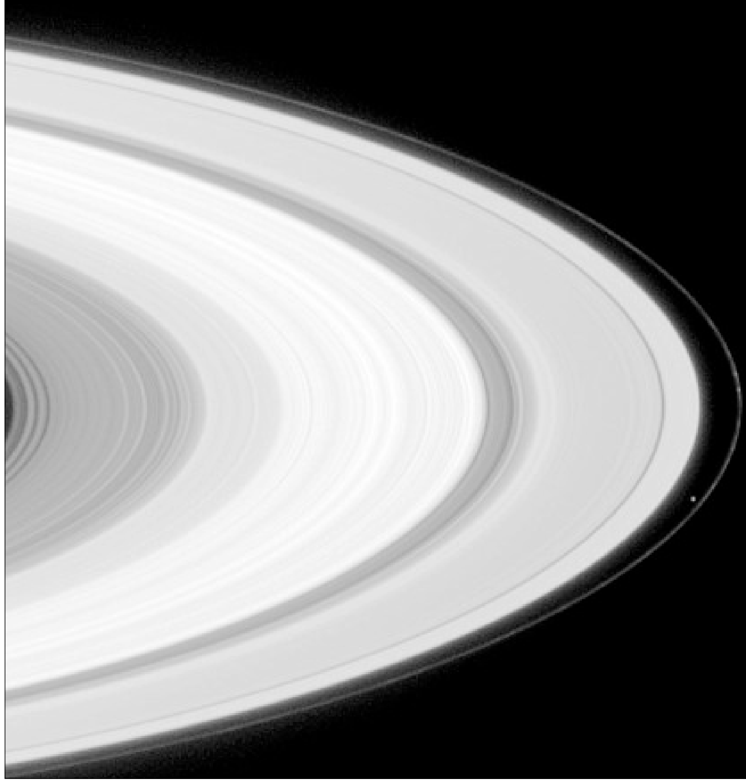
From closest to furthest from Saturn, there are seven sections to the ring system:

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	

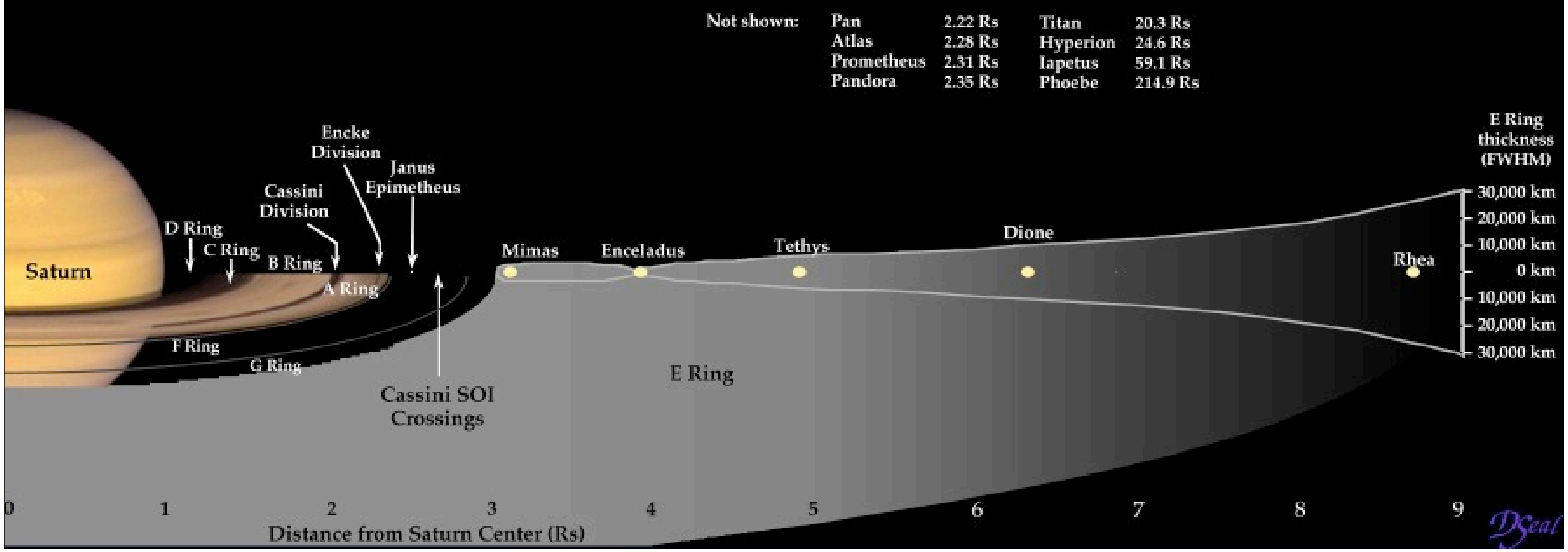
The D ring is the closest to Saturn and stretches down almost to the cloud tops. It contains few particles and is so dark and faint that it is invisible from Earth. Rings C, B and A are the three major rings of the ring system and can be seen from Earth. The C ring is the faintest of the three and is 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.

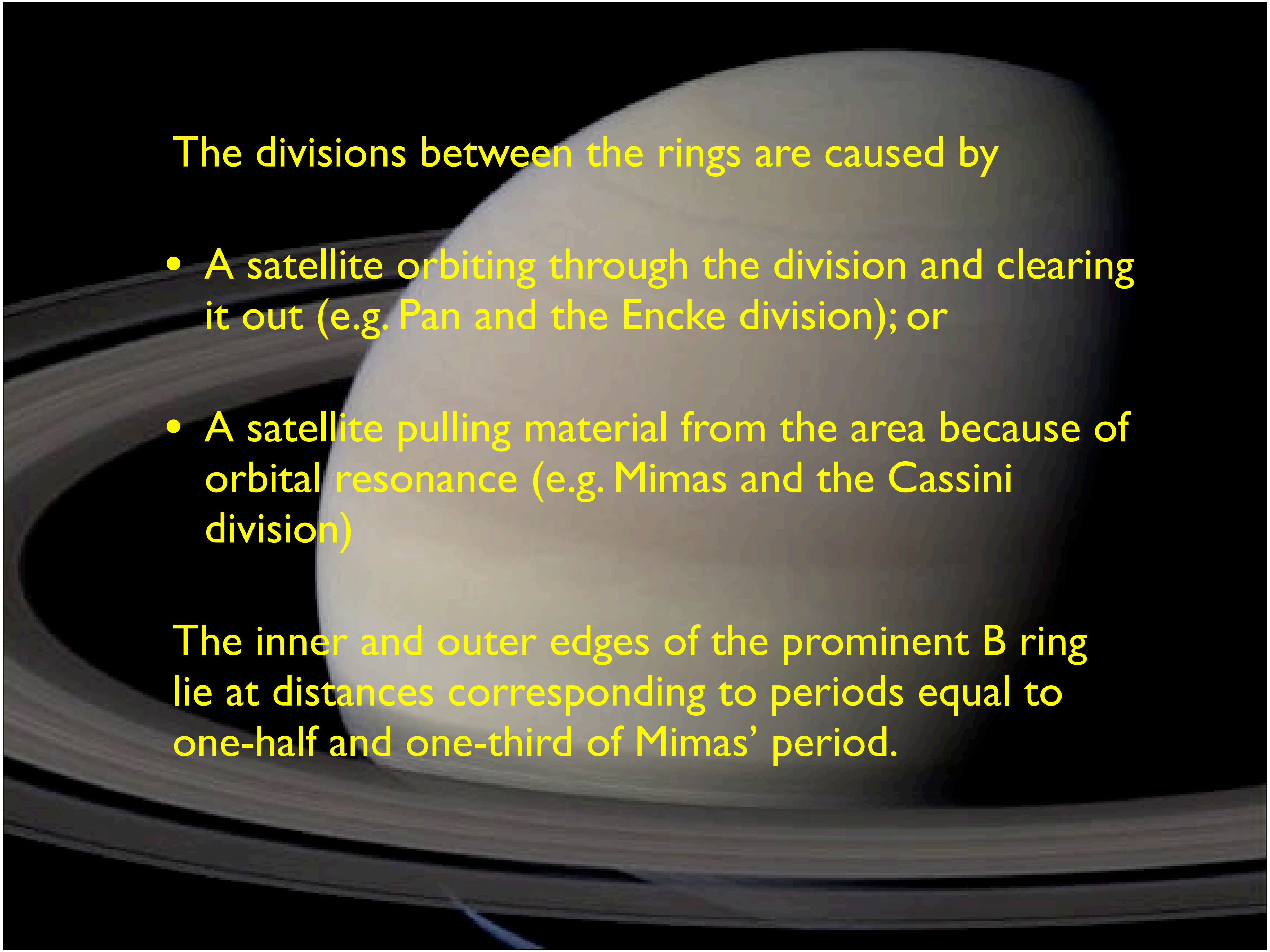


Just outside the A ring lies the F ring, the strangest ring of them all. It is faint, narrow and appears to contain bends and kinks. Close-up pictures show two narrow, braided, bright rings that trace distinct orbits.



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.





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)

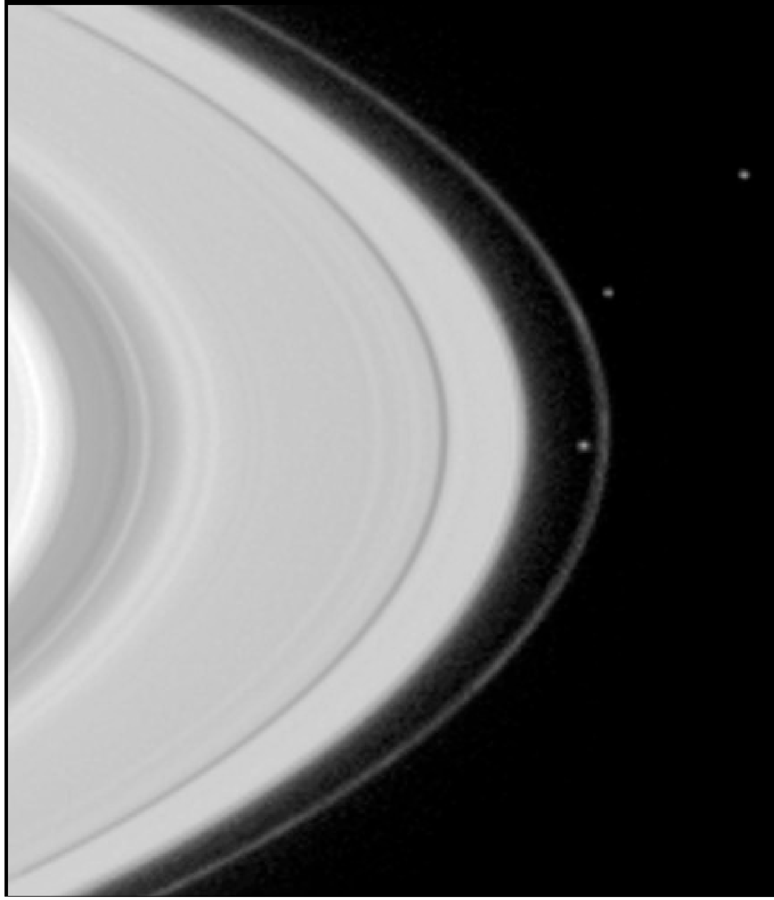
The inner and outer edges of the prominent B ring lie at distances corresponding to periods equal to one-half and one-third of Mimas' period.

The 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)

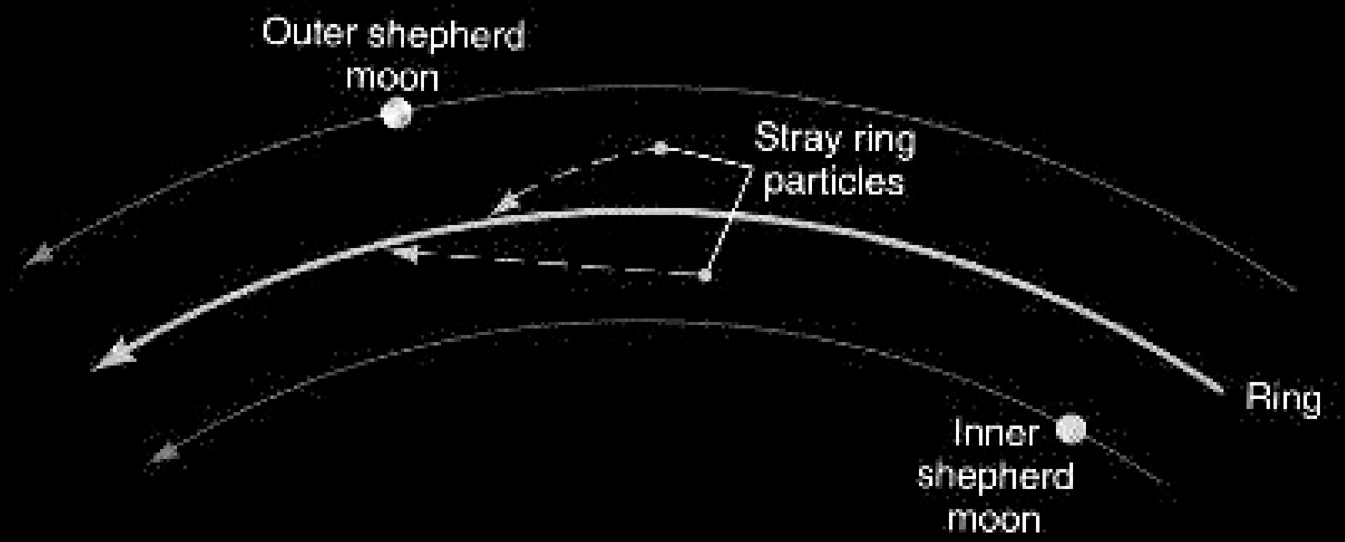
Several of Saturn's rings are maintained by "shepherd satellites". These are moons that keep the rings together and stabilised via gravitational attraction.

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



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

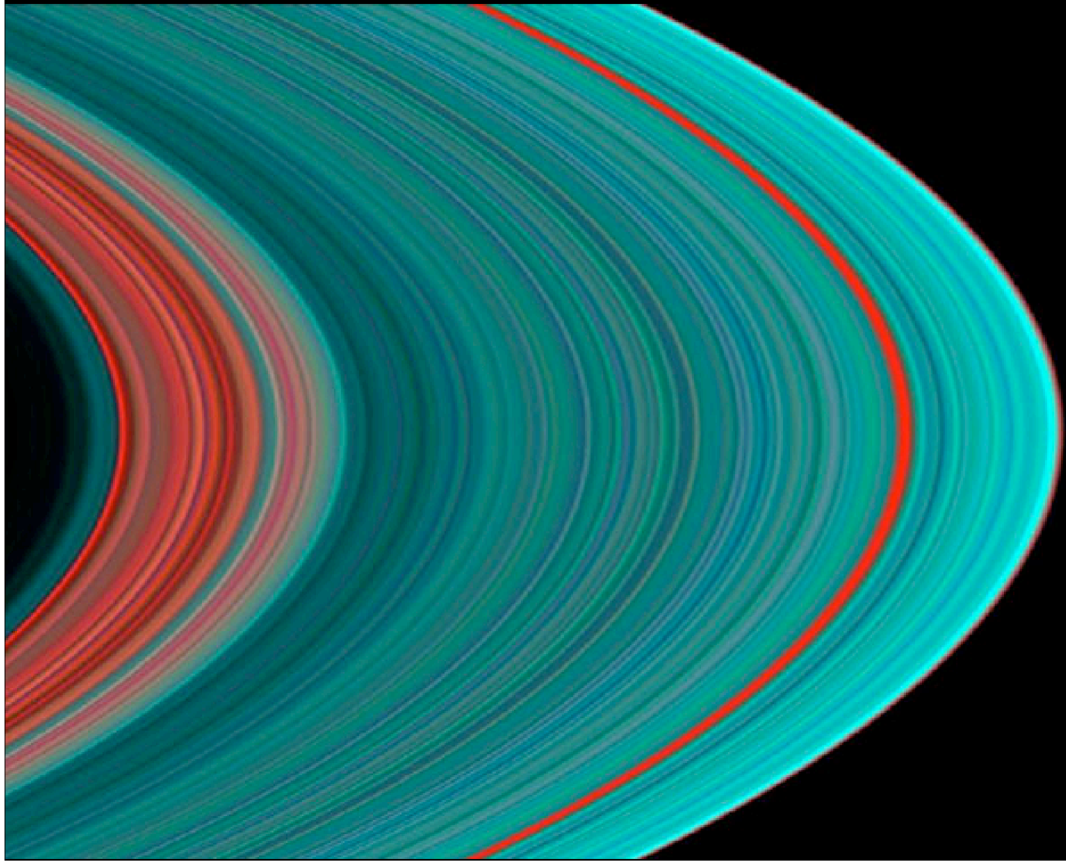
The two small, irregularly shaped moons exert a gravitational influence on particles that make up the F ring, confining it and possibly leading to the formation of clumps, strands and other structures observed there. Pandora prevents the F ring from spreading outward and Prometheus prevents it from spreading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



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

The F ring resolves into five separate strands. Potato-shaped Prometheus is seen here, connected to the ringlets by a faint strand of material, which may be material pulled away from the ring. The ringlets are disturbed in several other places. In some, discontinuities or "kinks" in the ringlets are seen; in others, gaps in the diffuse inner strands are seen. All these features appear to be due to the influence of Prometheus.

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.

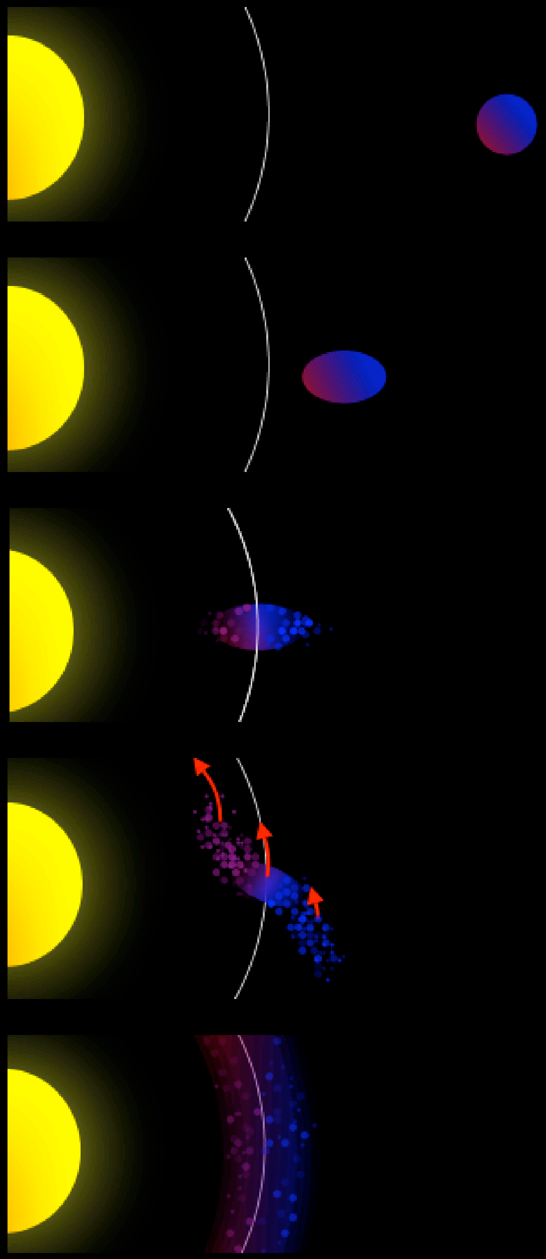


Cassini took this detailed image of the A ring in ultraviolet light. Blue represents areas rich in water ice, while red areas are rich in some sort of dirt. This and other images show that inner rings have more dirt than outer rings. The thin red band in the otherwise blue A ring is the Encke Gap. The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

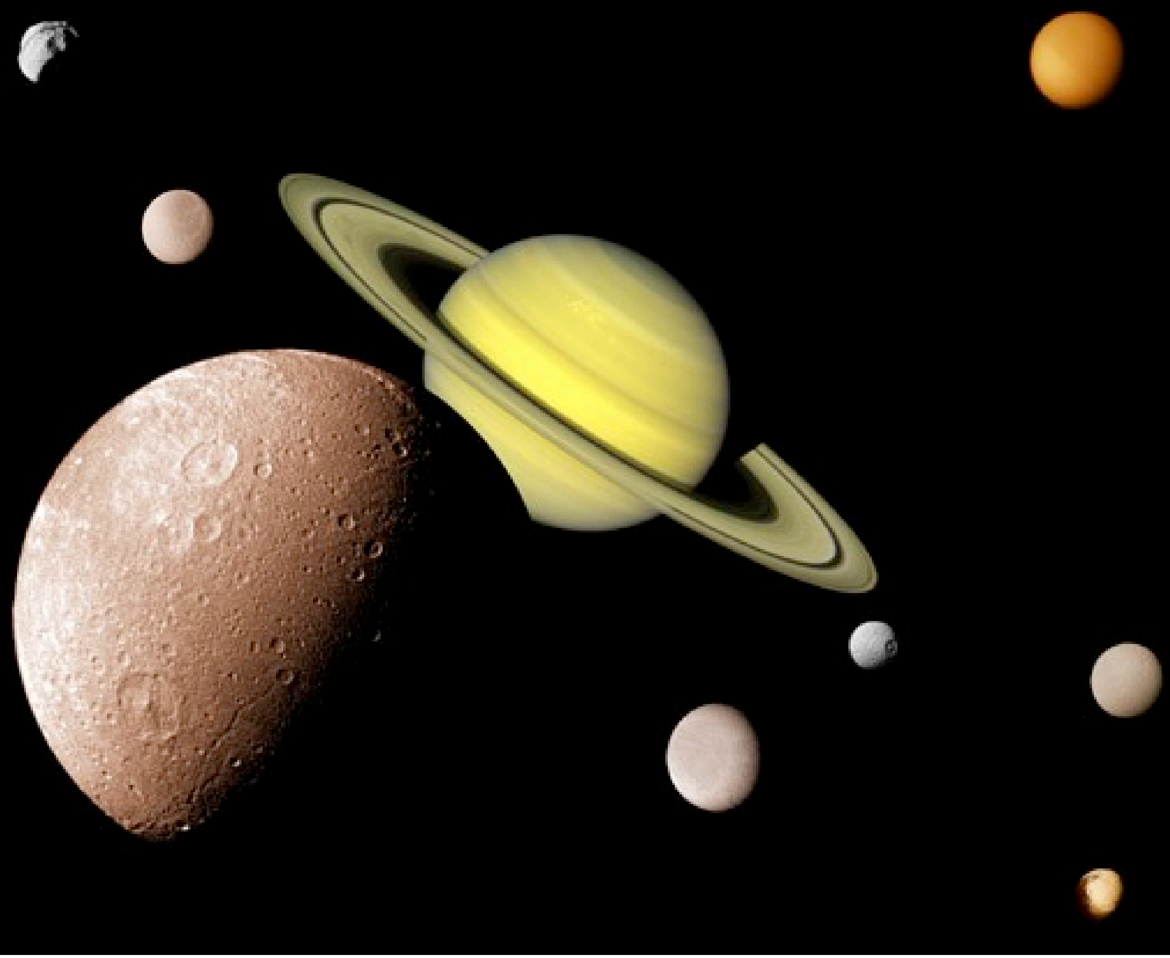
The above holds true for bodies held together solely by gravitational force. Solid bodies, which have tensile strength, can survive somewhat closer to the planet.

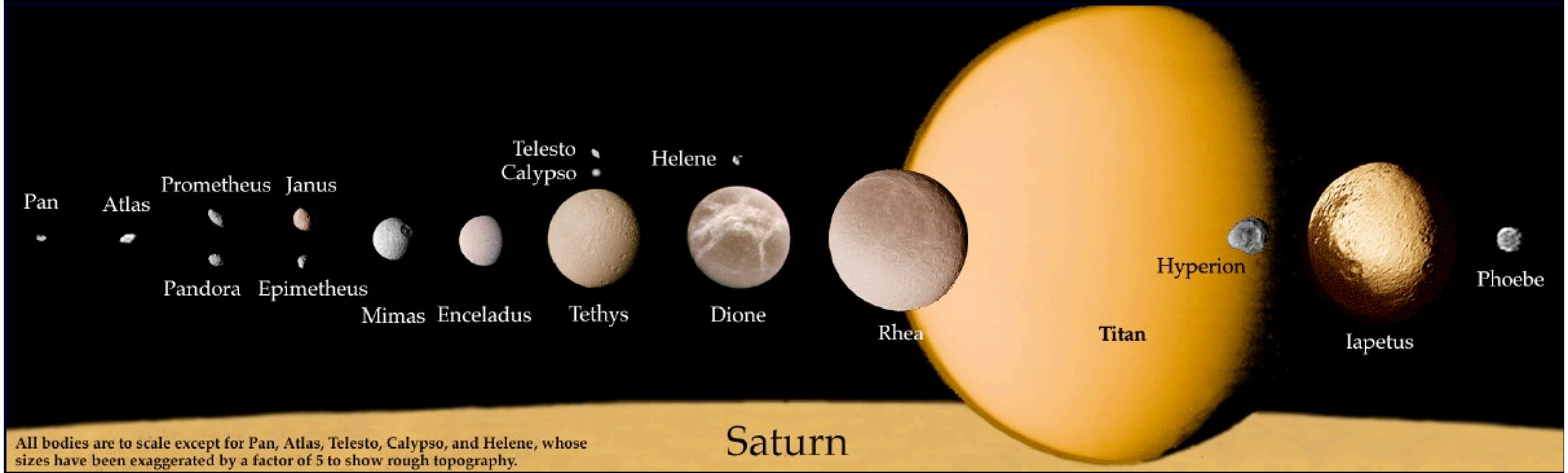


The ring systems are not stable: the rings are losing angular momentum to the small moons that orbit through the outermost regions of the ring system; the brightness of the rings also suggests they are reasonably young, perhaps only a few hundred million years old.

The total mass of material in the rings would make an icy moon one or two hundred kilometres wide, like Mimas. Perhaps such a moon was ripped apart by tidal forces, leaving beautiful but transient rings.

Saturn’s moons





Saturn has 33 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:

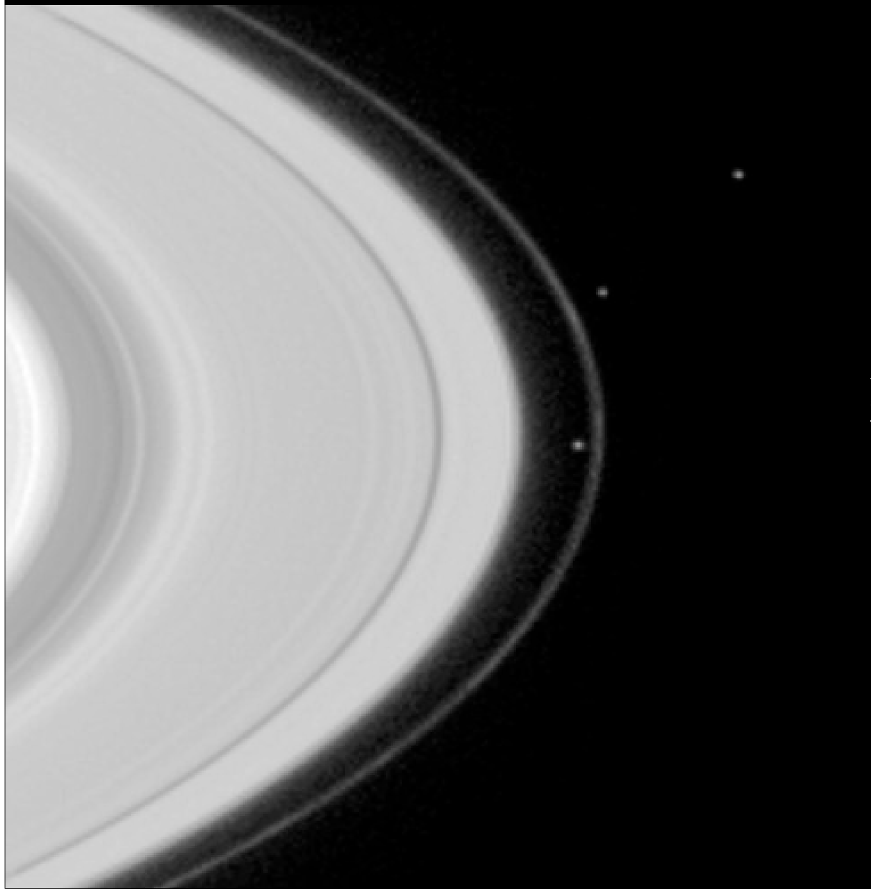
Name	Diameter (km)	Mass (10^{21} kg)	Density (g/cm^3)	Orbital distance (10^3 km)	Orbital period (d)
Prometheus	145x85x65	0.00027		139	0.613
Pandora	114x84x2	0.00022		142	0.629
Epithemus	144x108x98	0.00056	0.7±0.2	151	0.694
Janus	196x192x150	0.002	0.7±0.2	151	0.694
Mimas	390	0.038	1.14±0.03	186	0.942
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

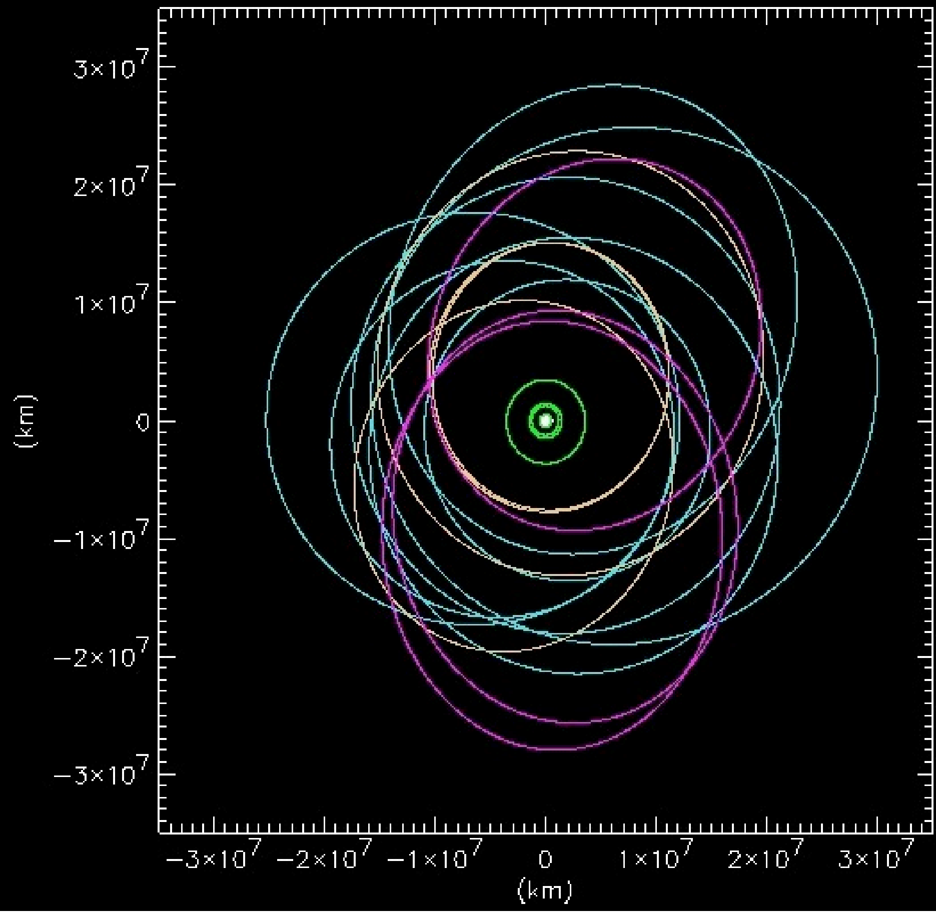
2:1 resonances

3:4 resonance

Sixteen satellites orbit within the main rings themselves.

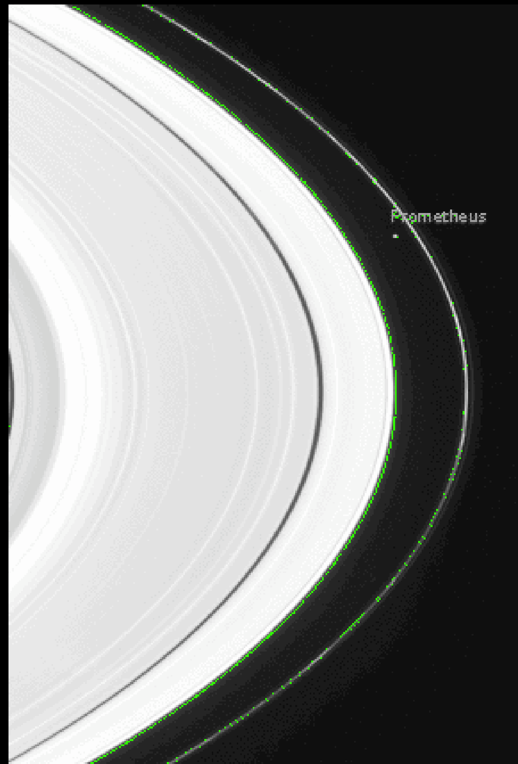
Outside the regular moons are a swarm of irregular moons, mostly captured asteroids.

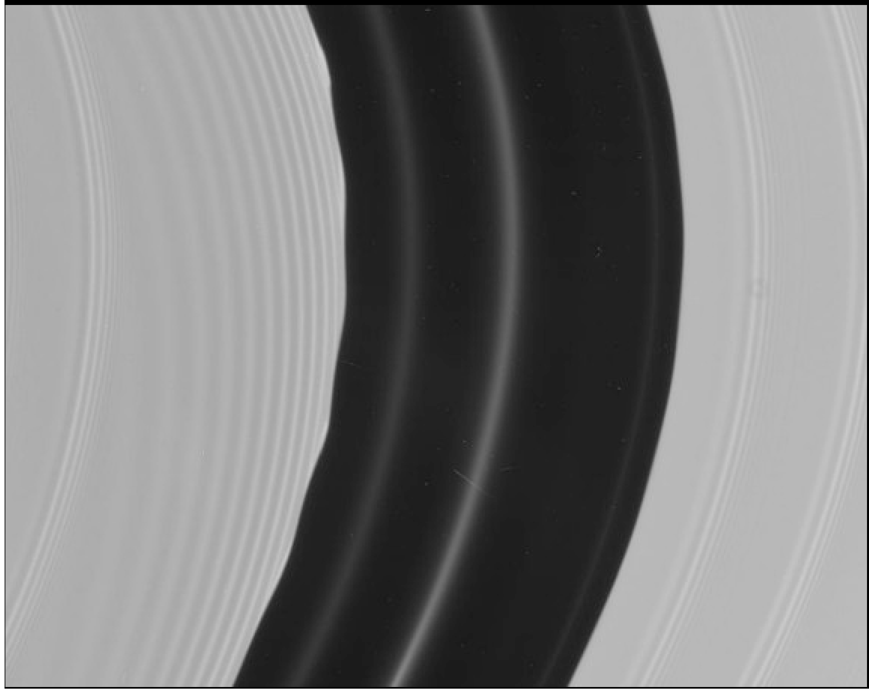




Pan (radius 10 km) is located in the Encke gap. Its existence was predicted by "clumping" in the adjacent A-ring.

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.

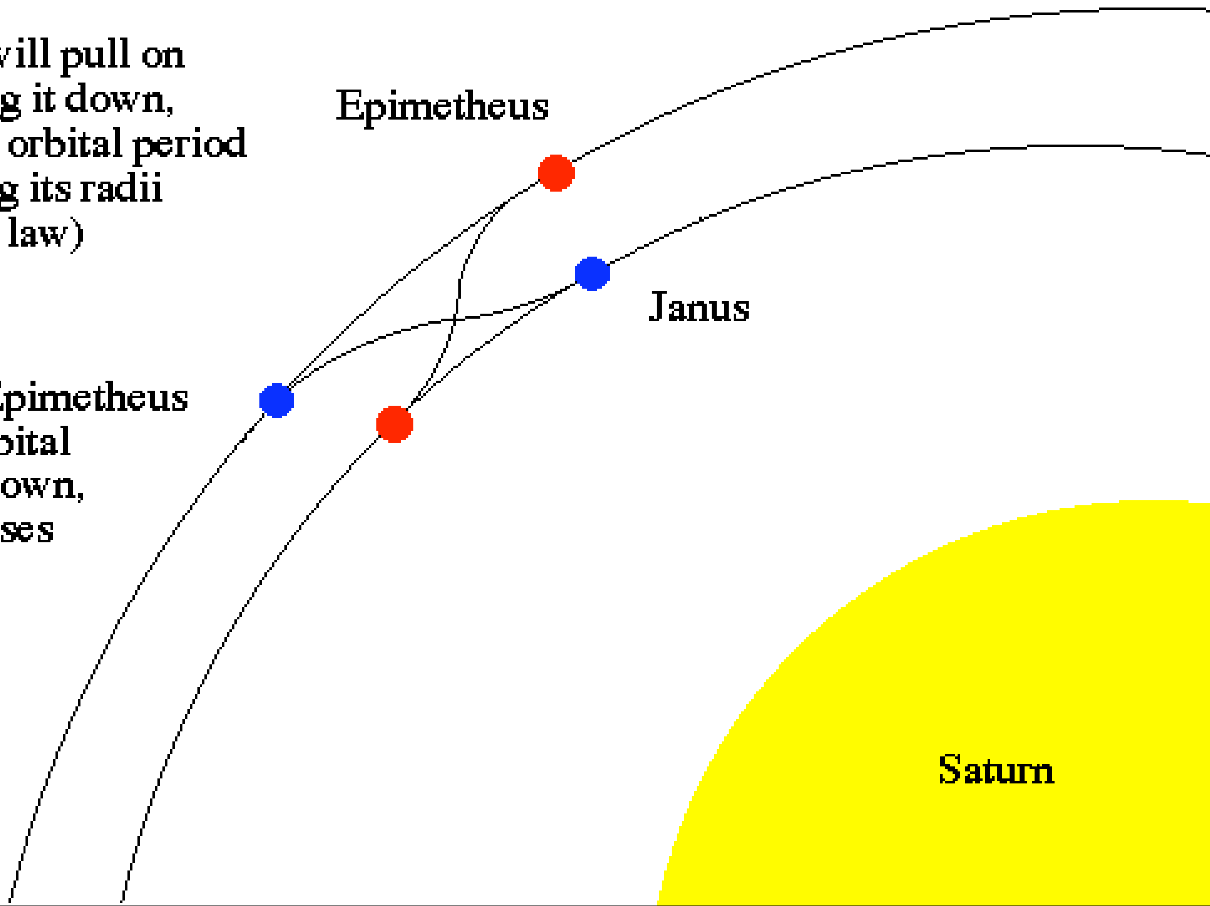
Prometheus (above) and Pandora (right), taken by Voyager 2. Prometheus shows a 20 km crater on one side.

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.

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



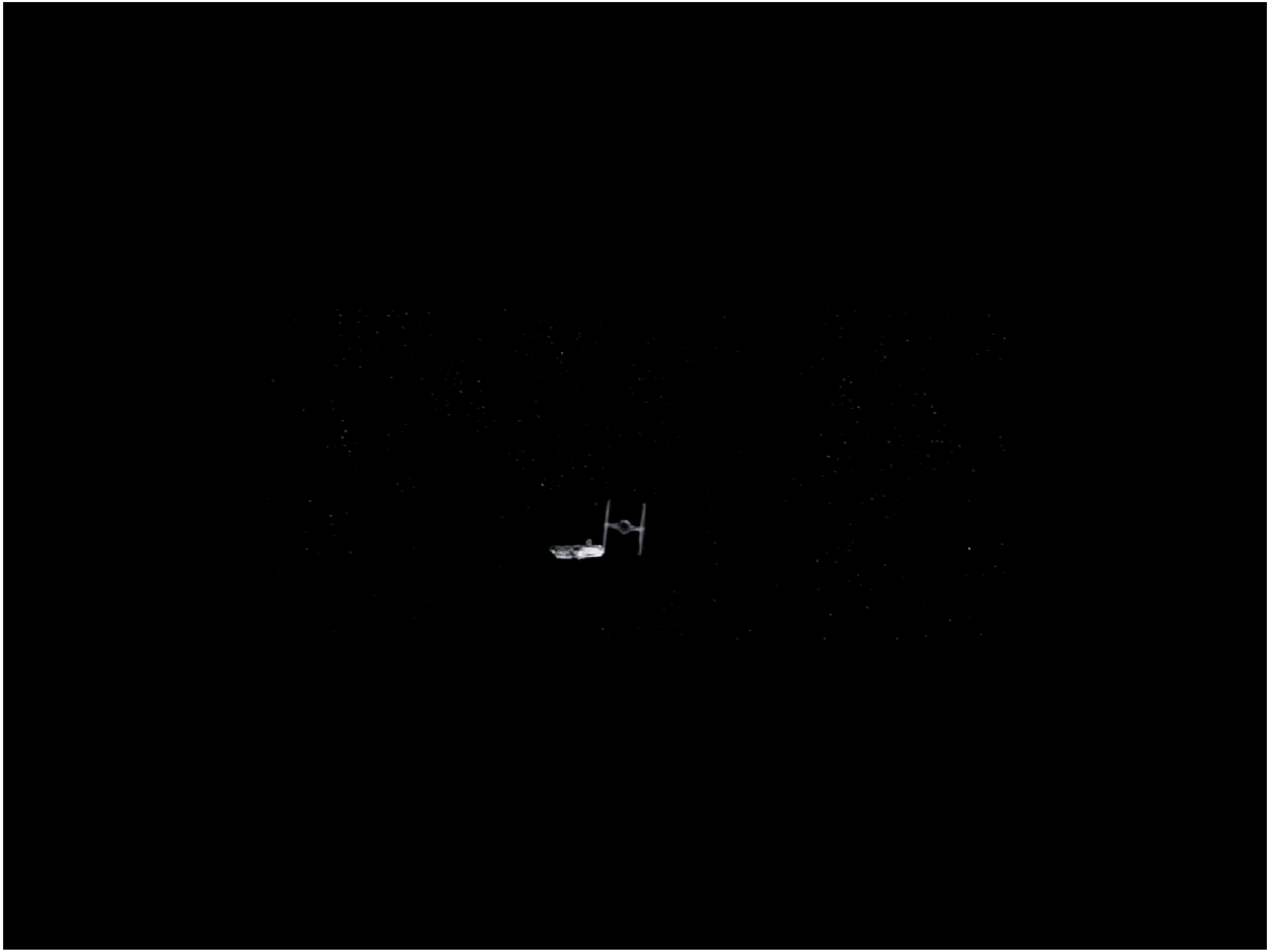
After the ring-shepherding satellites come the six medium-sized icy worlds. Unlike the relatively orderly Galilean satellites of Jupiter, Saturn's system of satellites shows few regularities.

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

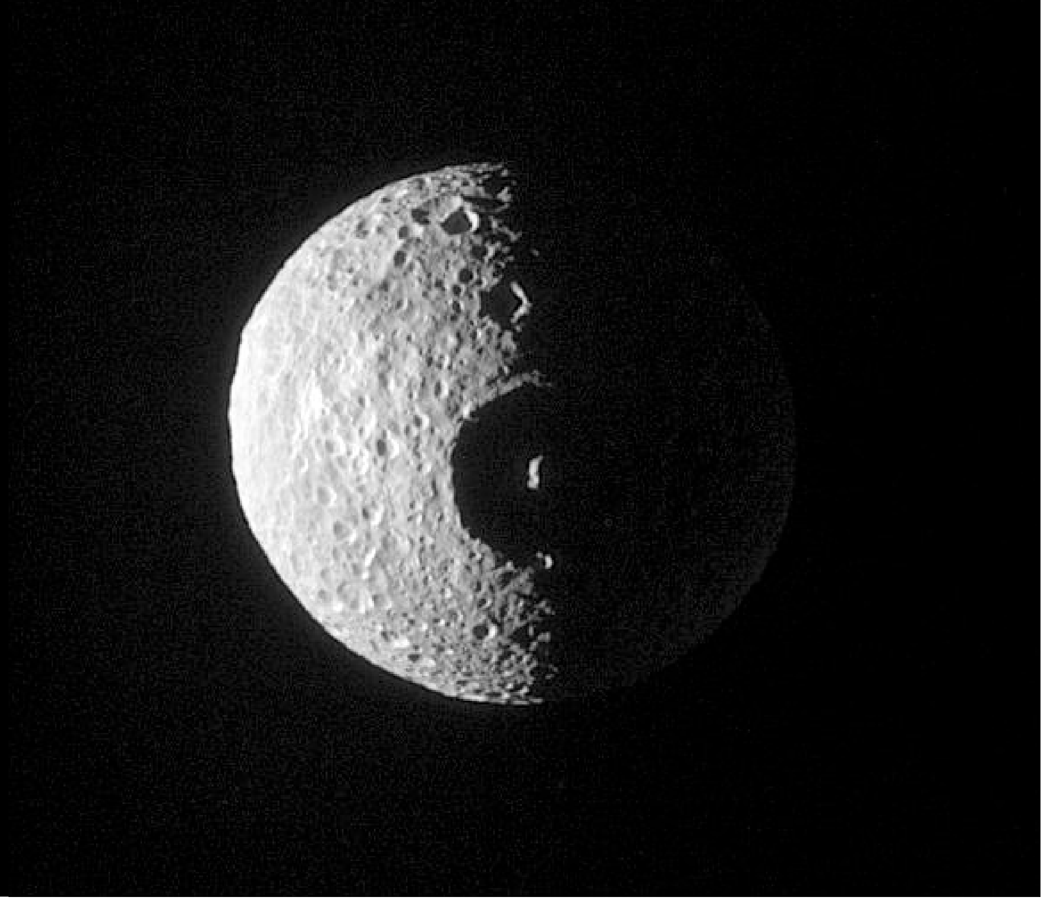
Our knowledge of the Saturnian system is very much a "work in progress". Since arrival in July 2004, *Cassini* has flown by Phoebe, Titan, Iapetus and Enceladus. In the rest of 2005, it will perform flybys of the following moons.

Moon	Date	Altitude (km)
Enceladus	14 July 2005	175
Mimas	2 August 2005	48,842
Titan	22 August 2005	3,758
Titan	7 September 2005	1,025
Tethys	24 September 2005	29,773
Hyperion	26 September 2005	1,010
Dione	11 October 2005	500
Titan	28 October 2005	1,451
Rhea	26 November 2005	500
Titan	26 December 2005	10,409

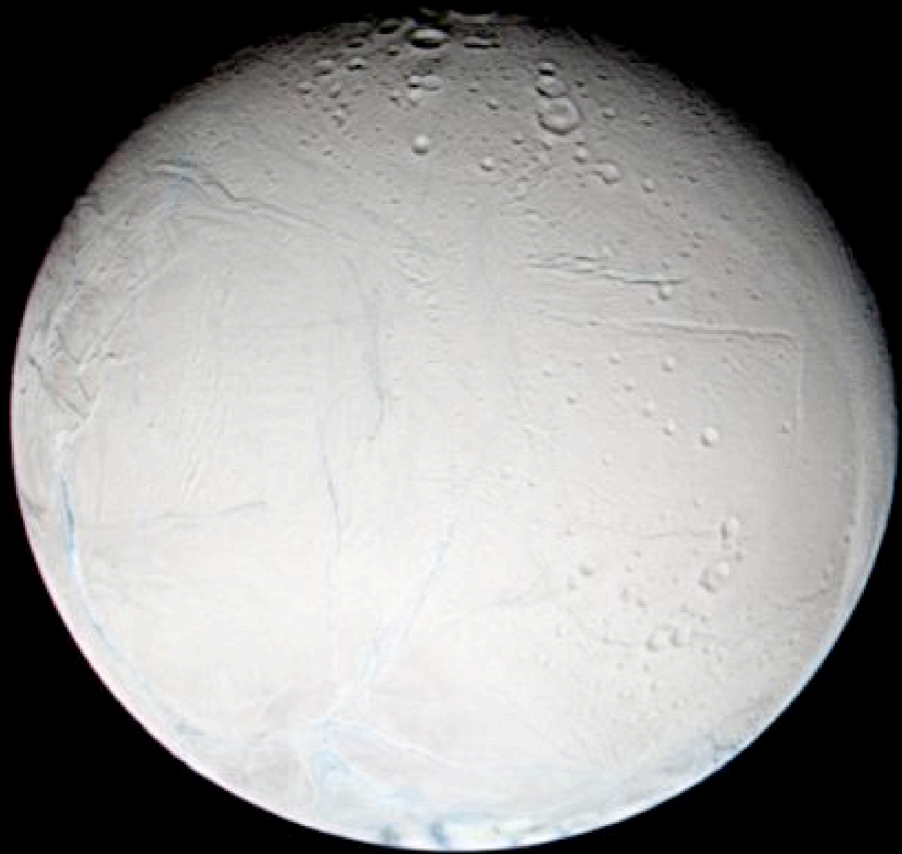
Mimas (radius 196 km) lies outside the main ring system but within the tenuous E ring. It has very low density, so it's mostly water ice. Its surface is saturated with impact craters. The largest crater is Herschel crater: 130 km across with walls 5 km high. The floor is up to 10 km deep and the central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

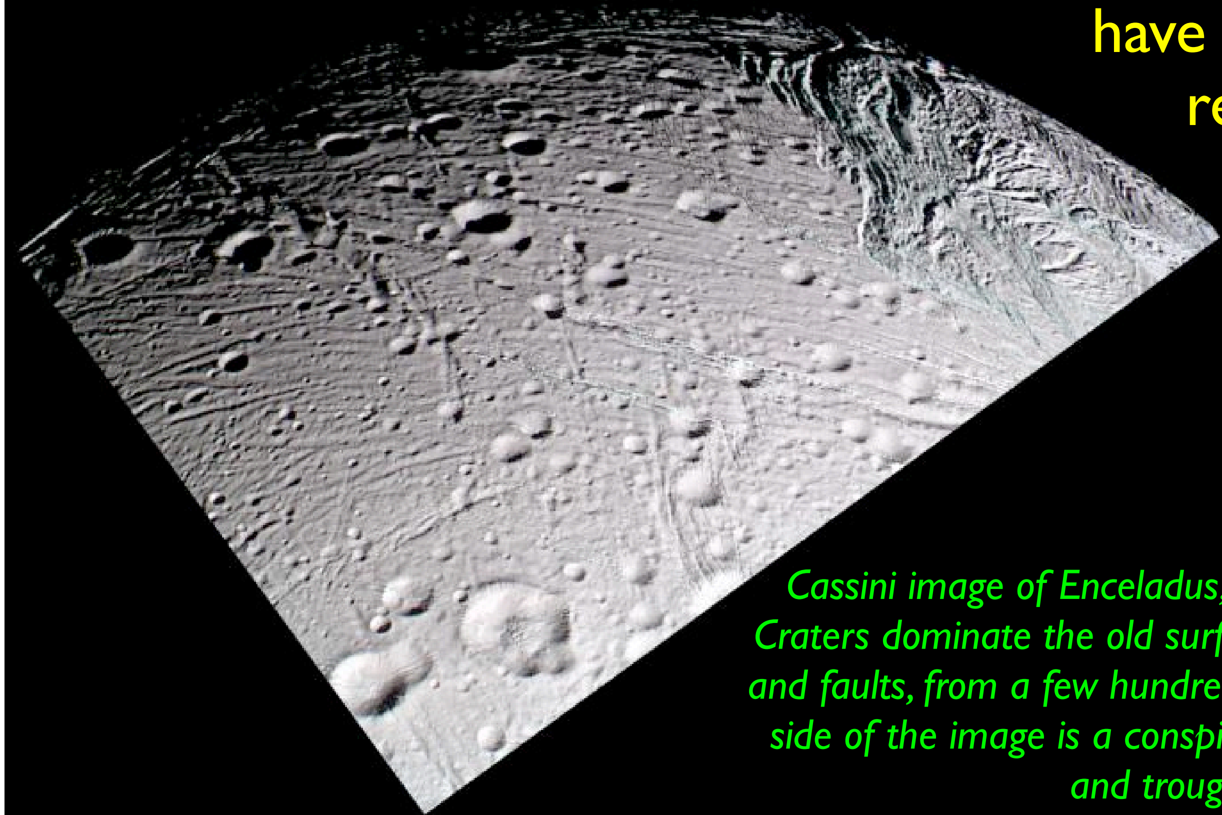


Enceladus (radius 260 km) has the highest albedo in the Solar System (albedo 0.99). Its surface is dominated by fresh, clean ice.



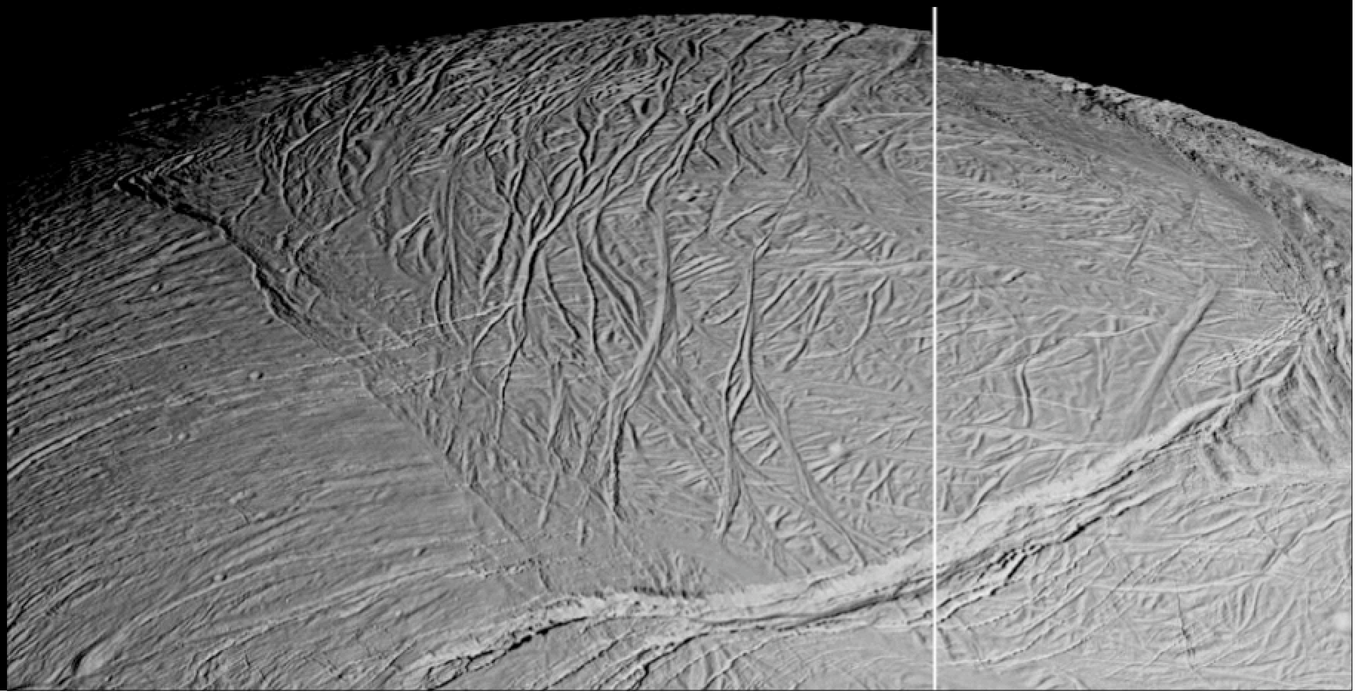
It shows many similarities with Europa. The surface has craters, which are overlain with extensive linear cracks and ridges. At least some of the surface is relatively young, probably less than 100 million years.

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



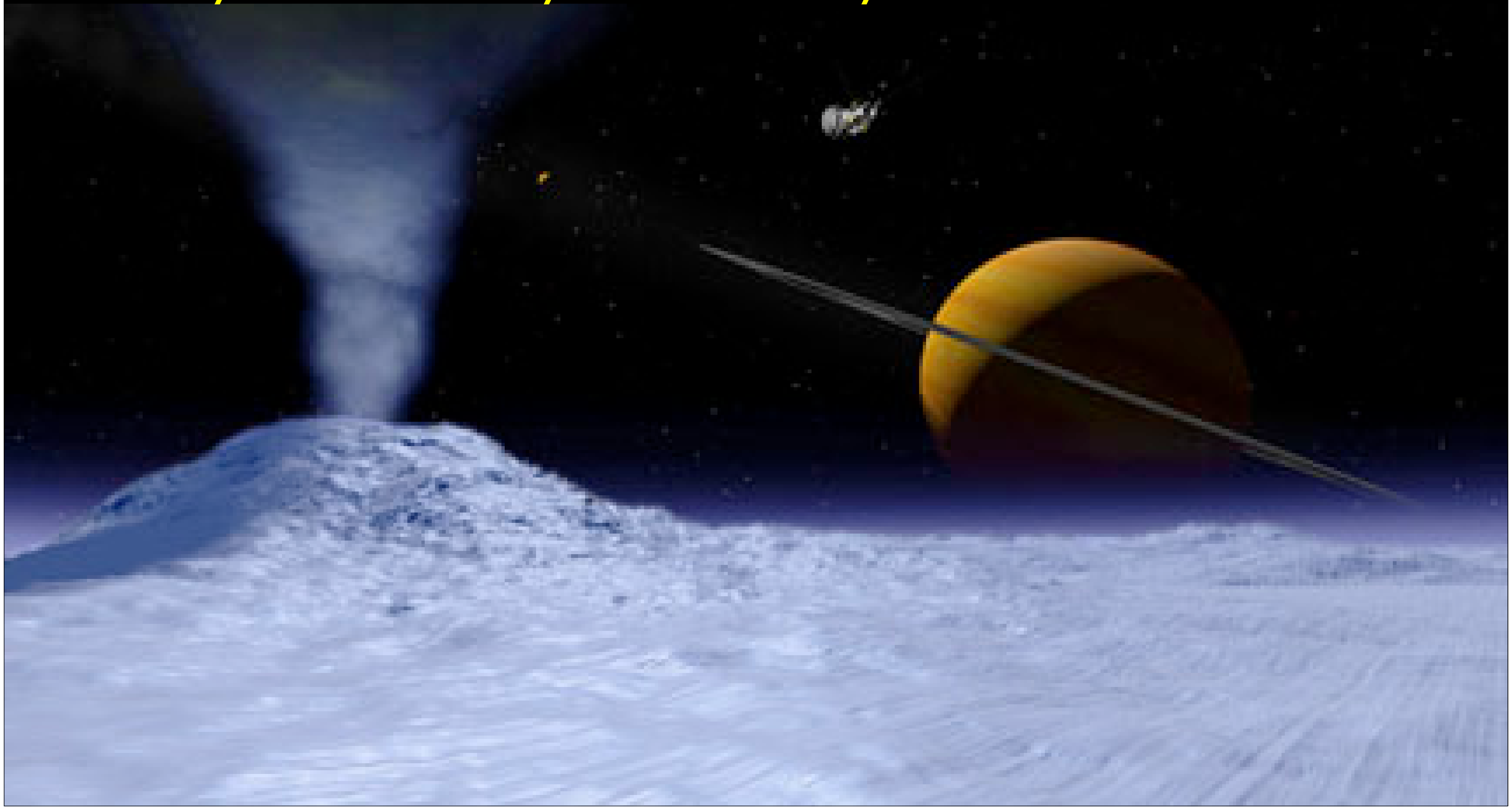
Cassini image of Enceladus, showing most of its diverse geology. Craters dominate the old surface, which is transected by fractures and faults, from a few hundred metres to 5 km wide. On the right side of the image is a conspicuous and twisted network of ridges and troughs forming a distinct tectonic region.

Cassini recently detected an atmosphere, which might be ionized water vapour. Since Enceladus is too small to hold on to an atmosphere for long, it must be replenished from some source, probably icy volcanoes or geysers. If such eruptions are present, Enceladus would join two other such active moons, Io at Jupiter and Triton at Neptune.



Cassini mosaic of a region of Enceladus, about 300 km across, showing a myriad of faults, fractures, folds, troughs and craters.

The same eruptions on Enceladus probably supply the material for Saturn’s E ring. Since the material cannot persist in the ring for more than a few thousand years, it may be due to very recent activity on Enceladus.



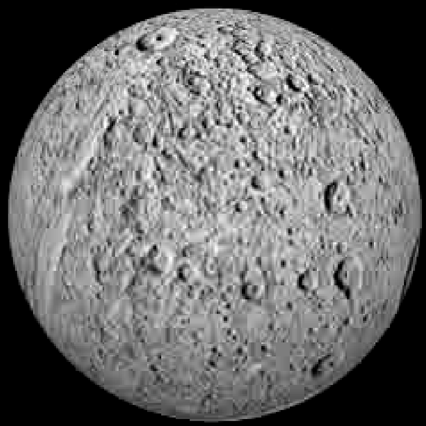
The density of Tethys (radius 530 km) is 1.21 g/cm^3, indicating that it is composed almost entirely of water-ice. It is relatively lightly cratered, so its surface must have been liquid at some stage to smooth the crater out.

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.

Two view of Tethys by Cassini

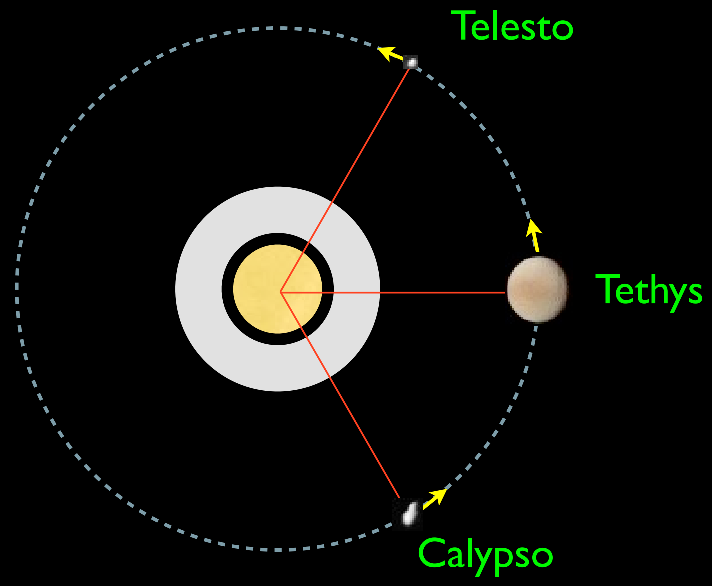
The second giant feature on Tethys is Ithaca Chasma, an enormous trough which extends at least three-quarters of the way around the globe. It is up to 100 km wide and reaches about 3 km in depth.

The fact that it is exactly opposite to the crater Odysseus suggests the latter impact may have been responsible for the formation of the chasma.

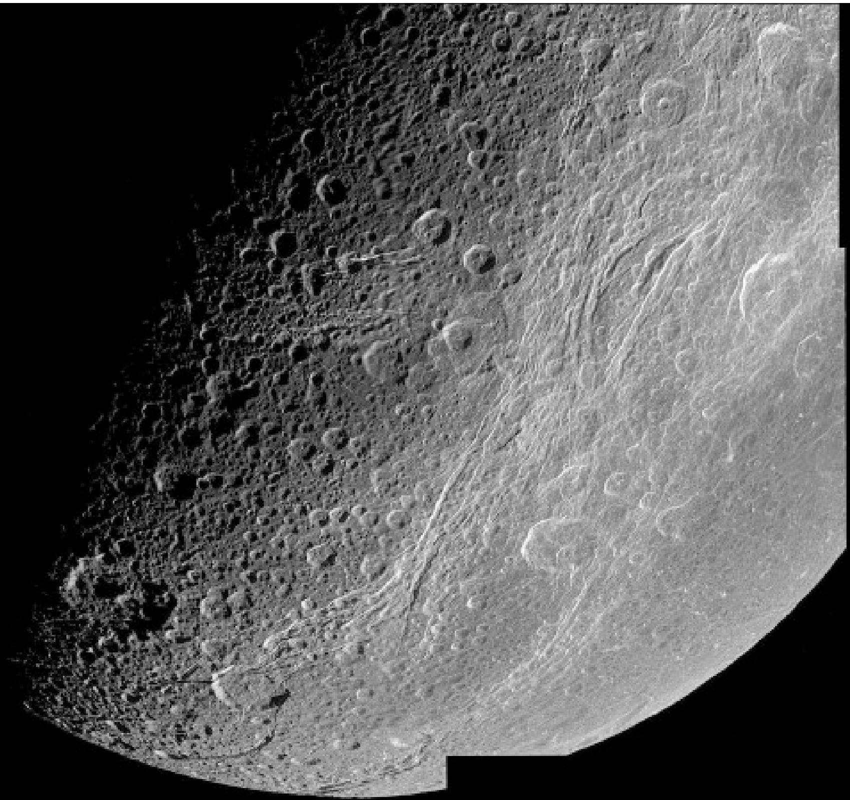


(above) Cassini image of Ithaca Chasma; (left) Animation of Tethys created from a mosaic of images taken by the Voyager spacecraft.

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 is trailing
hemisphere.

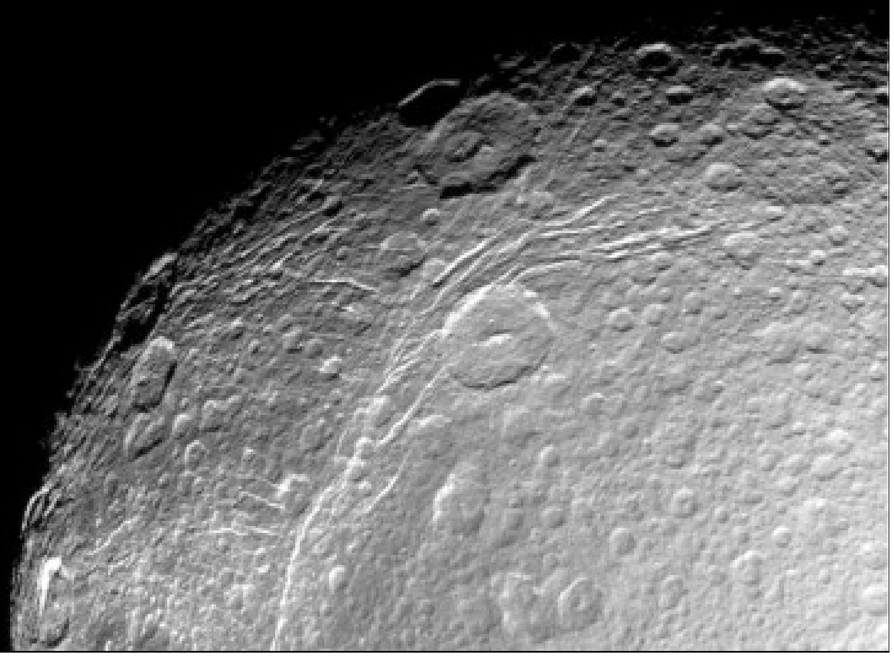


Dione's trailing hemisphere is heavily cratered and is uniformly bright. It also contains an unusual and distinctive surface feature: a network of bright, wispy streaks on a dark background that overlay the craters, indicating that they are newer. *Cassini* found this wispy surface consists of bright ice cliffs created by tectonic fractures.

Cassini image from closest approach on Dec. 14, 2004, centered on the wispy terrain. The wispy streaks turned out to be ice cliffs instead of ice deposits as expected.

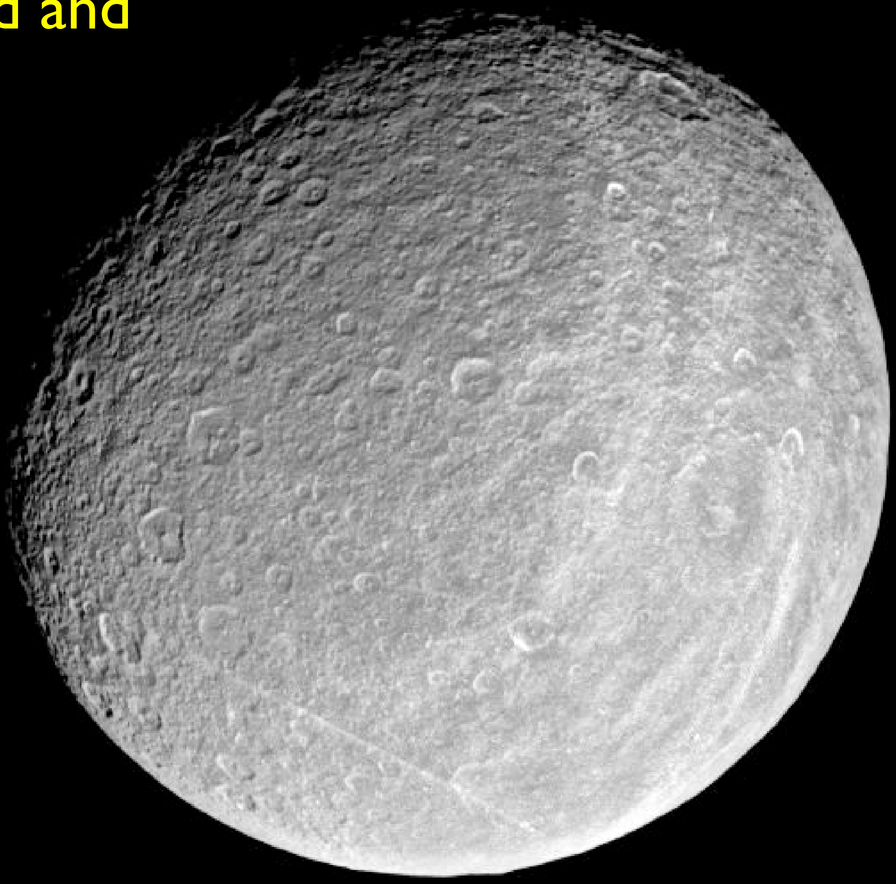
The heavily cratered terrain is mostly located on the trailing hemisphere, with the less cratered plains area existing on the leading hemisphere. This suggests that during the period of heavy bombardment, Dione was tidally locked to Saturn in the opposite orientation. A large impact then spun the satellite, possibly more than once. The pattern of cratering since then and the bright albedo of the leading side suggests that Dione has remained in its current orientation for several billion years.

Like Tethys, Dione has a Trojan satellite, Helena, orbiting 60° ahead of Dione.

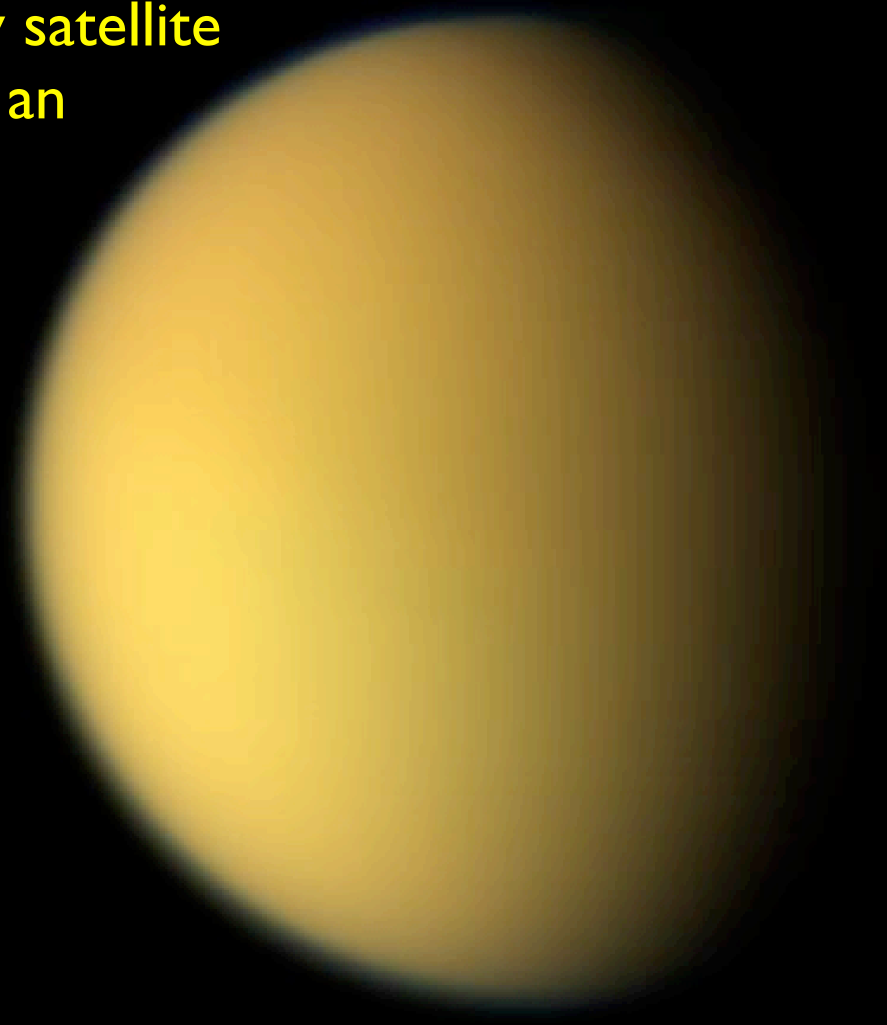


Cassini image of Dione, showing the wispy terrain.

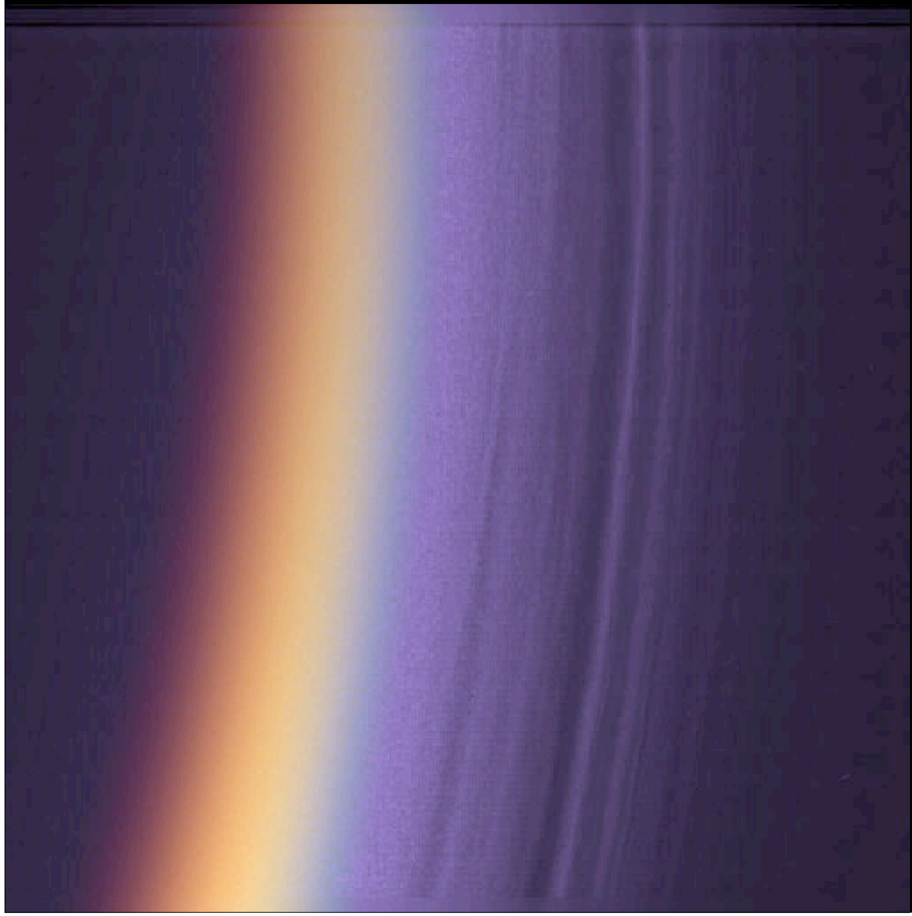
Rhea (radius 765 km) is the second largest of Saturn's moons. It is very similar to Dione: it also has vastly different leading and trailing hemispheres. The leading hemisphere is heavily cratered and uniformly bright. On the trailing hemisphere there is a network of bright swaths on a dark background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



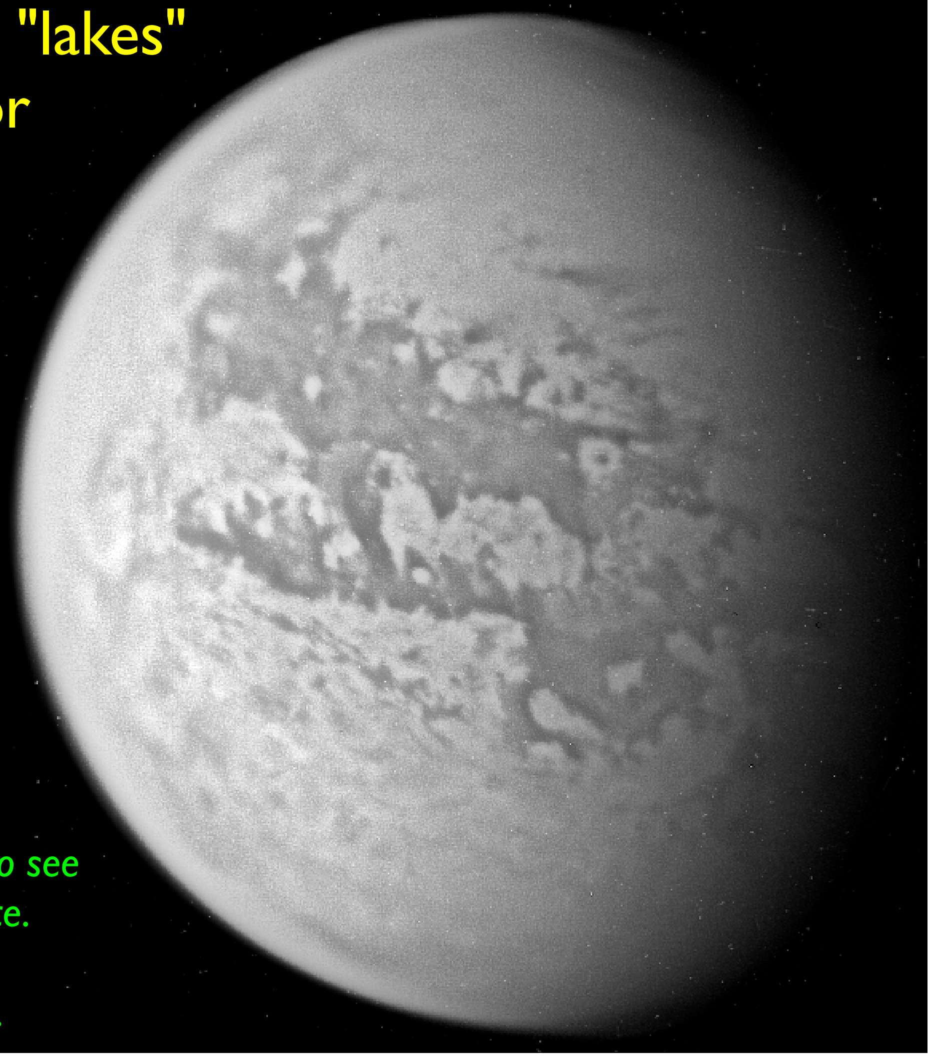
Titan (radius 2575 km) is Saturn's largest satellite and the second largest moon in the solar system (after Ganymede). It is the only satellite in the Solar System with an atmosphere.



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.

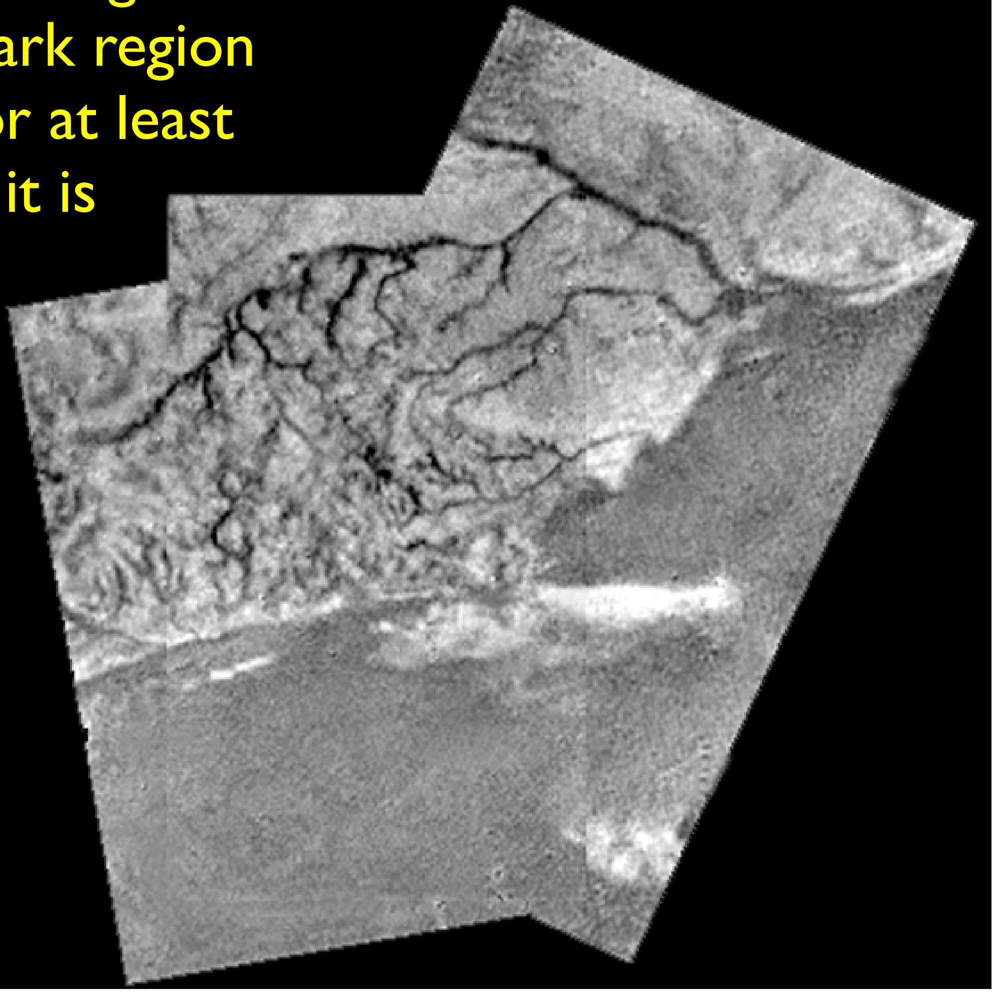


Titan's surface temperature is about –178°C. It was thought Titan might have oceans of methane on the surface: this does not appear to be the case. On the othe hand, it may be that the "lakes" are more slushy than liquid or that the basins are not filled with liquid at all times.

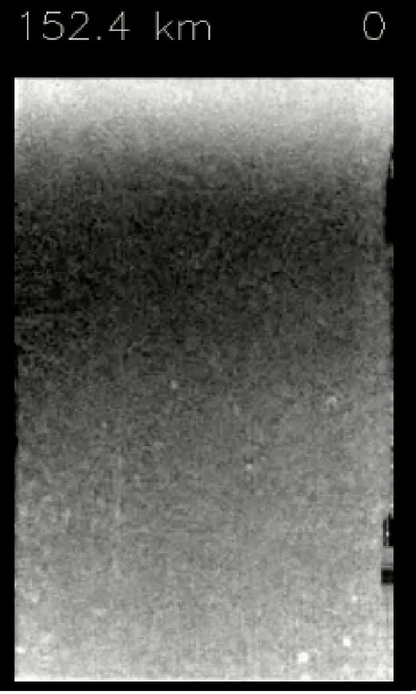


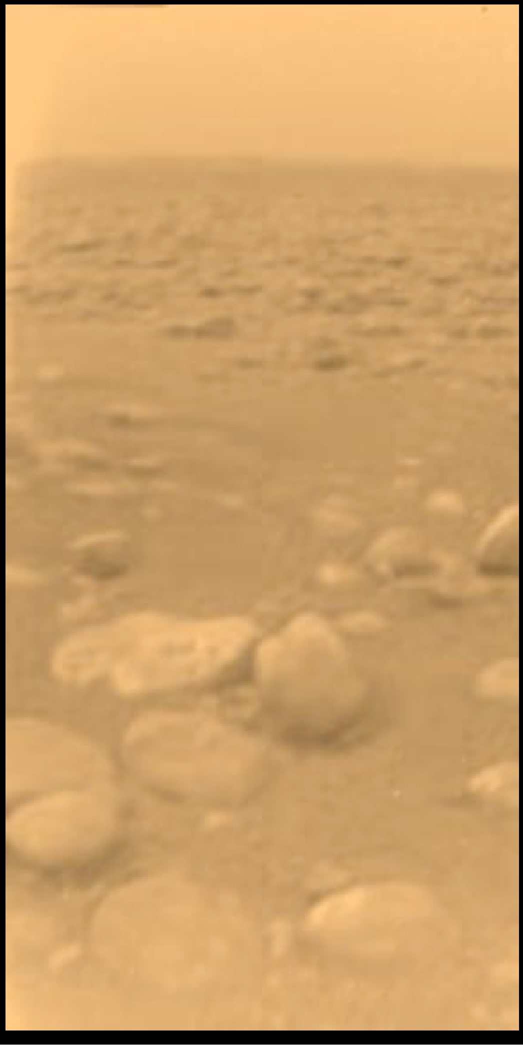
Cassini near-infrared image of Titan which allows us to see through the hazy atmosphere and down to the surface. The variations in brightness on the surface are real differences in the reflectivity of the materials on Titan.

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.



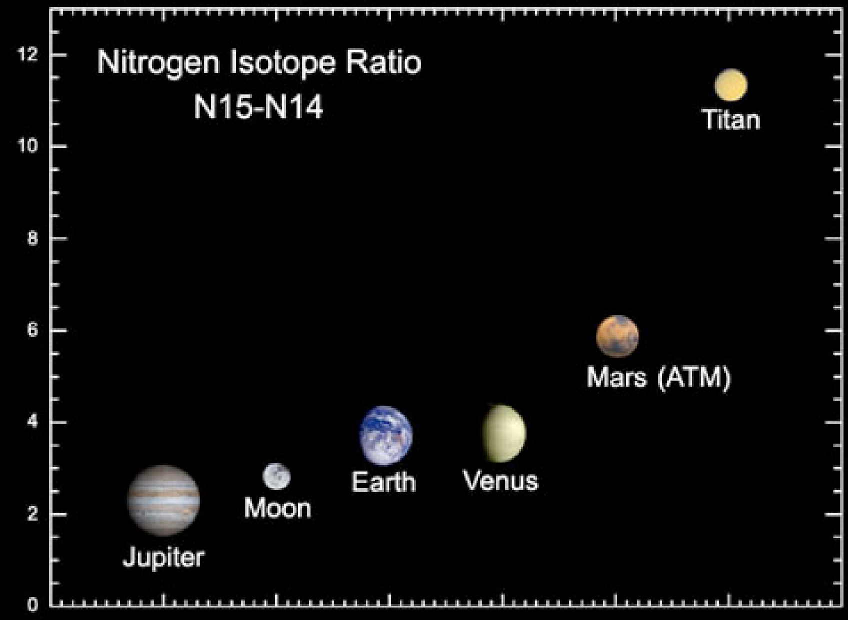
There is no immediate trace of liquid on the Huygens landing site. The images taken after the probe's landing show a flat plain covered in pebbles. The pebbles, which may be made of water ice, are somewhat rounded, which may indicate the action of fluids on them. It is possible that while Titan's rivers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





Measurements of the proportion of nitrogen-15 and nitrogen-14 in Titan's atmosphere indicate that up to 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.

Hyperion is locked in a 3:4 orbital resonance with Titan. Its orbit is chaotic, so is orientation is unpredictable. It seems to be the remnant of a much bigger satellite which was disrupted by a collision and was too close to Tian to have re-accreted.

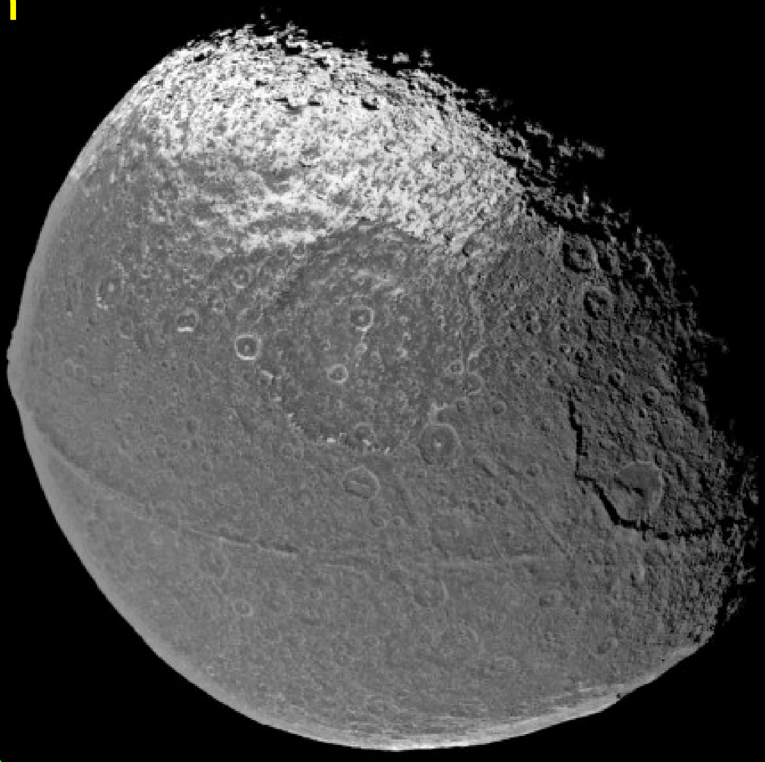
Iapetus (radius 730 km) is almost entirely water ice. Iapetus' leading and trailing hemispheres have very different albedos. The leading hemisphere has an albedo 0.03–0.05, while the trailing has albedo 0.5 – as bright as Europa.

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.

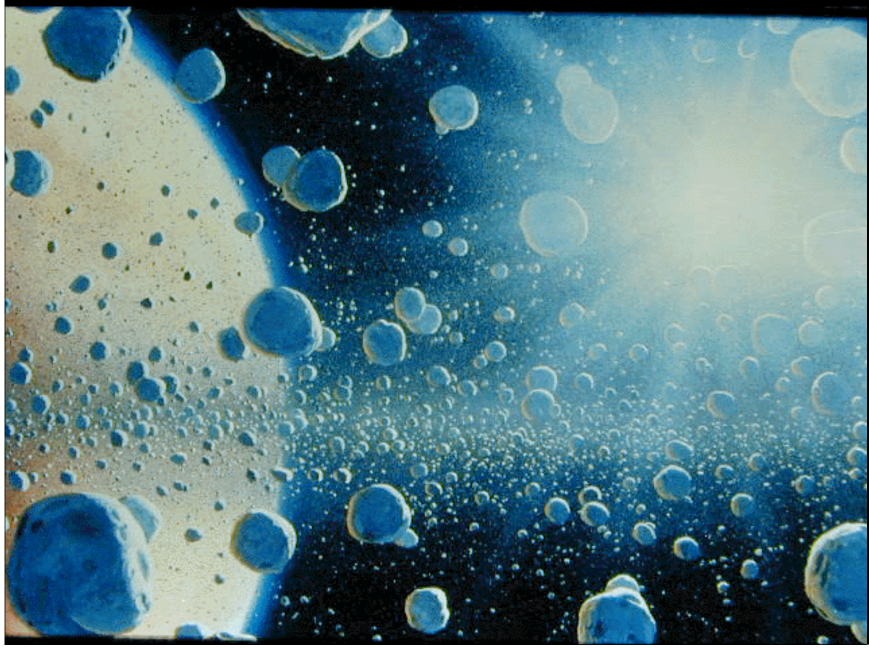
The dark side appears to result from some dark material deposited on the icy surface. The origin and nature of this material is unclear. It may be dark debris from Phoebe, or it might consist of volcanic deposits.



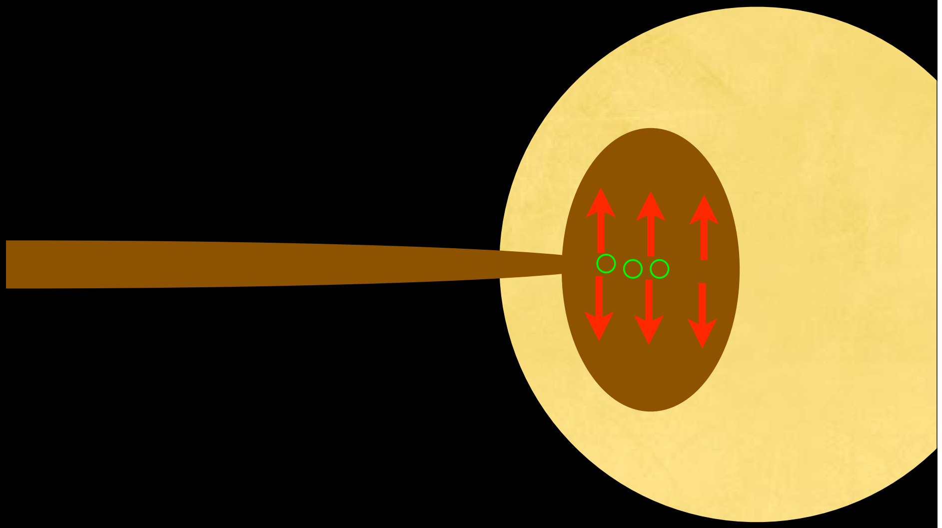
Cassini view of the leading hemisphere of Iapetus.

A recent paper (Freire 2005) suggested a possible explanation for Iapetus' unique features.

The hypothesis is that the ridge (or "rindge") was formed by a collision with a primordial ring of Saturn.



The rindge is formed from accumulated ejecta from millions of tiny impacts from ring particles. Dust from the collision is sprayed upward into a transient atmosphere and deposited symmetrically about the impact zone, forming the Cassini Regio.



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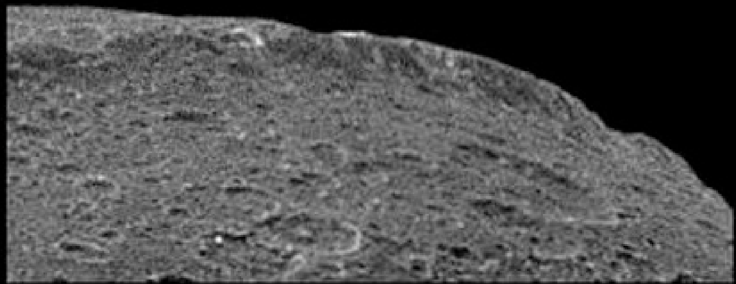
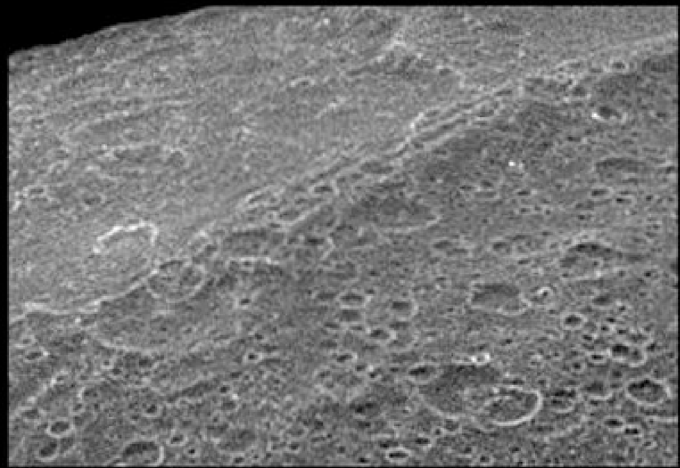
Cassini image of the northern part of the dark Cassini Regio and the transition zone to a brighter surface at high northern latitudes. Within the transition zone, the surface is stained by roughly north-south trending wispy streaks of dark material.

The ring collision scenario naturally explains the coincidence of the ring with Iapetus' equator, since this is where the ring plane intersects the surface of a moon with an equatorial orbit. Freire suggests the collision occurred when the moon's orbital parameters changed suddenly, probably due to a close encounter with another proto-satellite. The same collision may have left Iapetus in its present orbit – distant, elliptical, and slightly inclined (7°).





Cassini images of the rindge. The image above shows about 200km of the ringde; the image to the right shows craters along the length.

Phoebe (radius 110 km) is almost 4 times more distant from Saturn than its nearest neighbor (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 Pluto.

If the weather's fine, we'll also do some star viewing on the roof of the Physics Building for the second half of the lecture.

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. So I don't have any books to recommend this week.

- The Cassini mission home page is at **"Cassini–Huygens: Mission to Saturn and Titan"**, http://saturn.jpl.nasa.gov/home/index.cfm
- The book I mentioned last week, **"Satellites of the Outer Planets: Worlds in their own right"** by David Rothery (Oxford UP, 1999),
- 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
- There's a nice page about the possible age of Saturn's rings at **"Science@NASA: The Real Lord of the Rings"**, http://science.nasa.gov/headlines/y2002/12feb_rings.htm
- Paulo Freire's paper with a model for the formation of Iapetus' ridge and dichotomy is available on-line at http://xxx.lanl.gov/abs/astro-ph/0504653

Sources for images used:

- Spacecraft images: from NASA Solar System Exploration: Spacecraft images http://solarsystem.nasa.gov/multimedia/gallery.cfm?Category=Spacecraft
- All images of Saturn and its moons are from the NASA Planetary Photo Journal, unless otherwise indicated. http://photojournal.jpl.nasa.gov/target/Saturn
- 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
- Saturn's composition: from Journey through the Galaxy: Saturn, http://home.cwru.edu/~sjr16/advanced/saturn.html
- Saturn rotation: from NASA Planetary Photo Journal, http://photojournal.jpl.nasa.gov/animation/PIA06082
- Painting of Saturn's ring particles: by William Hartmann, http://www.psi.edu/hartmann/planets.html
- Ring shepherding satellites: from Astronomy 121: Saturn by Jim Schombert, http://abyss.uoregon.edu/~js/ast121/lectures/lec20.html
- Orbits of Epithemus and Janus: from Astronomy 121: Saturn by Jim Schombert , http://abyss.uoregon.edu/~js/ast121/lectures/epimetheus_and_janus.html
- Voyager images of Saturn's moons: from The Planetary Society, http://www.planetary.org/saturn/moons.html
- Roche limit: from Wikipedia: Roche Limit http://en.wikipedia.org/wiki/Roche_limit
- Artist's impression of icy volcano on Enceladus: from Science@NASA, 19 Feb 2002, http://science.nasa.gov/headlines/y2002/19feb_gonesaturn.htm
- Tethys rotation: from Calvin Hamilton's Views of the Solar System, http://www.solarviews.com/cap/sat/vtethys1.htm
- Huygens descent through Titan's atmosphere: from Cassini-Huygens Video, http://saturn.jpl.nasa.gov/multimedia/videos/video-details.cfm?videoID=79
- 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 rotation: from Calvin Hamilton's Views of the Solar System, http://www.solarviews.com/cap/sat/vhyper1.htm
- Ring particles: from Astro1B 4007 by Simon Balm, http://homepage.smc.edu/balm_simon/winter2004/astro4007b/lect15.html