Voyage to the Planets
Lecture 7:
Saturn

Lord of the Rings

Presented by

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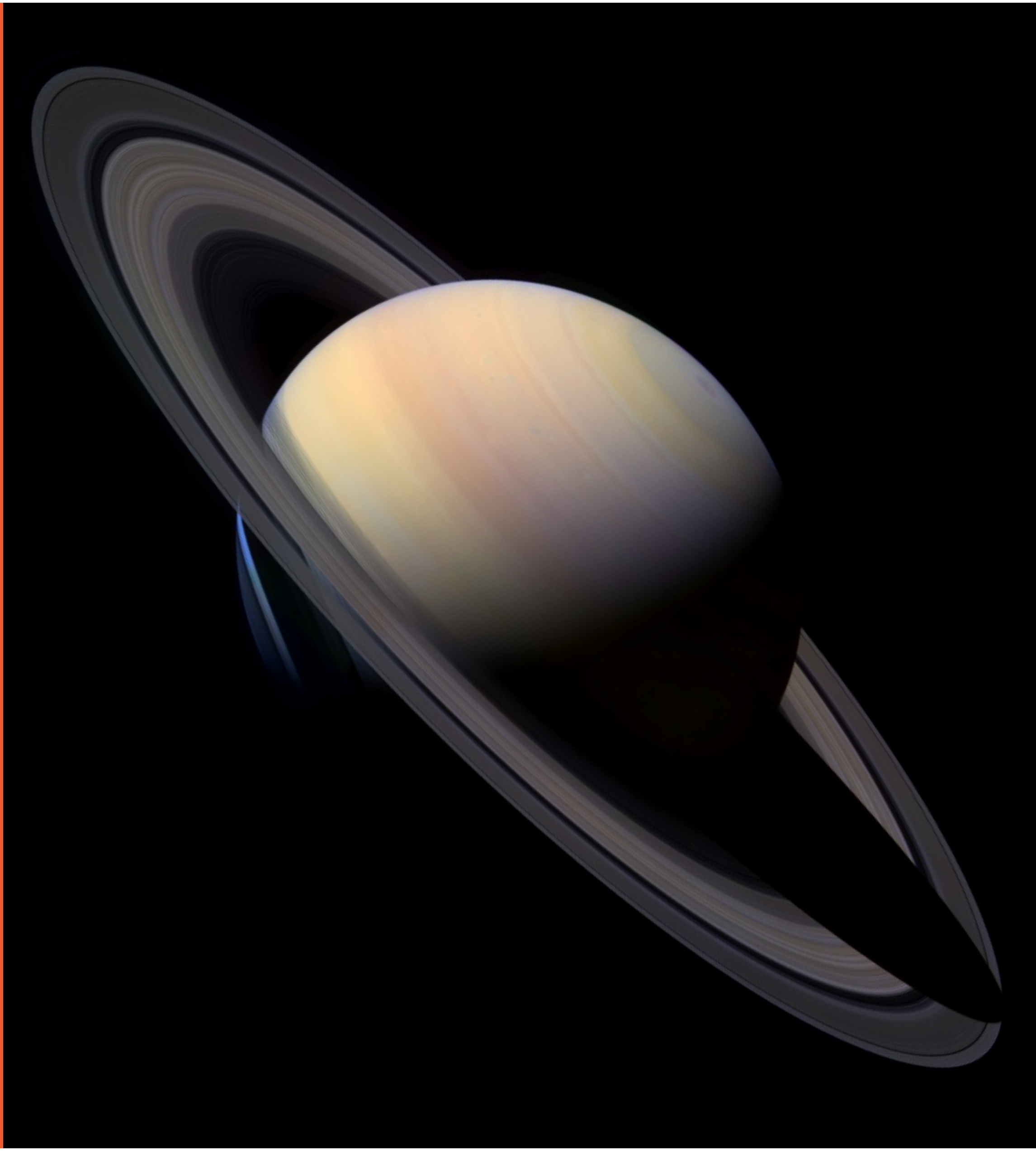
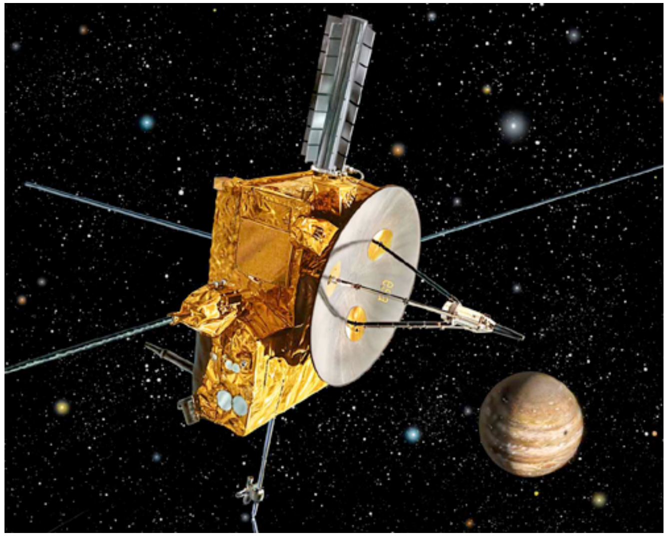
Spring 2017

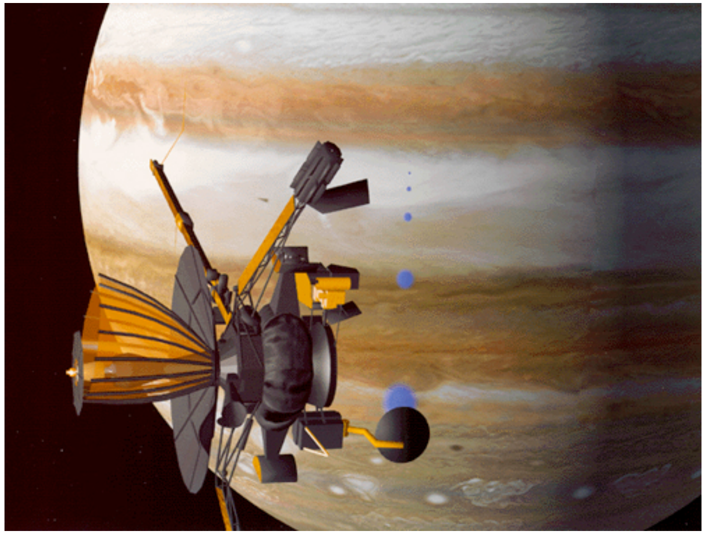
THE UNIVERSITY OF SYDNEY

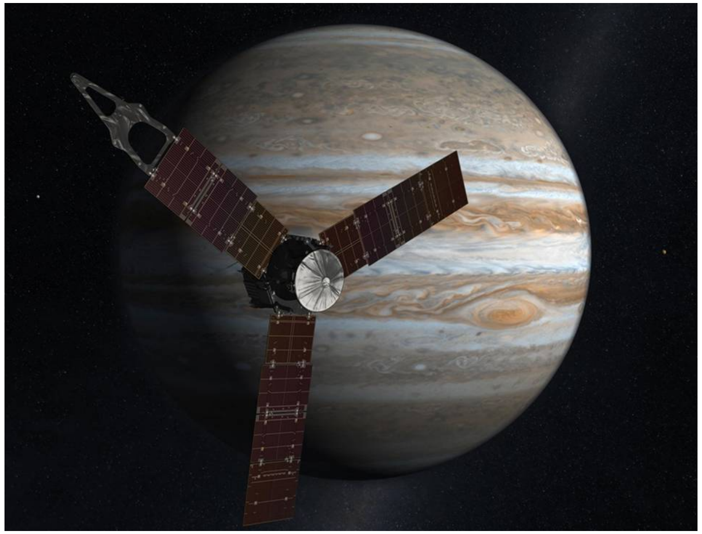


Three spacecraft have flown past Saturn, and one – *Cassini–Huygens* – orbited the planet from 2004–2017.

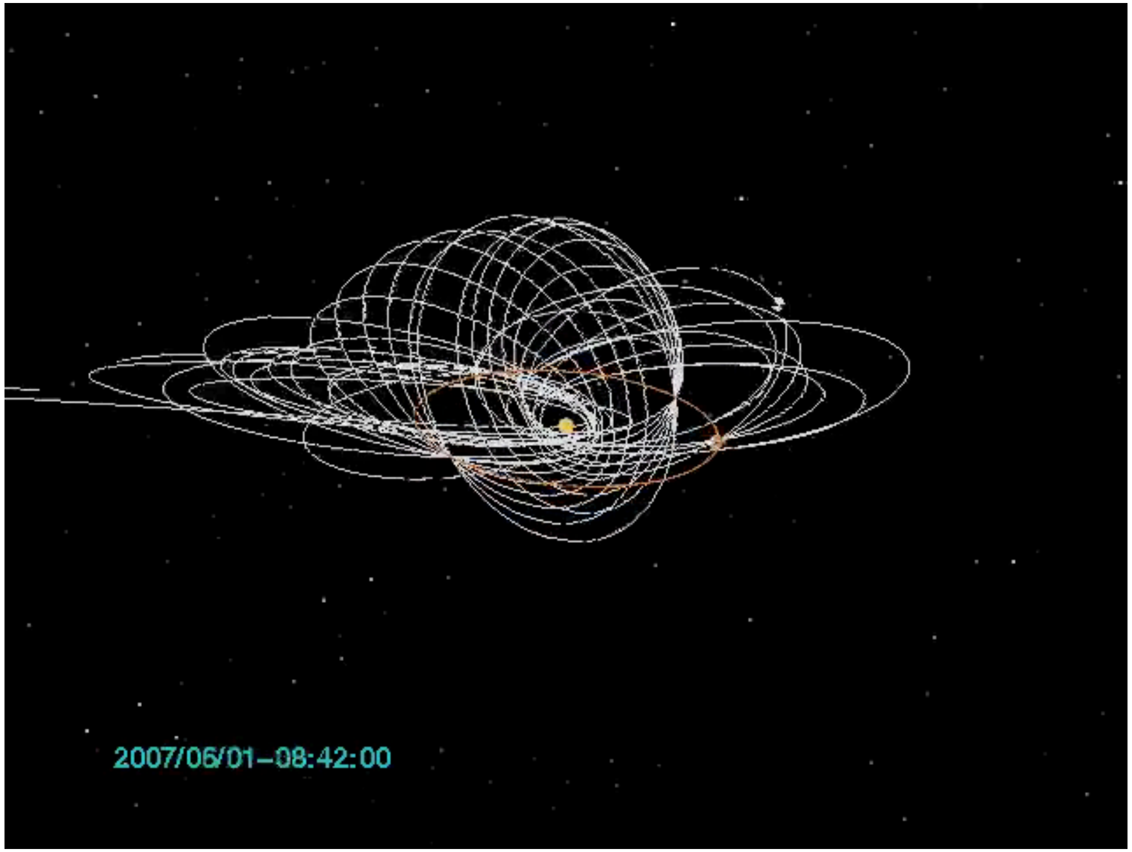
Pioneer 11	1979	Flyby
Voyager 1	1980	Flyby
Voyager 2	1981	Flyby
Cassini–Huygens	2004 – 2017	Orbiter and probe to Titan







Cassini began its tour of the Saturn system in 2004, passing as close as possible to as many moons as possible. It used close flybys of Titan to make gravity assists for course changes. Its official 4 year mission ended in June 2008; there were ultimately three mission extensions.



Saturn

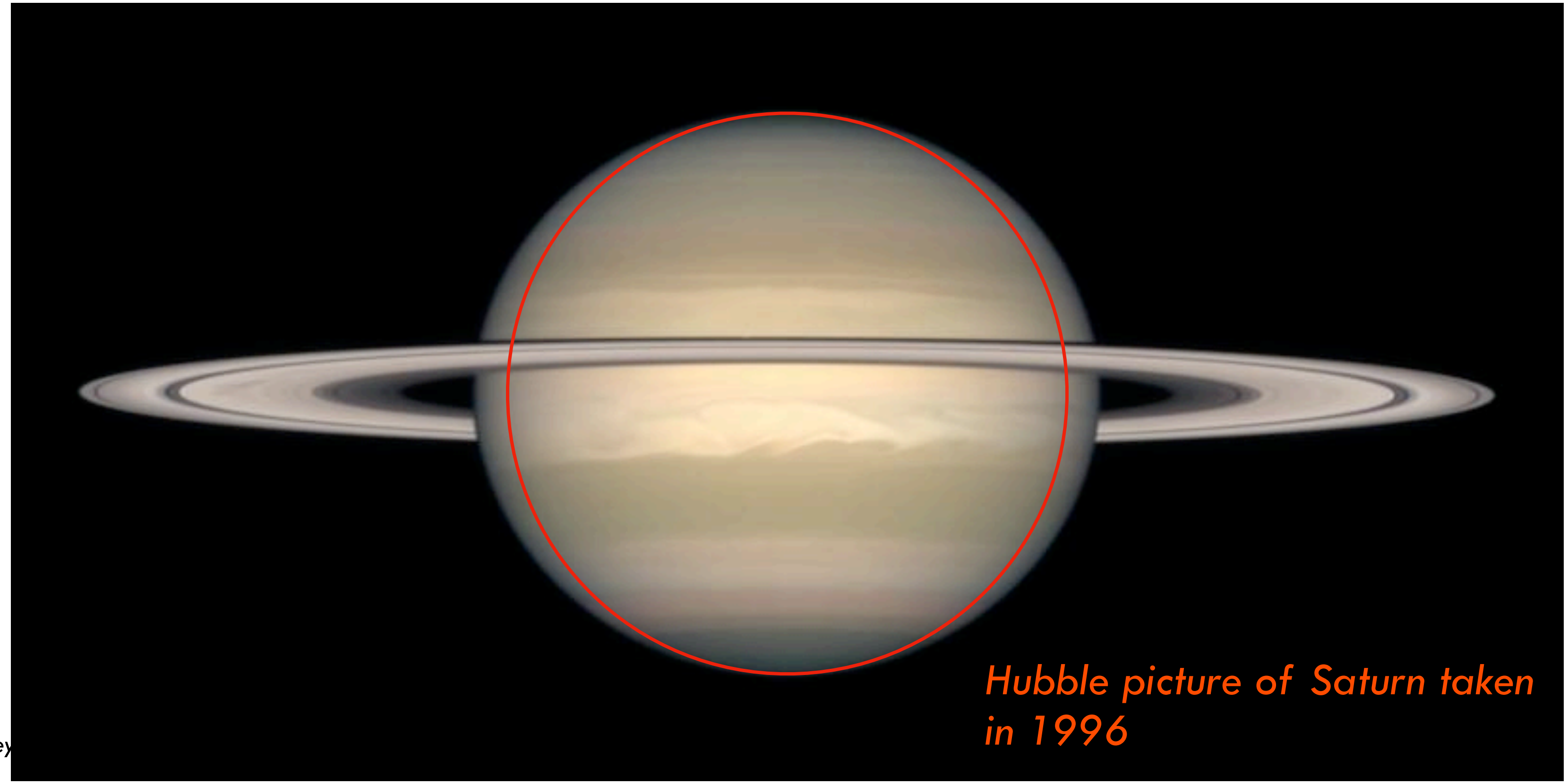
Basic data

	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°	1.14
Rotation period	10.656 h	0.445

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.

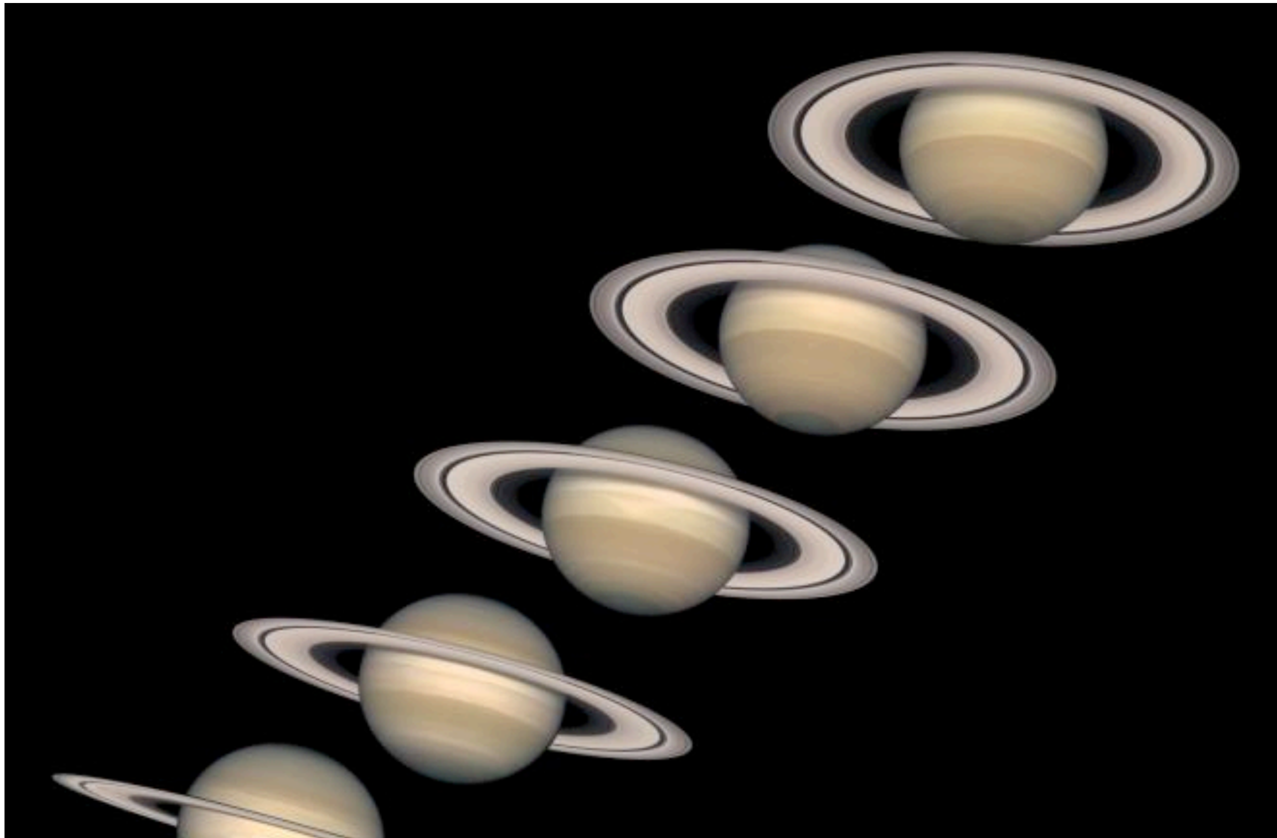
Saturn’s low density and rapid rotation make Saturn the most oblate planet: its equatorial and polar diameters vary by almost 10%.



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.

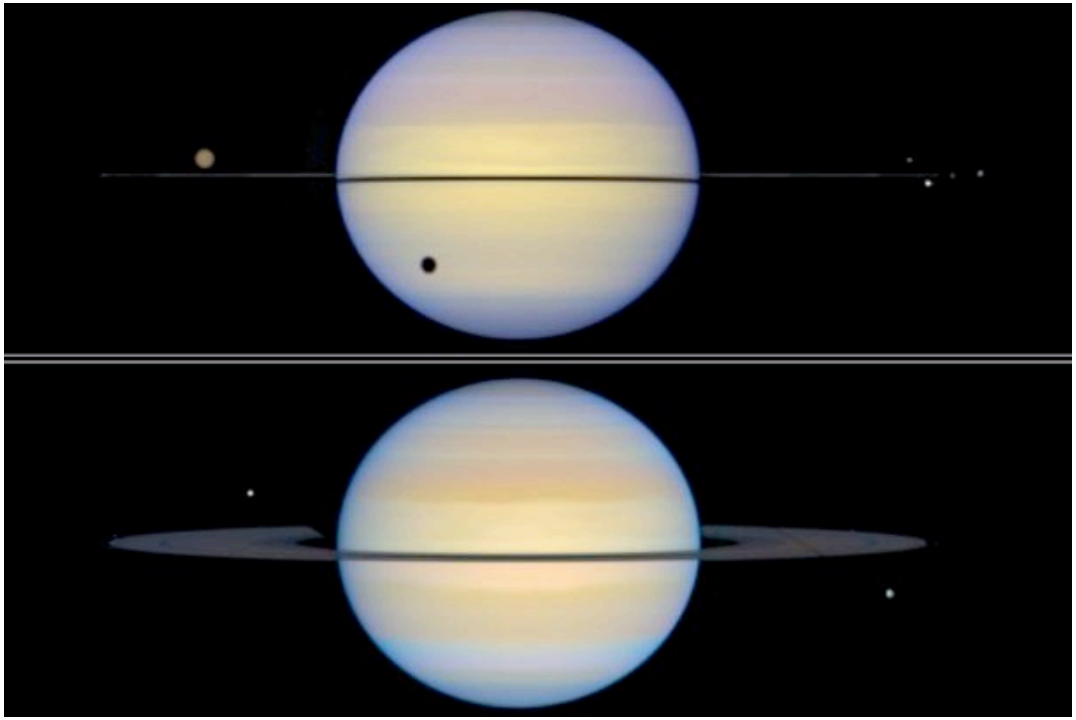
From the Earth, we can see Saturn's rings open up from edge-on to nearly fully open, then close again to a thin line as Saturn moves along its 29 year orbit.

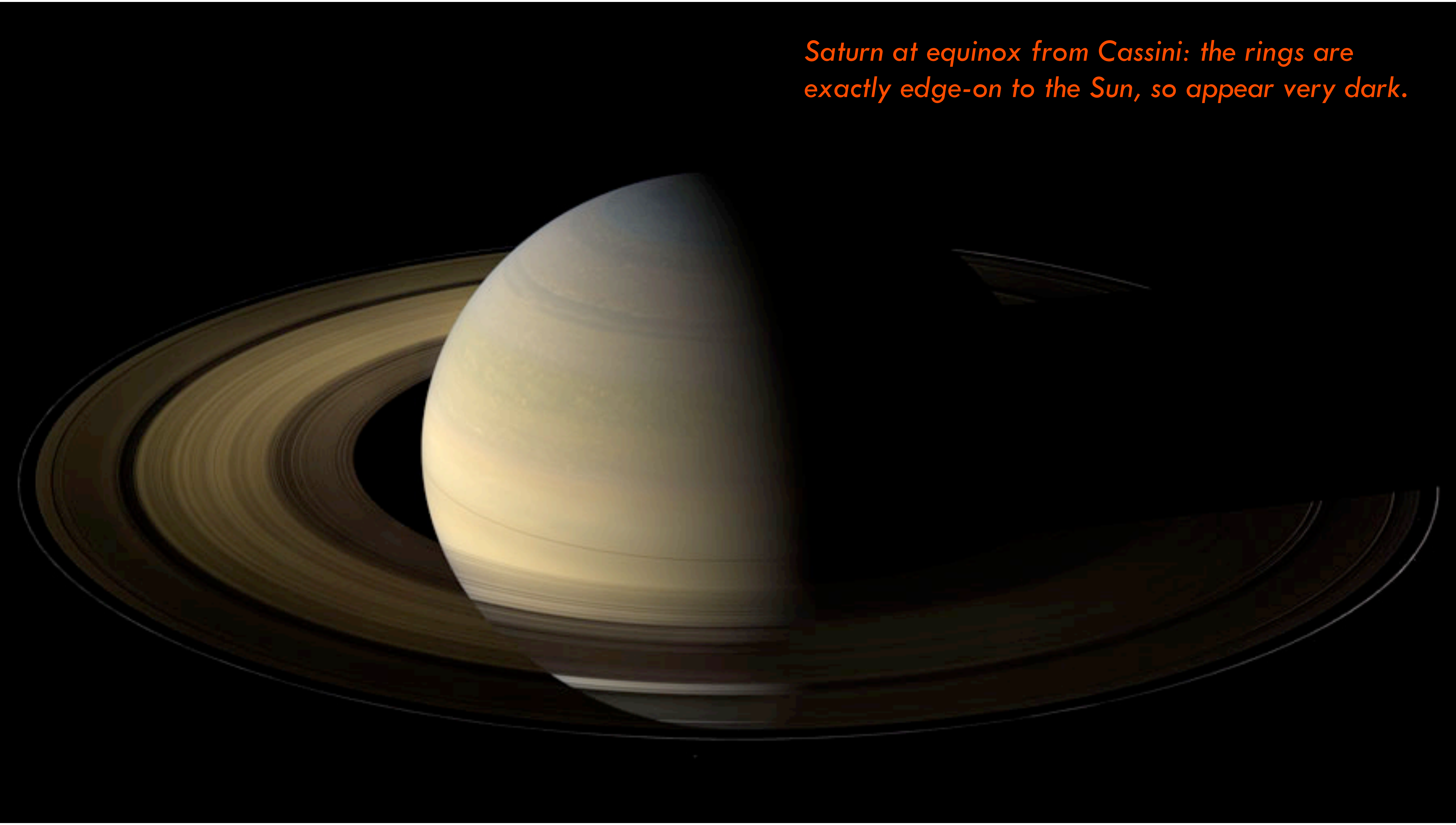
Saturn’s rings were last edge-on on 11 August 2009 (the Saturnian equinox), while *Cassini* was in orbit.



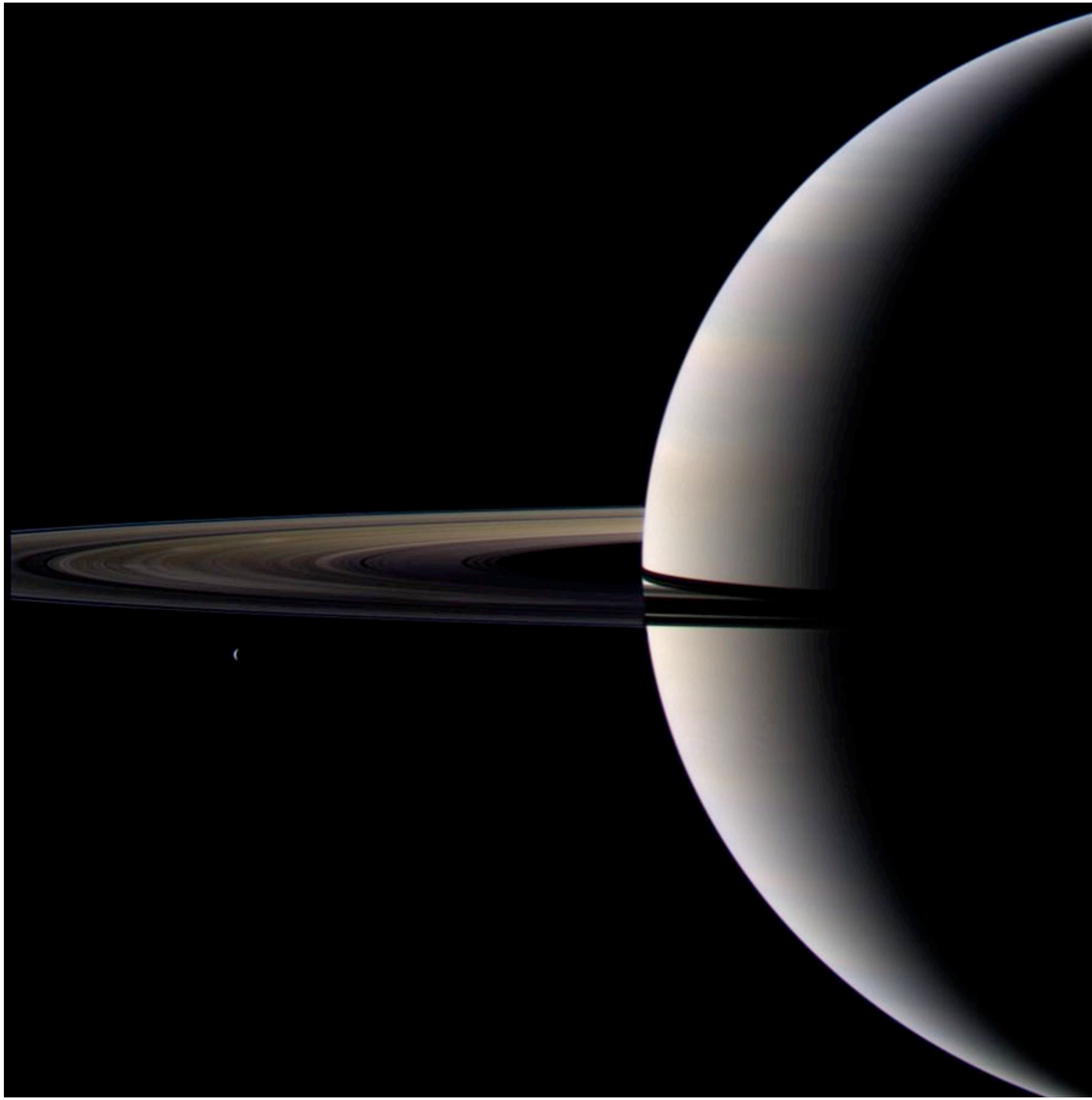
Sequence of Hubble pictures taken between 1996 and 2000.

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

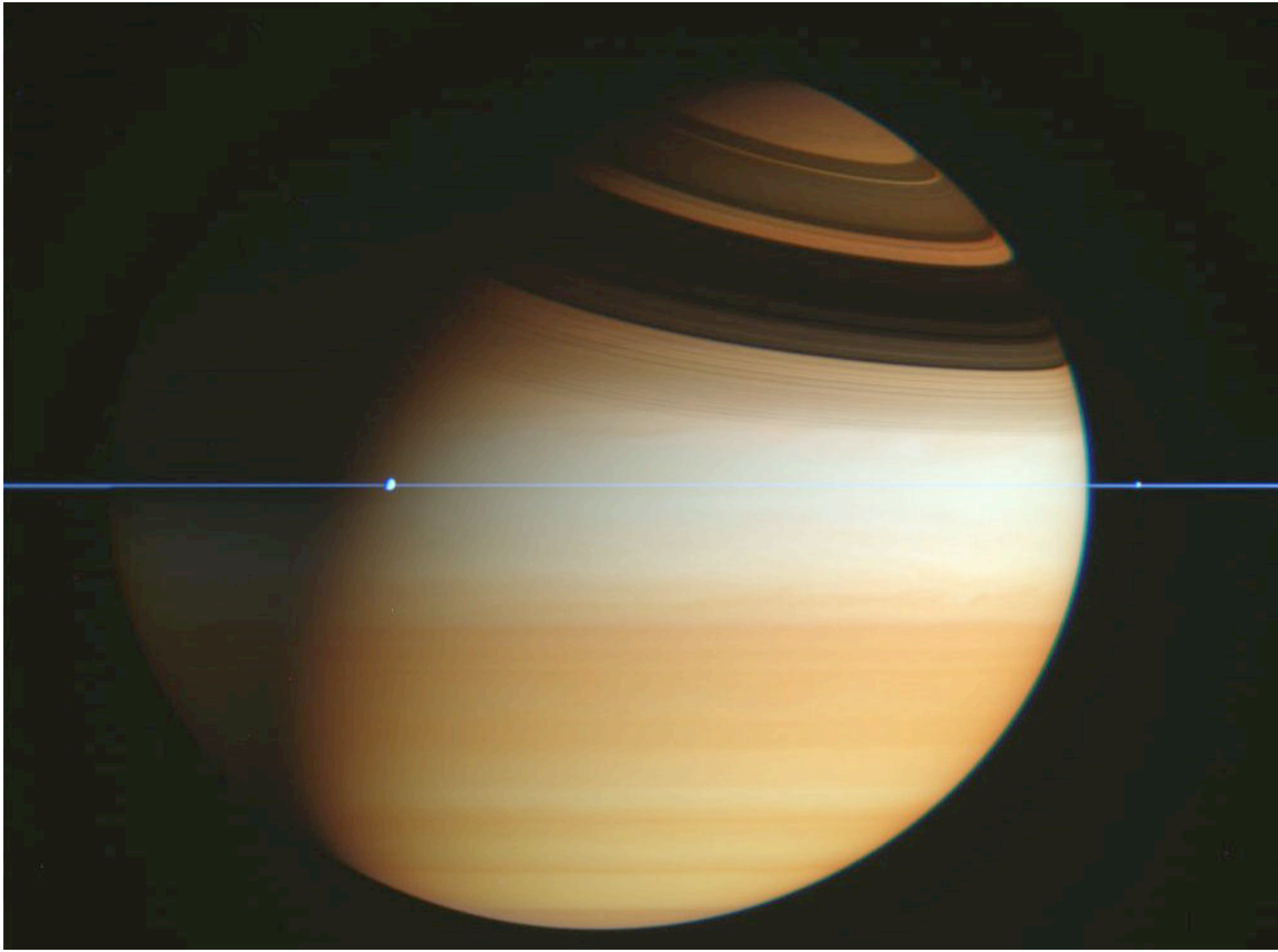




Saturn at equinox from Cassini: the rings are exactly edge-on to the Sun, so appear very dark.

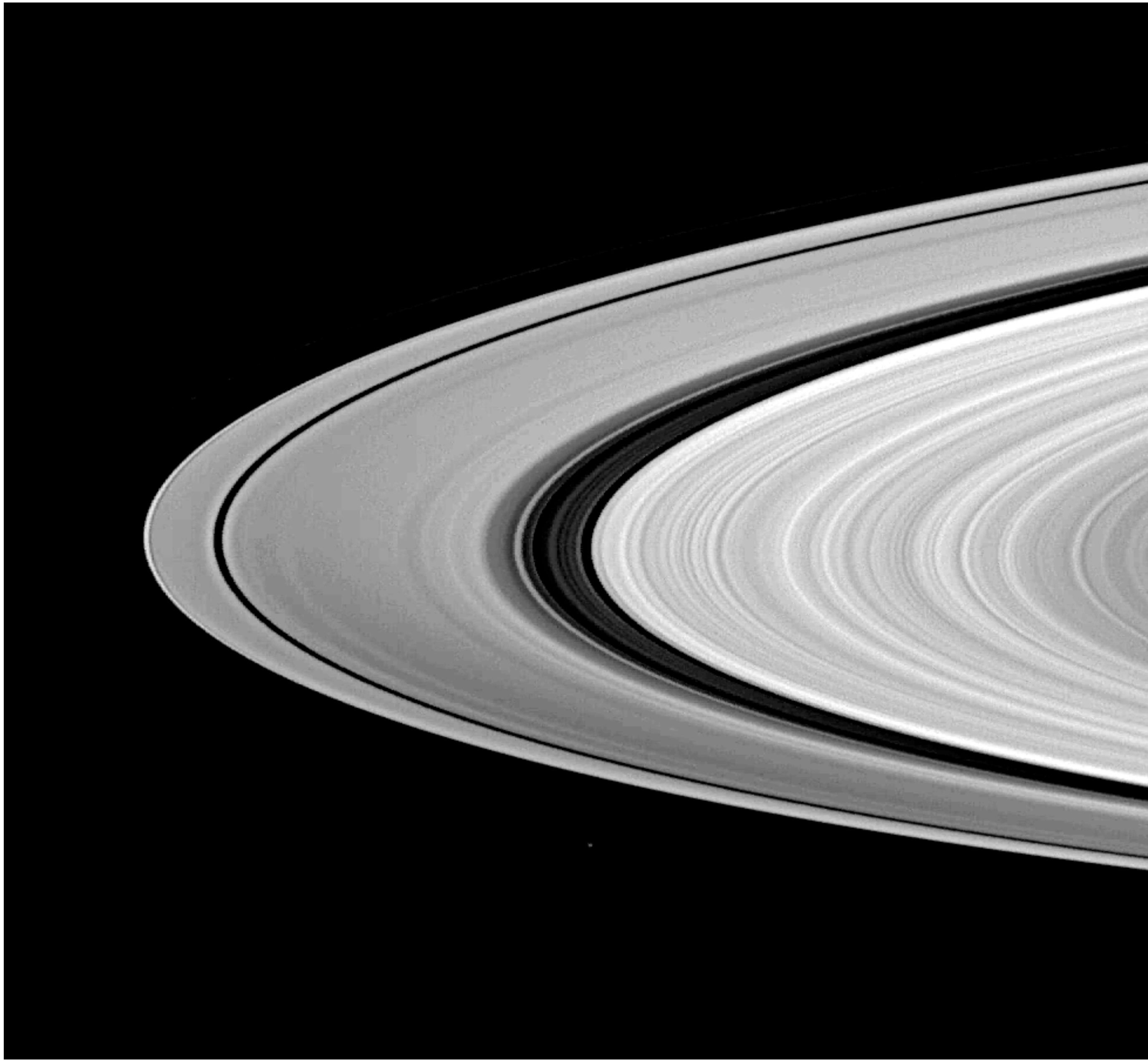


Saturn at equinox from Cassini: only a thin shadow of Saturn's rings is visible across the center of the planet



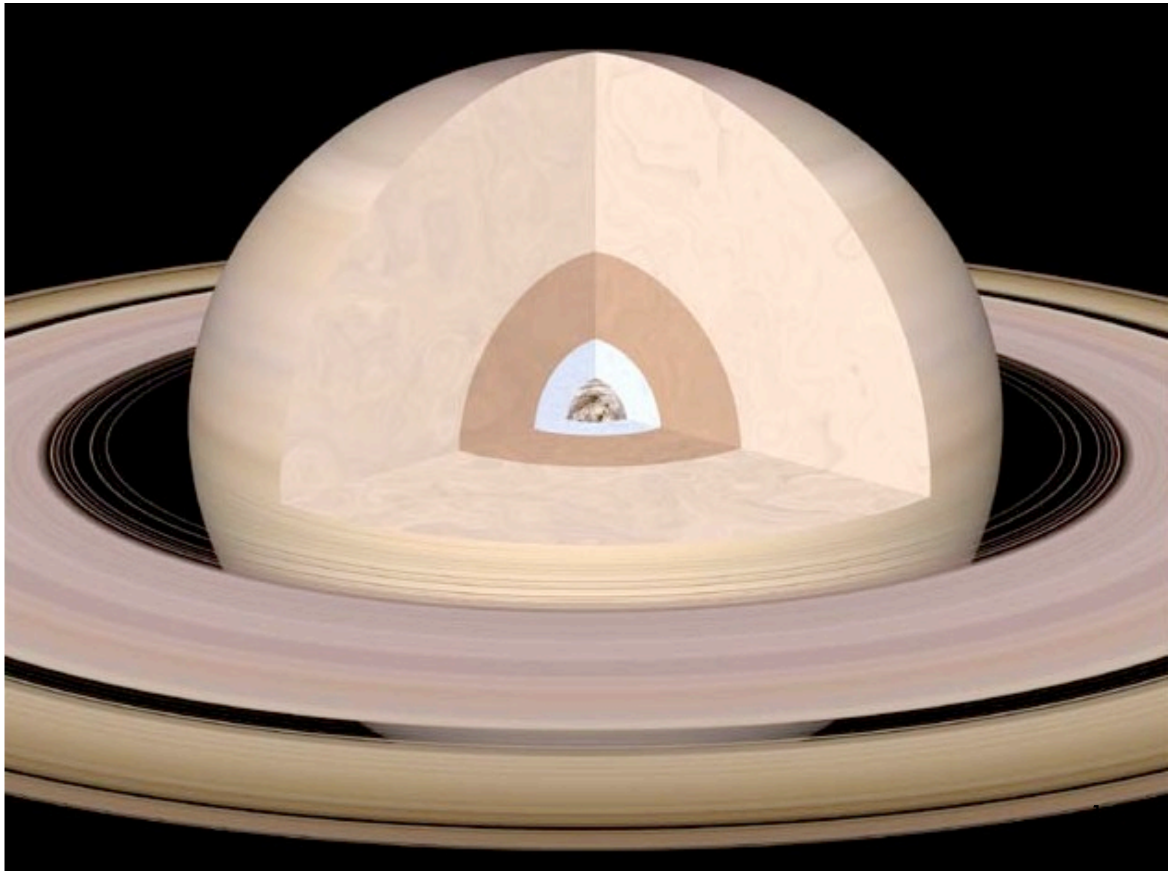
Cassini's ring plane crossing

Cassini saw ring plane crossings twice per orbit.

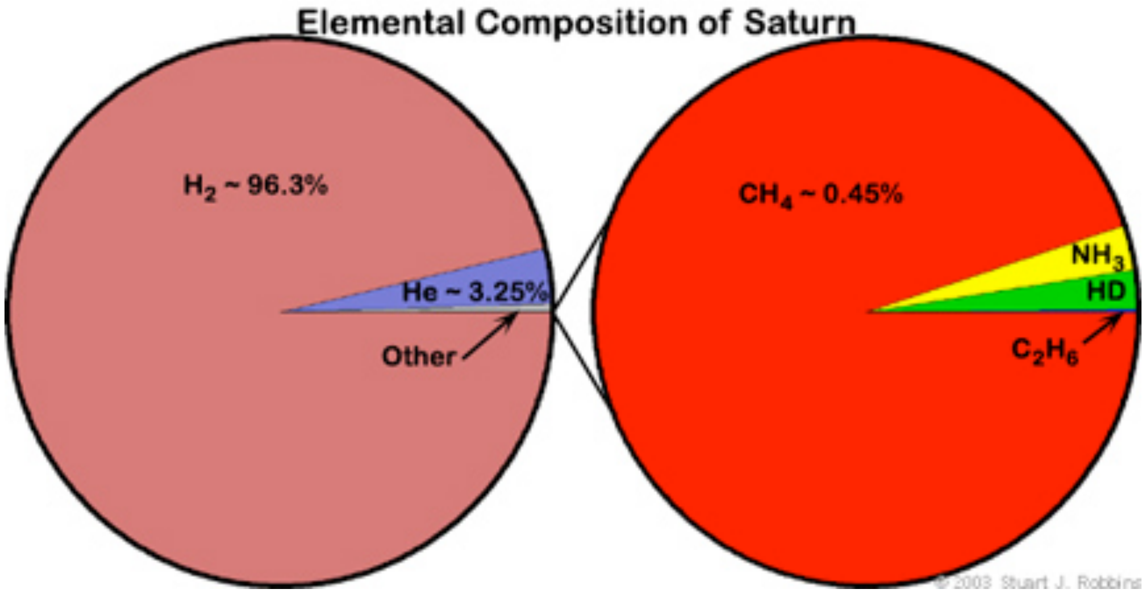


Movie made from 34 images taken during a ring-plane crossing from the sunlit side, in January 2007. The first large moon seen is Enceladus, showing its inclined orbit.

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.

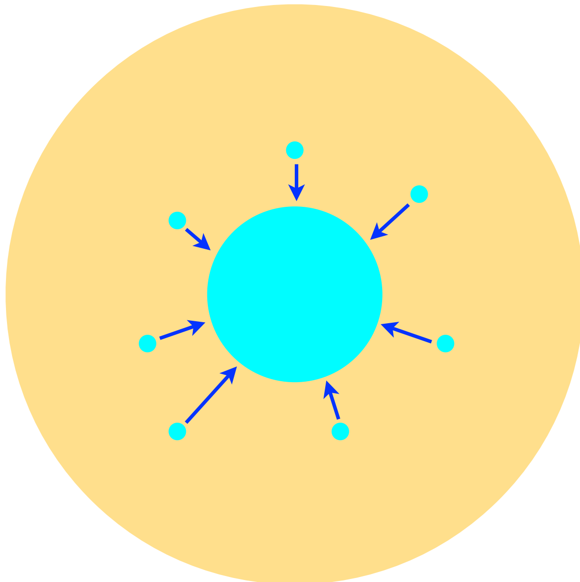


Saturn’s atmosphere is similar to Jupiter’s, consisting almost entirely of hydrogen and helium, with trace amounts of other gases. However, Saturn’s atmosphere is deficient in helium compared to Jupiter’s, which contains 10% helium.

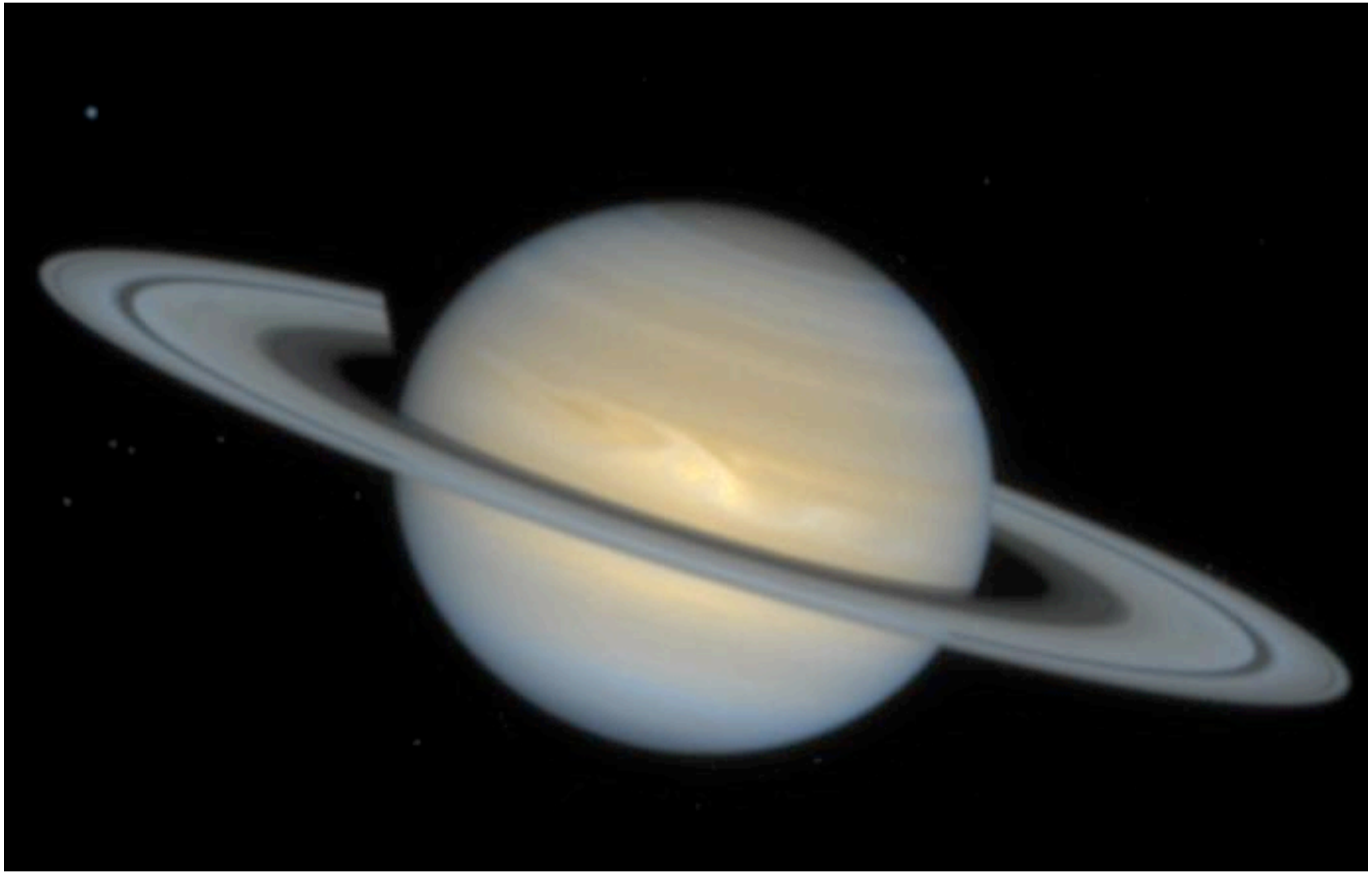


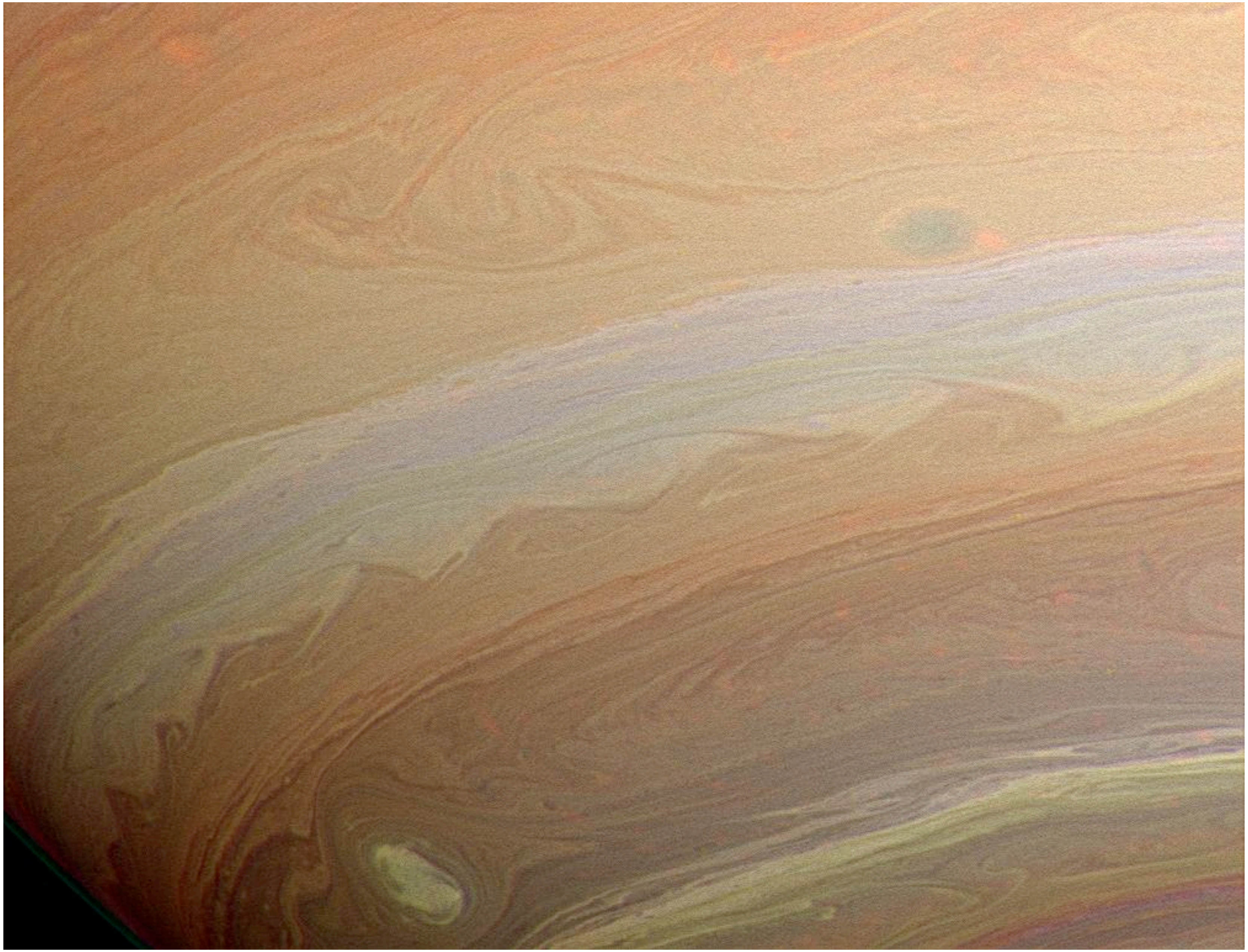
Like Jupiter, Saturn radiates more energy into space than it receives from the Sun: in fact, Saturn radiates more heat than Jupiter. Jupiter's remnant heat is leftover energy from the time of formation. But, since Saturn is less massive than Jupiter, it should have less leftover energy.

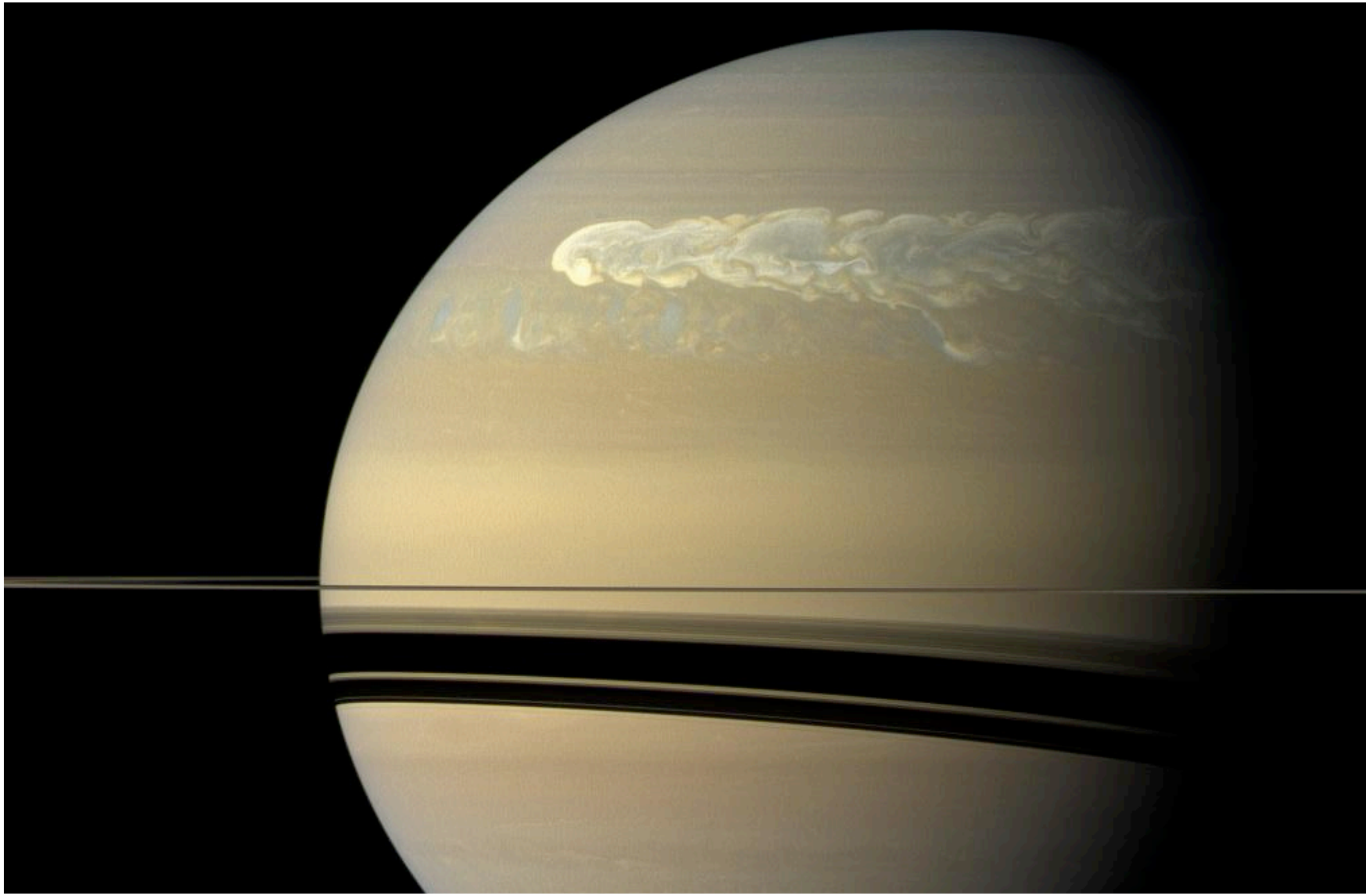
Instead, it is thought that Saturn’s atmosphere is separating out. Saturn’s atmosphere is colder than Jupiter’s, so helium forms droplets, which condense into helium rain. These sink towards the core, heating the atmosphere and depleting it of helium.



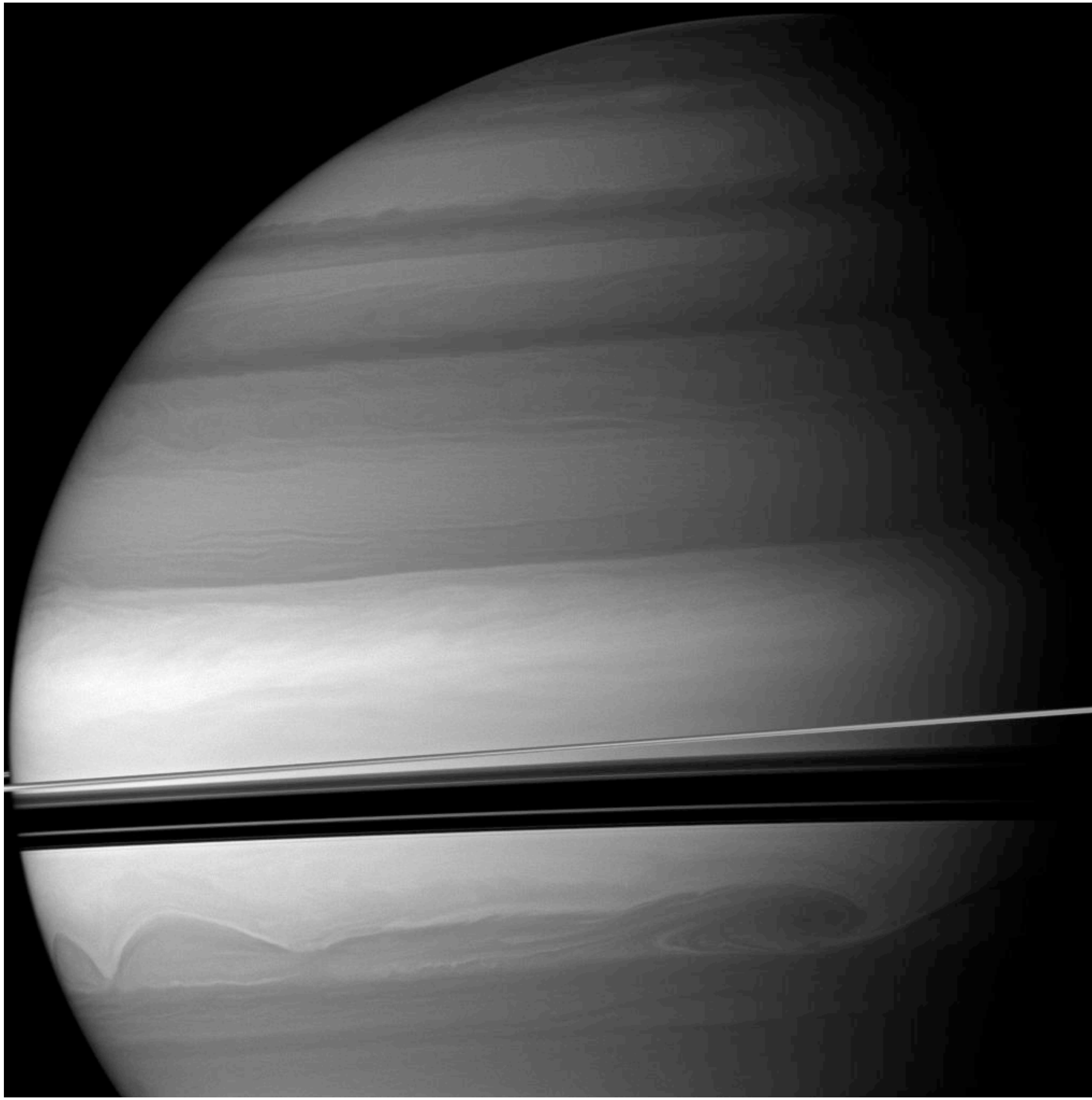
Saturn's atmosphere exhibits a banded pattern similar to Jupiter's, but Saturn's bands are much fainter.



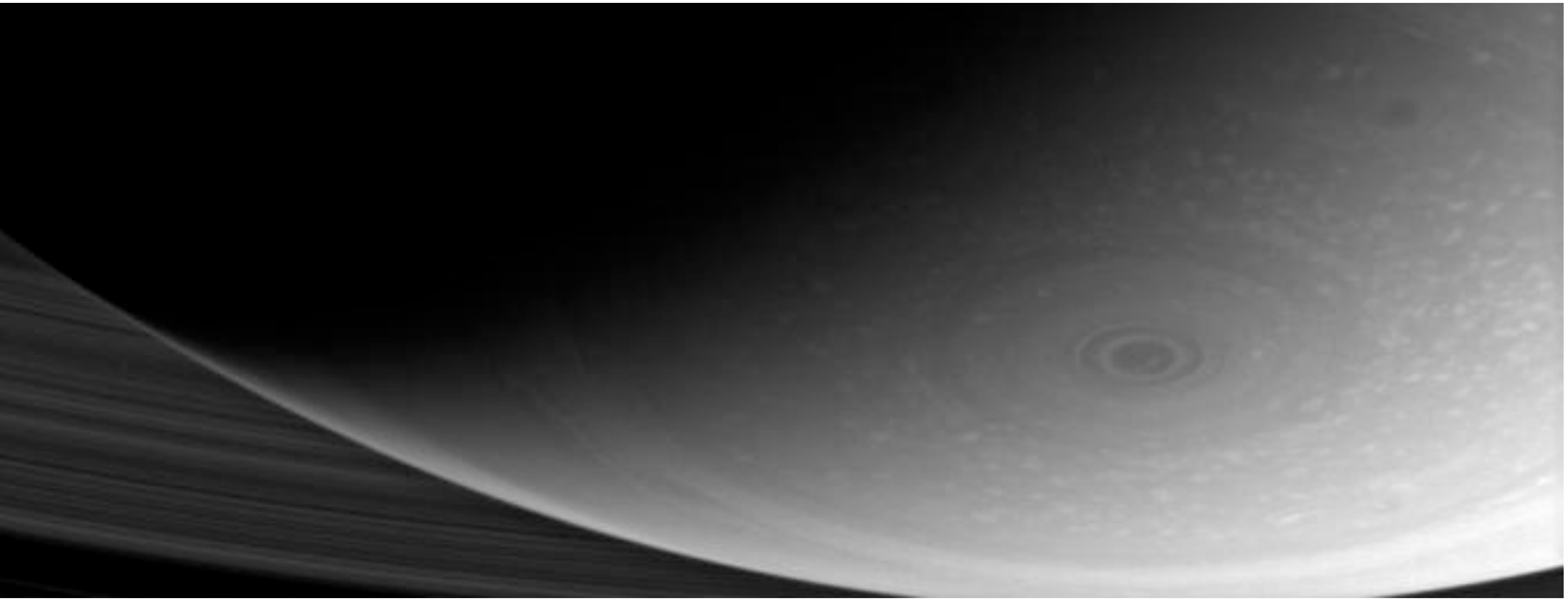


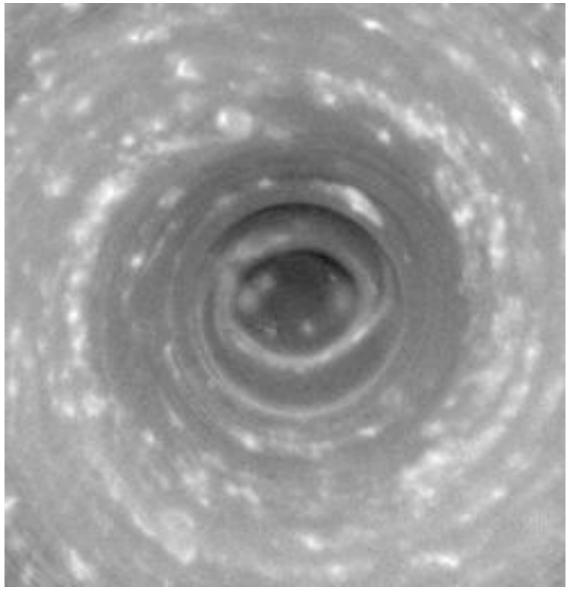


Cassini saw a huge storm during 2010–2011; eight times the area of the Earth, it is the most intense ever seen on Saturn. The shadow cast by Saturn's rings has a strong seasonal effect, and it is possible that the switch to powerful storms in the northern hemisphere is related to the change of seasons after the planet's August 2009 equinox.

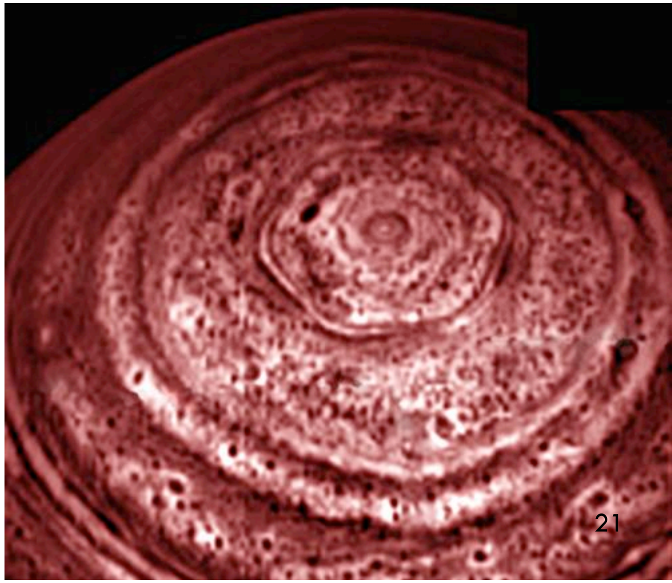


Huge clouds swirl through the southern latitudes of Saturn where the rings cast dramatic shadows.

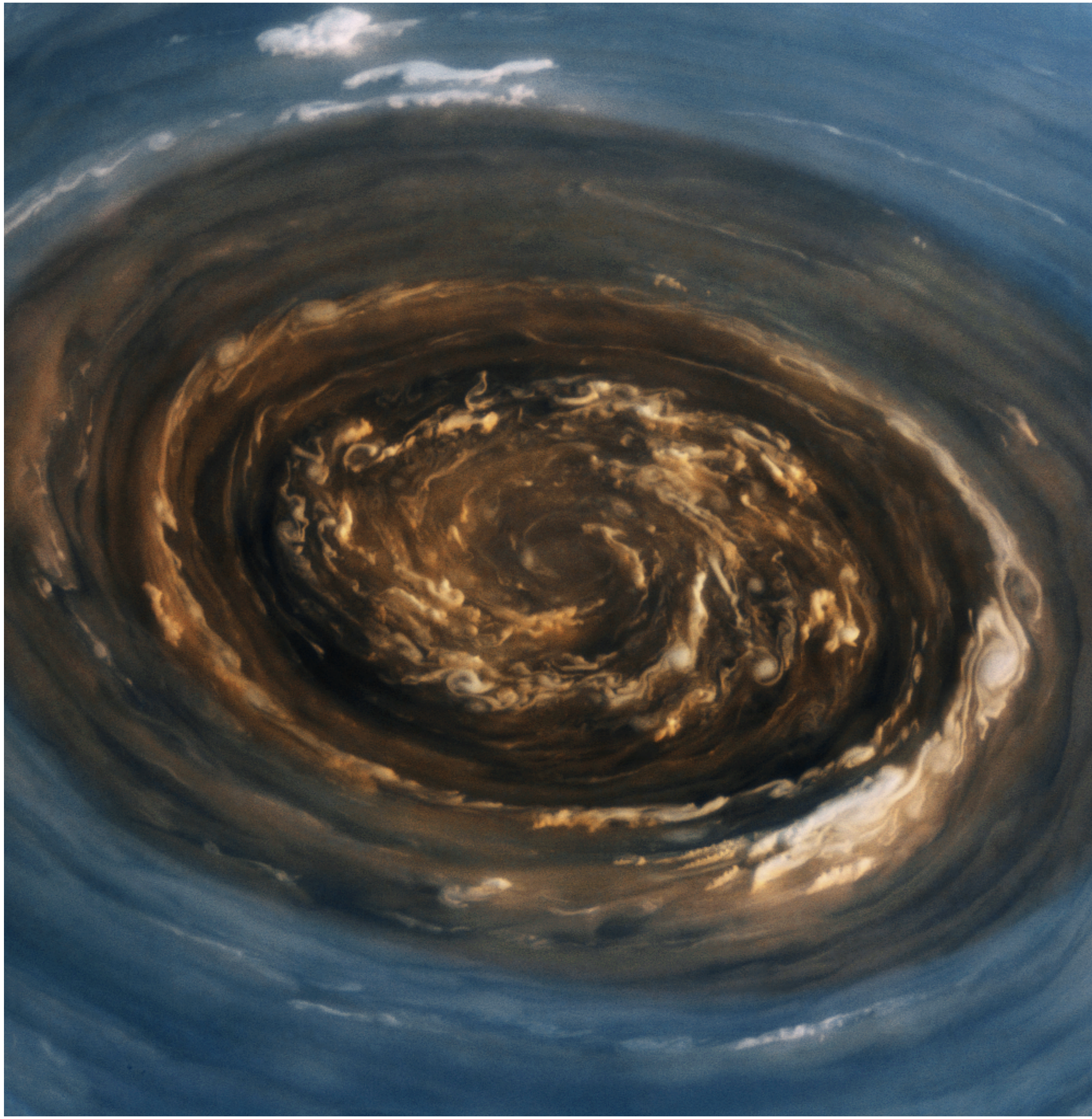




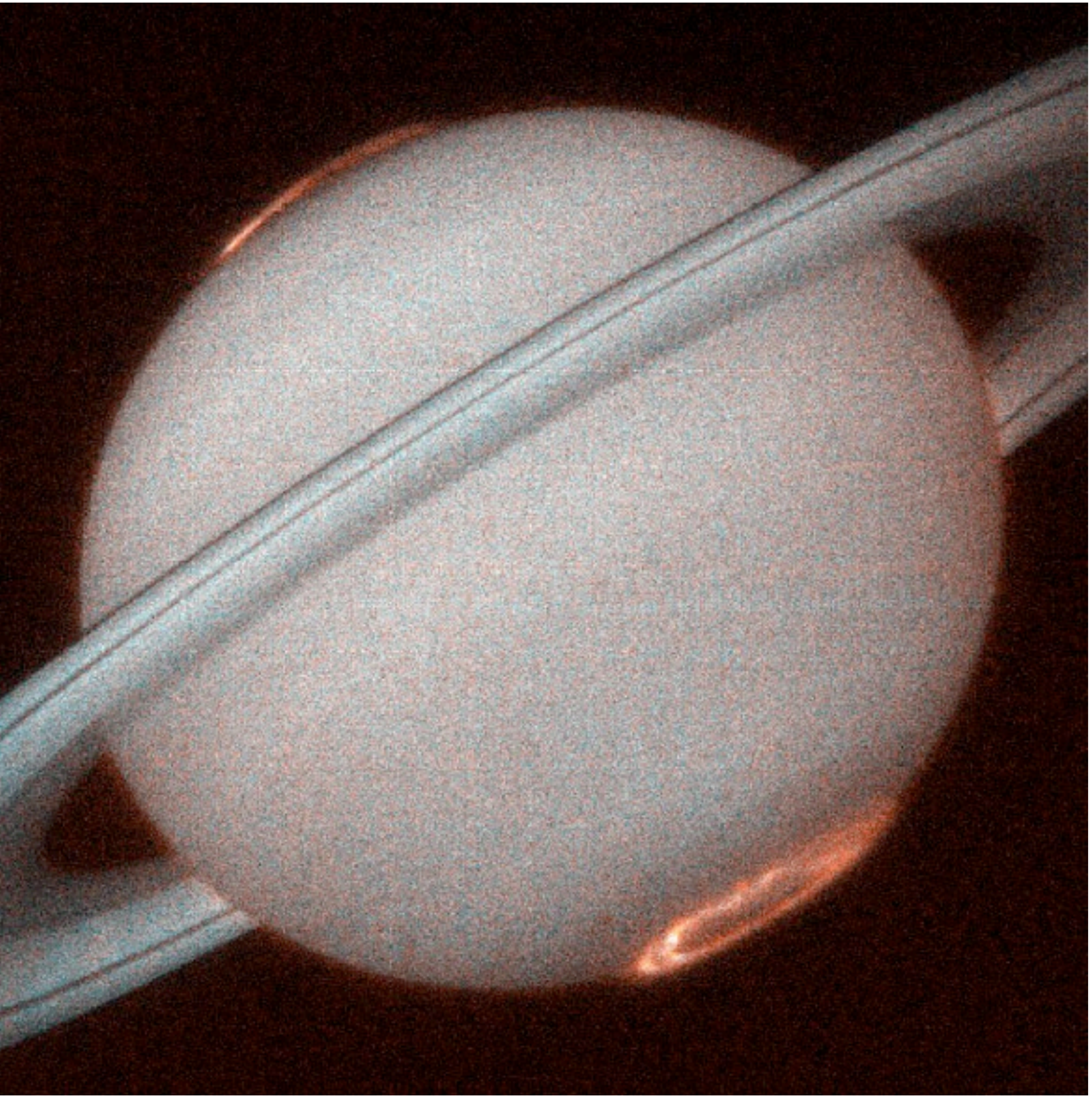
Polar vortex and hexagon



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.



Clouds at the centre of the north polar vortex, taken in 2012

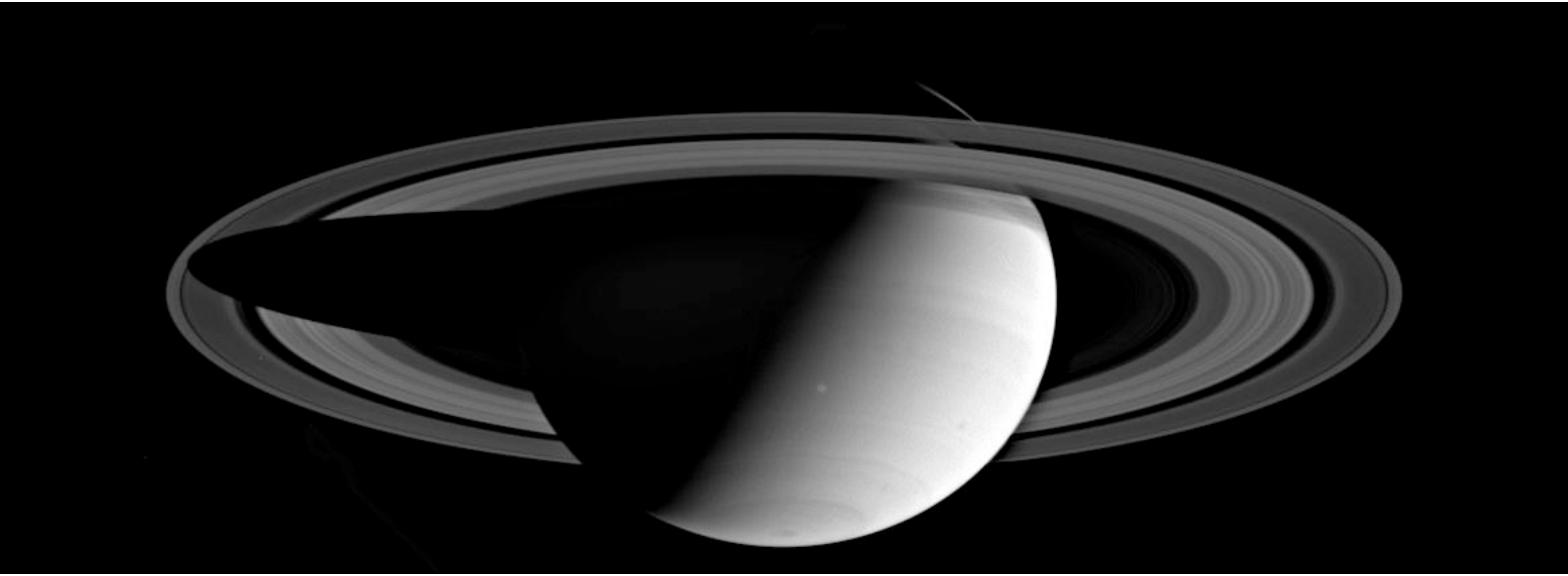


Like Jupiter, Saturn has a magnetic field, though Saturn’s field is less than half the strength of Jupiter’s. Unlike Jupiter’s (and Earth’s), Saturn's magnetic field is aligned with its axis of rotation.

Hubble imaged powerful auroras at both poles.

The most obvious feature of Saturn is 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, possibly only 10–200 m thick.

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

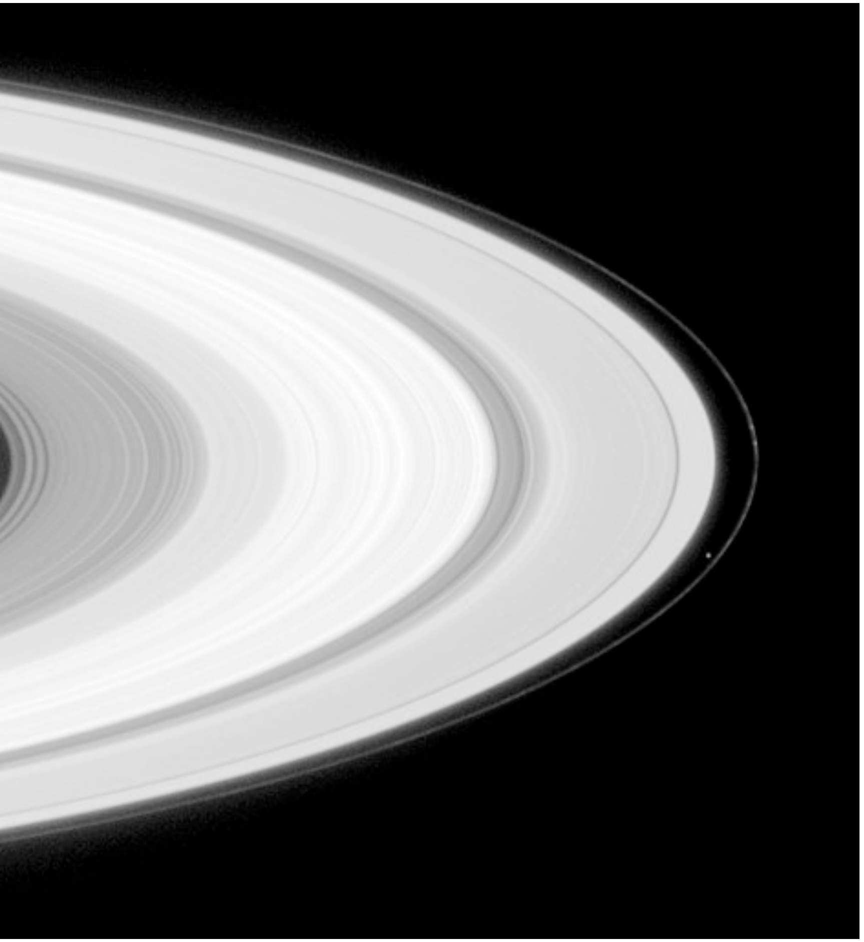
Crescent Saturn seen by Voyager

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

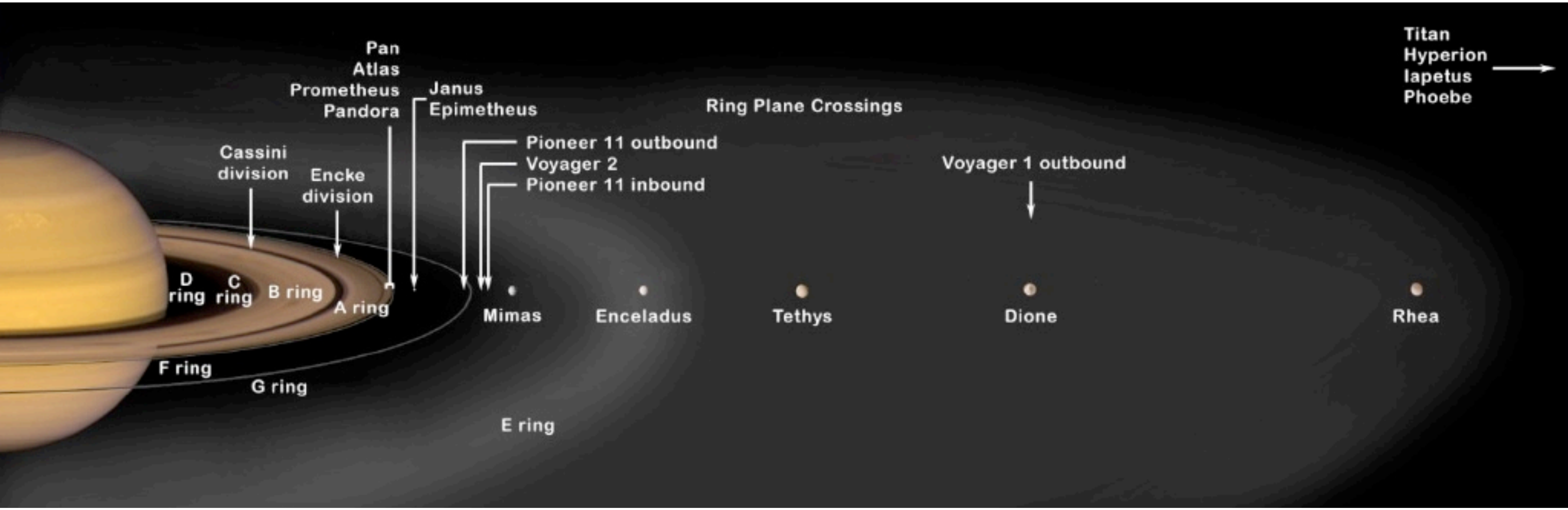
Name	Distance (10^3 km)	Width (10^3 km)	Thickness (km)	Albedo
D	67	7.5		
C	74.5	17.5		0.25
Maxwell gap	*87.5*	*0.27*		
B	92	25.5	0.1–1	0.65
Cassini division	*117.5*	*4.7*		*0.3*
A	122.2	14.6	0.1–1	0.6
Encke division	*133.6*	*0.325*		
Keeler gap	*136.5*	*0.035*		
F	140.2	0.03–0.5		
G	165.8	8	100–1000	
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.

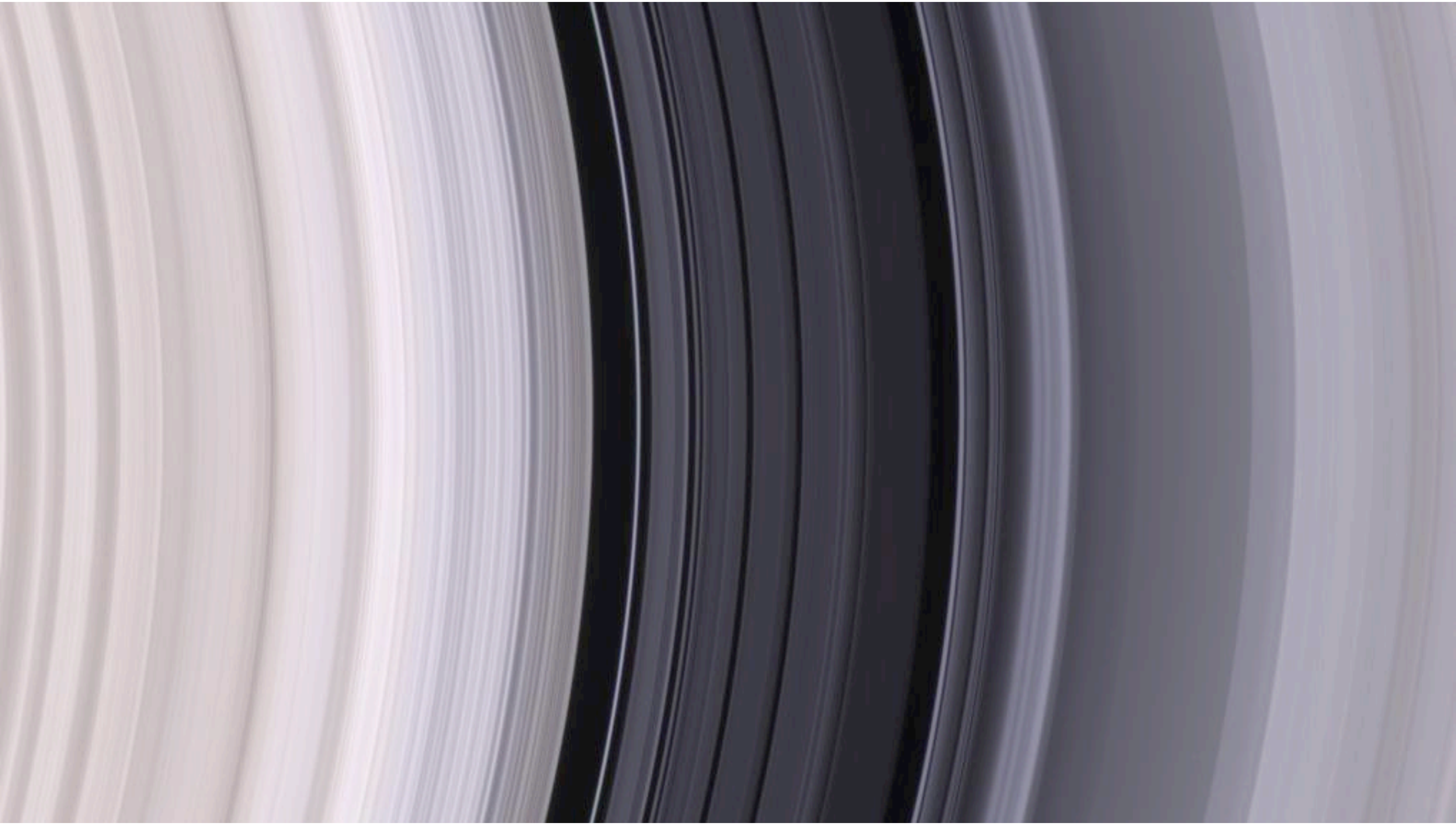
Just outside the A ring lies the F ring, the strangest ring of them all. It is faint, narrow and appears to contain bends and kinks. Close-up pictures show two narrow, braided, bright rings that trace distinct orbits.

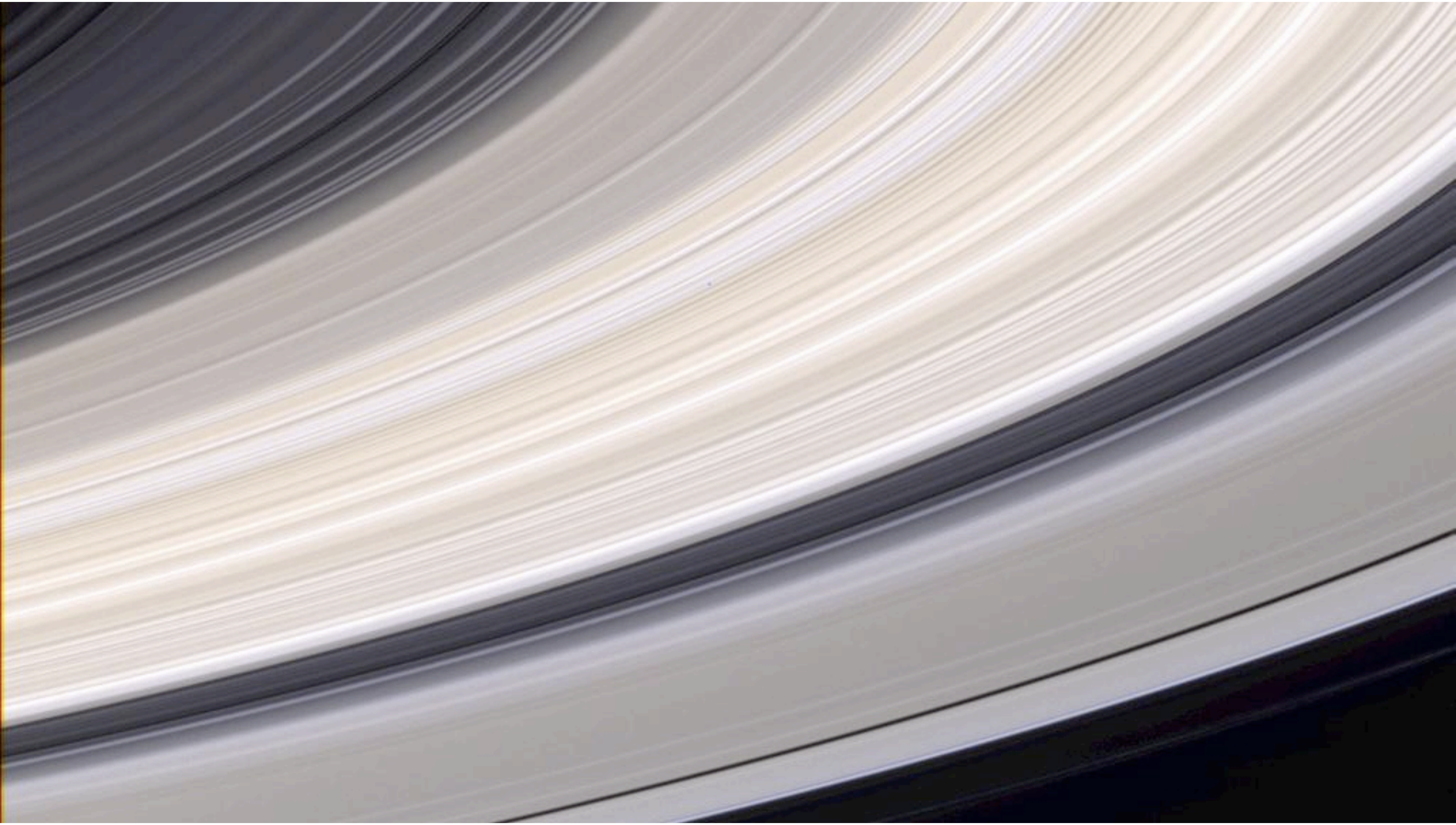


Following the F ring is the faint G ring and even farther out, well outside the main ring structure, lies the E ring. Unlike the main rings, the E ring has a vertical extent of several thousand kilometres, and is more like a cloud than a disk.



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

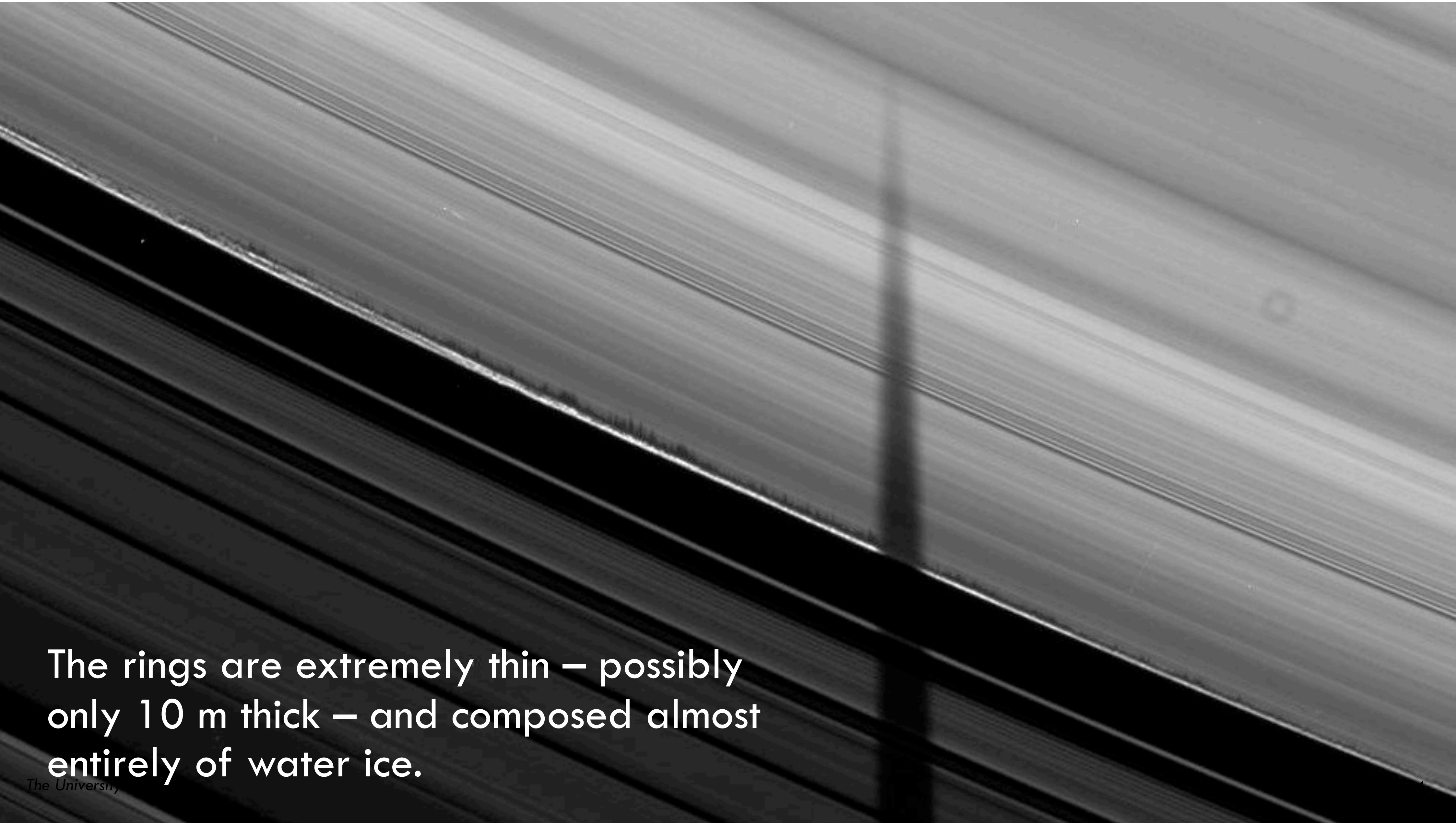




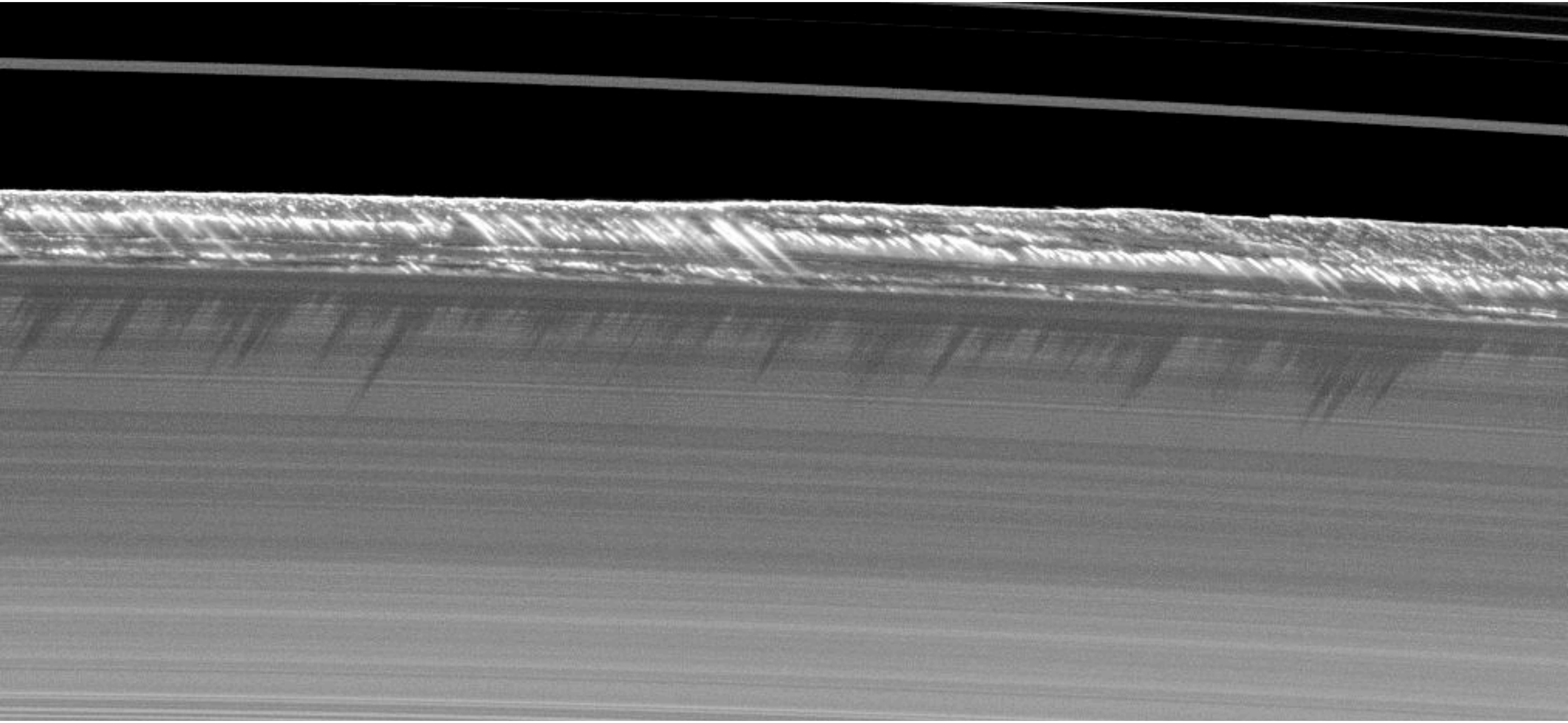
The divisions between the rings are caused by

- 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.



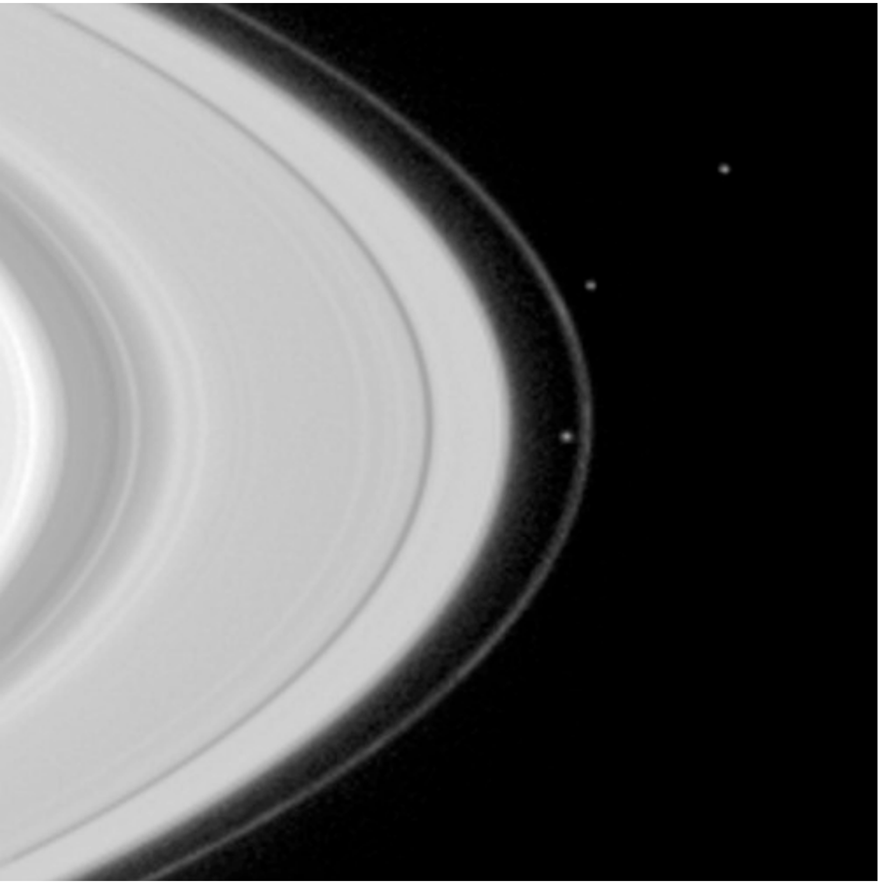
Vertical structures rise abruptly from the edge of Saturn's B ring to cast long shadows on the ring, two weeks before the planet's August 2009 equinox. The image shows a 1,200-kilometer-long section along the outer edge of the B ring. Vertical structures tower as high as 2.5 km above the plane of the rings -- a significant deviation from the vertical thickness of the main A, B and C rings, which is generally only about 10 m.

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.

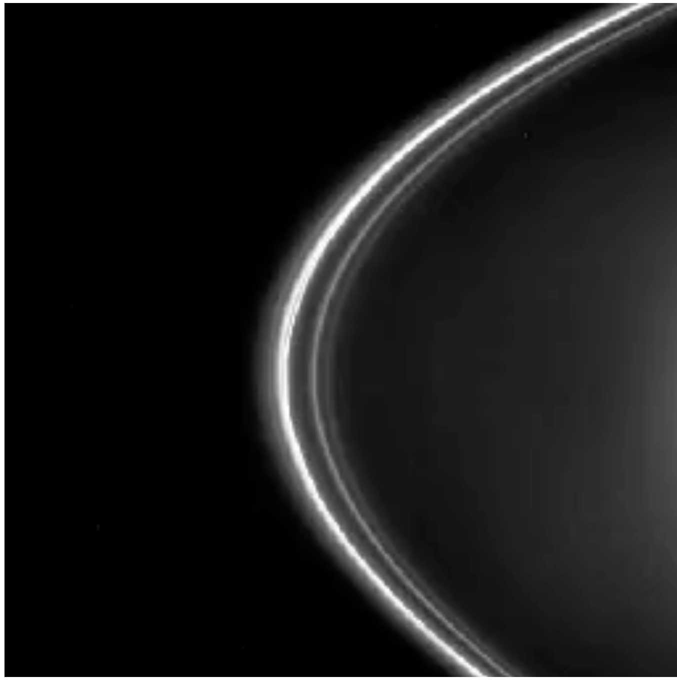
An artist's conception of the chunks and agglomerations of icy material making up the main rings of Saturn. (Painting by William Hartmann)

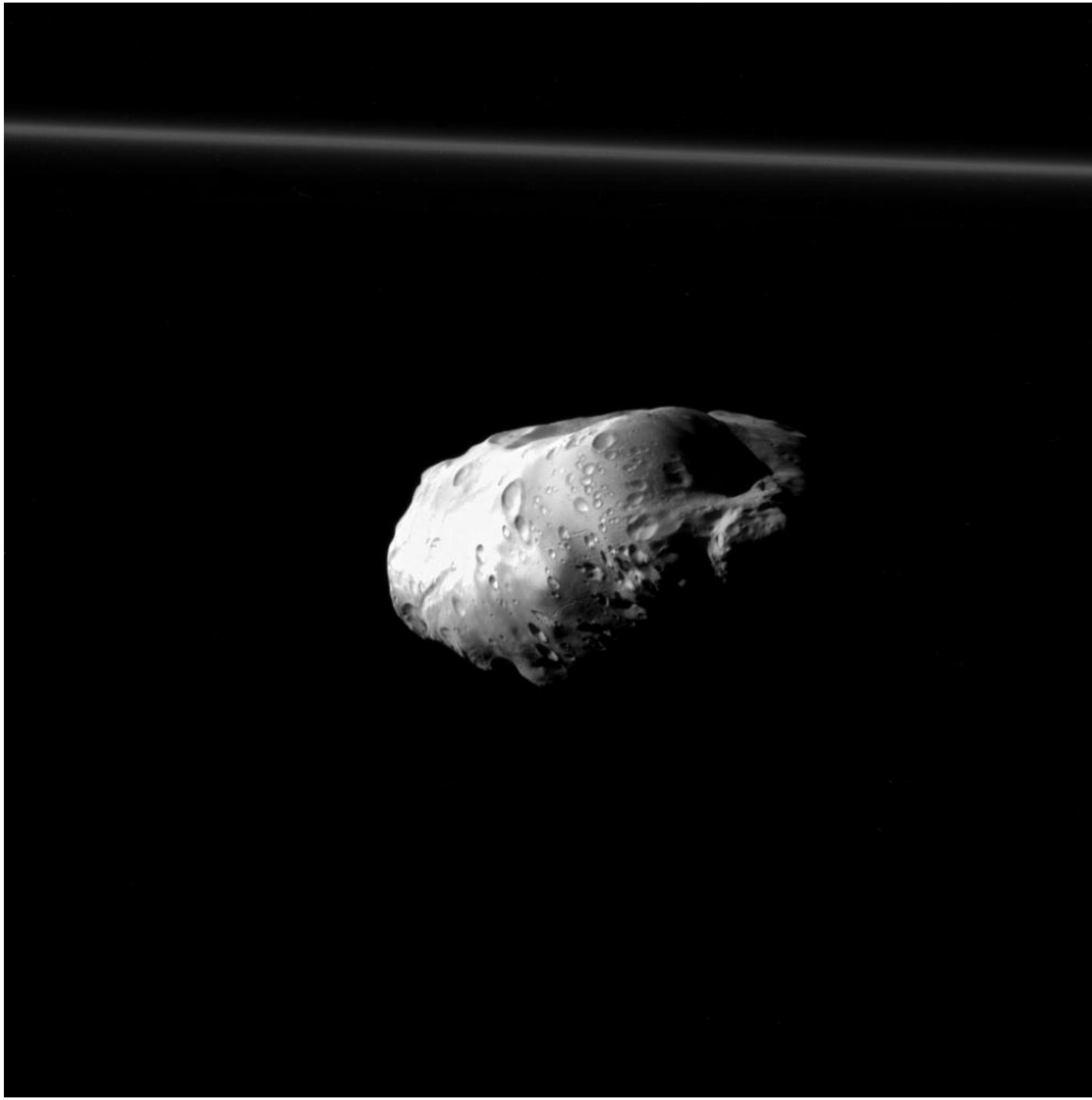
Several of Saturn's rings are maintained by "shepherd satellites". These are moons that keep the rings together and stabilised via gravitational attraction.

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



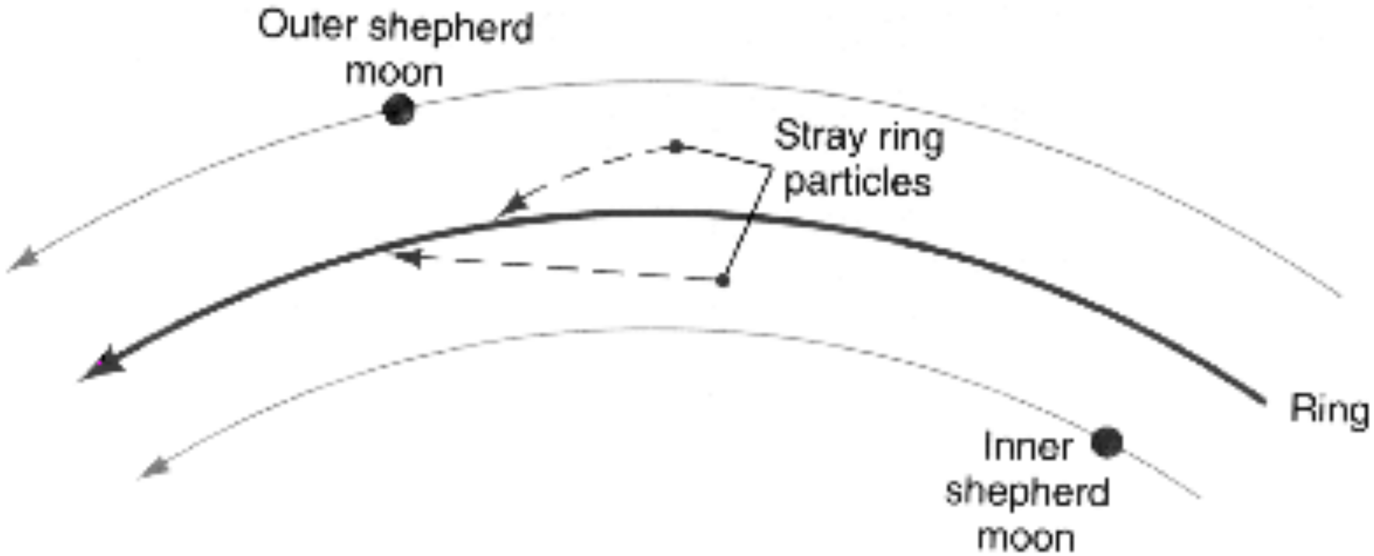
Prometheus orbits just inside the F ring, while Pandora orbits just outside.

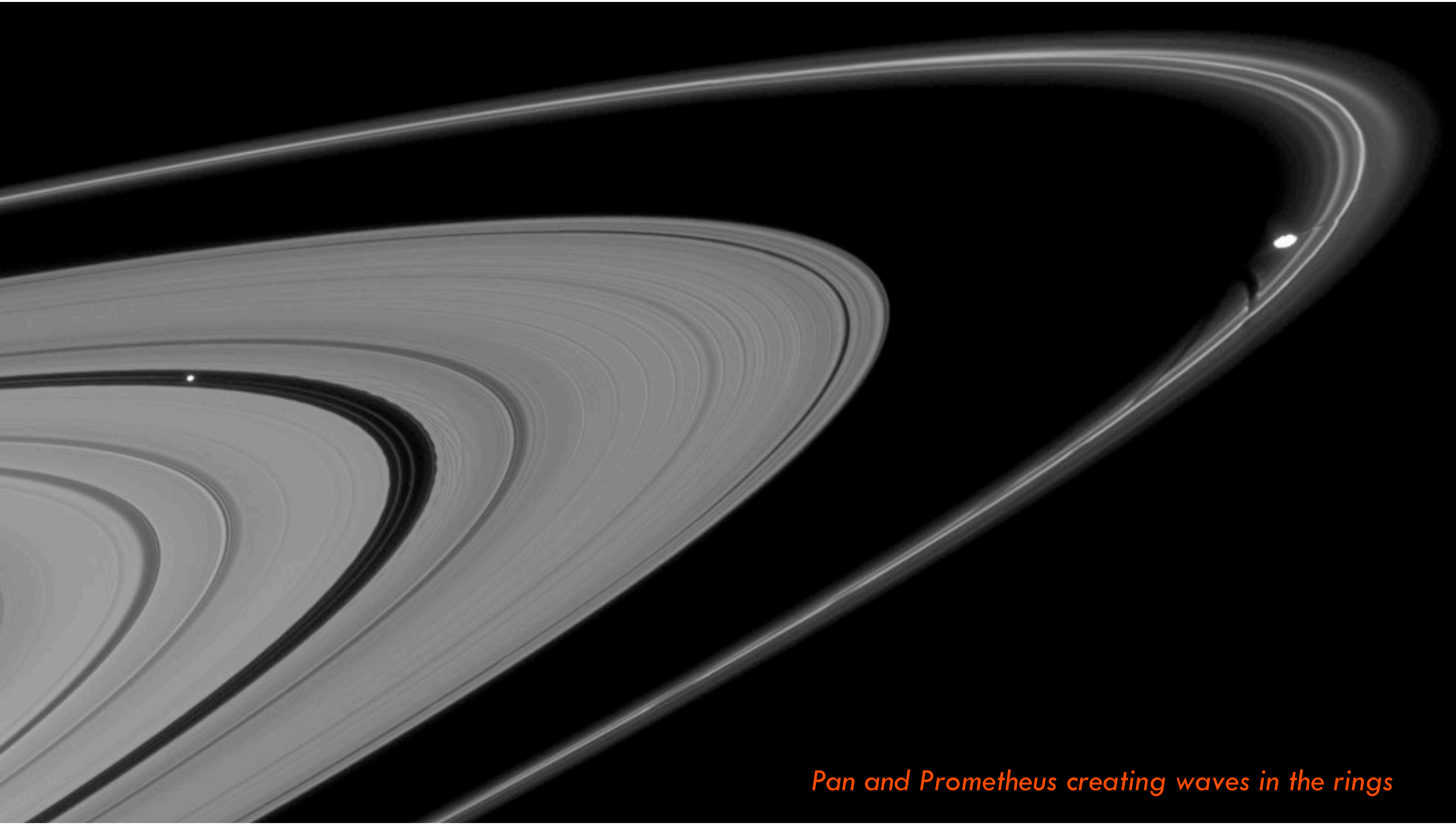




Pock-marked Prometheus, showing the side that faces away from Saturn. Prometheus orbits Saturn just inside the narrow F ring.

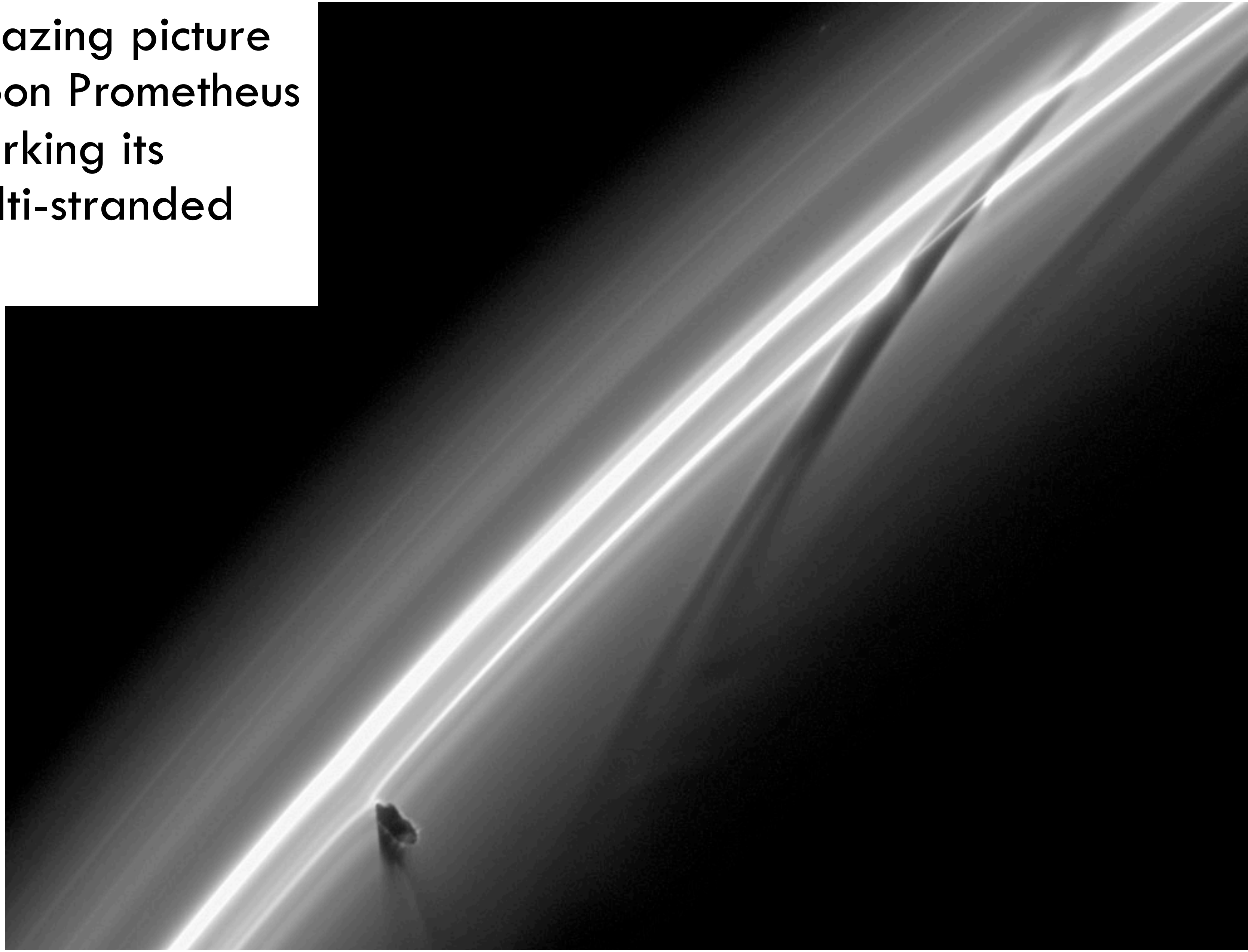
The two small, irregularly shaped moons exert a gravitational influence on particles that make up the F ring, confining it and possibly leading to the formation of clumps, strands and other structures observed there. Pandora prevents the F ring from spreading outward and Prometheus prevents it from spreading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





Pan and Prometheus creating waves in the rings

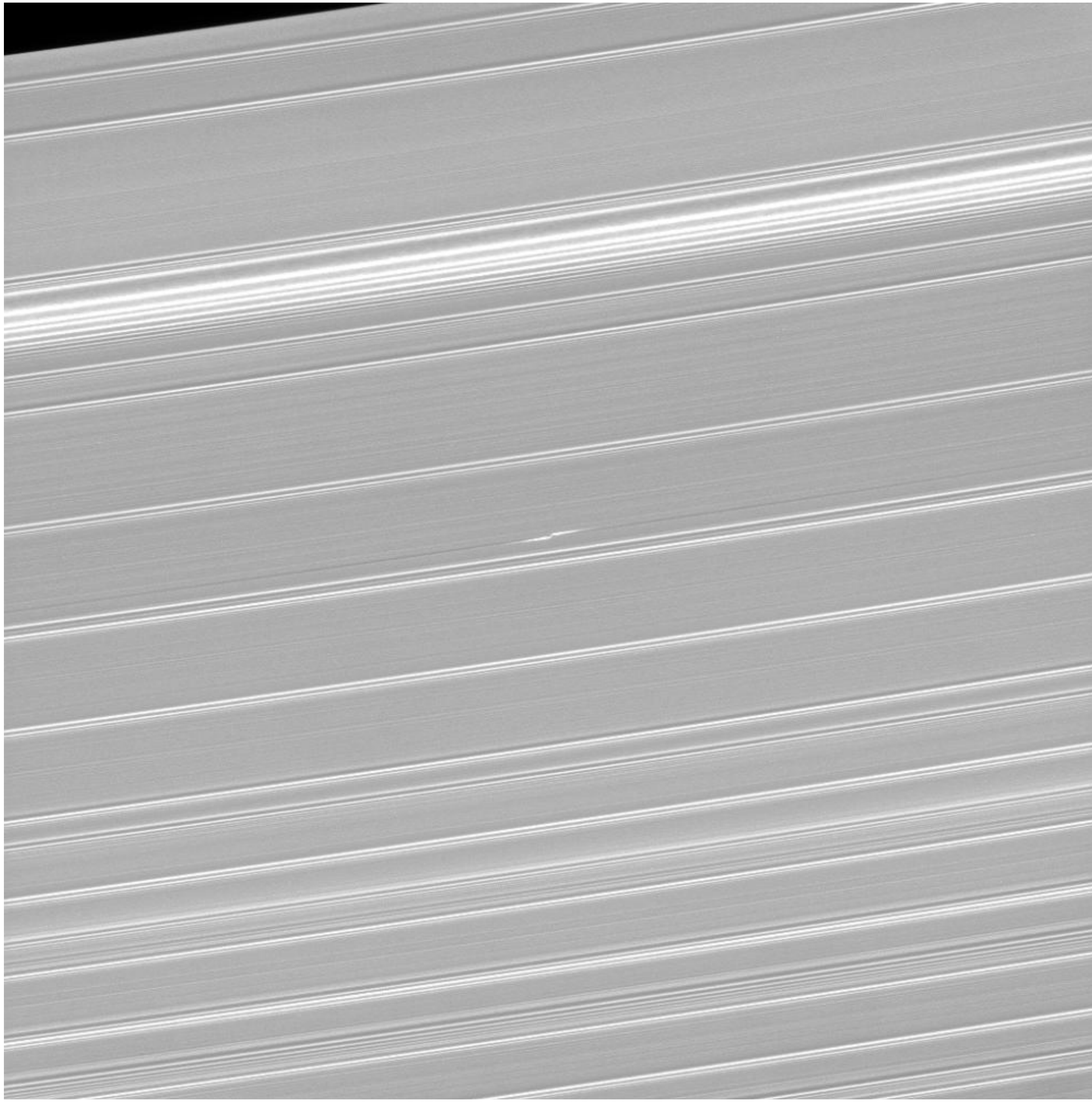
Cassini took this amazing picture of the shepherd moon Prometheus (102 km across) working its influence on the multi-stranded and kinked F ring.



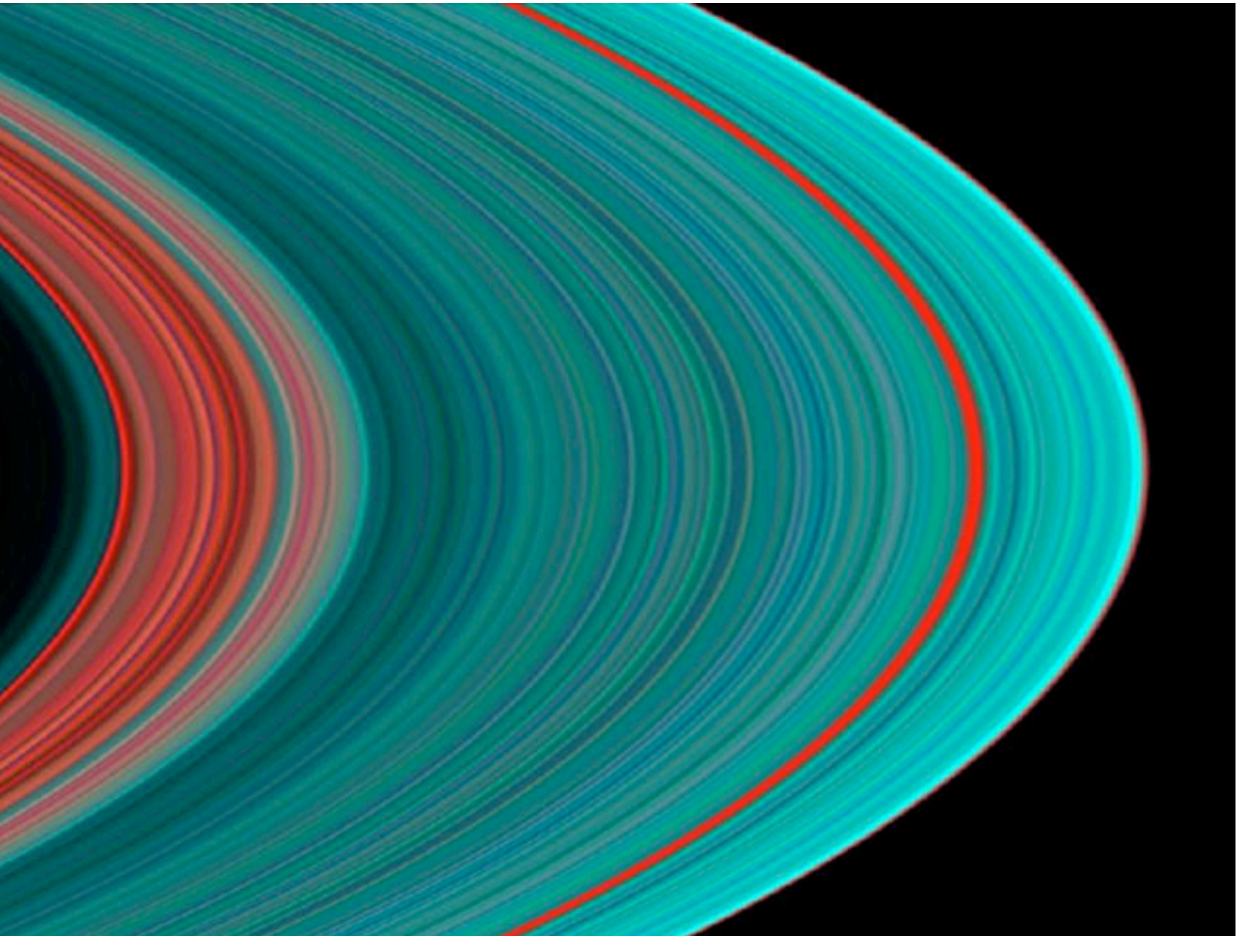
Prometheus is seen here with a long streamer of material that it has pulled out of the ring.

Propellers in the ring mark the presence of an object that is much larger than the particles that surround it, yet too small to clear out a complete gap in the rings. Although the moonlet at the core of the propeller is itself too small to see, the disturbances in the rings caused by its gravity betray its presence.

The propeller Bleriot



The colours of the ringlets and the different ways they reflect radio waves suggest that they are sorted by particle size and possibly also by composition.

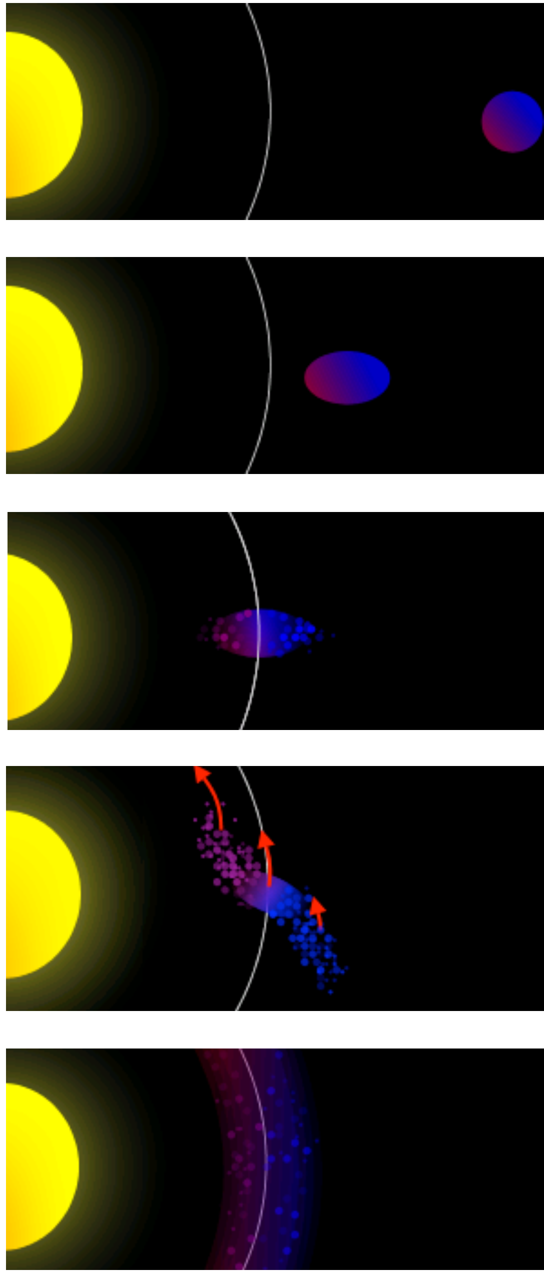


Cassini took this detailed image of the A ring in ultraviolet light. Blue represents areas rich in water ice, while red areas are rich in some sort of dirt. This and other images show that inner rings have more dirt than outer rings. The thin red band in the otherwise blue A ring is the Encke Gap. The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

Saturn's rings are inside the *Roche limit*, which is the the closest that an object can approach its primary body without being torn apart by tidal forces.

As the object moves towards the Roche limit, it is stretched by tidal forces; at the limit, the object 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. Thus the shepherd moons actually orbit within the Roche limit.



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.

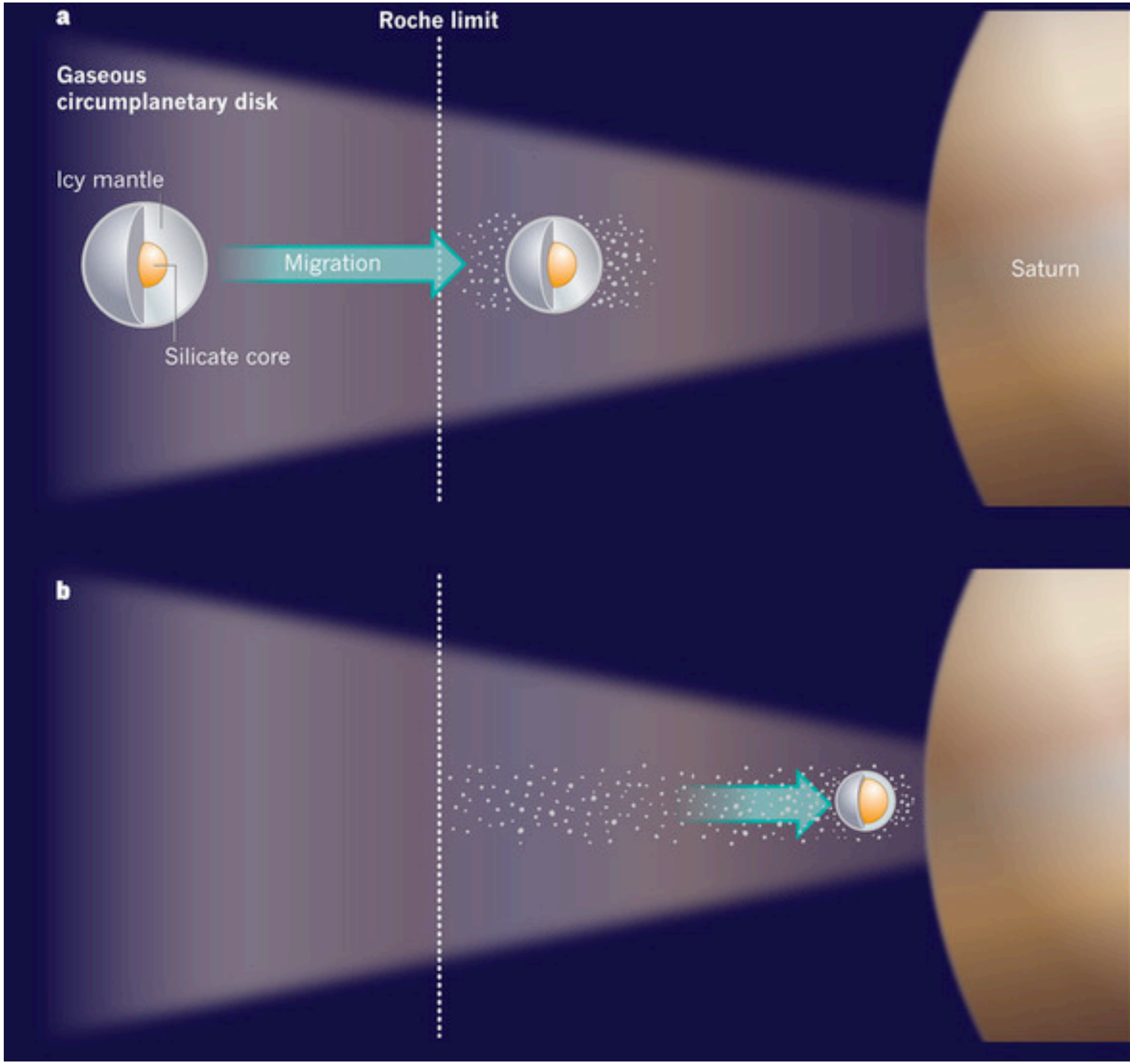
The two main theories for the origin of the rings are that they are the remains of an icy comet breaking up in Saturn's vicinity, or a small moon was pulled in by the planet's gravitational field.

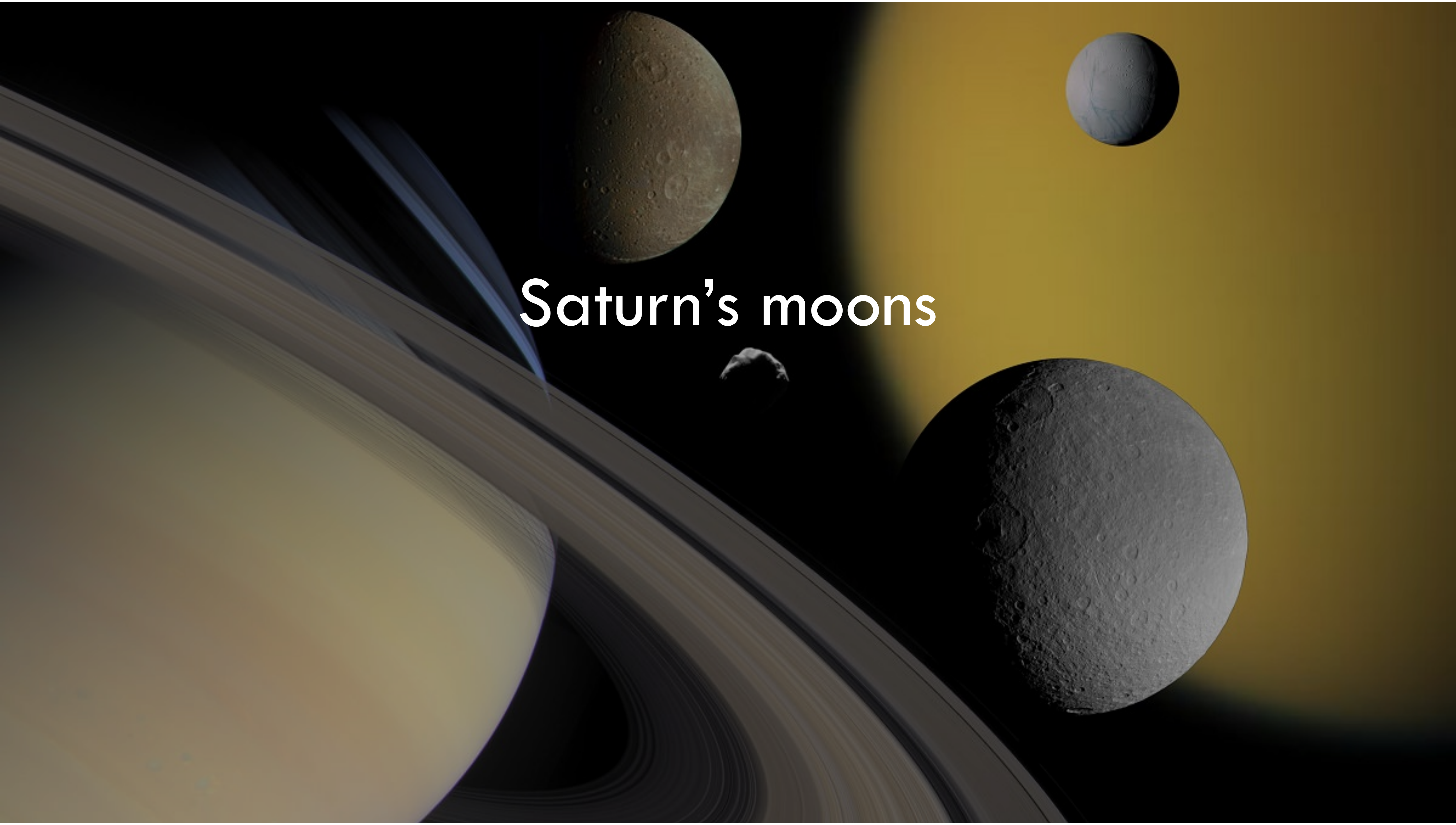
The problem that any model has to explain is why the rings are so icy (90–95% water ice, unlike the rings of the other planets), and why is Saturn the only giant planet to have a massive ring system?

A comet would give you mostly water ice, but would have to be large, hundreds of kilometres across. Only in the very early days of the solar system were such comets common. Plus, of all the giant planets, Saturn should capture the smallest number of comets, so all the other giant planets should have ring systems.

A disrupted moon, on the other hand, should contain both ice and rock, so where did all the rock go?

One suggestion is that a differentiated satellite, about the size of Titan, had its icy mantle pulled to pieces by Saturn's tides as it crossed the Roche limit. The satellite's rocky core continued to migrate inwards and eventually disappeared into Saturn, leaving behind the ice boulders that make up the rings.




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:

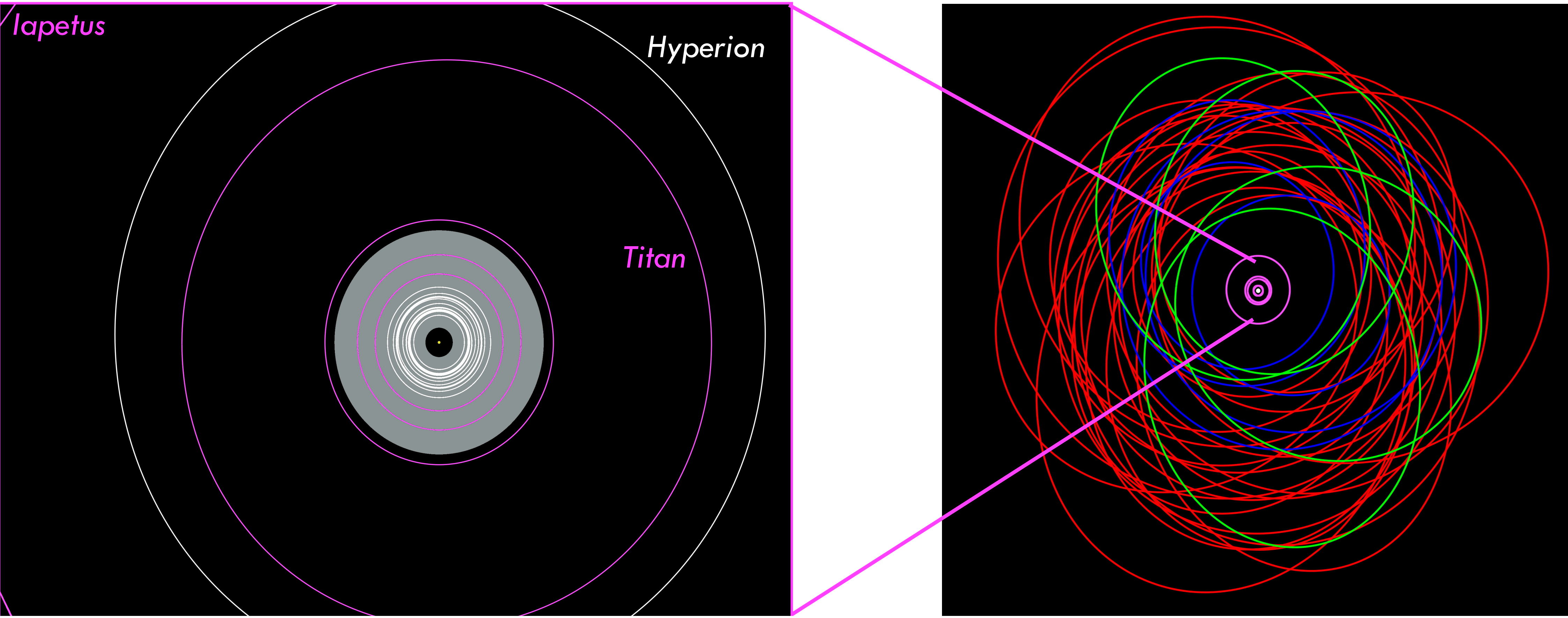
2:1 resonances

3:4 resonance

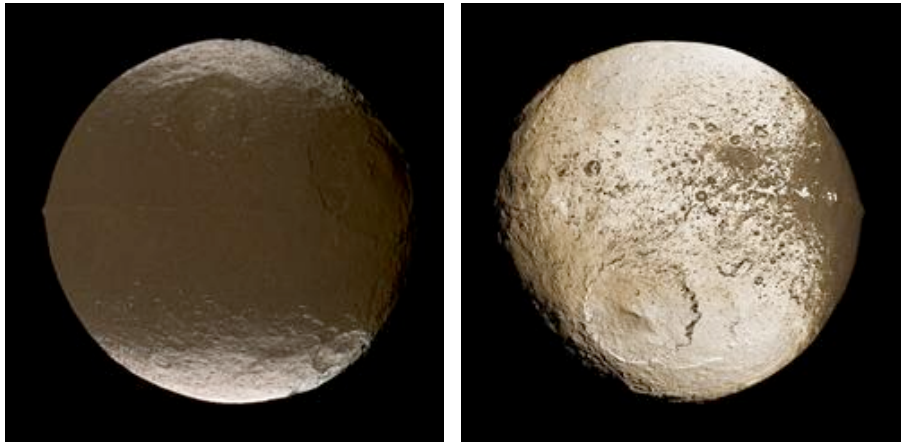
Name	Diameter (km)	Mass (10^{21} kg)	Density (g/cm3)	Orbital distance (10^3 km)	Orbital period (d)
Prometheus	145x85x65	0.00027		139	0.613
Pandora	114x84x2	0.00022		142	0.629
Epimetheus	144x108x98	0.00056	0.7±0.2	151	0.694
Janus	196x192x150	0.002	0.7±0.2	151	0.694
Mimas	390	0.038	1.14±0.03	186	0.942
Enceladus	500	0.084	1.01±0.02	238	1.37
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

Sixteen satellites orbit within the main rings themselves.

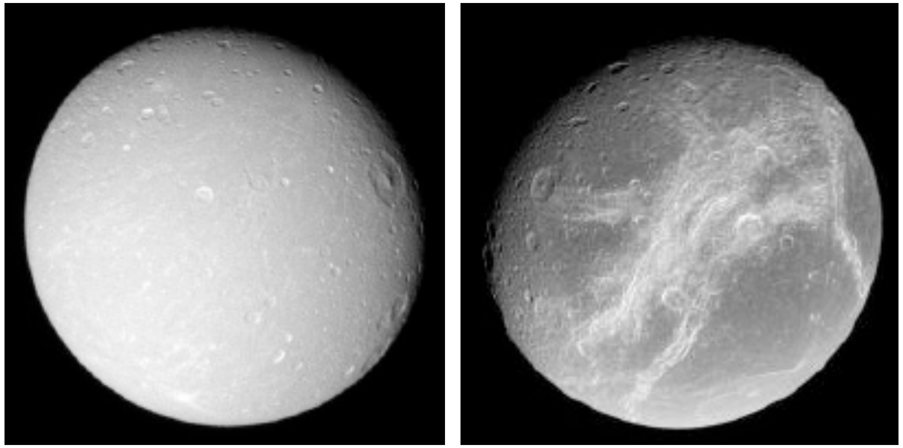
Outside the regular moons are a swarm of irregular moons, mostly captured asteroids.



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.

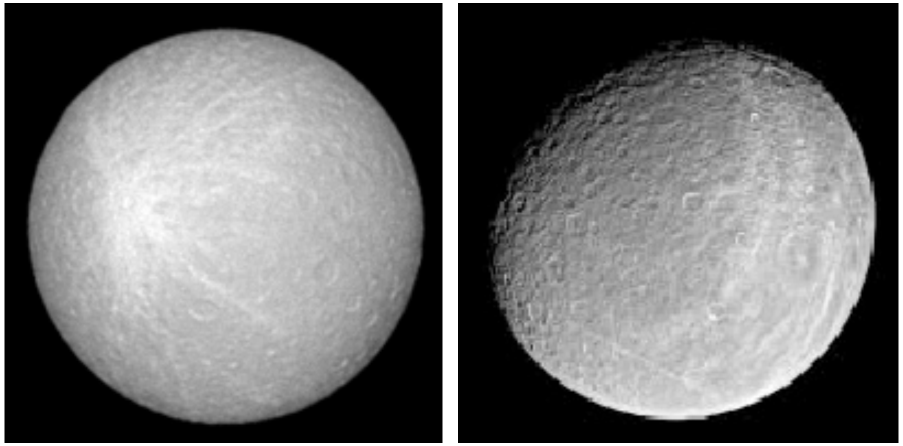


Iapetus



Dione

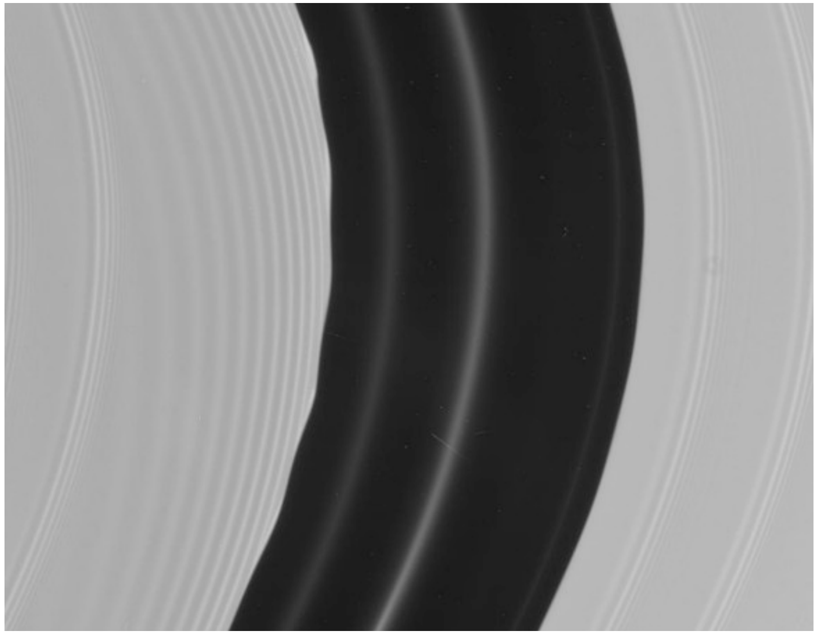
Rhea

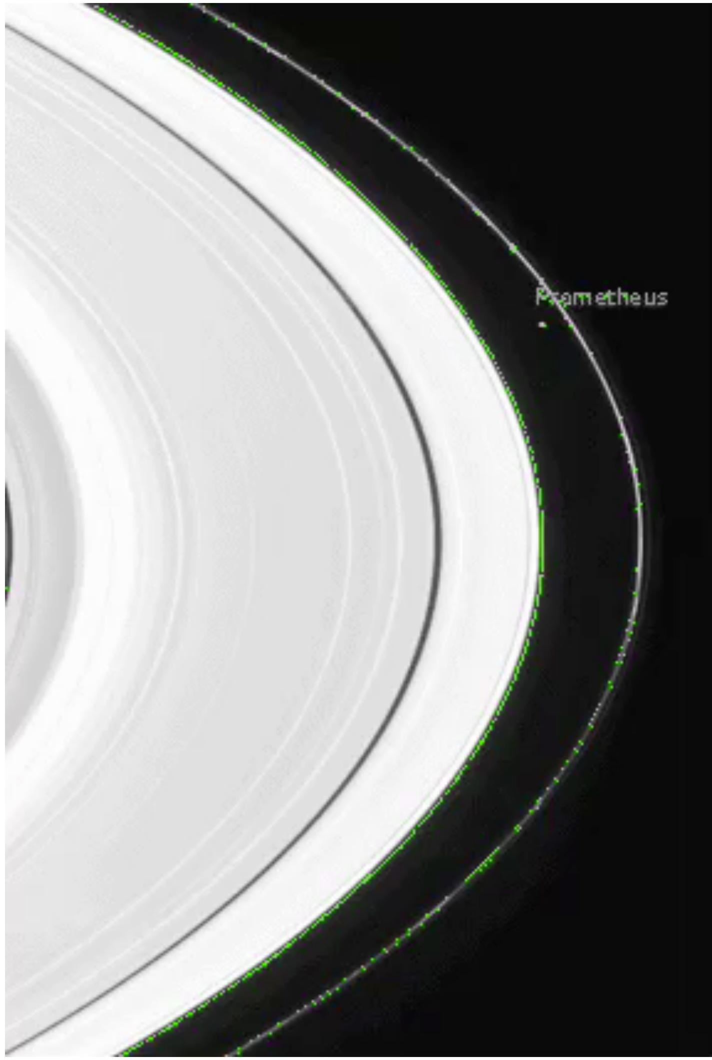


The innermost moons are the ring-shepherding satellites. We have already seen Prometheus and Pandora.

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.

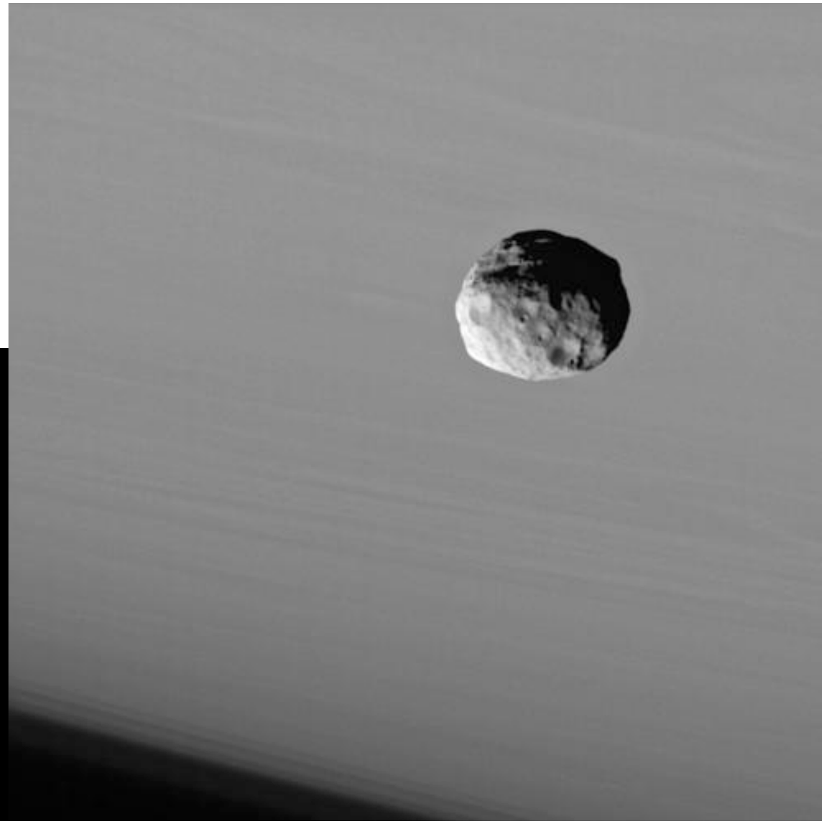




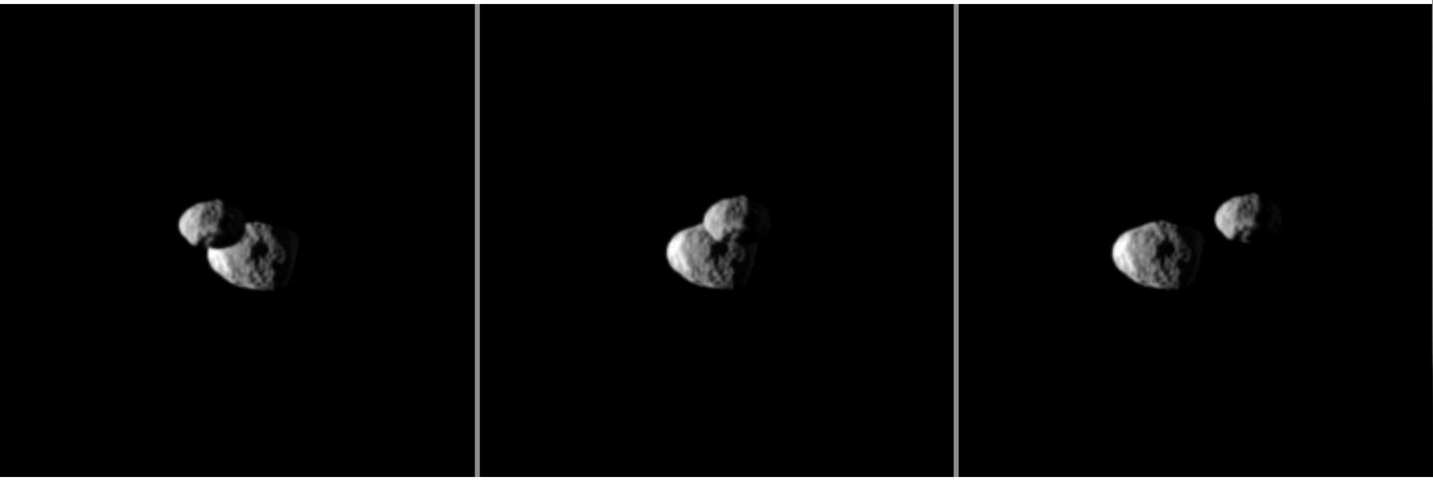
(left) Scalloping of the A-ring, caused by Pan. (right) Cassini images showing Pan orbiting in the Encke gap. Atlas, Prometheus, and Pandora are also visible in this animation.

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 in front of Saturn



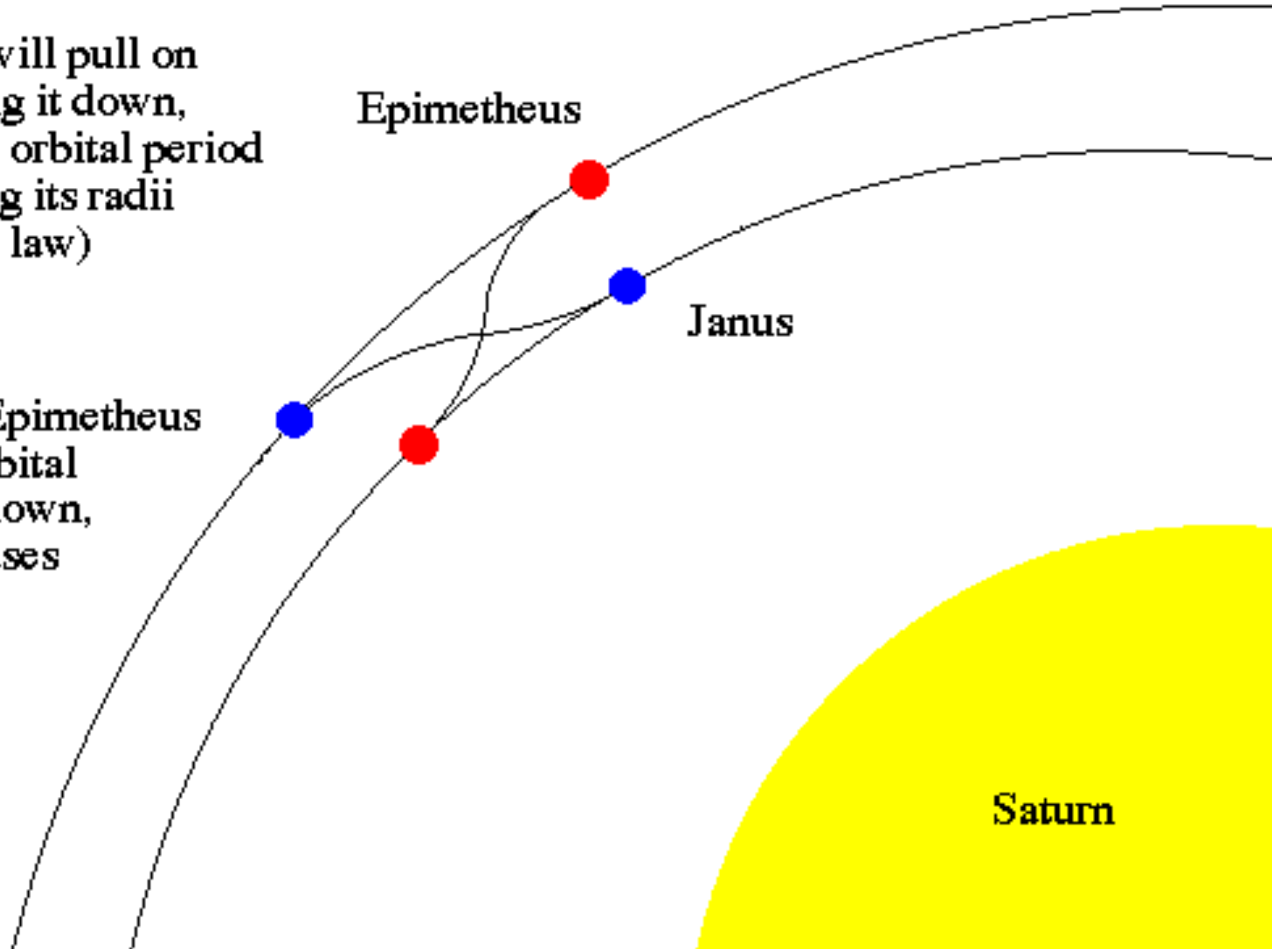
Epimetheus passes in front of Janus. Janus was the outermost of the pair between 2010 and January 2014, when they last switched positions.

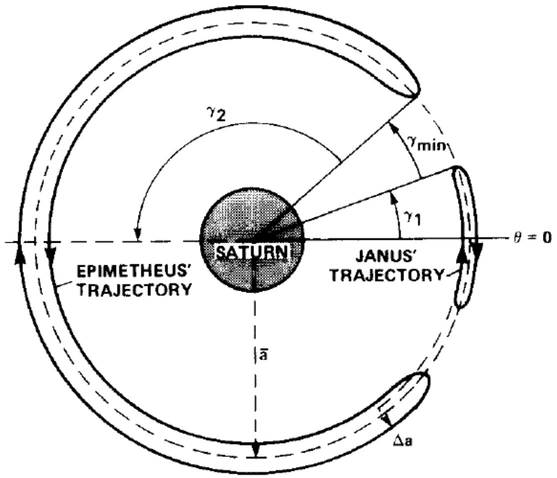


Epimetheus and Janus travel in orbits separated by only 50km, and actually exchange places every few years.

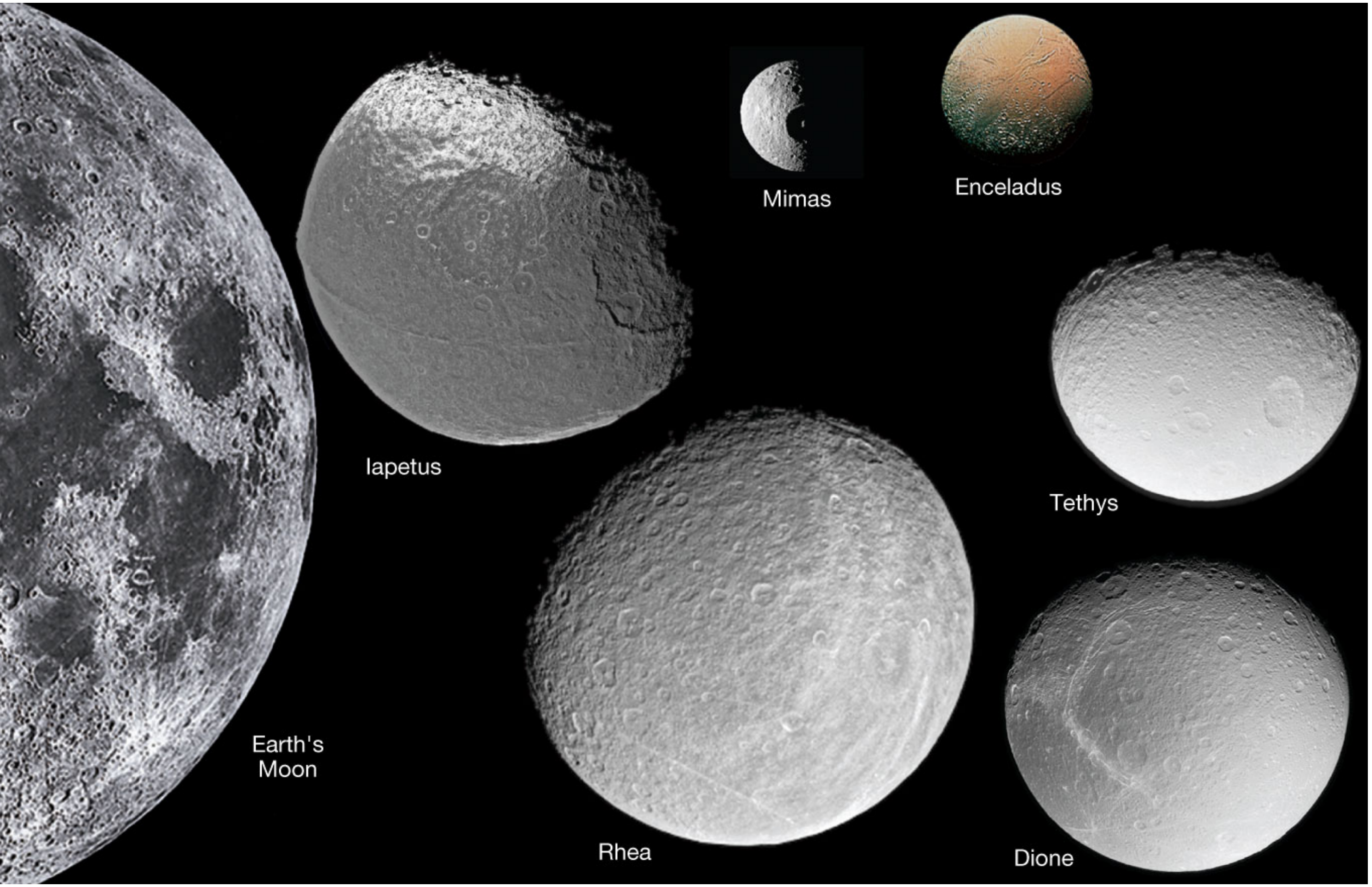
Epimetheus will pull on Janus, slowing it down, increasing its orbital period and increasing its radii (Kepler's 3rd law)

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



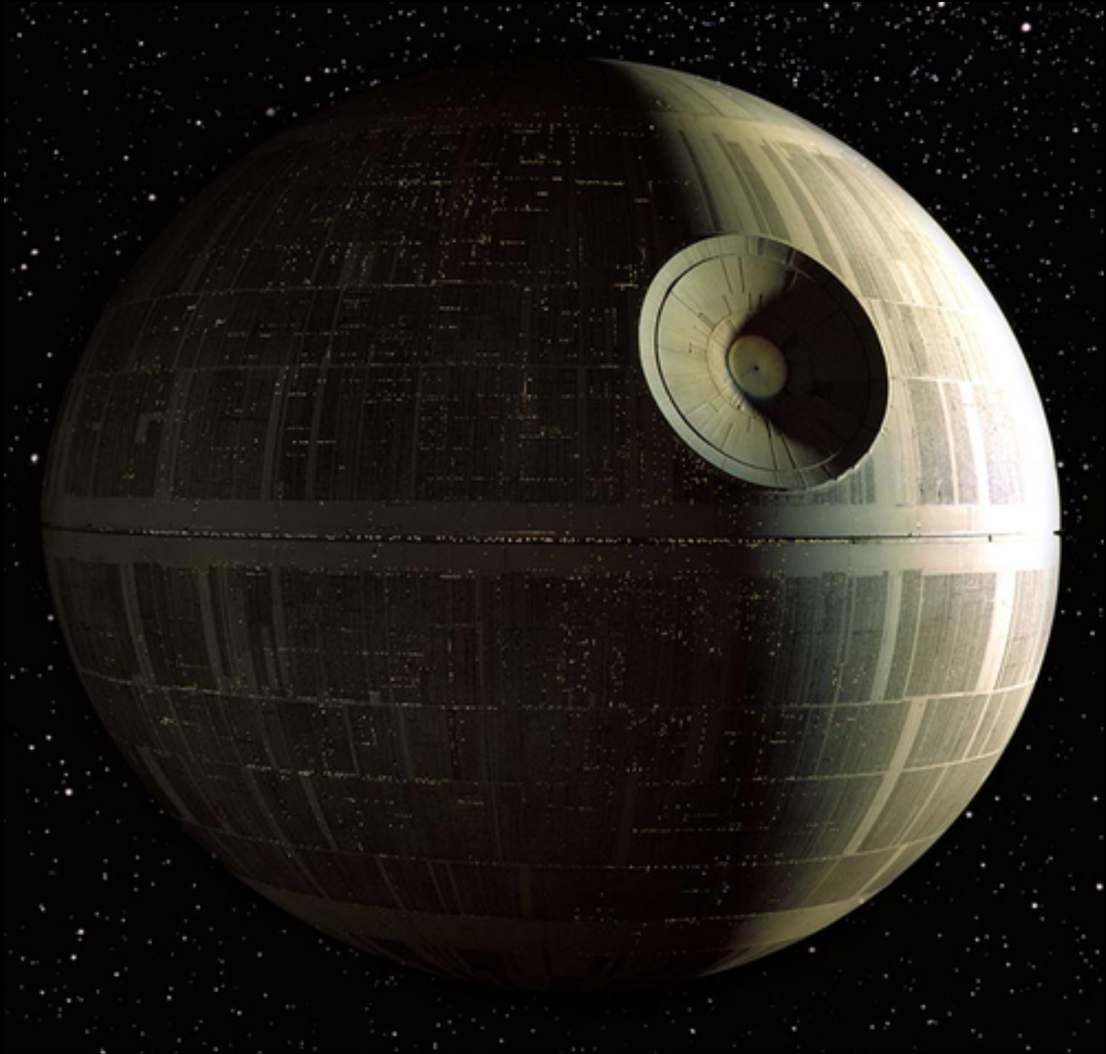


After the ring-shepherding satellites come the six medium-sized icy moons. Unlike the relatively orderly Galilean satellites of Jupiter, Saturn's system of satellites shows few regularities.

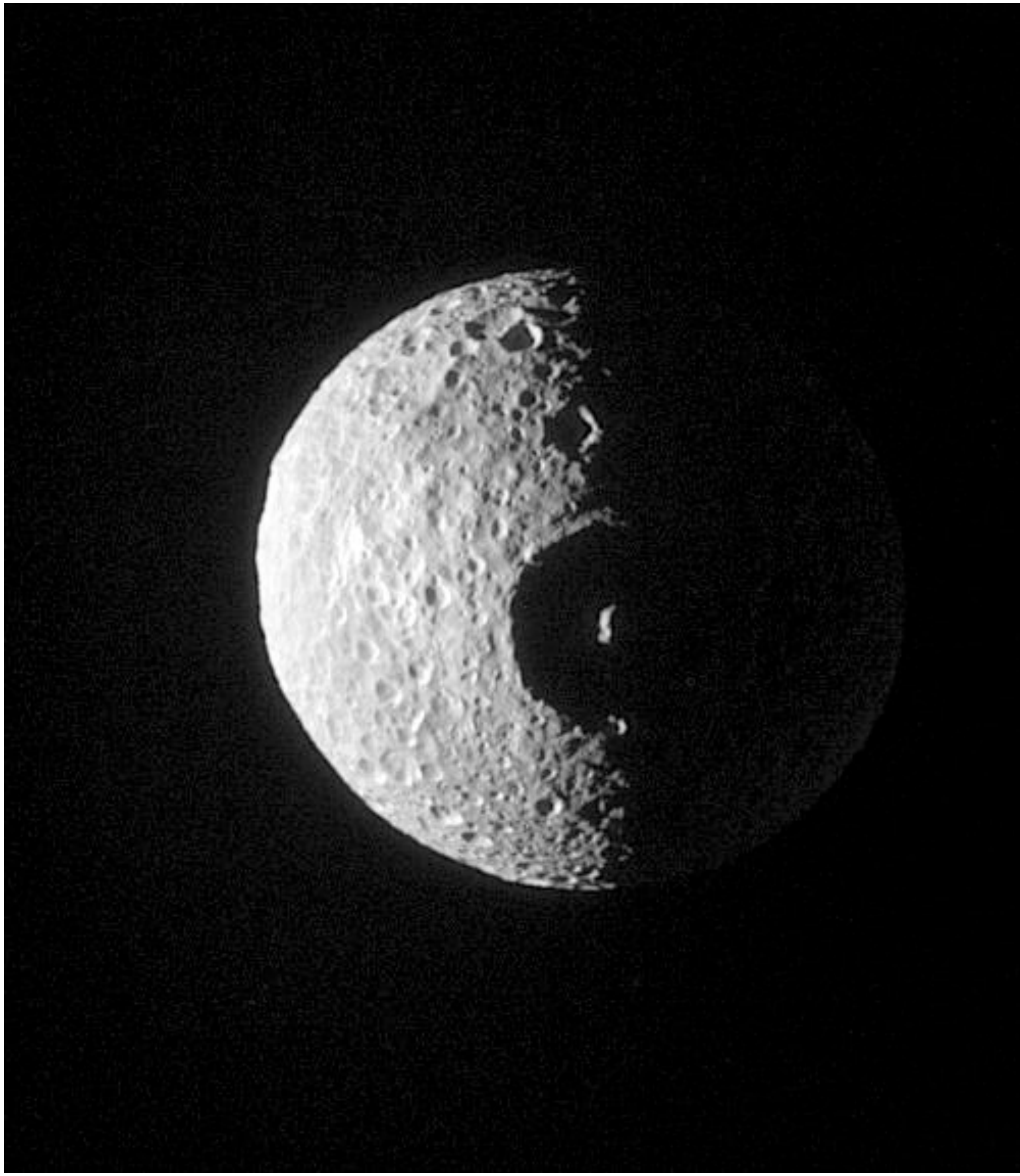


The medium sized Saturnian moons, with Earth's moon for comparison.

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.

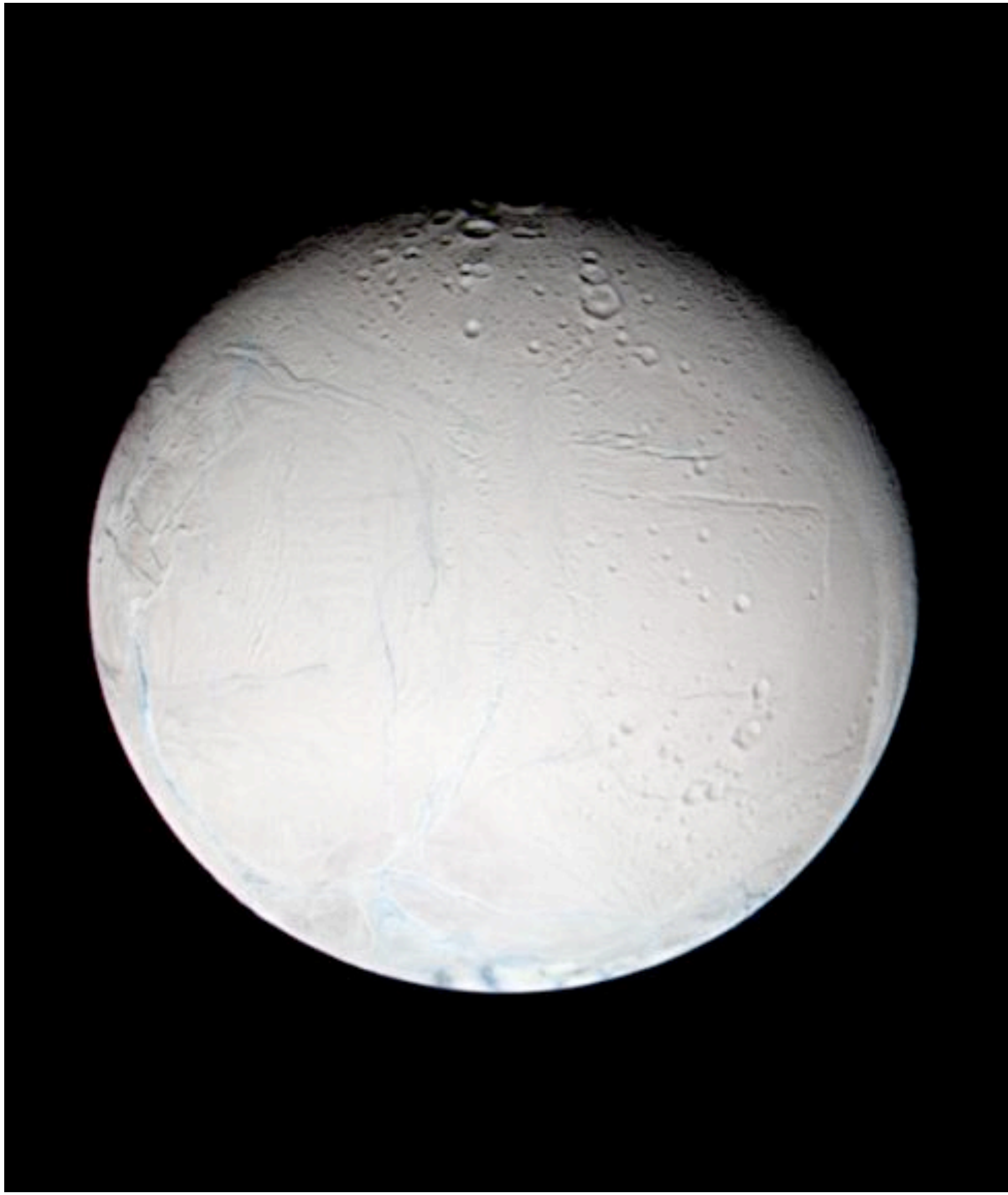
No other large impact craters are present on Mimas. This suggests that it has been re-surfaced, probably by large impacts. It later solidified and coalesced again, and was then cratered again.

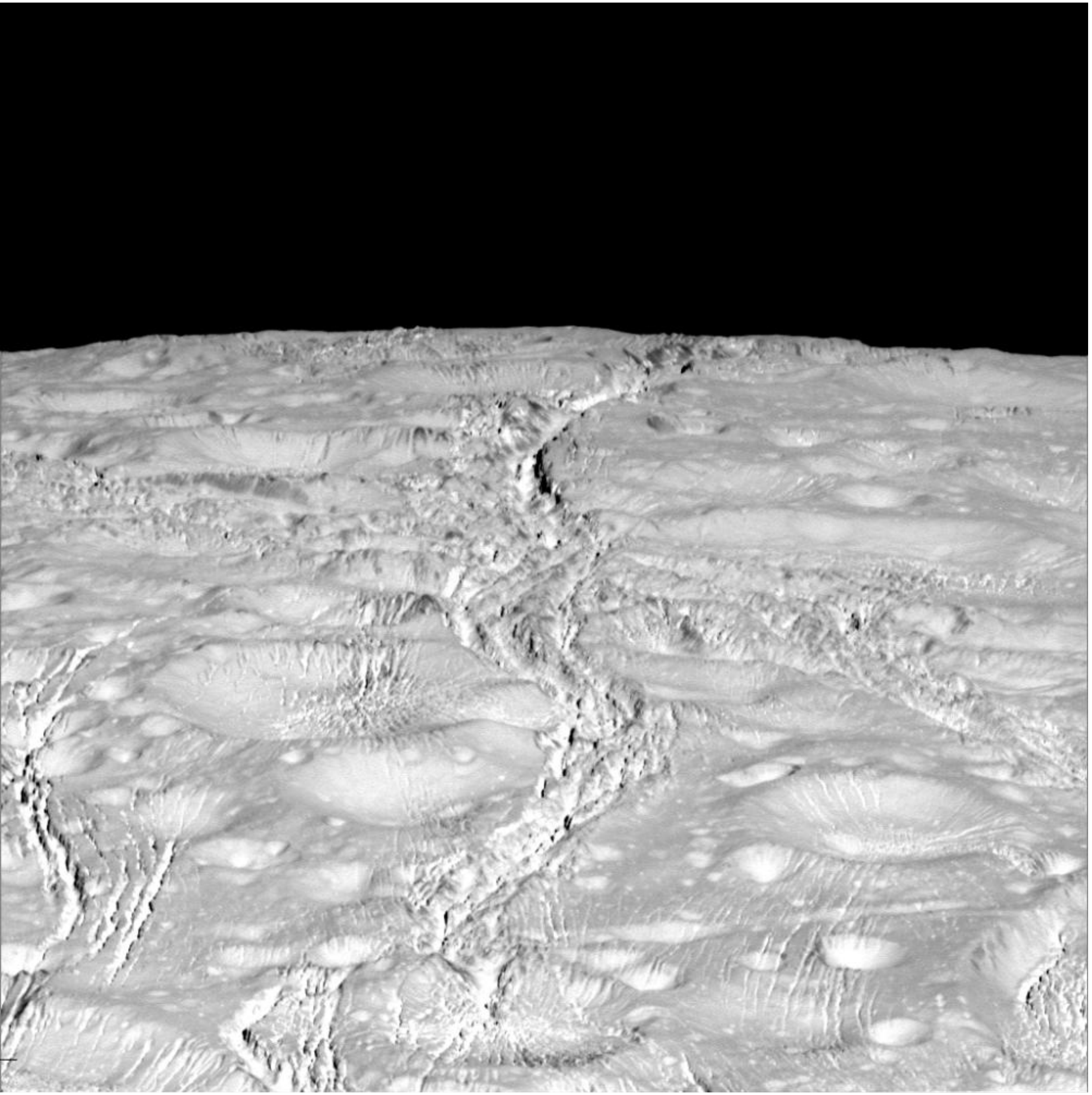


Mimas in front of Saturn's northern hemisphere, shadowed by the rings. The bright streak is light passing through the Cassini division.

Enceladus (radius 260 km) is the brightest object 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). This results in tidal deformation, which heats Enceladus' interior.

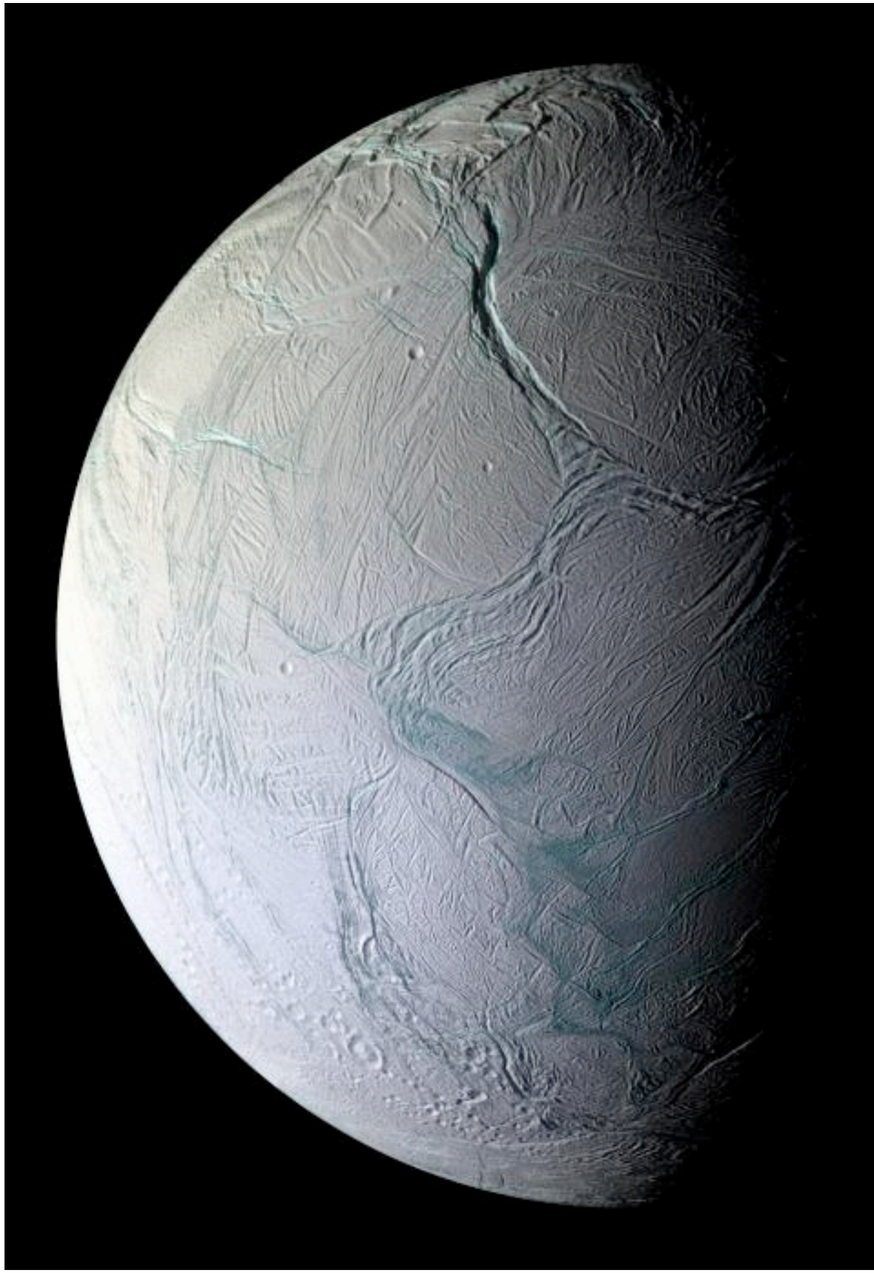




Enceladus is very similar to Europa. Some regions have craters, which are overlain with extensive linear cracks and ridges.

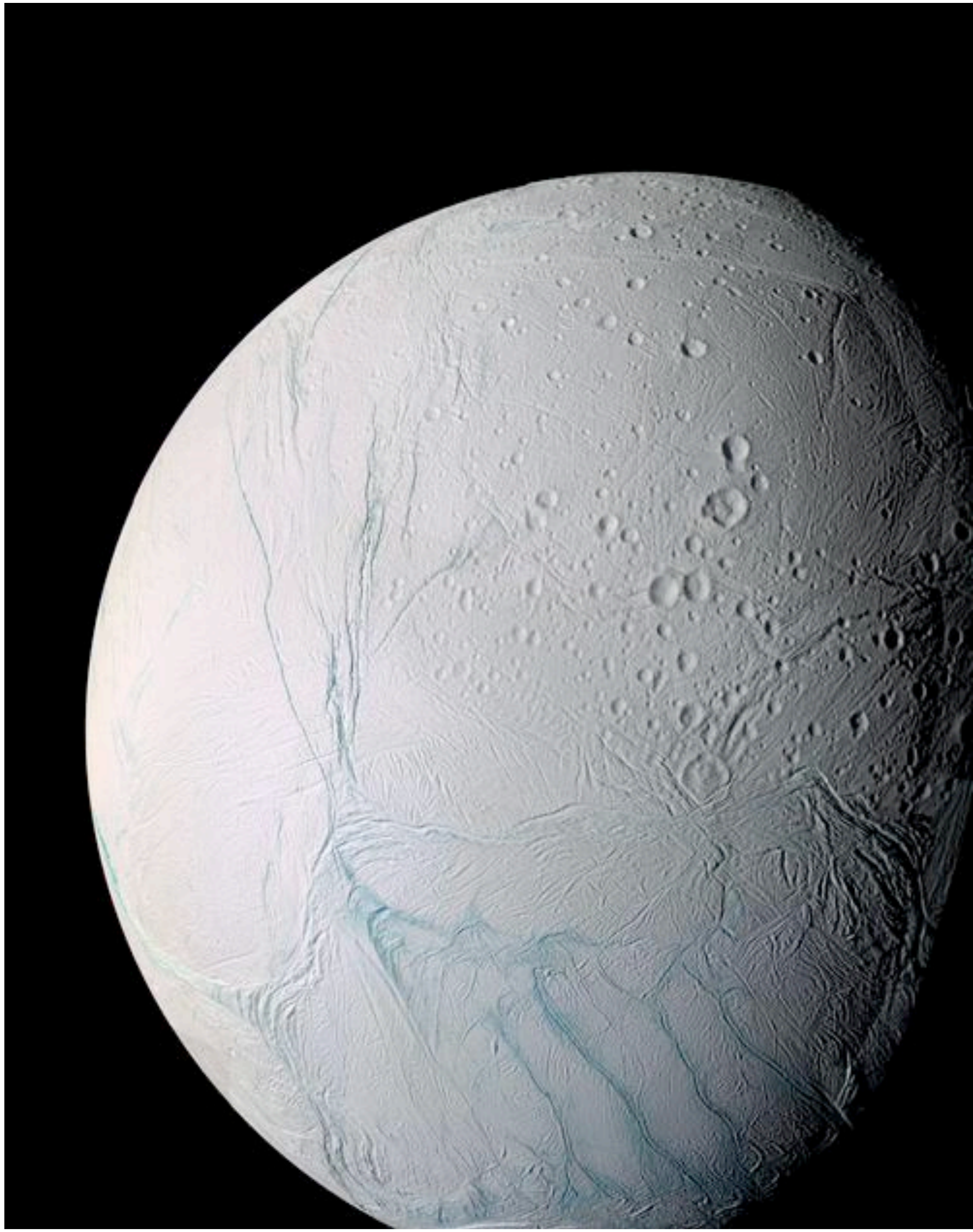
The north polar region of Enceladus, showing craters cut through with thin cracks.

Other regions show a host of tectonic features: fractures, folds, 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”.



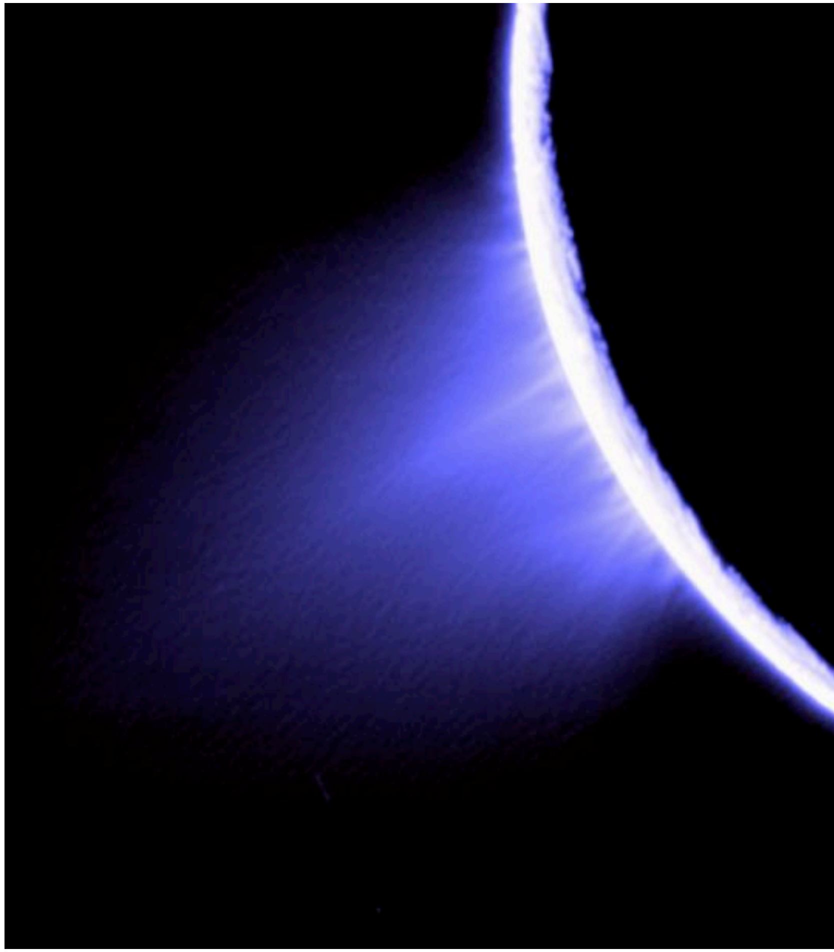
Cassini view of Enceladus, taking during a close flyby. This southern region of the moon's Saturn-facing hemisphere shows the surface covered with fractures, folds, and ridges. In this enhanced-color view, regions that appear blue-green are thought to be coated with larger grains than those that appear white or gray.

The south-polar region is smooth, and marked with a set of almost parallel fractures dubbed “tiger stripes”.

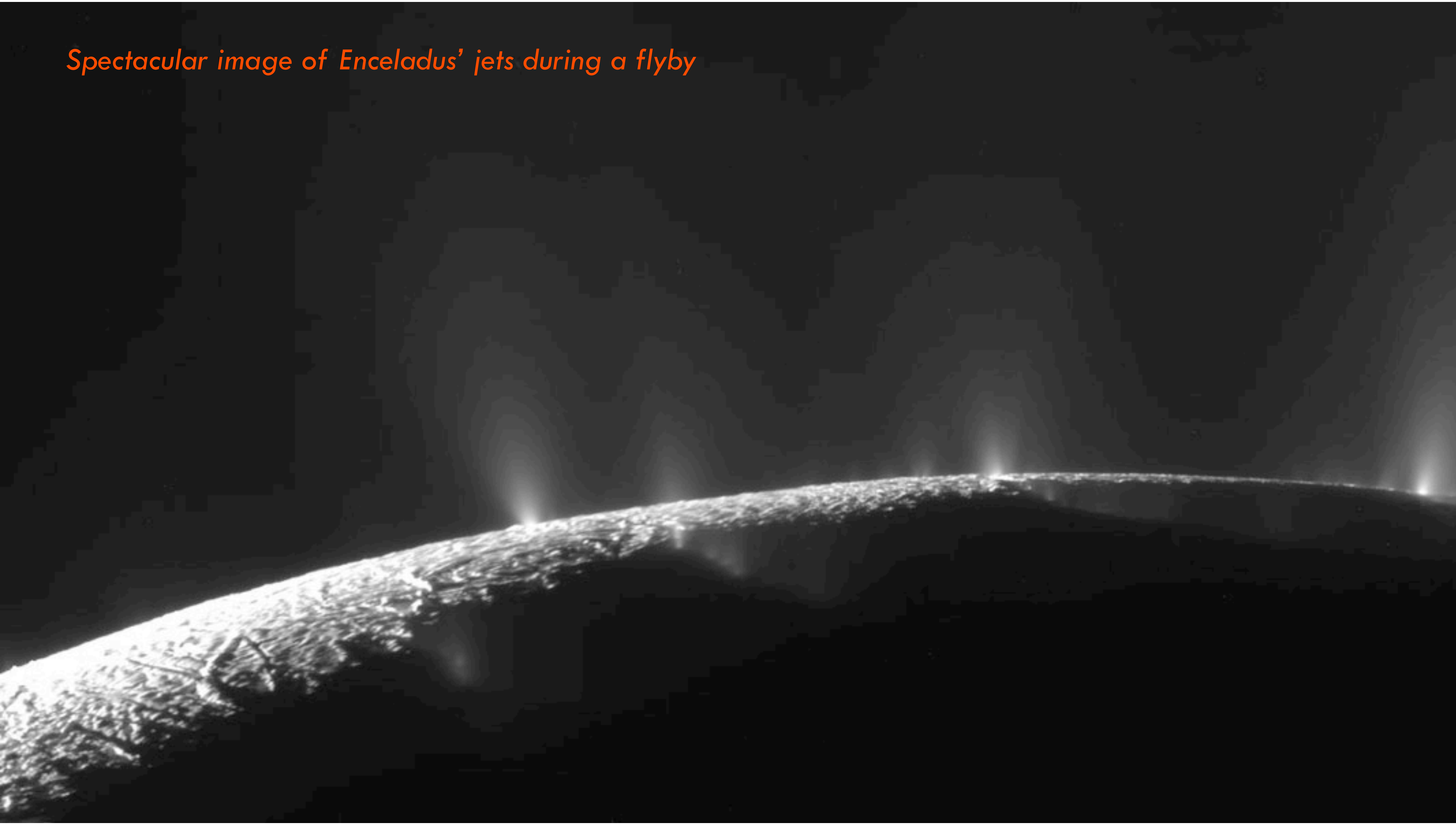


Enhanced color view of Enceladus, largely of the southern hemisphere and including the south polar terrain at the bottom of the image. The blue regions are the “tiger stripes”

During flybys in 2005, *Cassini* imaged icy jets erupting off Enceladus. So, like Io at Jupiter and Triton at Neptune, Enceladus is an "active moon". The jets consist largely of water vapour and dust, but also contains carbon dioxide, methane, nitrogen and propane.



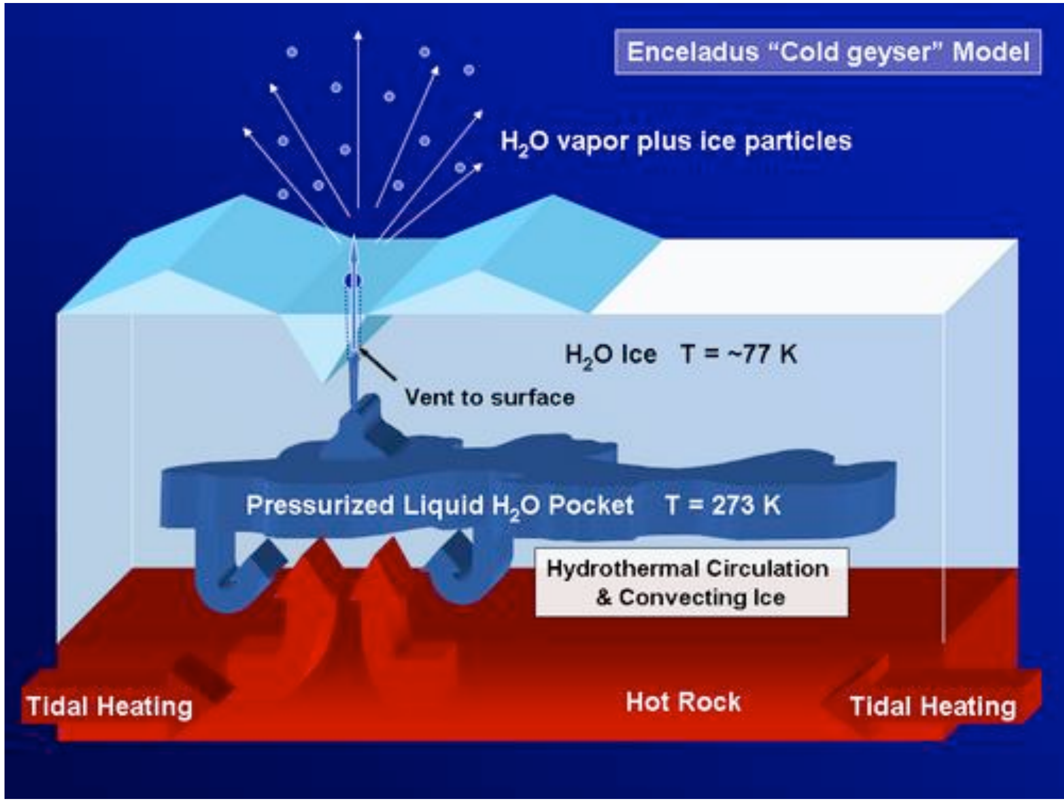
Cassini images of Saturn's moon Enceladus backlit by the sun, showing the fountain-like sources of the fine spray of material that towers over the south polar region. Several discrete sources are visible.


Spectacular image of Enceladus' jets during a flyby

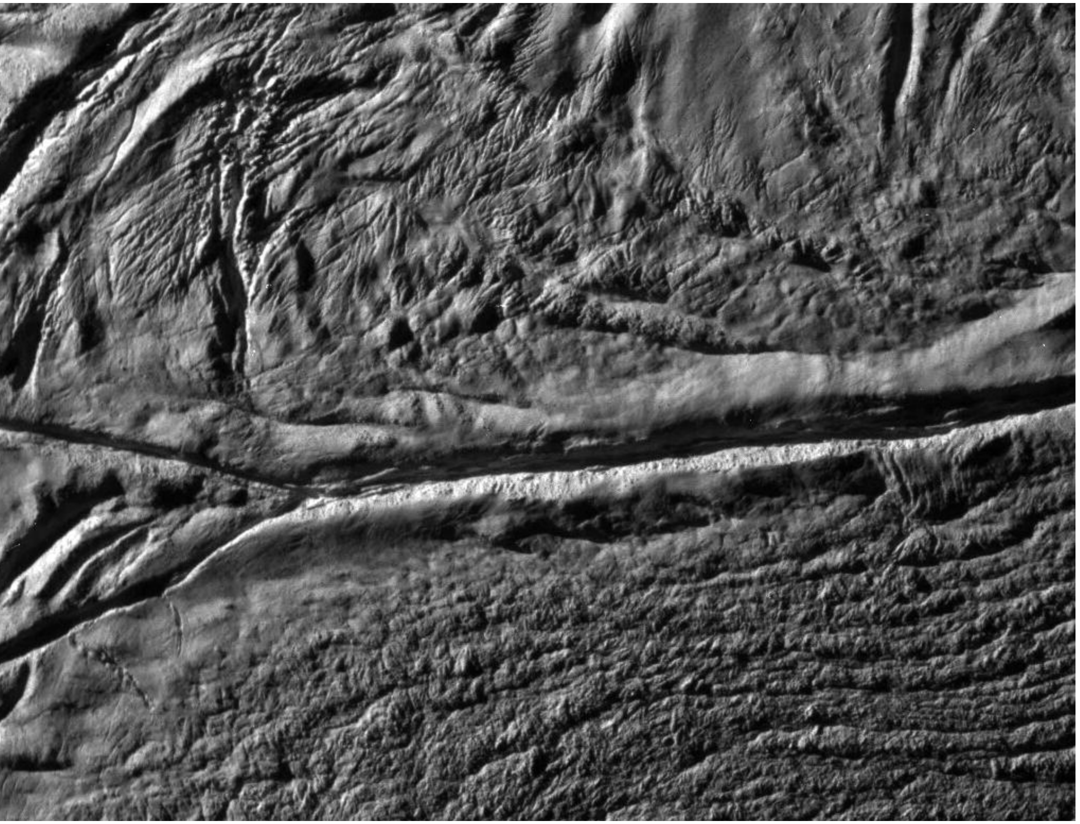
The eruptions produce about 150 kg of material per second, and are almost certainly the source of the E ring.

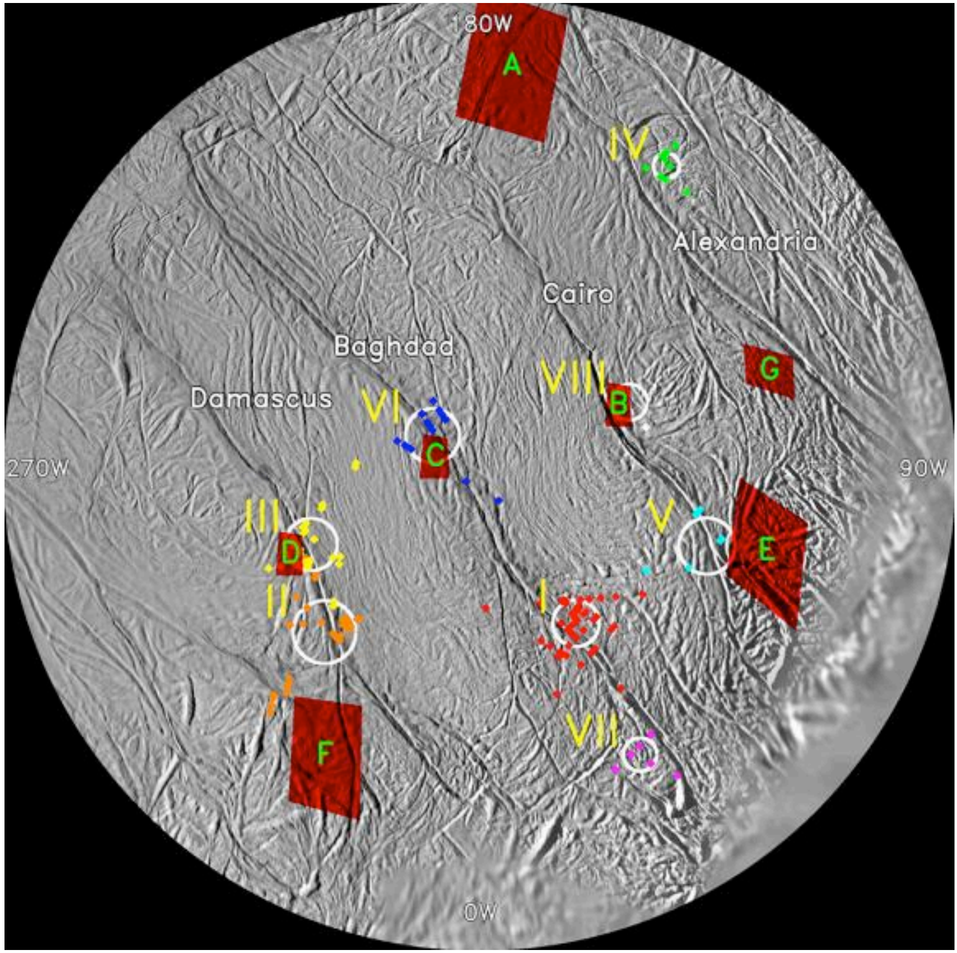
The most likely scenario is that the jets are erupting from near-surface pockets of liquid water above 0° Celsius, no more than tens of metres below the surface.

When *Cassini* flew through the plumes, it detected salty grains, strongly suggesting the presence of a salt-water reservoir.

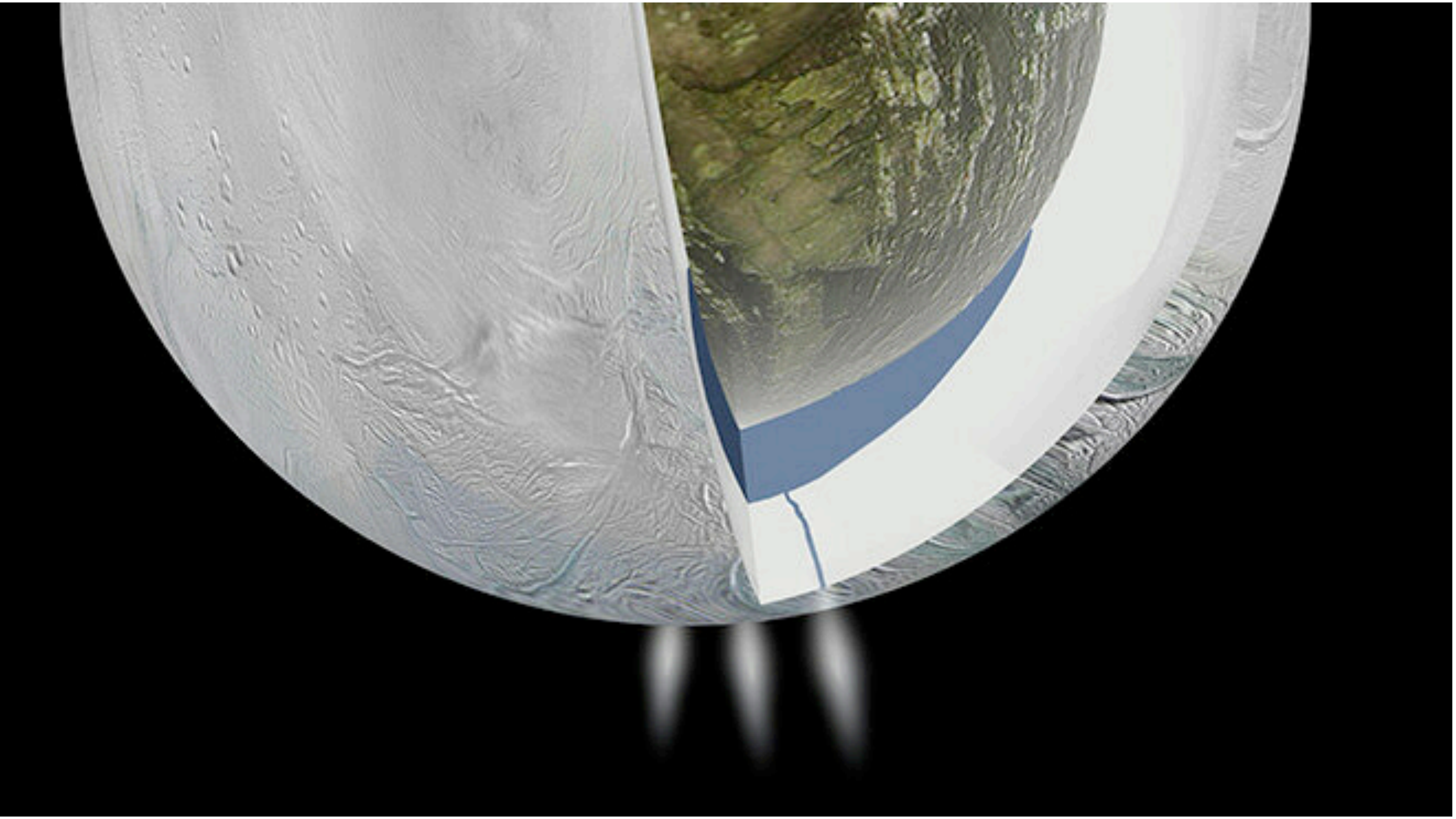


Cassini pinpointed the tiger stripe fractures in the south polar region as the source for the jets.

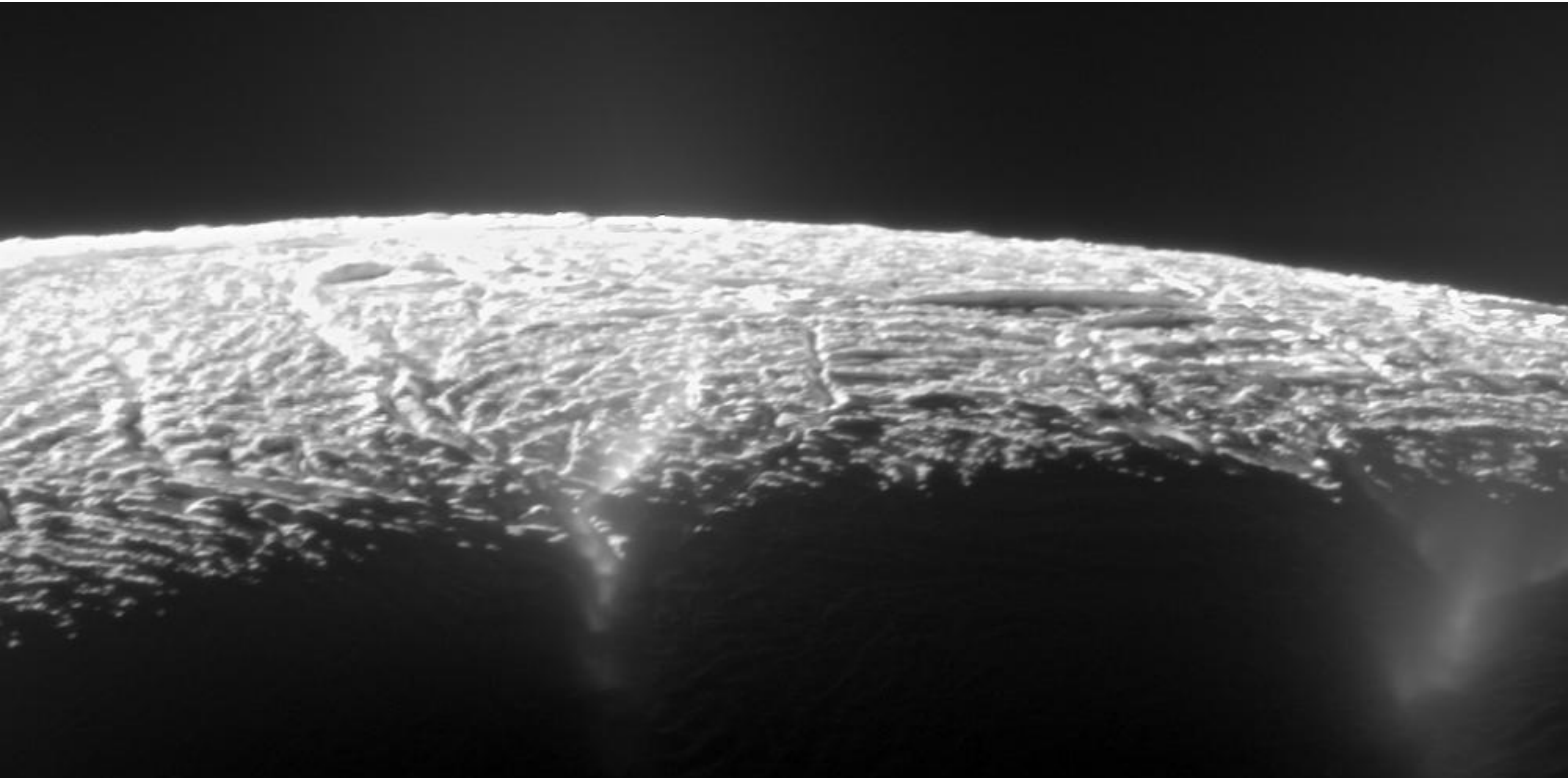




The great fissure running across the image from left to right is Damascus Sulcus — one of the fractures through which the moon's salty ocean sprays into space



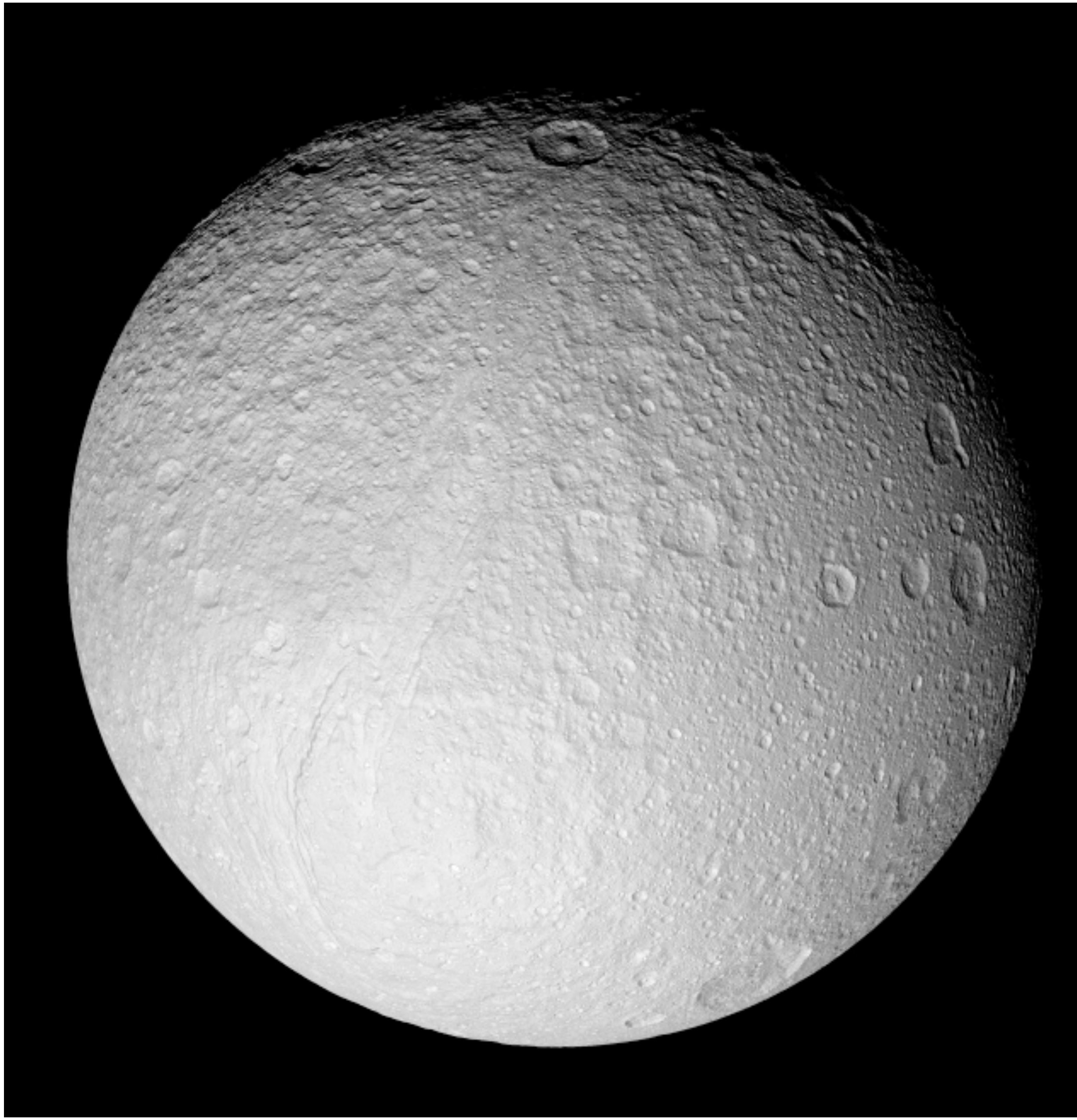
Cassini's gravity measurements suggest a large, possibly regional, ocean about 10 km deep, beneath an ice shell about 30 to 40 km thick.



View over the south pole, showing the ends of the Baghdad and Damascus fractures that face Saturn. The segments of the fractures seen here are among the most active and warmest in the whole region.

Tethys (radius 530 km) 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 craters out.

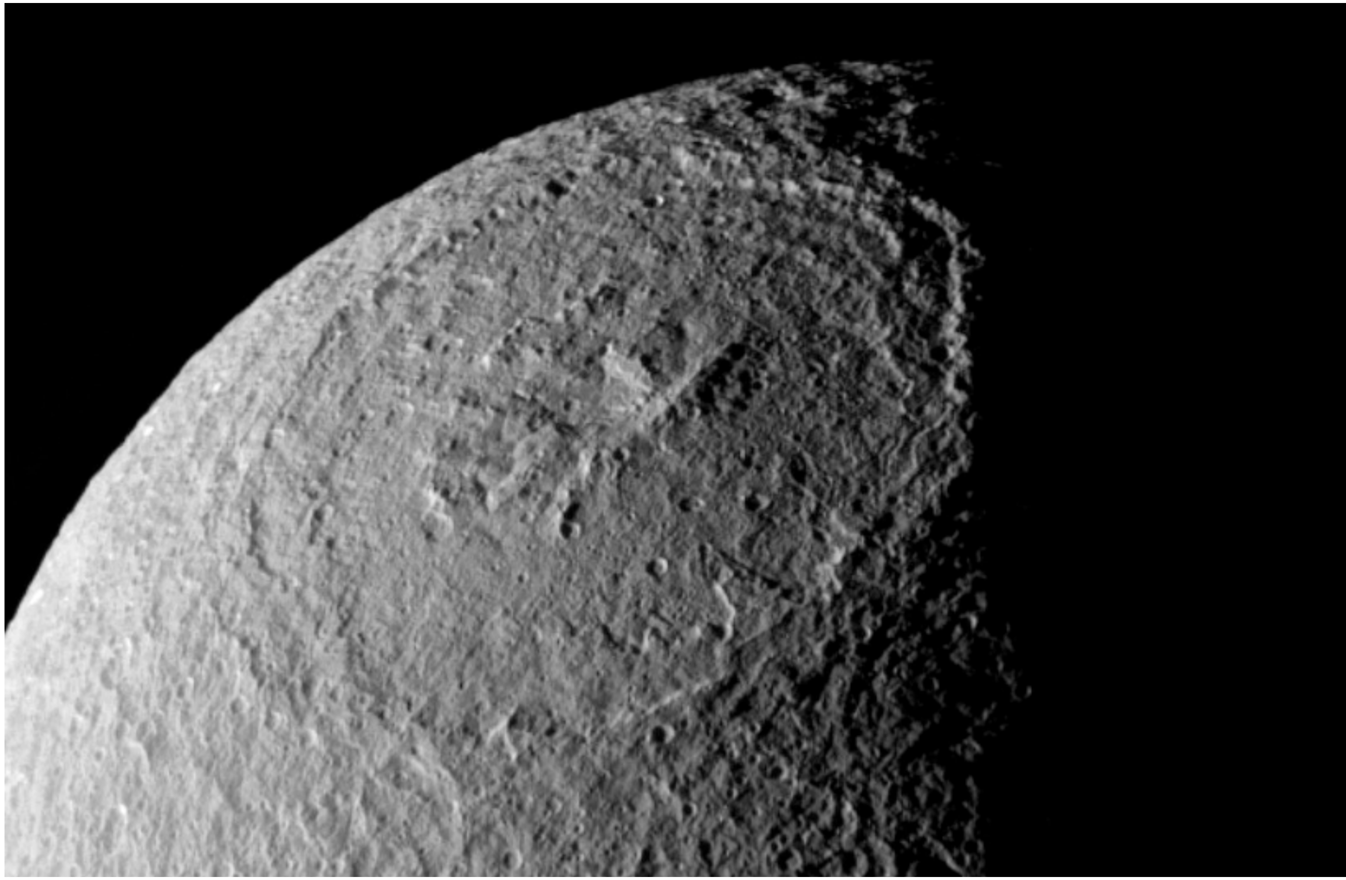
Ithaca Chasma is an enormous trough which extends at least three-quarters of the way around the globe. It is up to 100 km wide and reaches about 3 km in depth.



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

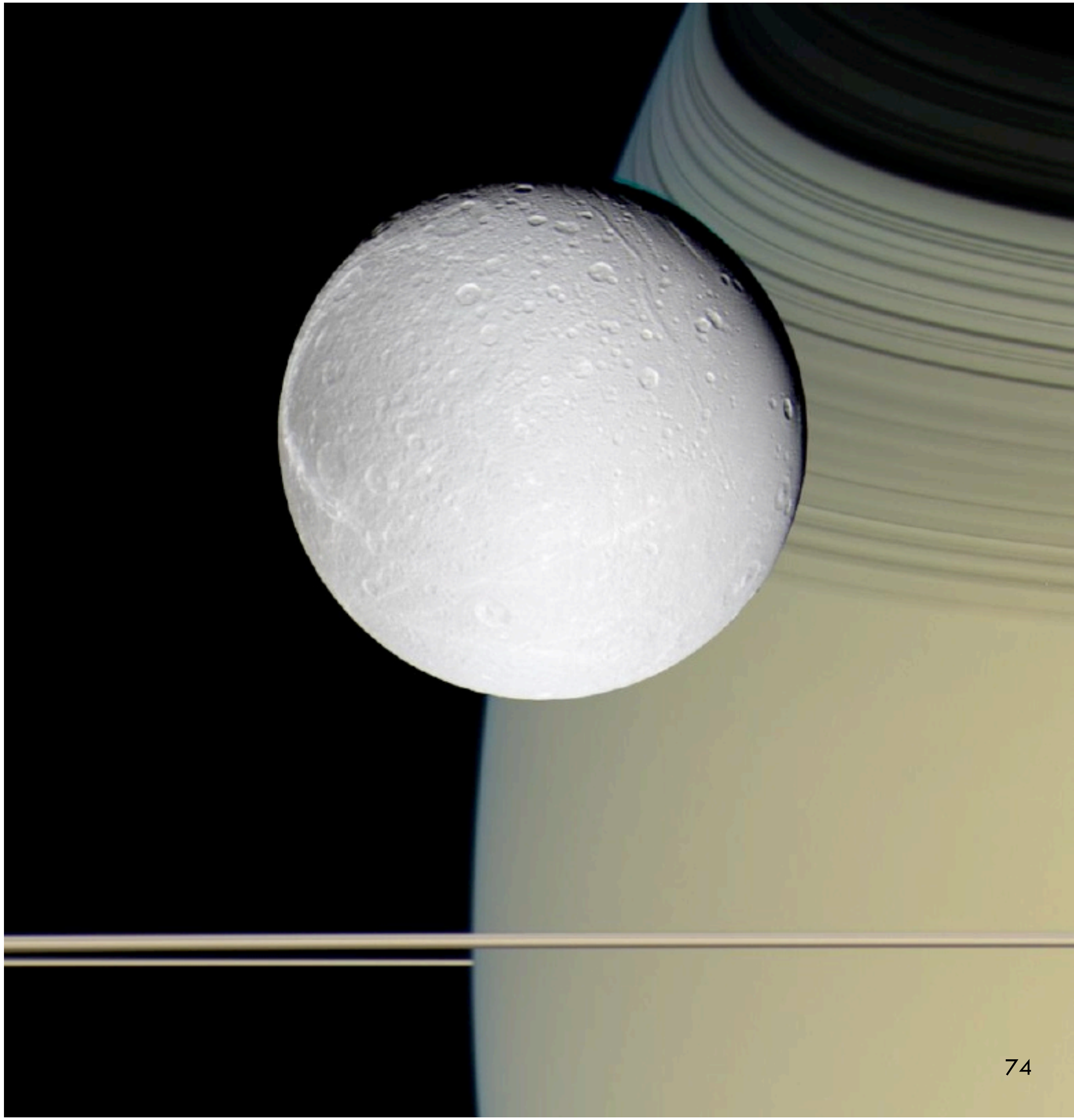
Tethys is dominated by the Odysseus crater (400 km across). The flatness of the crater implies that Tethys must have been malleable at the time of impact.

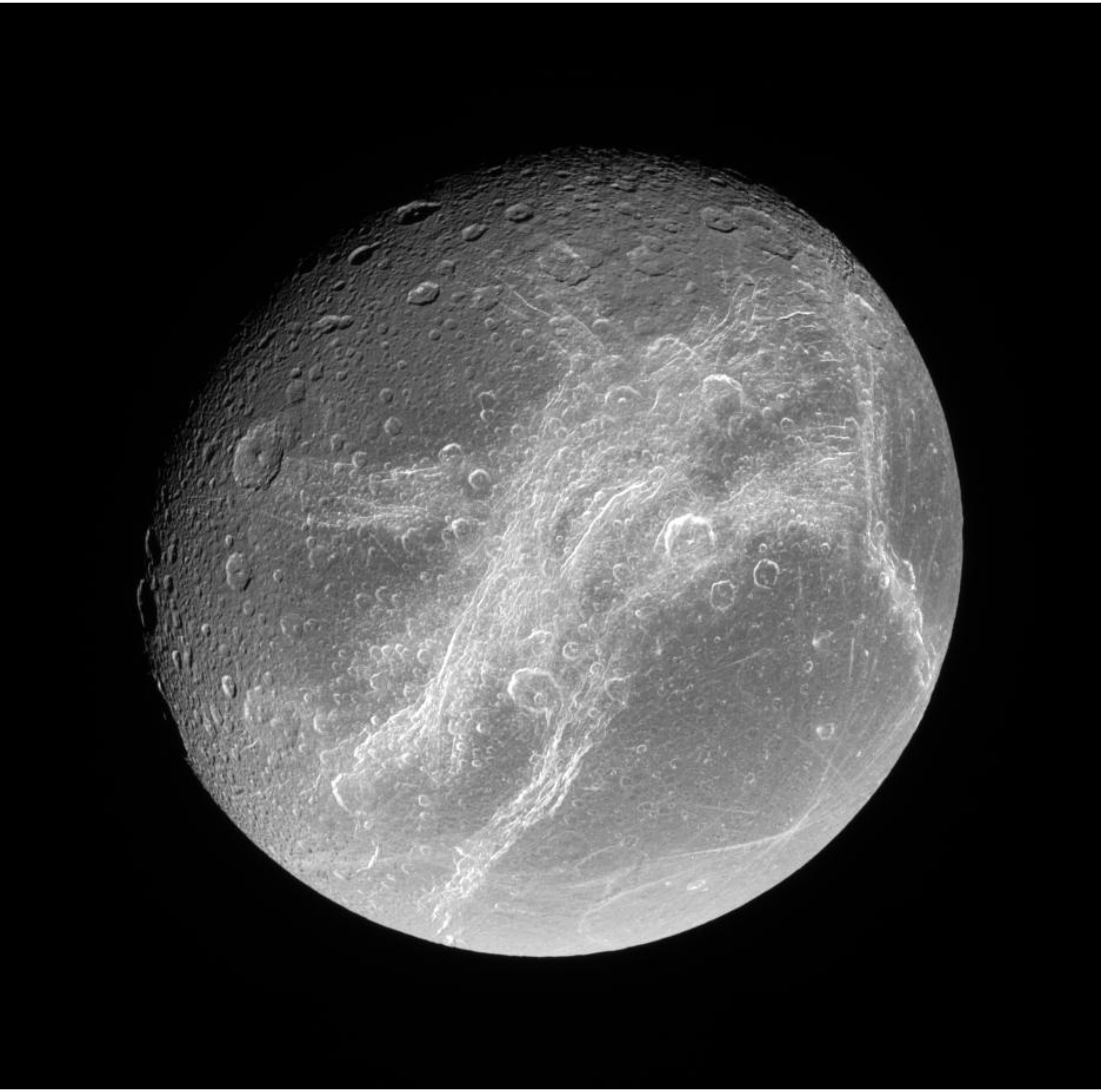
Odysseus is exactly opposite to the Ithaca Chasma, which suggests the impact may have been responsible for the formation of the chasma.



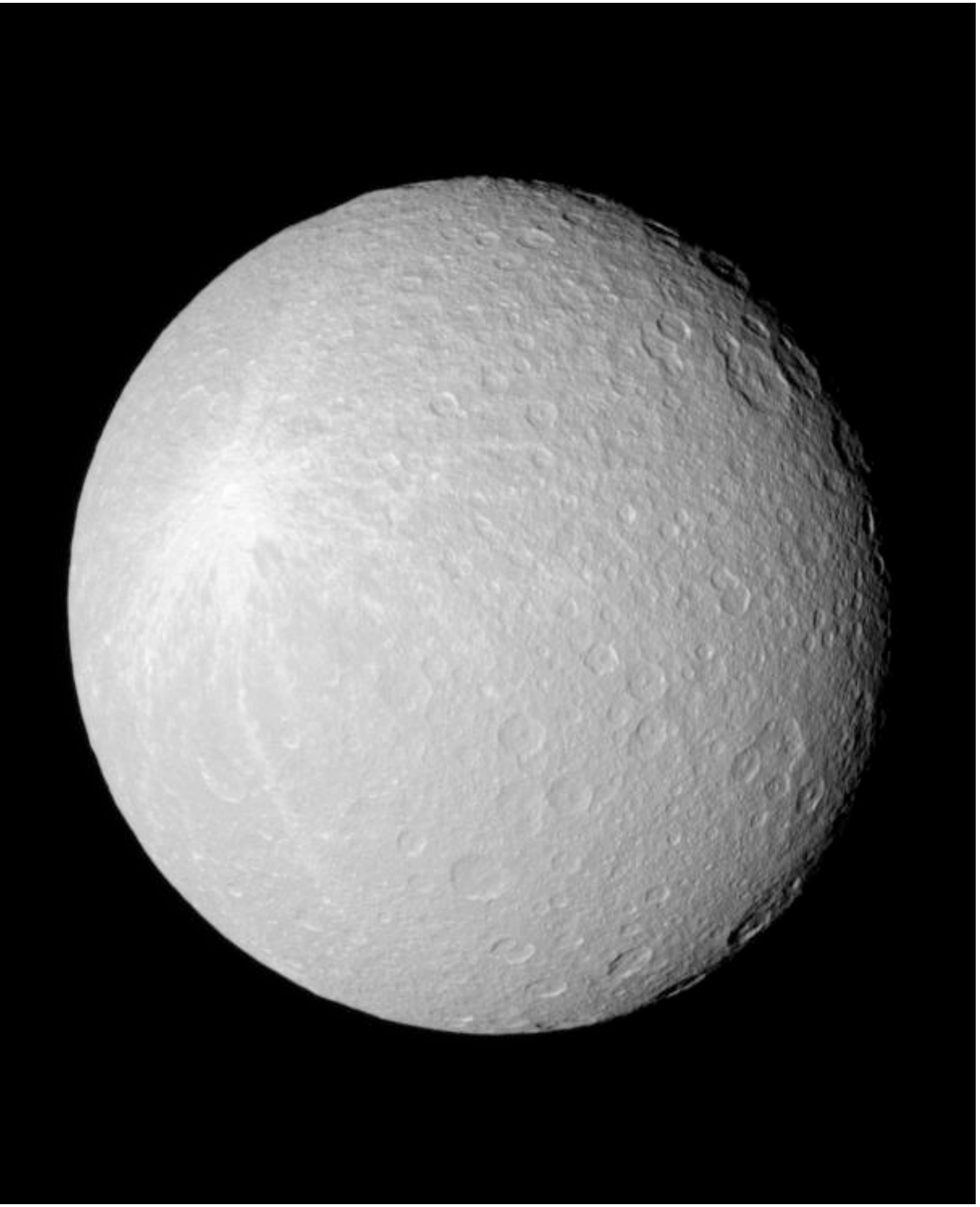
Odysseus Crater, on the leading hemisphere of Tethys.

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.



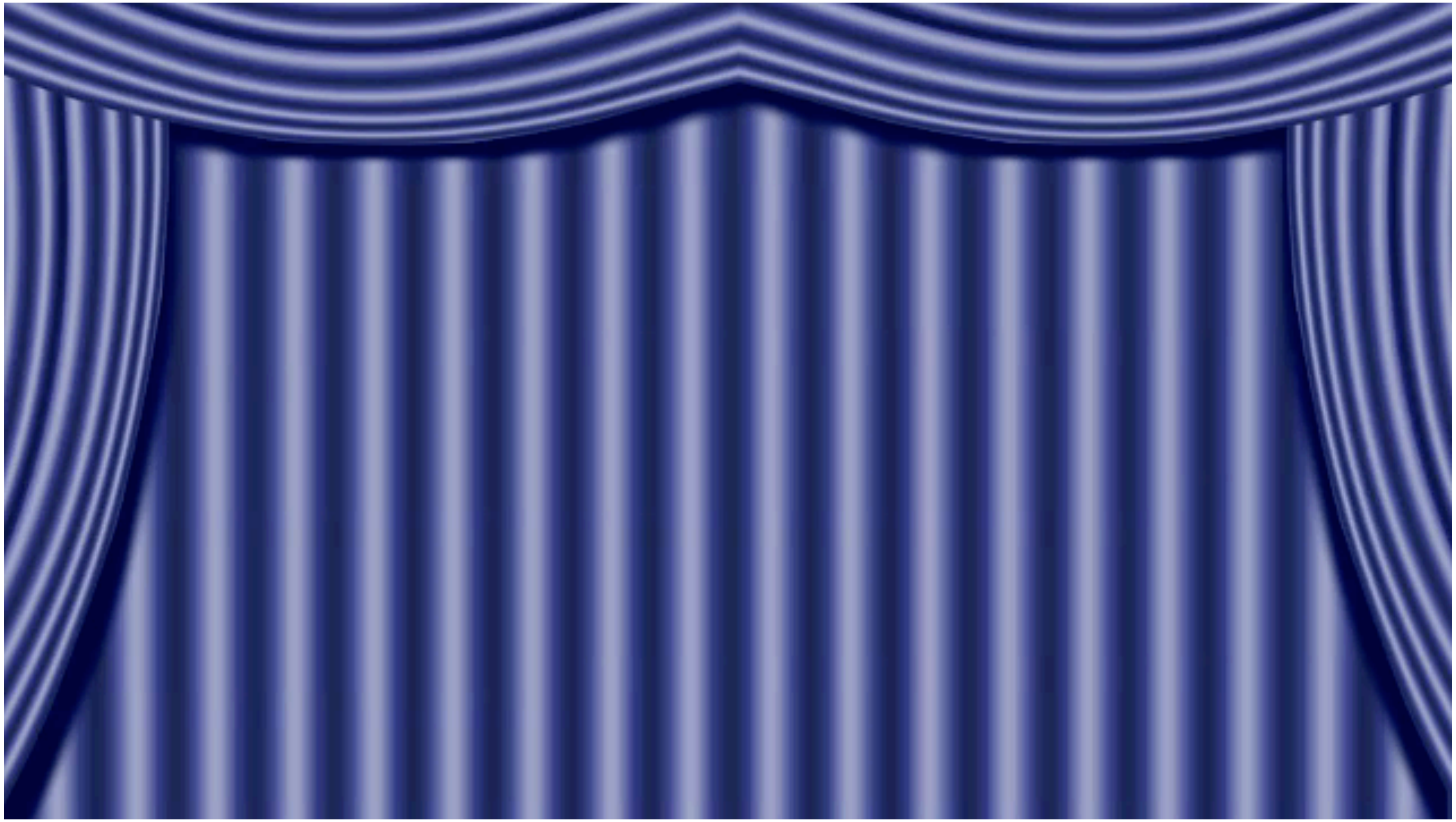


Dione's trailing hemisphere is heavily cratered, with an unusual network of bright, wispy streaks on a dark background that overlay the craters, indicating that they are newer. *Cassini* found these wispy streaks are actually ice cliffs.

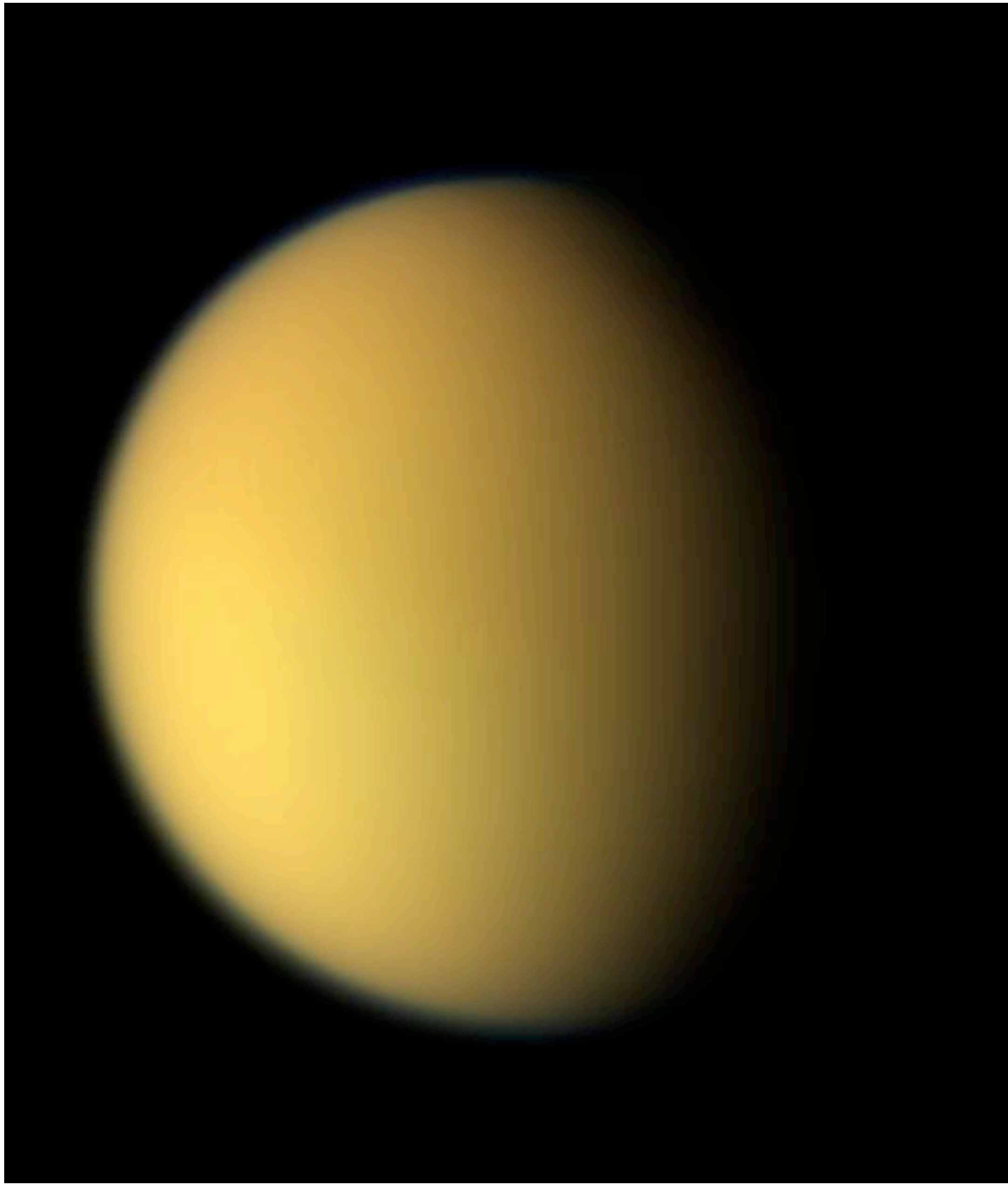


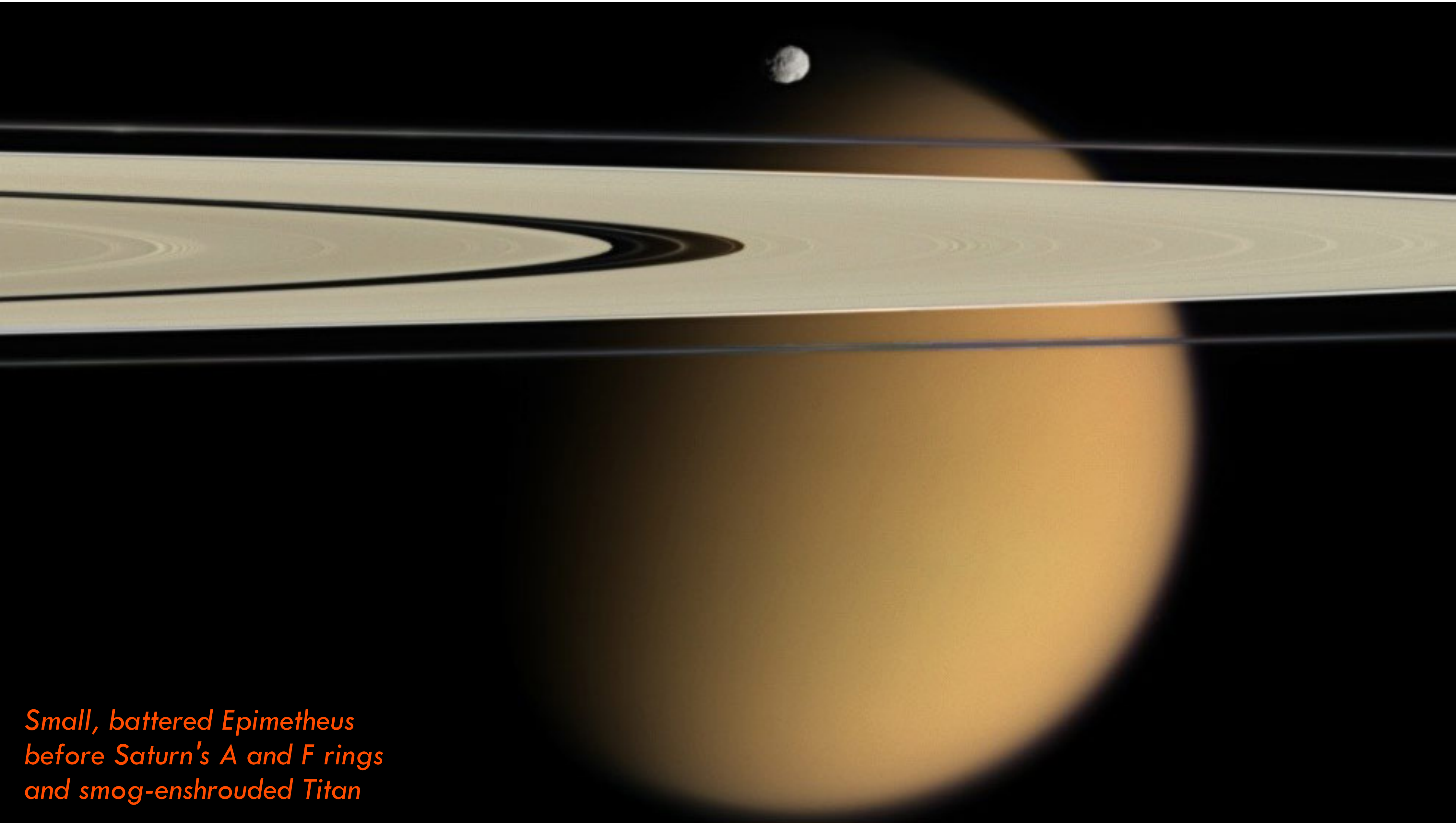
Rhea (radius 765 km) is the second largest of Saturn's moons. It is very similar to Dione: it also has vastly different leading and trailing hemispheres. The leading hemisphere is heavily cratered and uniformly bright. On the trailing hemisphere there is a network of bright swaths on a dark background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

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

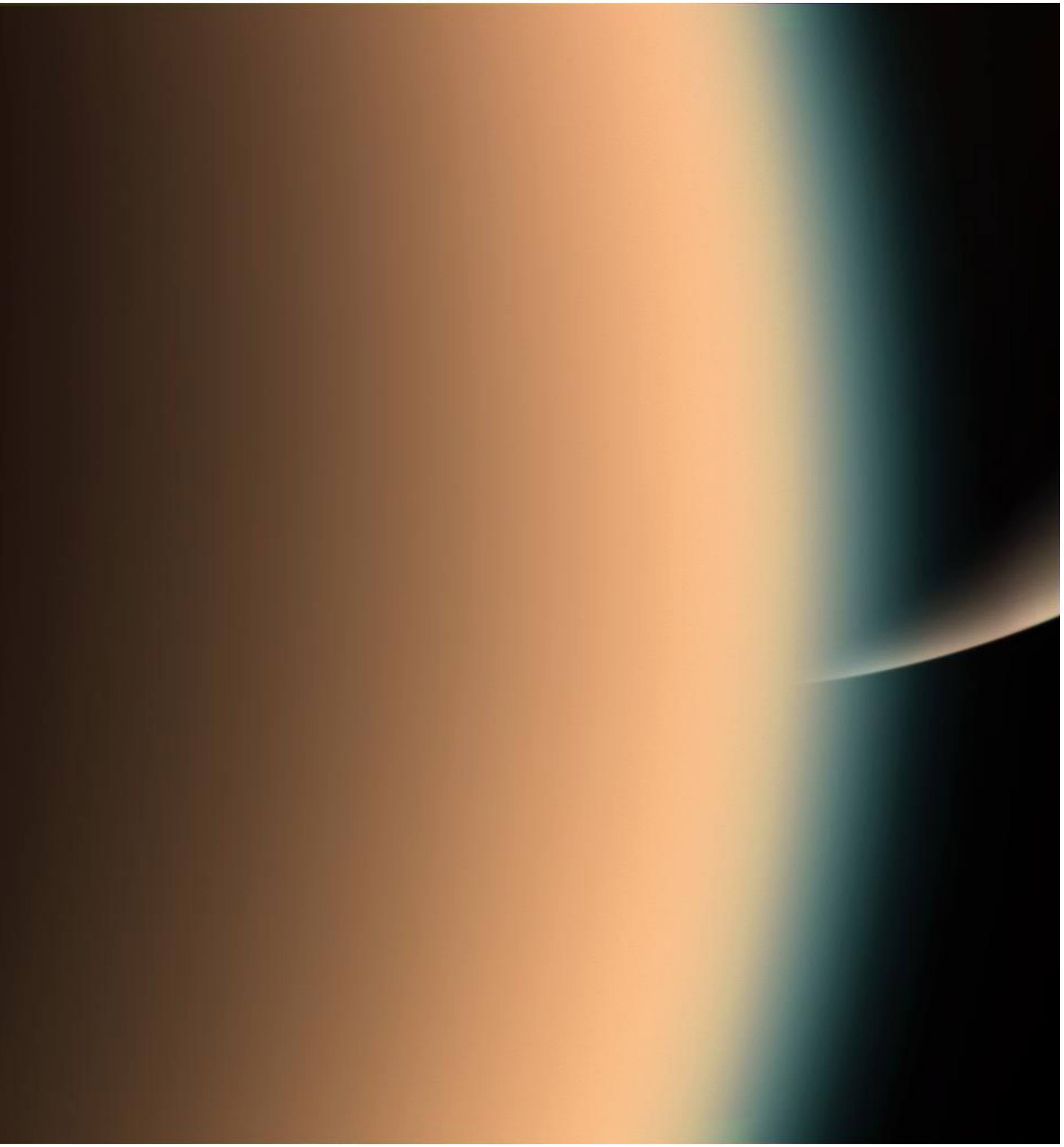


Titan (radius 2575 km) is Saturn's largest satellite and the second largest moon in the solar system (after Ganymede). It is the only satellite in the Solar System with an atmosphere. It is almost identical to Ganymede in mass and size, but is otherwise very different.

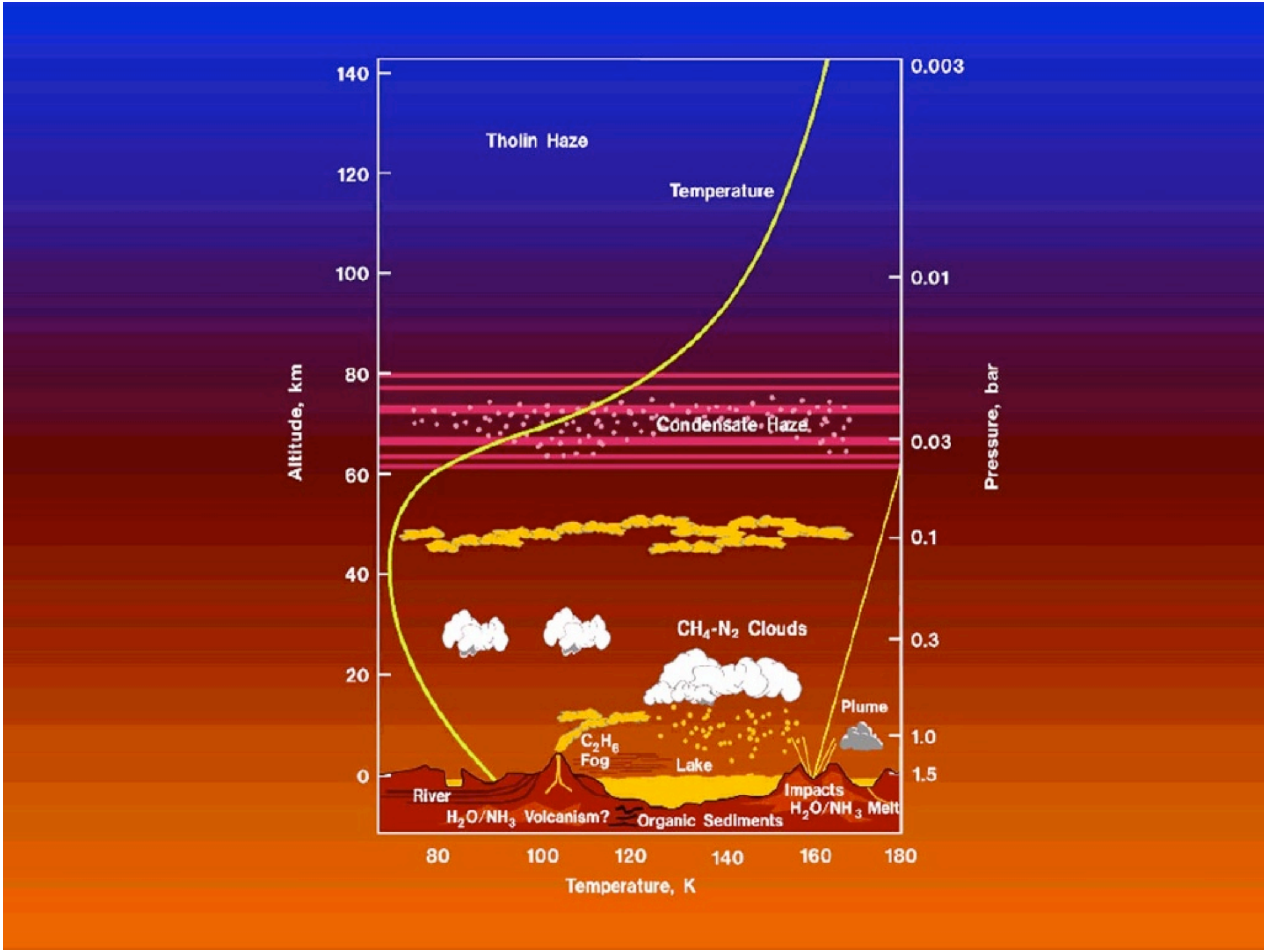




*Small, battered Epimetheus
before Saturn's A and F rings
and smog-enshrouded Titan*

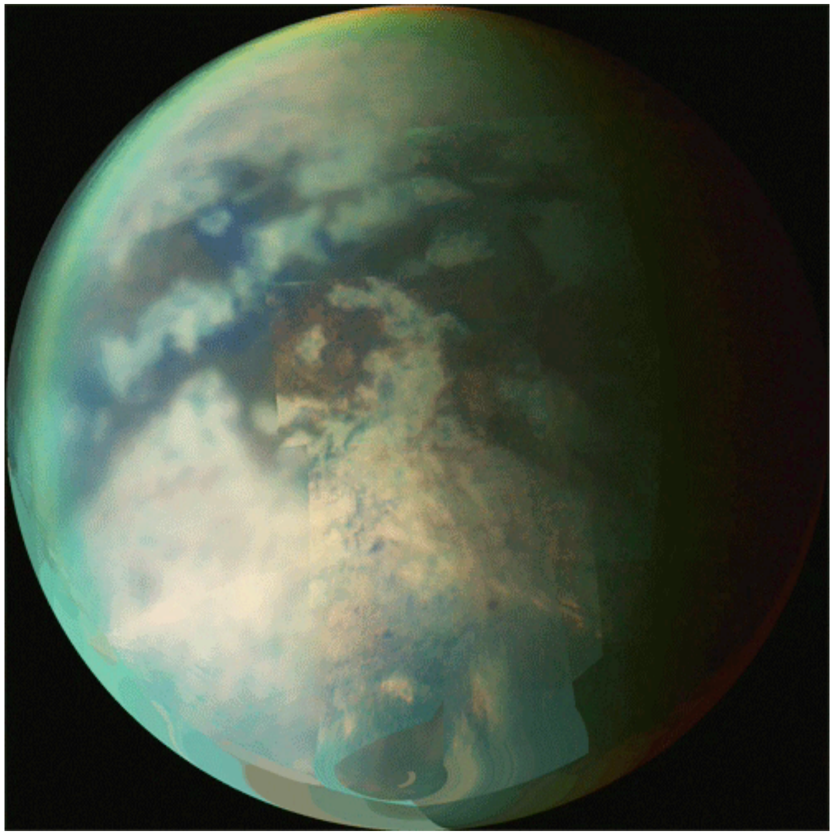


Titan’s surface pressure is more than 1.5 bar (50% higher than Earth's). The atmosphere is 94% nitrogen, with significant traces of various hydrocarbons making up much of the remainder. The organic compounds are formed when methane is destroyed by sunlight, so Titan’s atmosphere is similar to the smog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



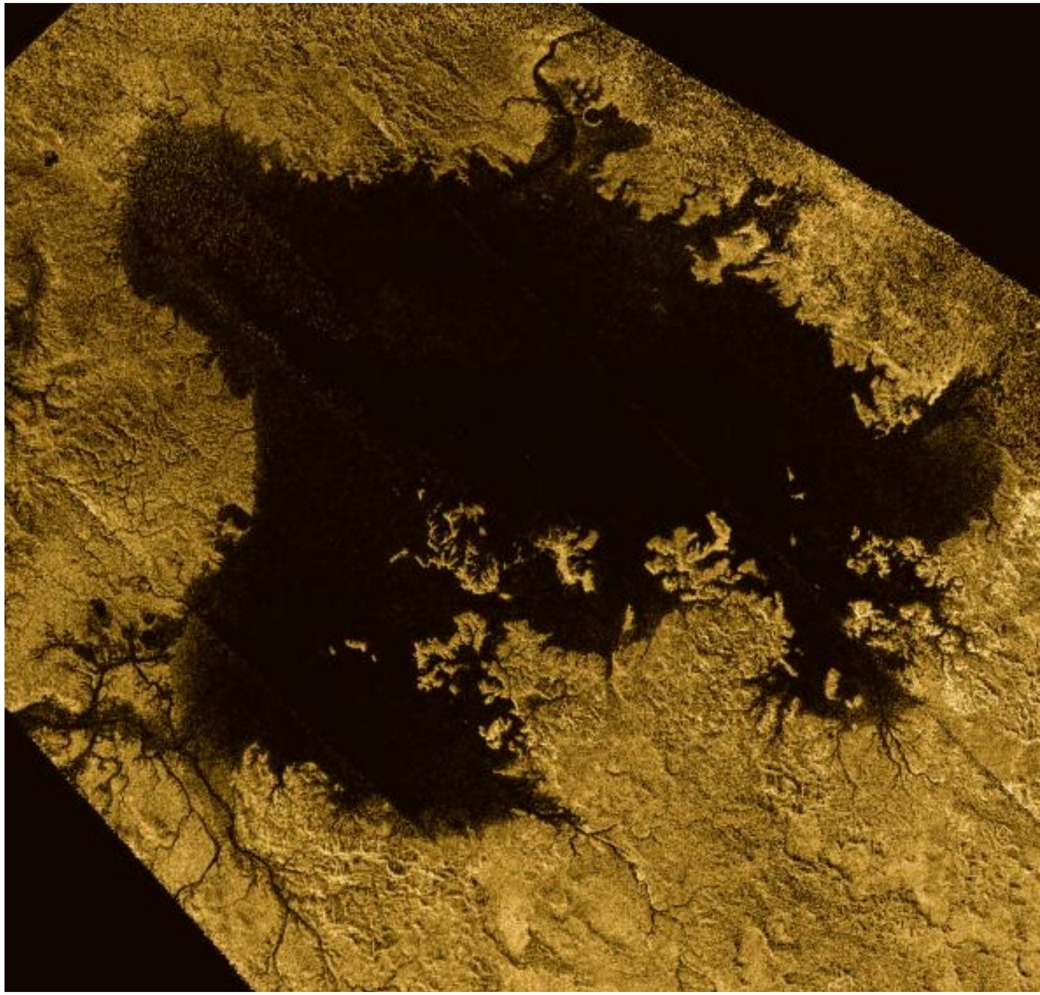
Tholin Haze
Temperature
Condensate Haze
CH4-N2 Clouds
Plume
C2H6
Fog
Lake
River
H2O/NH3 Volcanism?
Organic Sediments
Impacts
H2O/NH3 Melt
Altitude, km
140
120
100
80
60
40
20
0
Pressure, bar
0.003
0.01
0.03
0.1
0.3
1.0
1.5
80
100
120
140
160
180
Temperature, K

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.

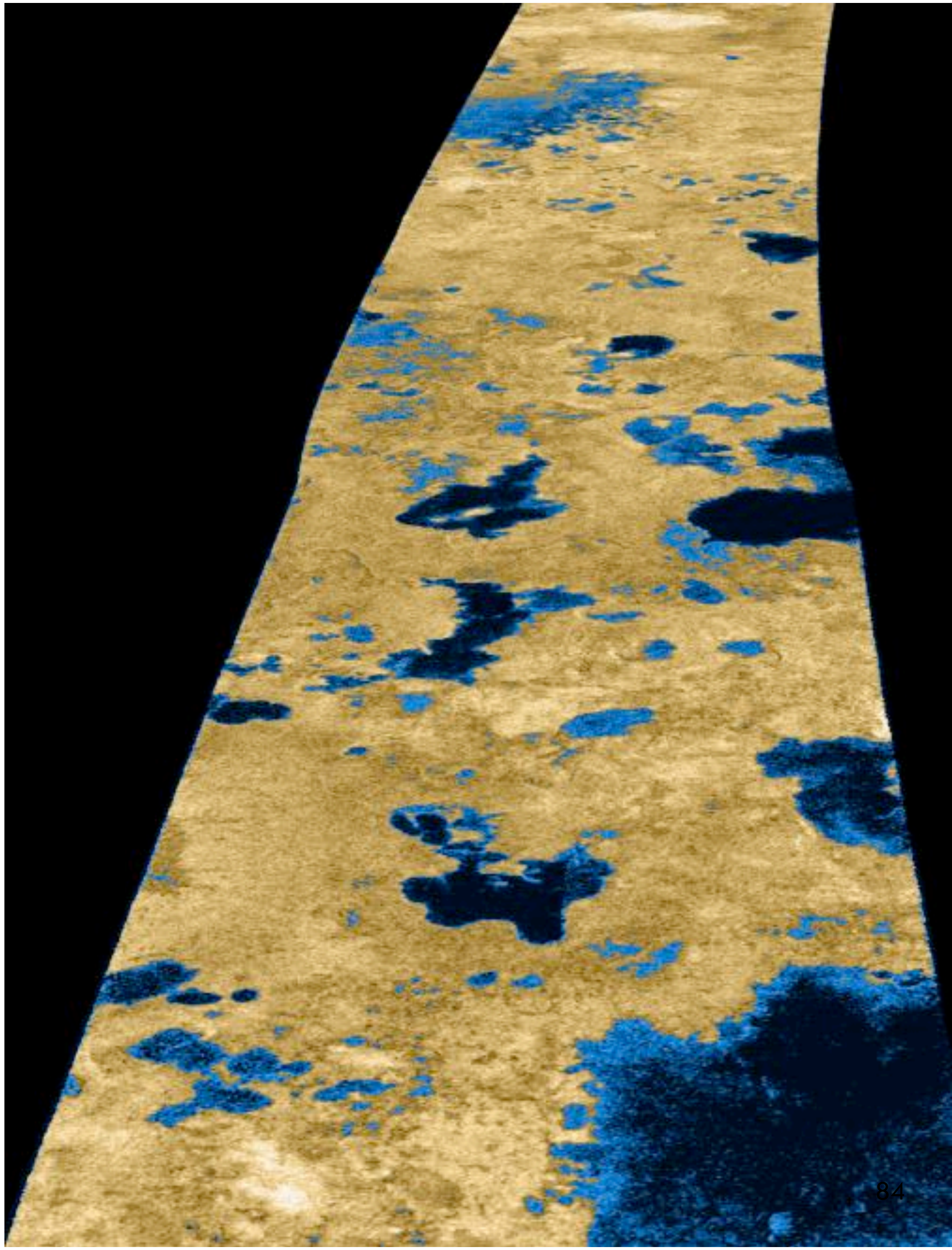
Cassini took radar images during flybys of very smooth, dark features near Titan's north and south poles. These are almost certainly seas, probably filled with a combination of methane and ethane.



A recent analysis found the composition of the lakes to be:

- ethane (76-79%)
- propane (7-8%)
- methane (5-10%)
- hydrogen cyanide (2-3%)
- butene (1%)
- butane (1%); and
- acetylene (1%).

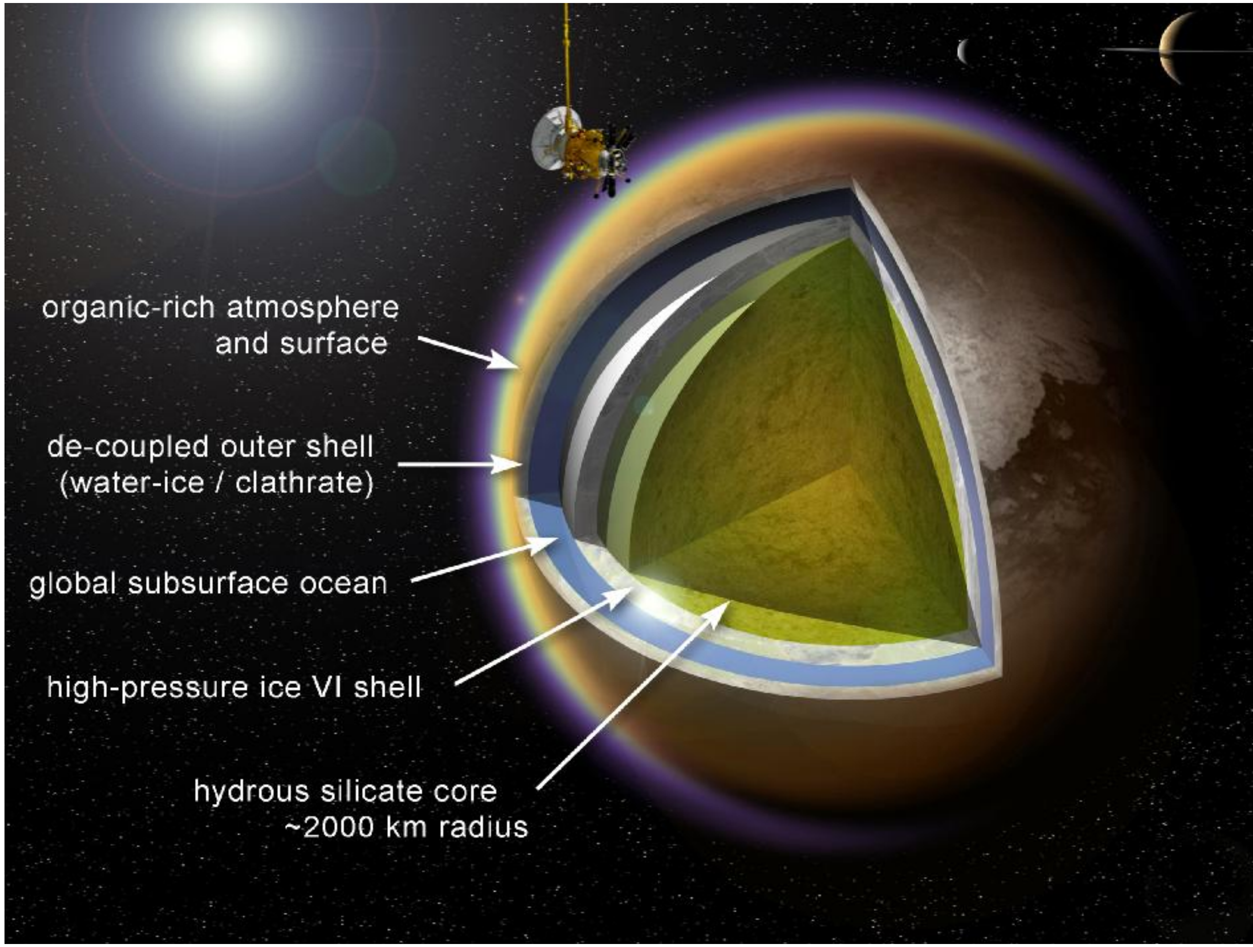
These lakes are the strongest evidence yet that Titan has an active hydrological cycle, though with a liquid other than water. As Titan's seasons change over the 29-year cycle of Saturn's orbit around the sun, lakes in the winter hemisphere should expand by steady methane rain, while summer hemisphere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



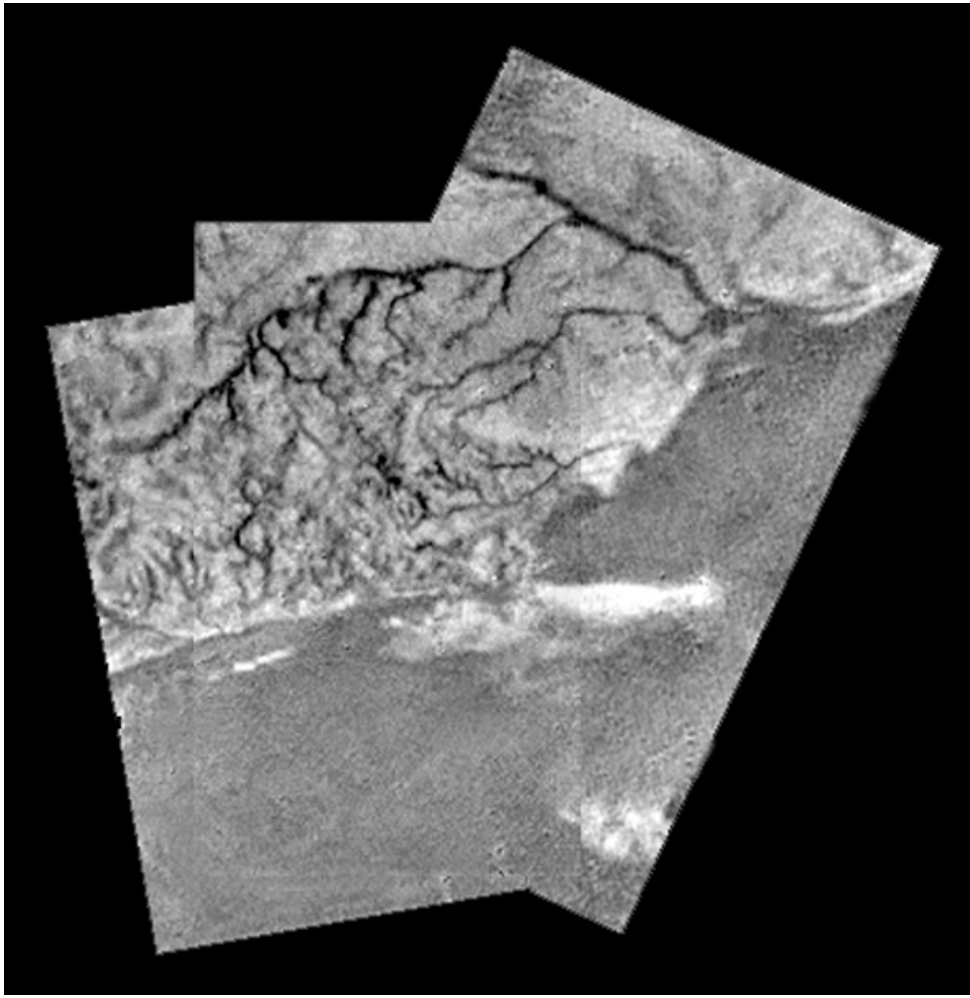
False-colour perspective view of radar images of lakes; the image is 140 km across.

Cassini found a peculiar shift in landmarks on Titan's surface of up to 30 km between October 2004 and May 2007. The best explanation is a moon-wide underground ocean that disconnects Titan's icy crust from its rocky interior. The surface consists of about 100 km of ice sitting on top of a global layer of water.

Titan's core is rocky, and surface "rocks" on Titan are made of ice.

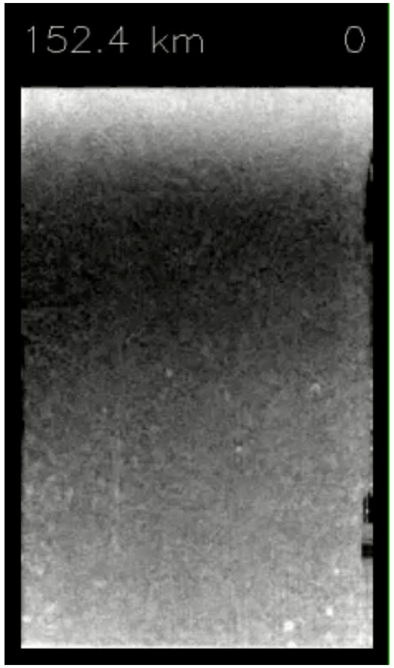


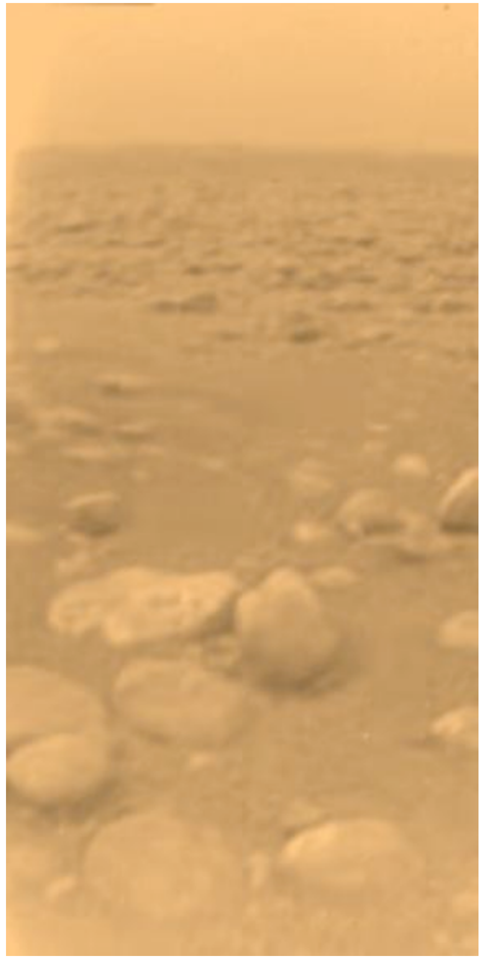
The *Huygens* probe descended to the surface of Titan on 14 January 2005. The *Huygens* images show pale hills criss-crossed with dark drainage channels. The channels lead into a wide, flat, darker region. It was initially thought that the dark region might be a lake of a fluid or at least tarry substance. However, it is now clear that *Huygens* landed on the dark region, and it is solid. So the features are a remnant of past liquid flow, though we don't know how long ago.



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 thought that dark organic compounds may rain from Titan's atmosphere and be washed down the hills by methane rain.



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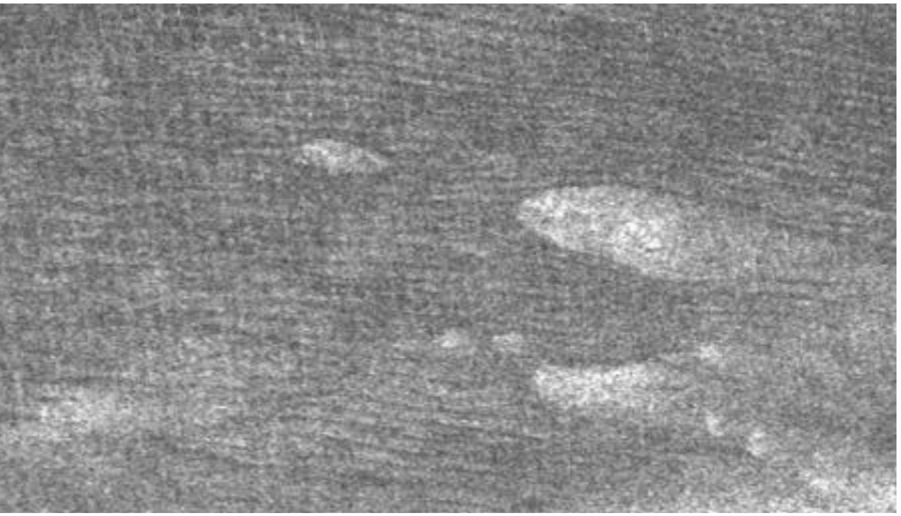
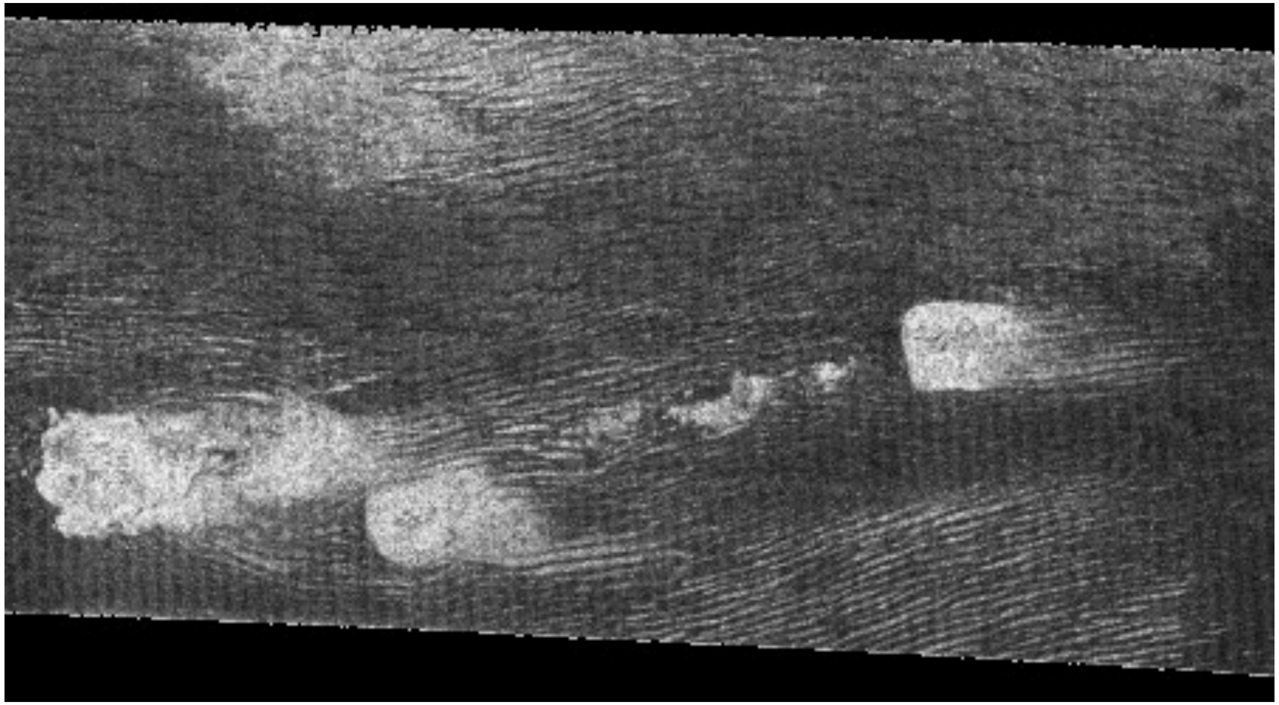
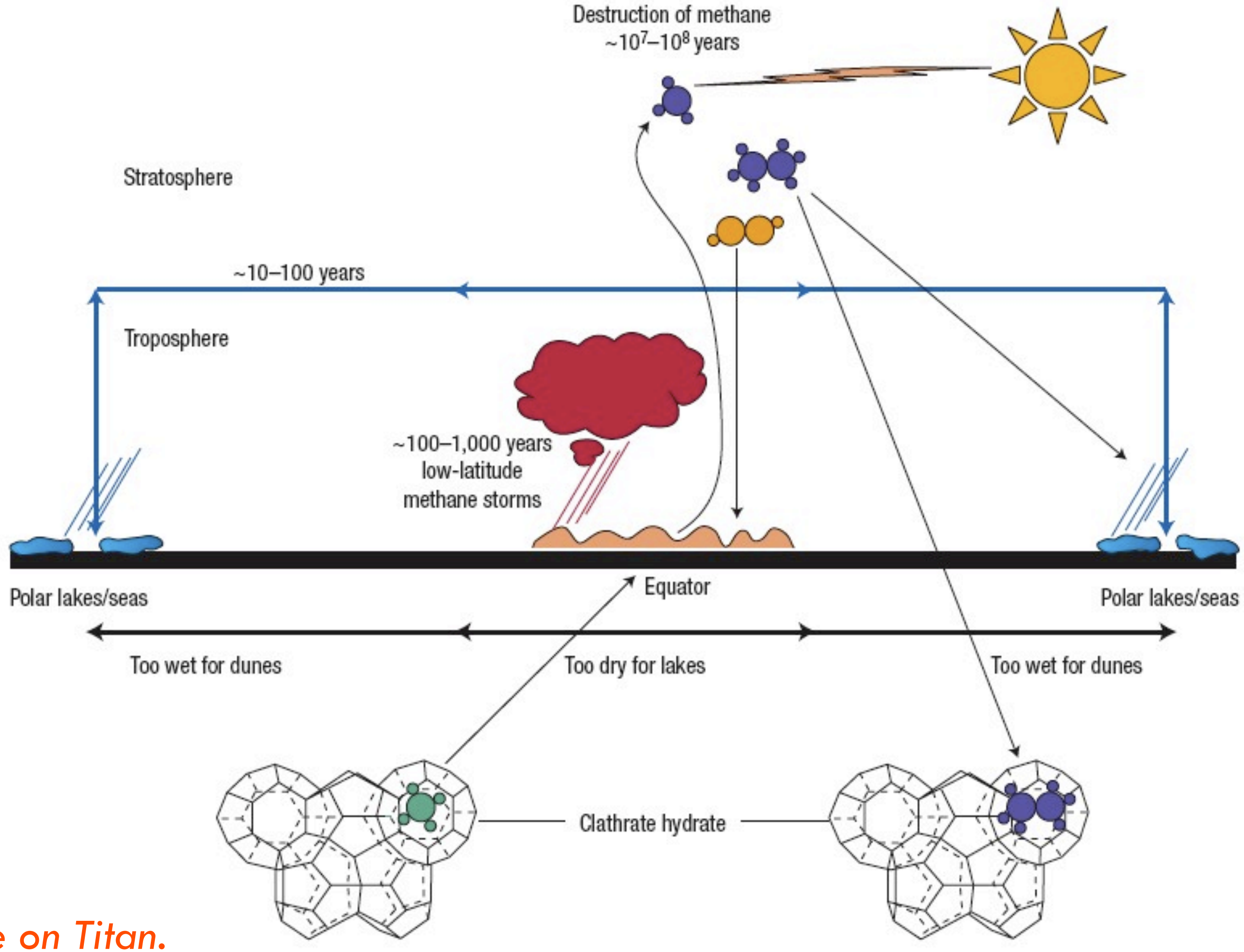
Cassini radar images near the equator saw long dark ridges that curve around the bright terrain. It is believed they are dunes that winds have blown across the surface of Titan from left to right.





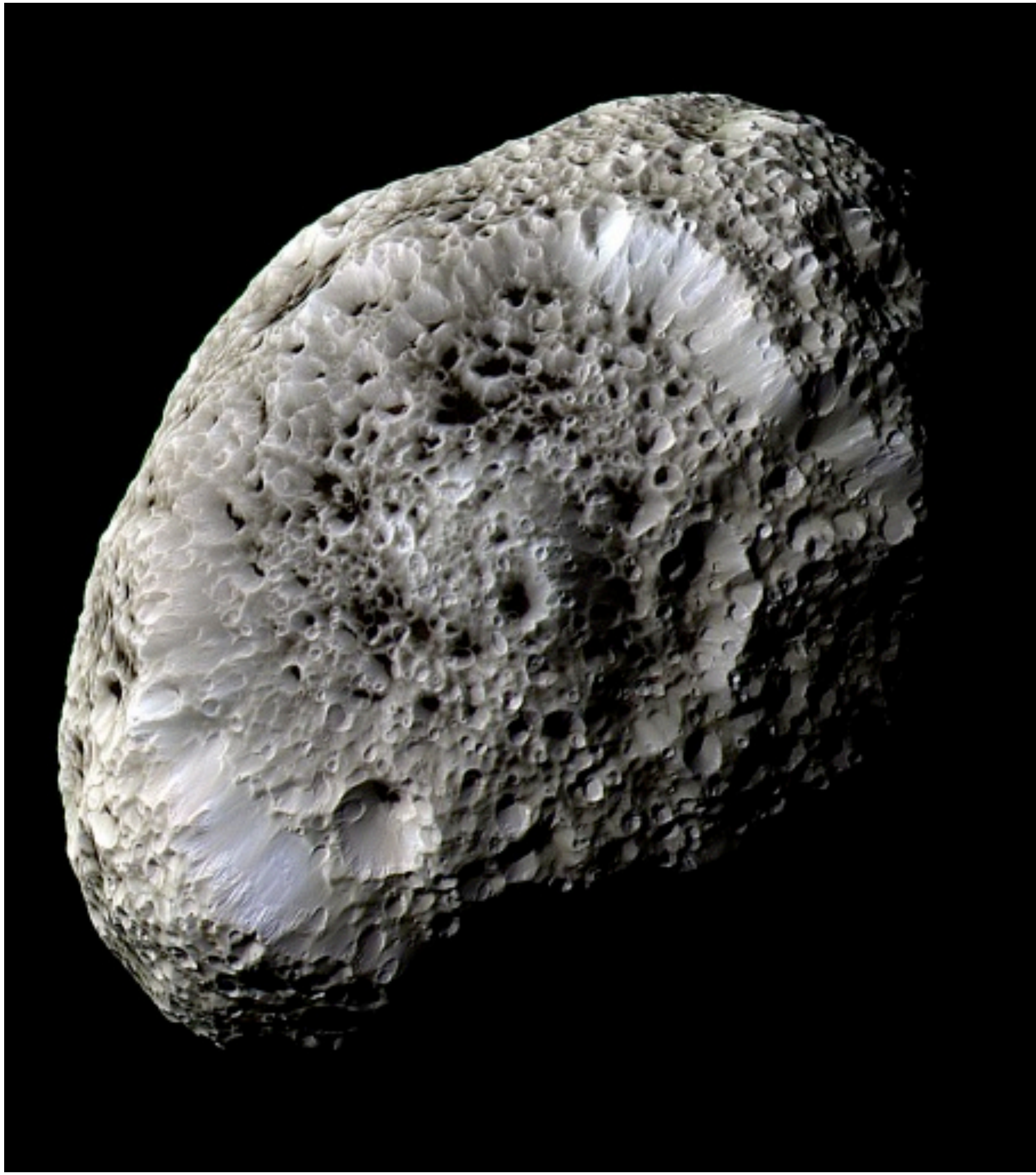
Titan has an active methane cycle. Methane vapour forms storms which produce methane rain. However, methane is destroyed by sunlight, converted into complex hydrocarbons, so it must be replenished, possibly from cryovolcanoes.



The methane cycle on Titan.

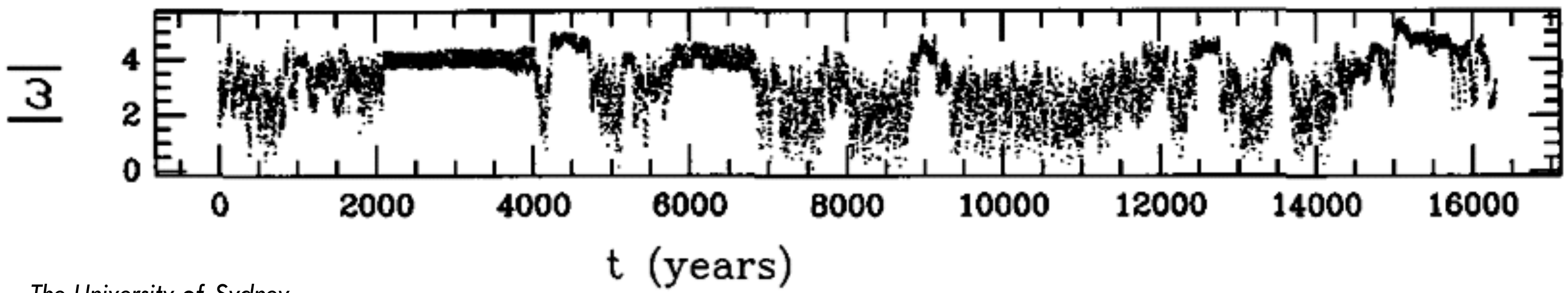
Hyperion (radius 143 km) is a highly irregular body. Its surface is uniform and very dark: it may be covered in material from Iapetus.

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

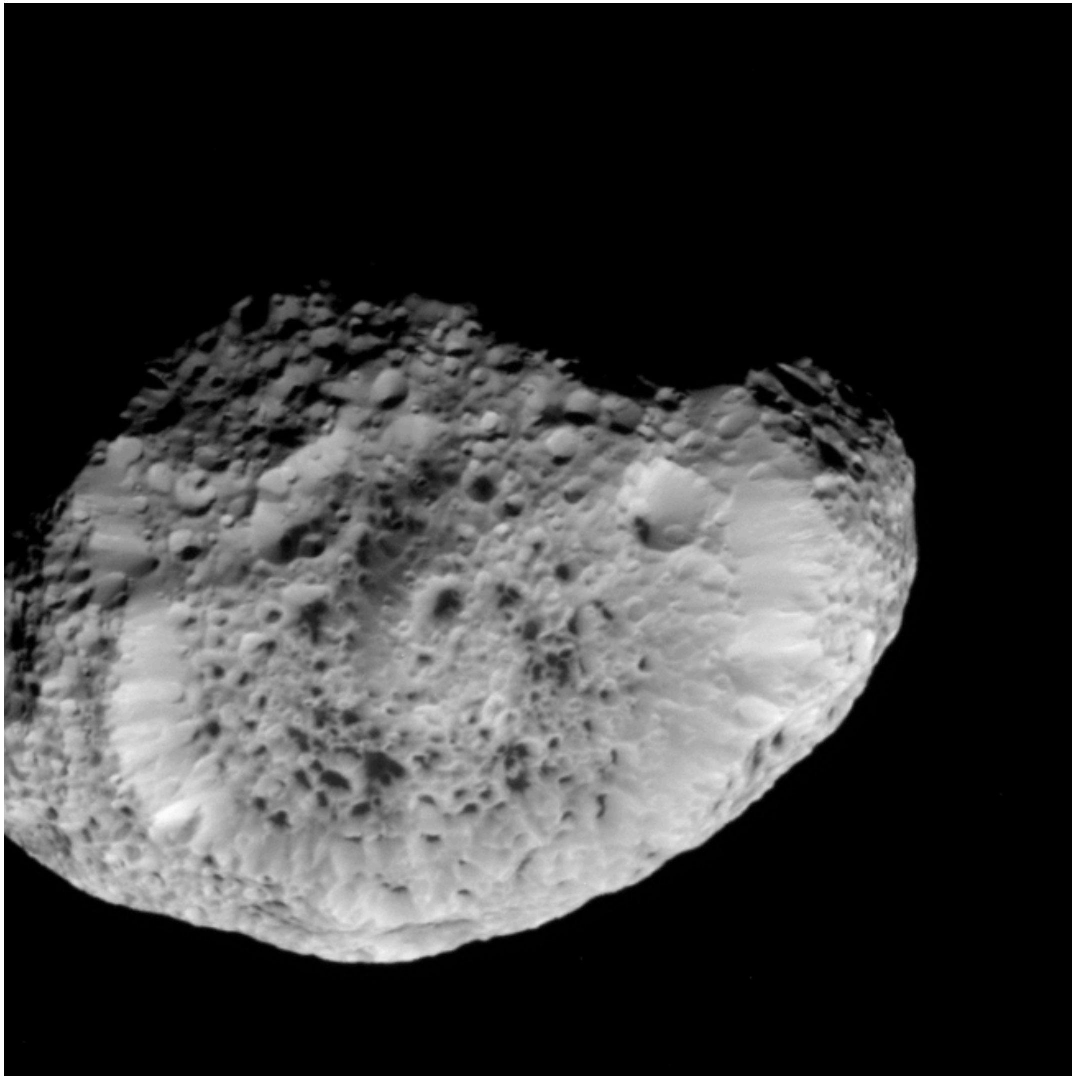


Hyperion is locked in a 3:4 orbital resonance with Titan. It has an irregular shape, and it tumbles through its orbit (that is, it doesn't spin at a constant rate or in a constant orientation).

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.

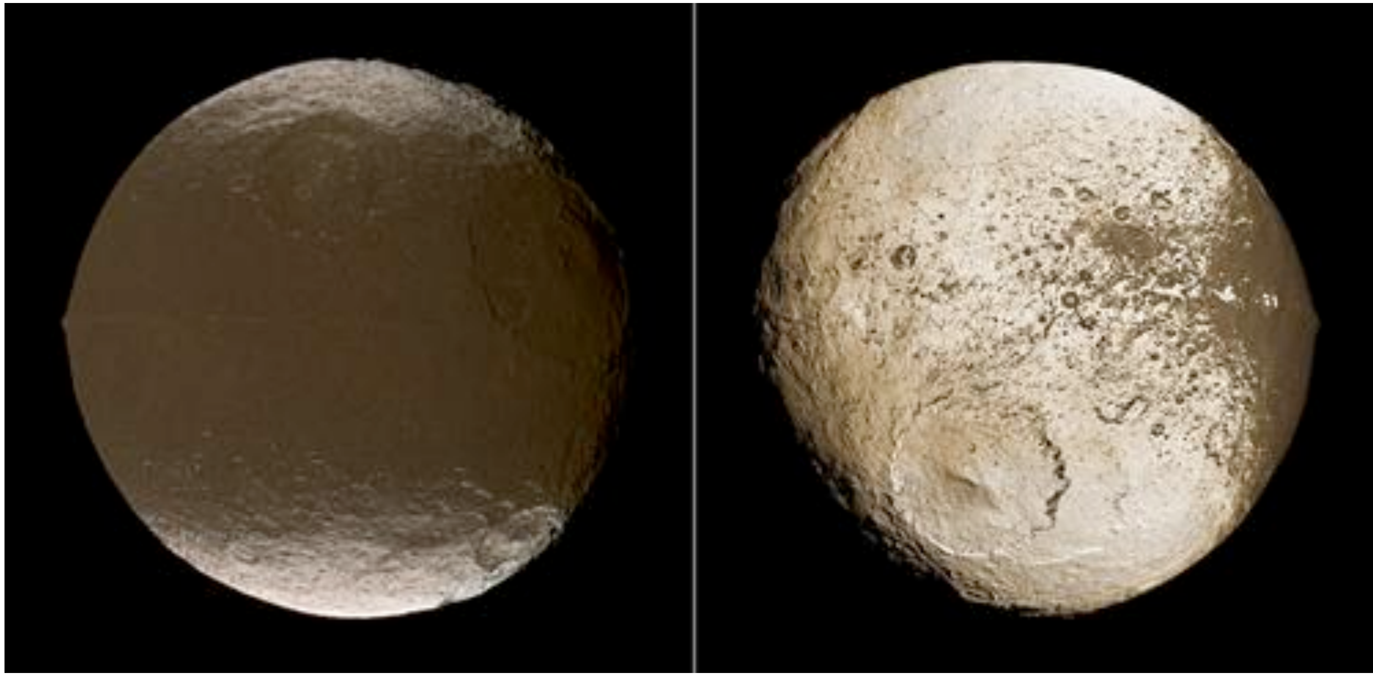


Changes in Hyperion's spin frequency when integrated over 1,000,000 orbits. The motion varies from periods of complete chaotic tumbling to periods of regular looking behaviour (from Black et al. 1995)

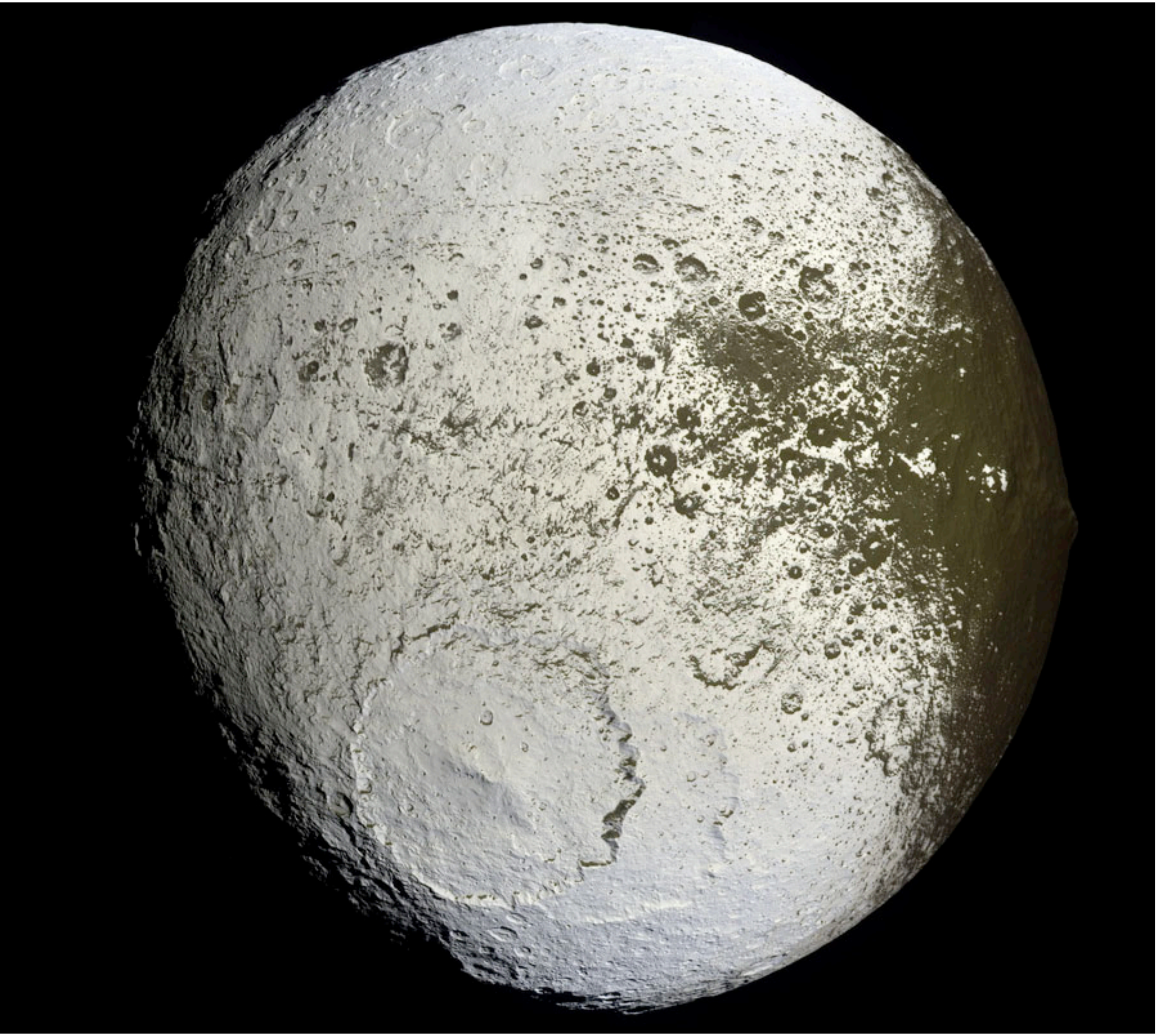


Iapetus (radius 730 km) is almost entirely water ice. Iapetus' leading and trailing hemispheres have very different albedos. The leading hemisphere has an albedo 0.03–0.05, while the trailing has albedo 0.5 – as bright as Europa.

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.



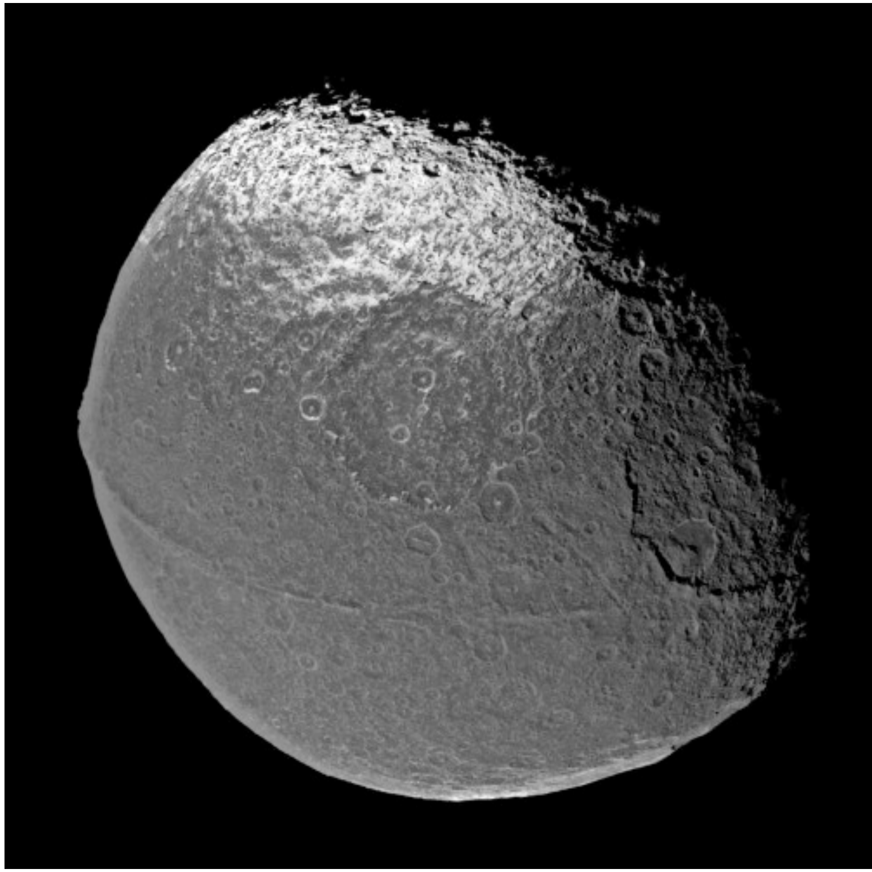
The extreme brightness dichotomy of Iapetus.



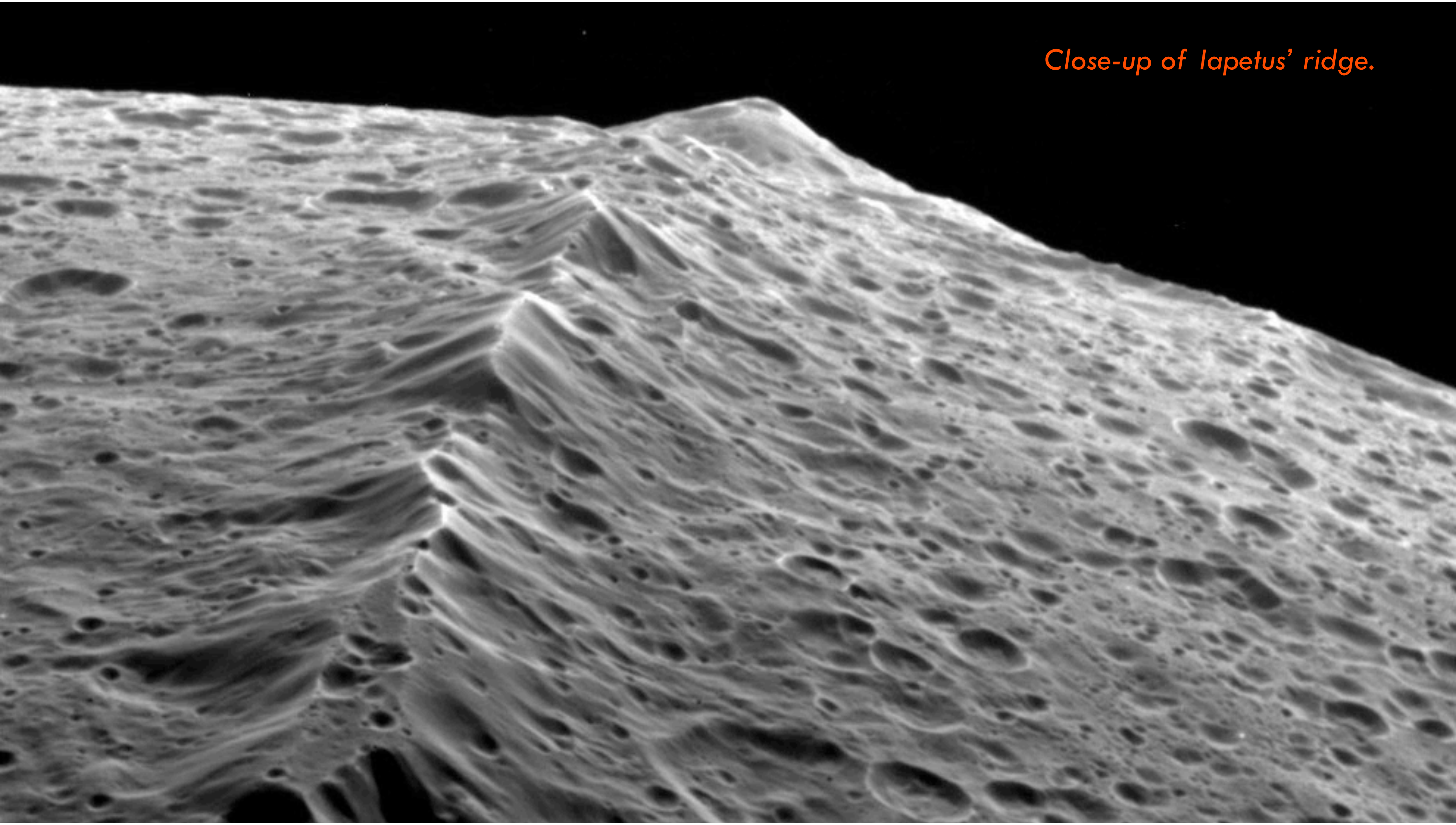
Close-up of the trailing hemisphere. The dark material is a coating, possibly carbon, which is less than a metre thick.

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 material is a deposit on the icy surface, probably material blasted off the moon Phoebe by micrometeorites.

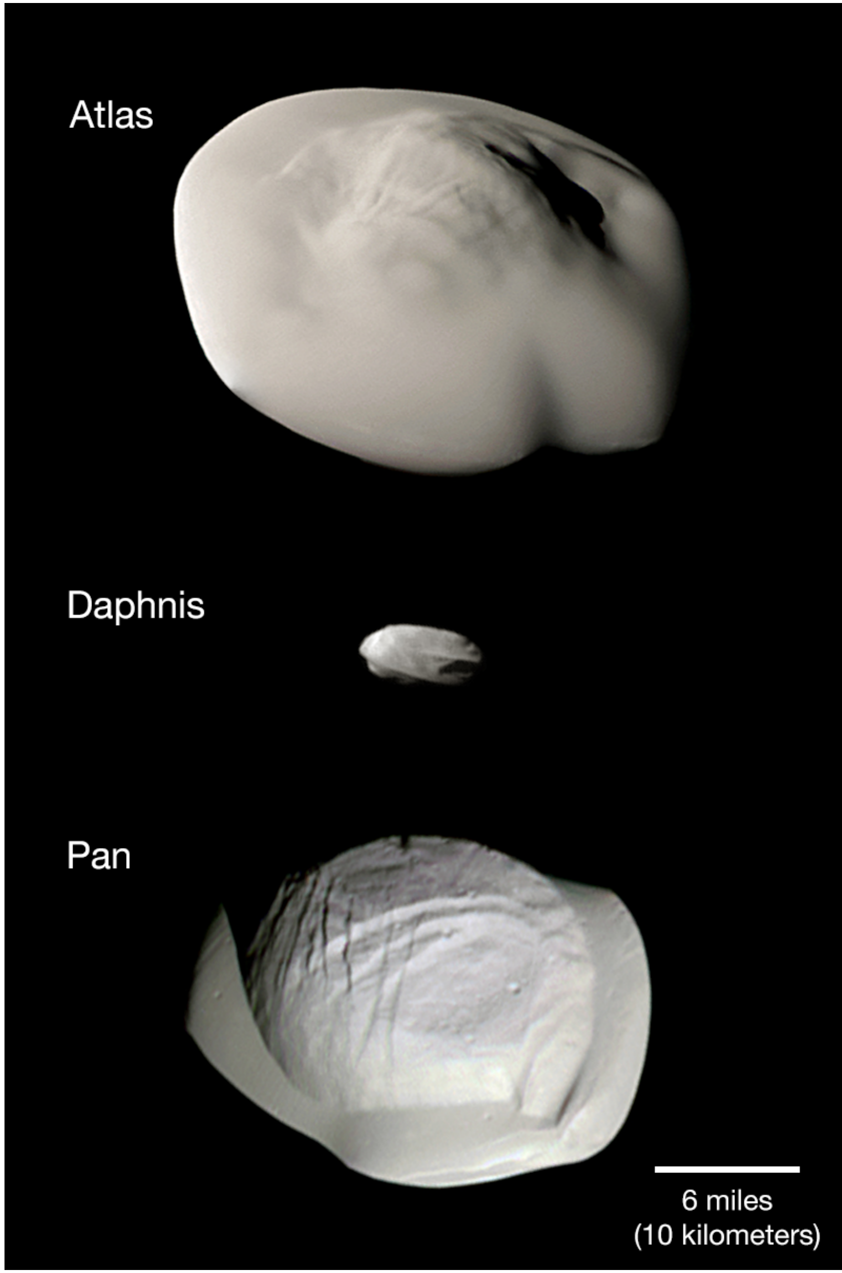


Cassini view of the leading hemisphere of Iapetus.



Close-up of Iapetus' ridge.

Three of Saturn's tiny moons – Atlas, Daphne and Pan – also have equatorial ridges. These appear to be made from material swept up from the rings. Possibly Iapetus' ridge was formed in the same way.



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

Its albedo is only 0.05; Phoebe is responsible for the dark surfaces of Hyperion and the leading hemisphere of Iapetus.

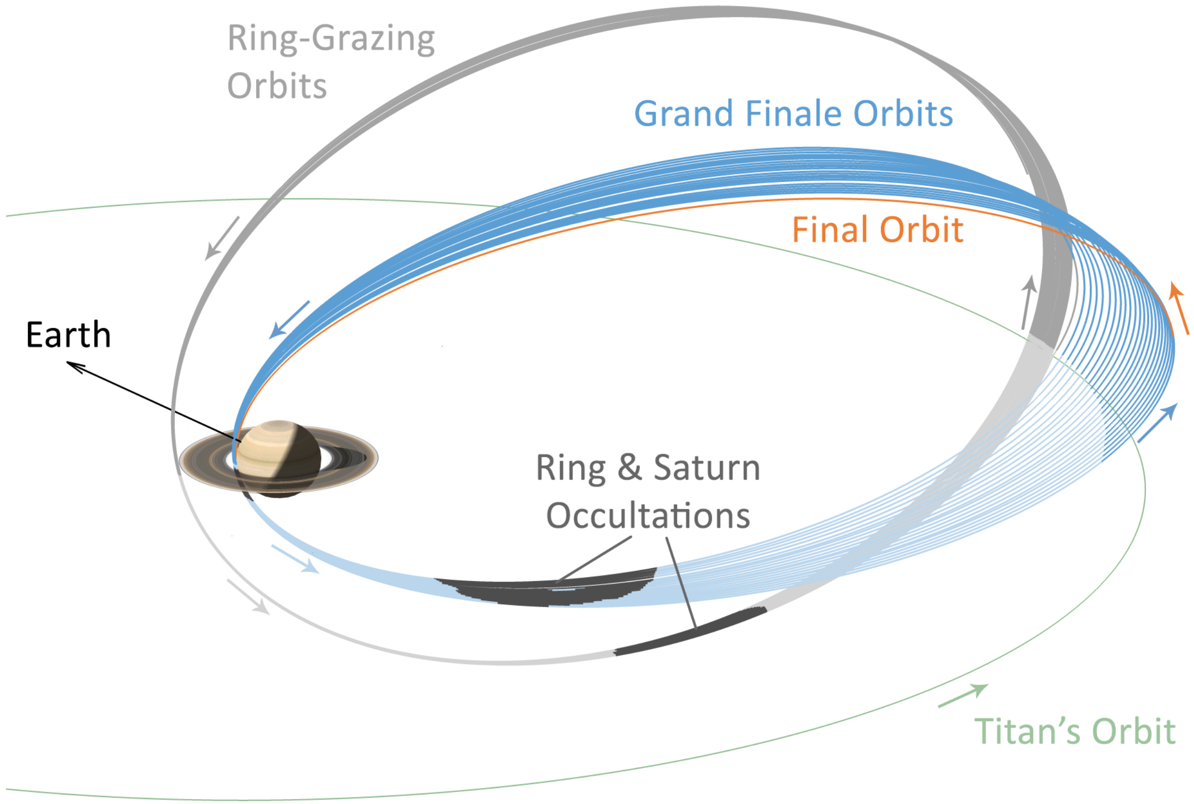
Cassini image of Phoebe taken in June 2004 from a distance of only 32,500 km.

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

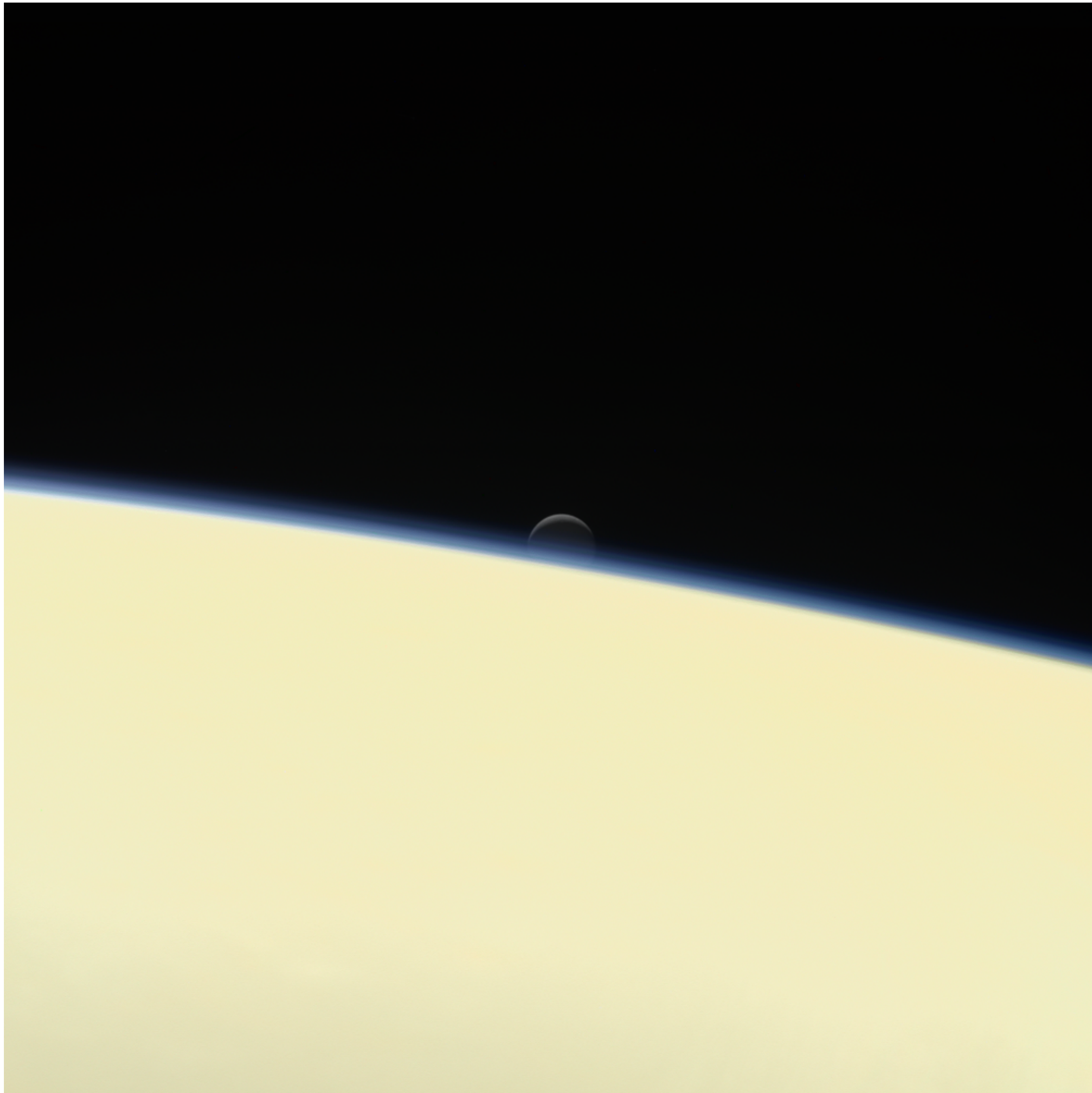
Cassini's final mission began in 2016. It was first put in an orbit that took it closer than it had ever been to the edge of the rings. Then in April 2017 it flew past Titan to send it on a trajectory that went through the gap between Saturn and its inner ring.

On Sept. 15, 2017, *Cassini* plunged into Saturn's atmosphere, where it finally burned up and disintegrated.



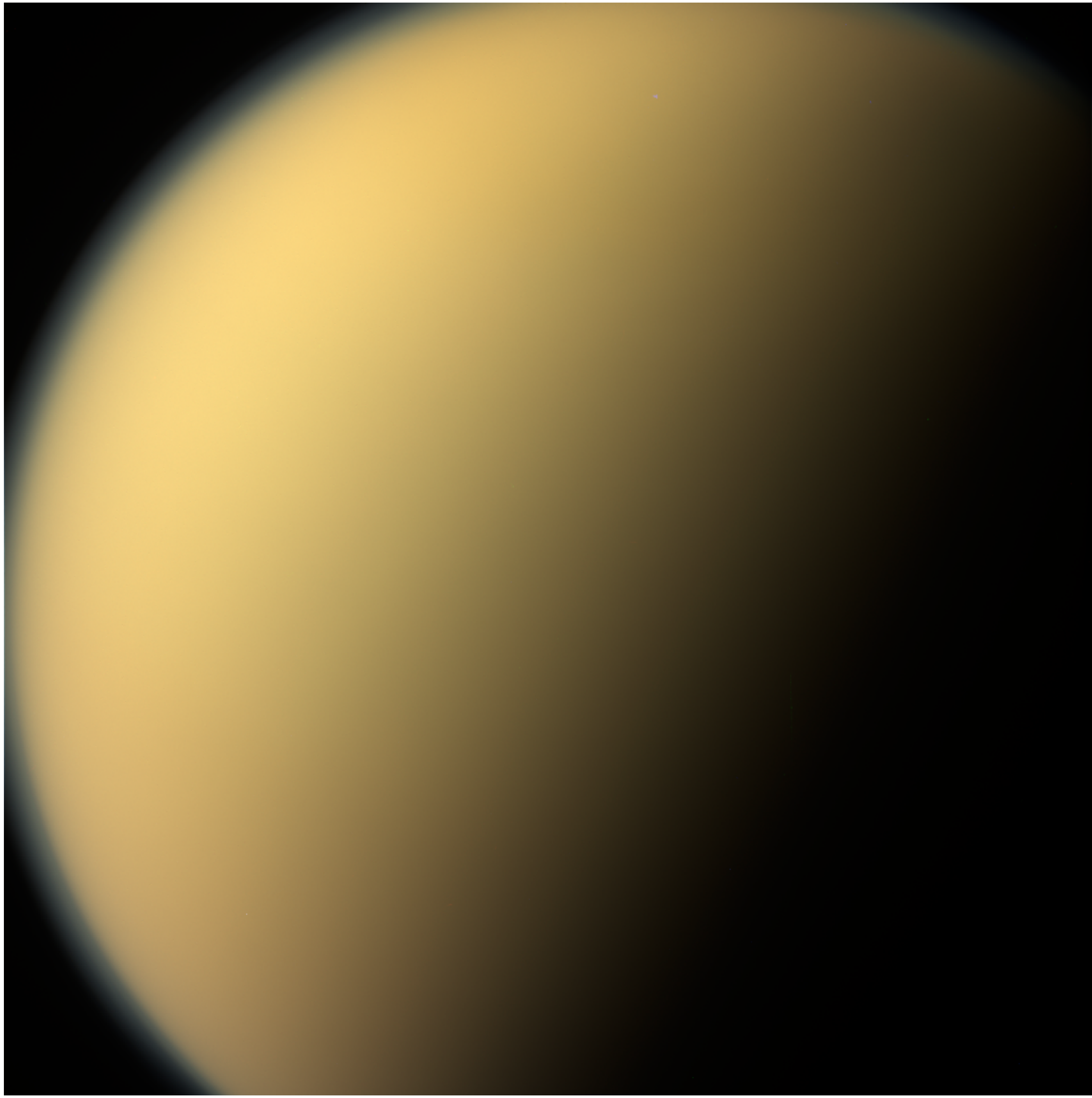
Some of *Cassini*'s final images:

Enceladus setting behind Saturn



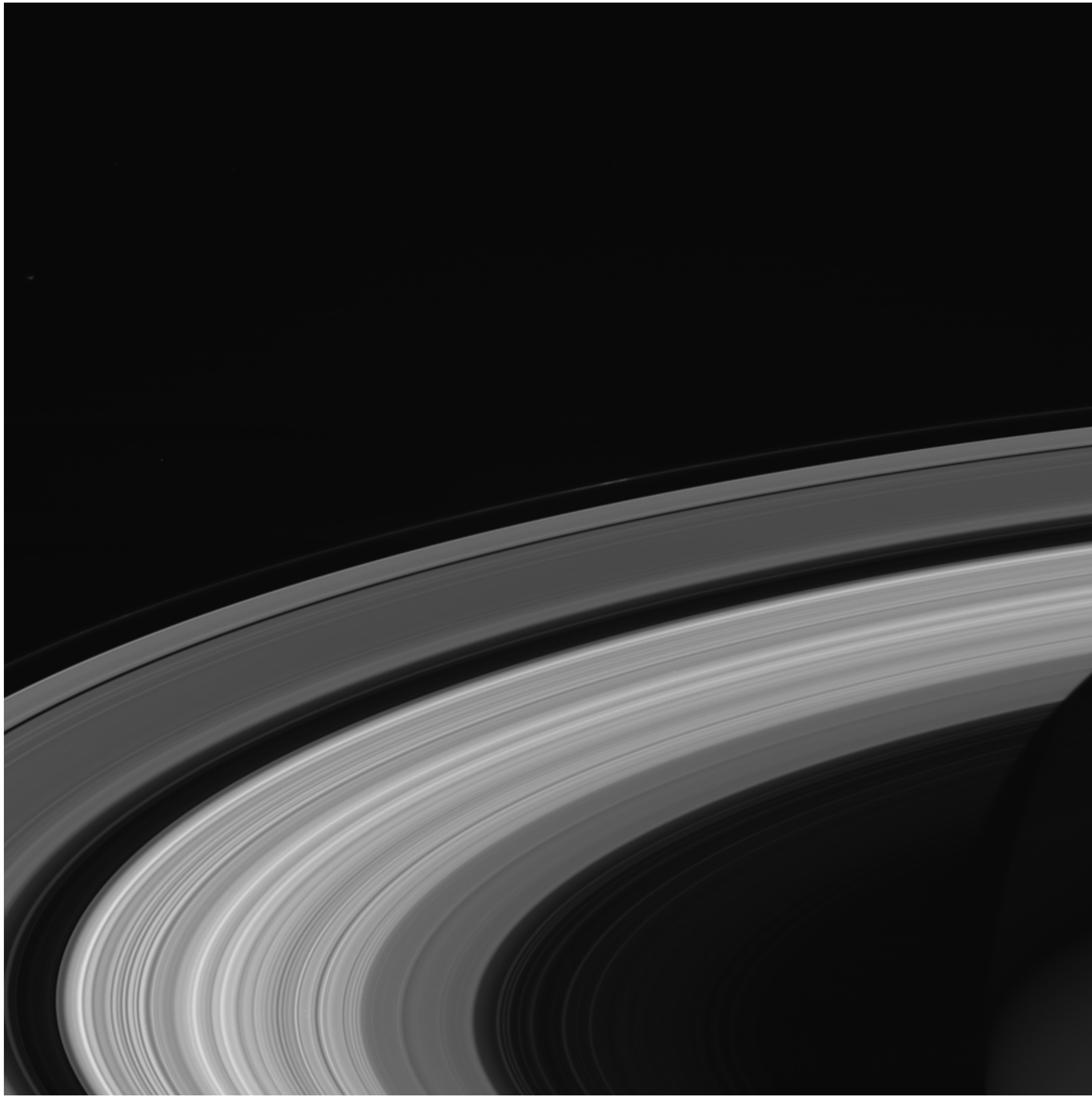
Some of *Cassini*'s final images:

A last look at Titan



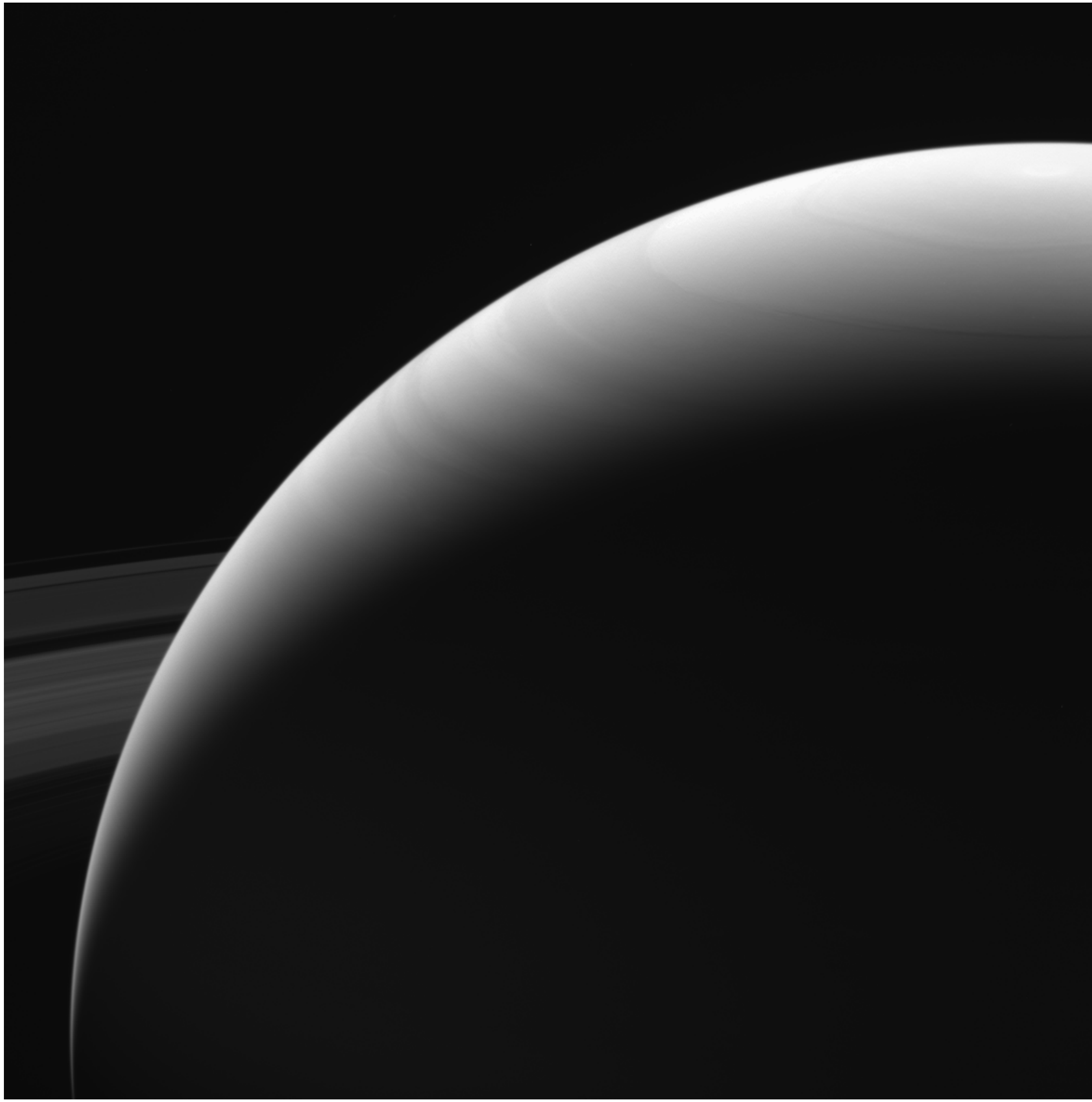
Some of *Cassini*'s final images:

Final ringscape



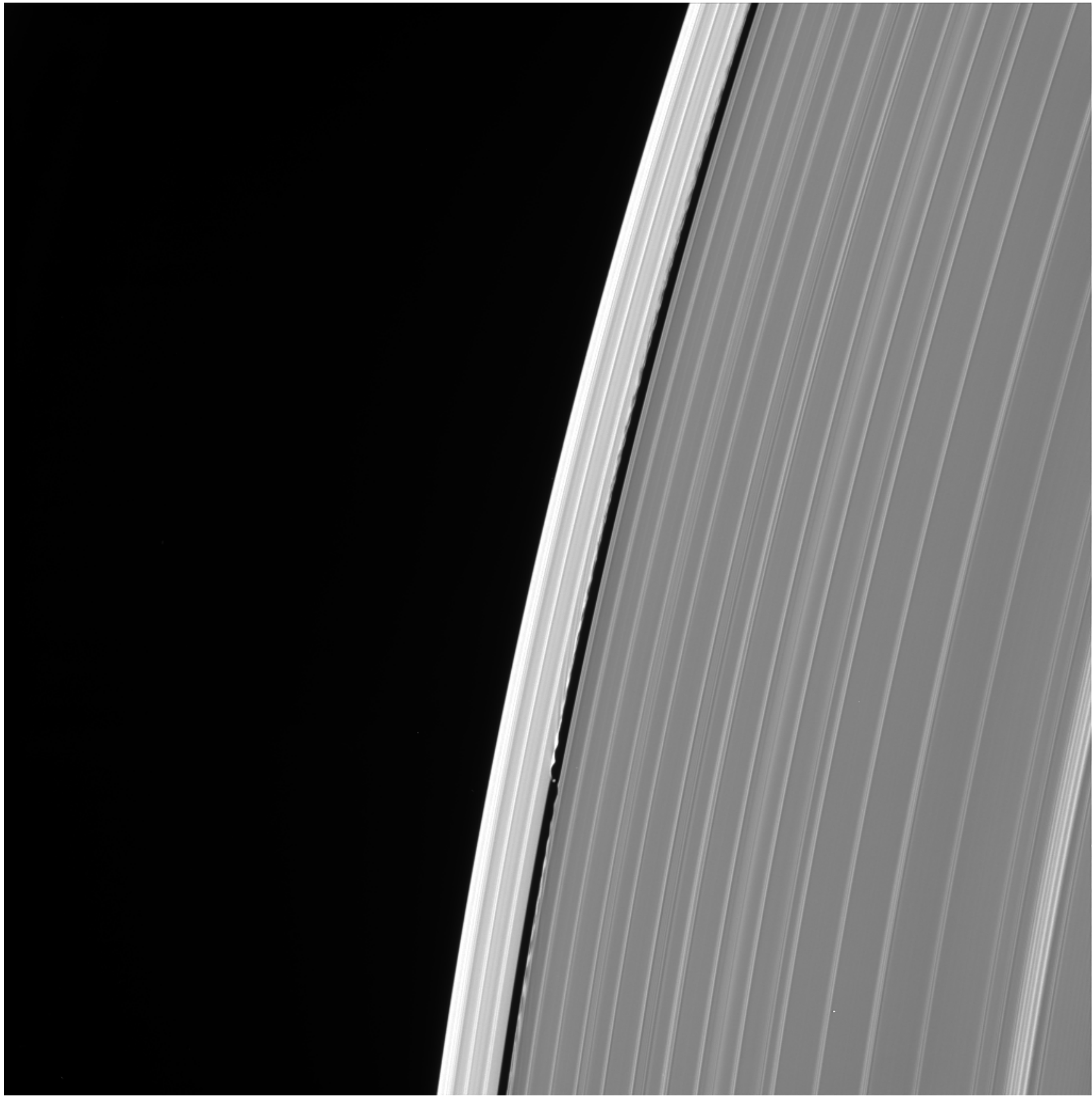
Some of *Cassini*'s final images:

Saturn before the plunge



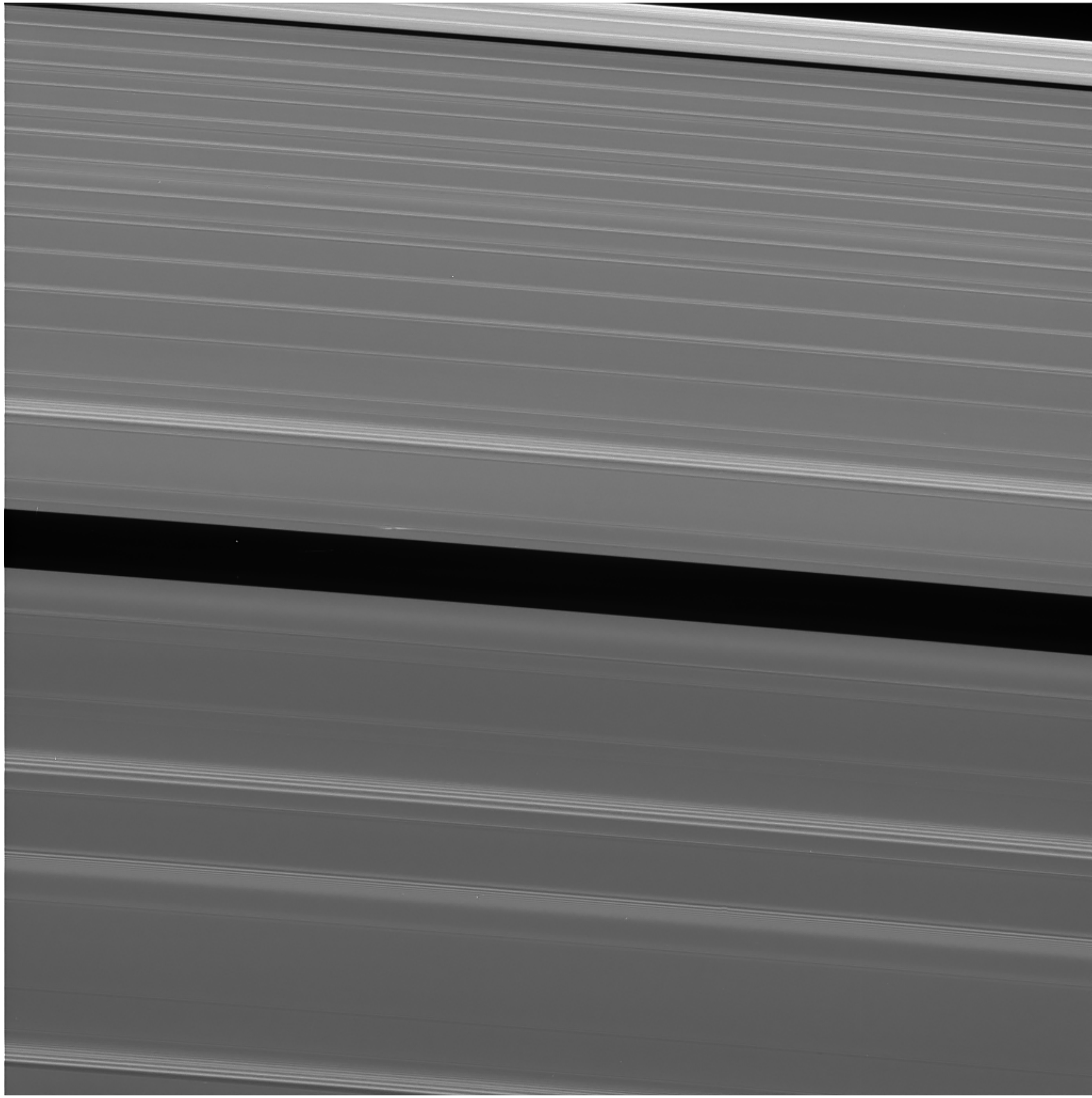
Some of *Cassini*'s final images:

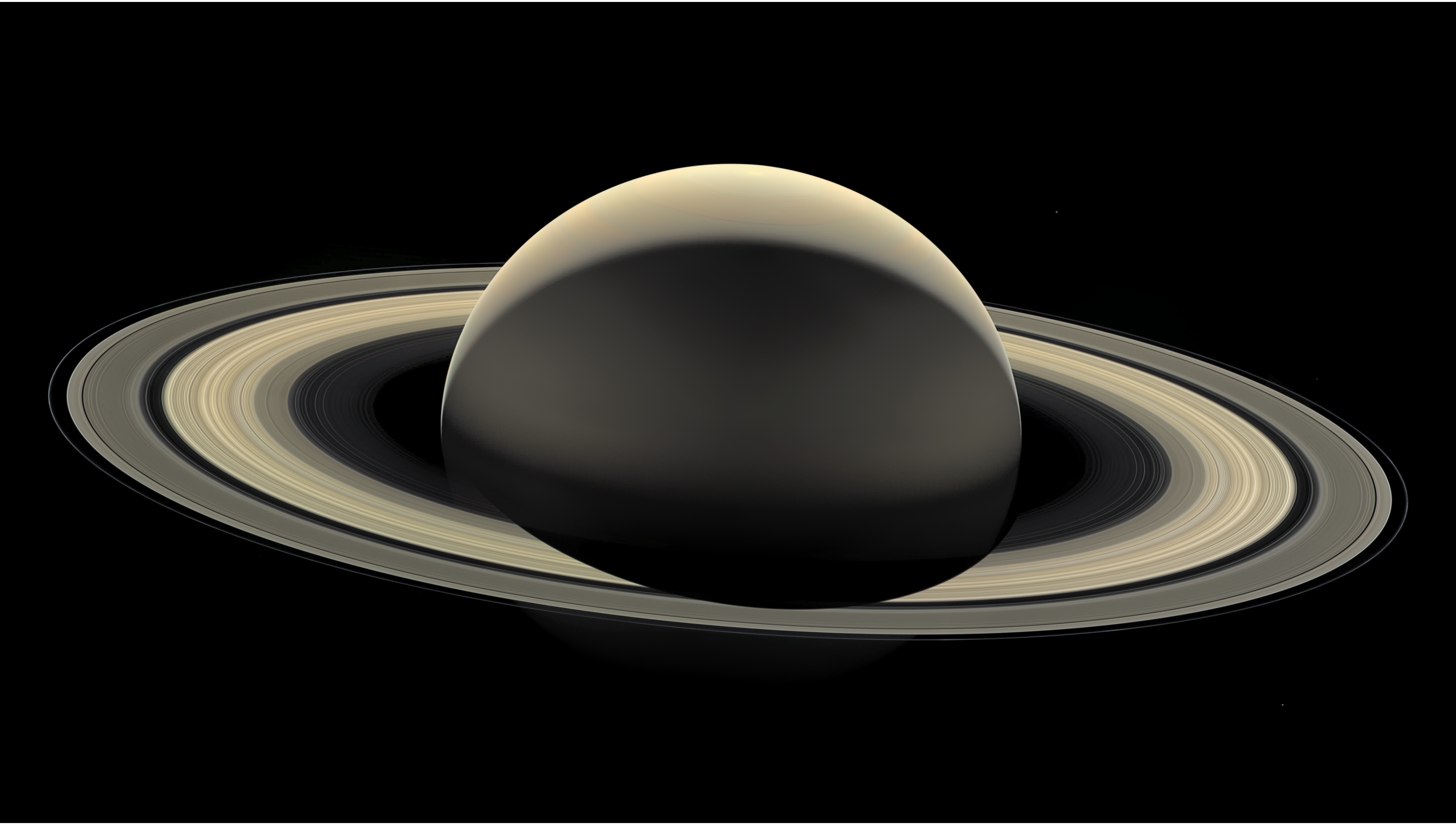
Daphnis and its waves



Some of *Cassini*'s final images:

A lone propellor in the A ring





Next week

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

Further reading

I haven't read any good popular books with results from *Cassini* yet: we're going to have to wait a few years before we get one of those.

- "**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. They're all from early in the *Cassini* mission; it would be good to see an update with later images.
- 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* Hall of Fame: http://saturn.jpl.nasa.gov/photos/halloffame/
- NASA has produced a free e-book called "The Saturn System Through the Eyes of *Cassini*", available at https://www.nasa.gov/connect/ebooks/the-saturn-system.html
- And another beautiful set of images: http://ciclops.org/view_event/108/In_Celebration_of_Galileo

- Alan Taylor – the same chap who made the “All Solar System Bodies” image I recommended – 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
- Several articles discussing Robin Canup’s model for the formation of the rings: http://www.universetoday.com/75071/saturns-rings-formed-from-large-moons-destruction/ and http://www.space.com/10468-saturn-rings-remains-ripped-moon.html
- We didn’t have time to discuss Iapetus in much detail, but there’s a fascinating talk by Hal Levison, with more great images, at http://www.boulder.swri.edu/~hal/talks/iapetus/DDA/iap000.html
- 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

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