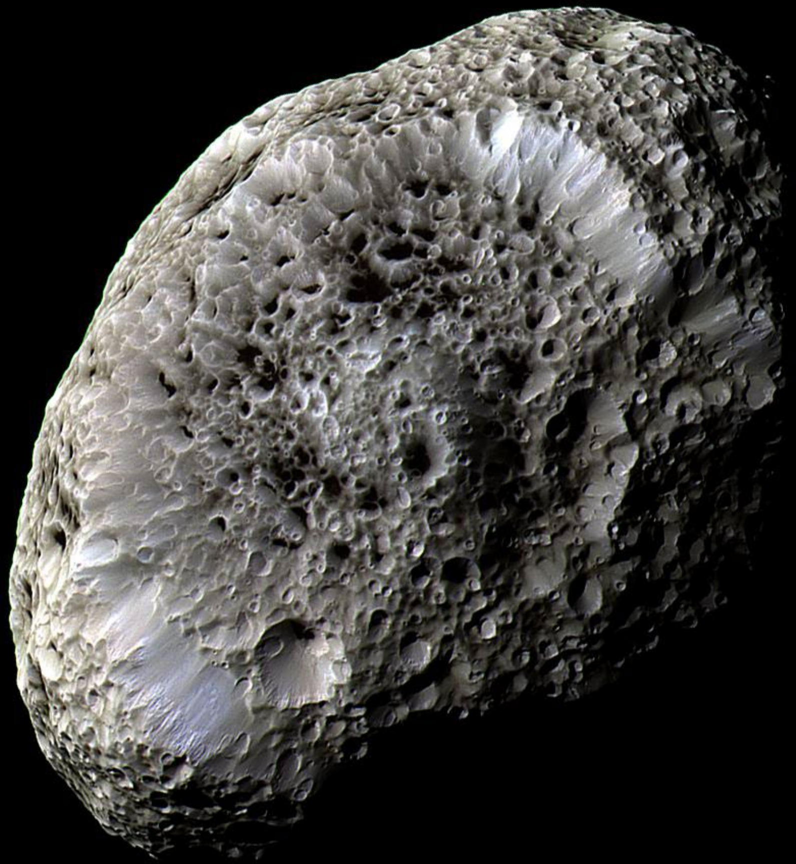
Today in Astronomy 111: the moons of Saturn, Uranus and Neptune

- Names
- General features: structure, composition, orbits, origins
- Special moons
  - Mimas
  - Titan
  - Enceladus
  - Iapetus
  - Miranda
  - Triton



No, it's not a sponge, or a coral, but Hyperion (Saturn VII), seen from Cassini (JPL/NASA).

Planetary and lunar nomenclature

- **Jupiter's** moons are named after the mythological girlfriends and boyfriends of Zeus, but are given their Greek, rather than Latin, names.
    - This tradition was started by Simon Mayer, who discovered the first four moons independently of Galileo but a few days later. Galileo tried to call them "Siderea Medicea", in (successful) hope of Cosimo II's patronage.
- **Saturn's** moons are named after other Titans: the giant Greek deities of Saturn's generation, who, despite having eaten Zeus's generation, were displaced violently by Zeus and his siblings.
    - Saturn (= Kronos) was Jupiter's (= Zeus's) father; for the former and part of the latter, see next page.
    - Giovanni Cassini – whose many discoveries include Dione, Tethys, Rhea and Iapetus – tried unsuccessfully to get these four and Titan named "Siderea Lodoicea" in honor of his patron King Louis XIV of France.
        - Titan itself was discovered, but not named, by Christiaan Huygens. IDK how Galileo could have missed it.
    - John Herschel preferred the Titans to Louis; these names, first used in the mid-1800s, have stuck.
        - John was the son of William Herschel – whose many discoveries include Mimas and Enceladus – and nephew of William's sister Caroline Herschel, the first woman to become a professional astronomer.

Francisco Goya,
Saturno devorando a su hijo (1823),
Museo del Prado

Planetary and lunar nomenclature (continued)

- Soon after the *Voyager* missions, we ran out of Greek Titans. Since then, giants from Norse, Celtic and Inuit mythology have served for new discoveries in the Saturn system – when they're named at all.

- **Uranus's** moons are named after (usually) magical characters in Shakespeare's comedies, with the exception of Umbriel and partial exception of Ariel, magical characters in Alexander Pope's *The Rape of the Lock*.
  - Uranus himself – same in Greek and Latin – was the father of Saturn/Kronos.
  - Johannes Bode, first to measure its orbit to be is nearly circular and thus not cometary, named the planet.
    - But not before the planet's discoverer William Herschel tried unsuccessfully to get the new planet named "Sidus Georgium" after King George III of Britain.
    - George III is reviled in the USA for good reasons. But he contributed hugely to astronomy by hiring the Herschel siblings as court astronomers, relieving them of the necessity to support themselves with a millinery business, and by working as a church organist (William) and singer (Caroline).
  - John Herschel chose Shakespeare's Oberon and Titania for the two his father discovered, and Pope's Umbriel and Ariel for the two discovered by William Lassell. Kuiper chose to continue the first theme, with Miranda.

Planetary and lunar nomenclature (continued)

- The moons of **Neptune** (= Greek Poseidon) are given the Greek names of children or attendants of Poseidon.
  - The moon-naming tradition was begun by Camille Flammarion in the late 1800s.
    - William Lassell discovered, but did not name, Triton, about two weeks after the planet was discovered. That's why one of Neptune's rings is named in his honor.
  - As for the planet, the theme of the Greco-Roman sea god was Urbain LeVerrier's idea, but was a second choice, under international pressure, apparently supported by its blue color.
    - Johann Galle, the discoverer of Neptune, tried to get the planet named "Janus," after the two-faced beginnings/transitions god of Roman mythology.
    - LeVerrier, who had correctly predicted its position for Galle, had first tried to get it named after himself, getting the French Academy to acquiesce to the extent of referring to Uranus as "Herschel" for a while.
    - Only bad luck prevented Galileo from discovering Neptune. Wonder what he would have called it.
- See here for more details of Solar system names.

General features of the outer-planet moons

- There are lots of them: currently Saturn is known to have 146, Uranus 27, and Neptune 14, of which 8, 5 and 1 are considered Major or **regular**, the rest Lesser or **irregular**.
- The major moons are all very icy. Almost all of their bulk densities are below those of the Galilean moons. Some are differentiated, e.g. Titan ($I = 0.341MR^2$, Iess et al 2010); some depart enough from hydrostatic shapes that it is hard to determine their inertial moments from their gravity, e.g. Enceladus (McKinnon 2015).
- The major moons are in low-eccentricity, low-inclination orbits, and rotate synchronously with their revolution.
  - All but Triton have prograde orbits and rotation. They probably formed with the host planet.
  - Triton is major but irregular. Its rotation is synchronous with its revolution but its orbit is retrograde (see Homework #10, problem 1).
  - Thus **Triton did not form with Neptune**.
- Inner, irregular moons tend to be closely associated with the rings, and tend to be similar in composition to the rings.
  - Very icy in Saturn, not quite so icy in the others.

General features of the outer-planet satellites (continued)

- Outer, lesser moons are all small, and tend to be substantially darker (less surface ice) than the regulars or inner-lessers.

- Outer-lessers also tend to have eccentric, highly inclined orbits, as often retrograde as prograde.
  - As it is for Jupiter's outer-lesser, these are probably captured asteroids, comets, or **trans-Neptunian objects.** They formed elsewhere, separately from the host planet,.

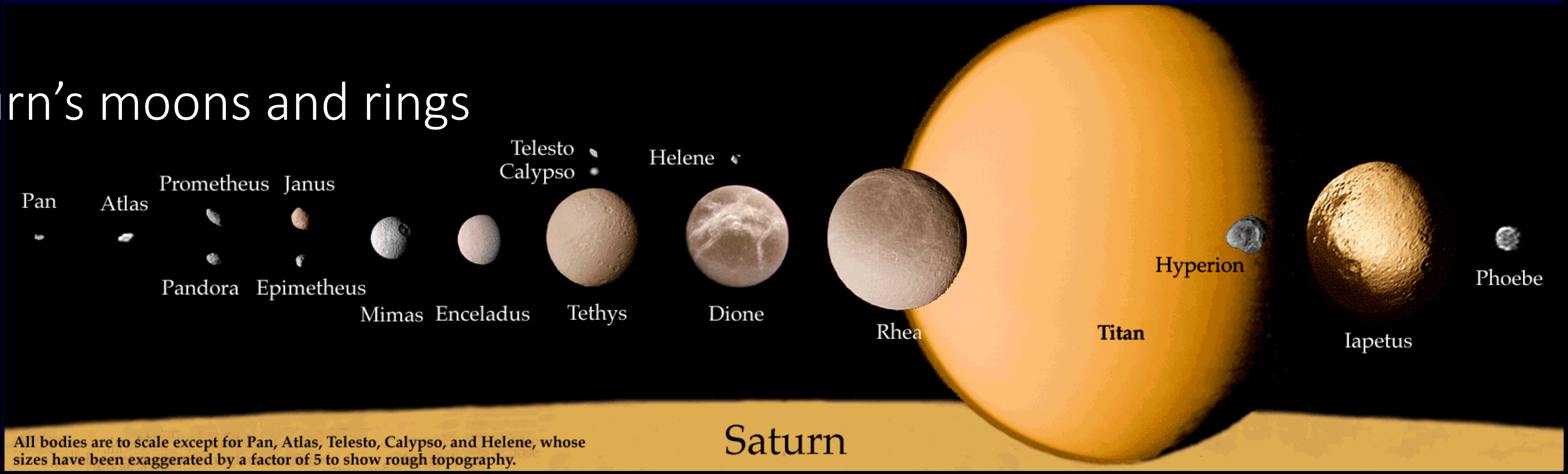
- Strong mean-motion resonances among the orbits are common. (See Homework #9, problem #2.)
  - Which raises the spectre of tidal heating for the larger, innermost ones.

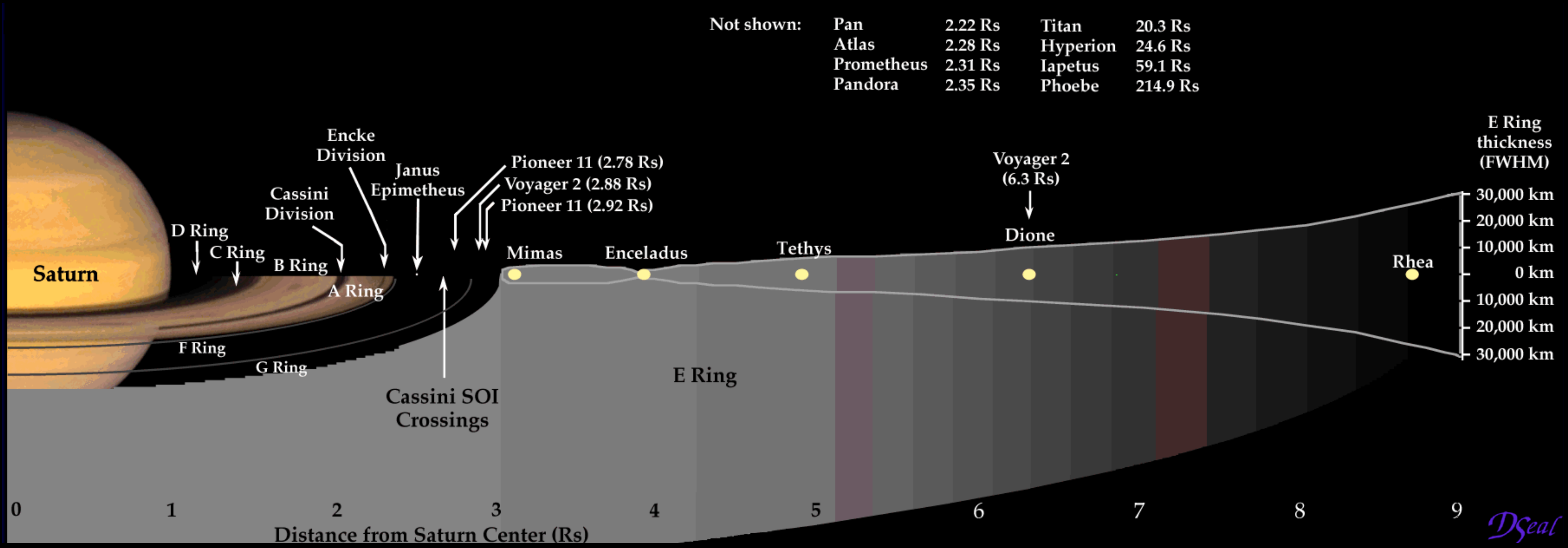
The major moons of Saturn, Uranus and Neptune

	Mass 10^{23} gm	Radius 10^{5} cm	Bulk density gm cm^{-3}	Visual geometric albedo	Orbital semimajor axis 10^{8} cm	Orbital semimajor axis Planet radii	Orbital period days	Orbital obliquity degrees	Orbital eccentricity
Mimas (SI)	0.379	209x196x191	1.15	0.6	185.52	3.0783	0.942422	1.53	0.0202
Enceladus (SII)	1.08	257x251x248	1.61	1	238.02	3.9494	1.370218	0.00	0.0045
Tethys (SIII)	6.18	536x528x526	0.99	0.8	294.66	4.8892	1.887802	1.86	0.0000
Dione (SIV)	11.0	563x561x560	1.48	0.7	377.40	6.2620	2.736915	0.02	0.0022
Rhea (SV)	23.1	765x763x762	1.24	0.7	527.04	8.7449	4.517500	0.35	0.0010
Titan (SVI)	1345.52	2574.73	1.88	0.22	1221.83	20.2730	15.945421	0.33	0.0292
Hyperion (SVII)	0.056	180x133x103	0.55	0.3	1481.10	24.5750	21.276609	0.43	0.1042
Iapetus (SVIII)	18.1	746x746x712	1.09	0.05/0.5	3561.30	59.0910	79.330183	14.72	0.0283
			Porous?						
Miranda (UV)	0.66	240x234.2x232.9	1.20	0.32	129.9	5.082	1.413479	4.34	0.0013
Ariel (UI)	12.9	581.1x577.9x577.7	1.59	0.39	190.9	7.469	2.520379	0.04	0.0012
Umbriel (UII)	12.2	584.7	1.46	0.21	266.0	10.41	4.144176	0.13	0.0039
Titania (UIII)	34.2	788.9	1.66	0.27	436.3	17.07	8.705867	0.08	0.0011
Oberon (UIV)	28.8	761.4	1.56	0.23	583.5	22.83	13.463234	0.07	0.0014
Triton (NI)	214.0	1,353.40	2.05 (!!)	0.72	354.76	14.328	-5.876854 Retrograde	157.345 -22.65 (!!)	0.000016

All but Triton are regular. From the NSSDC Saturnian, Uranian and Neptunian Satellite Fact Sheets.

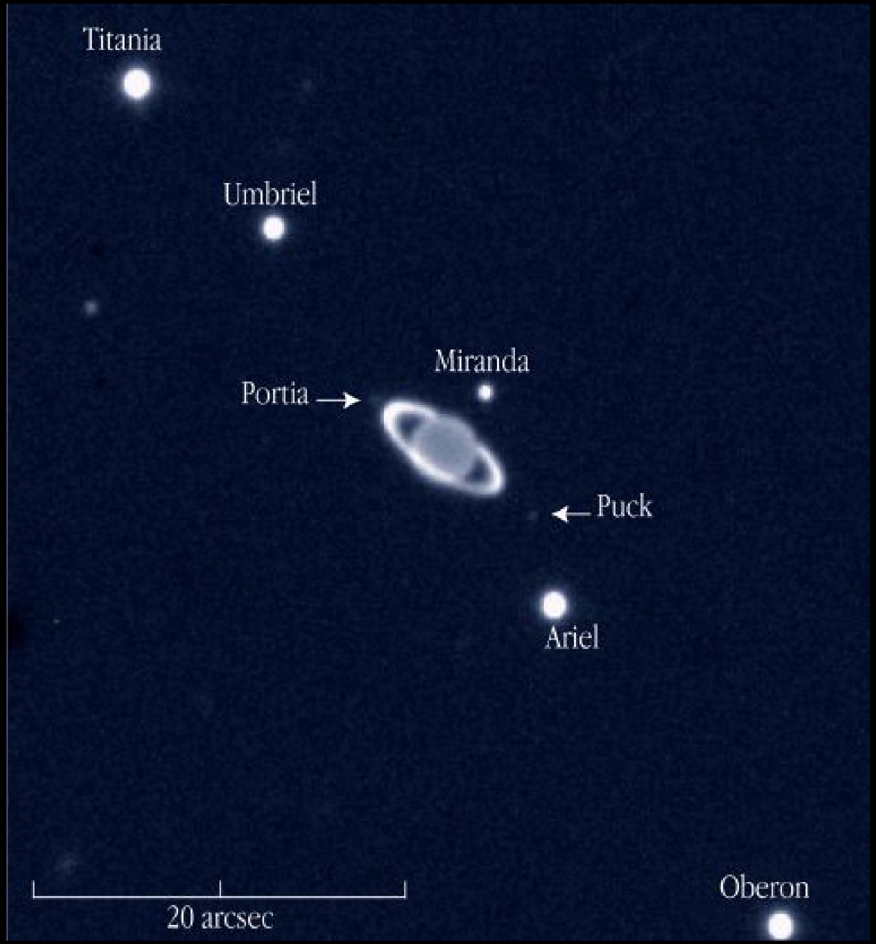
Saturn’s moons and rings





Cassini/JPL/NASA

Family portrait of the Uranian system



Uranus and several of its moons, in the infrared at 2.17 μm wavelength, by E. Lellouch et al. with the ESO VLT Antu telescope (left); the moons at closer range, on a common scale, and as seen by Voyager 2 (JPL/NASA)(right).

Special moons: Mimas

Mimas, at the inner edge of the E ring, is involved in many important orbital resonances.

- Notably with the rings, e.g. the Cassini division.
- Its most famous feature is the gigantic crater Herschel. The impact that created Herschel must have come close to destroying the moon. (Note the central peak.)
- Its resemblance to the Death Star in *Star Wars* is accidental. The movie came out a few years before the Voyagers got to Saturn.

Cassini/JPL/NASA

Special moons: Mimas (continued)

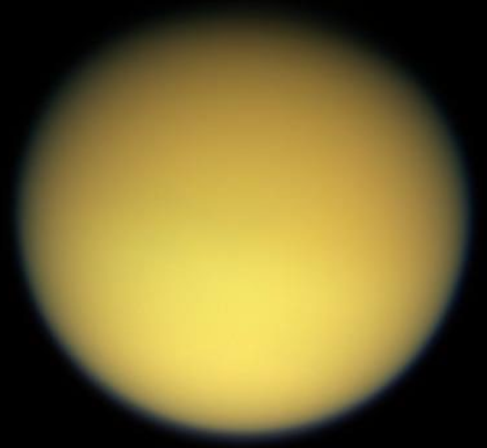
- Even apart from Herschel, Mimas is much more heavily cratered than is usual in the Saturnian system.
  - Similar to Iapetus and Hyperion in this regard.
  - Why it is not heated sufficiently to be resurfaced like Io or Europa is a mystery (see Homework #9) ...
  - though there are some non-mysterious explanations that sorta work (Rhoden & Walker 2022).

Flying over Mimas (Cassini/JPL/NASA)

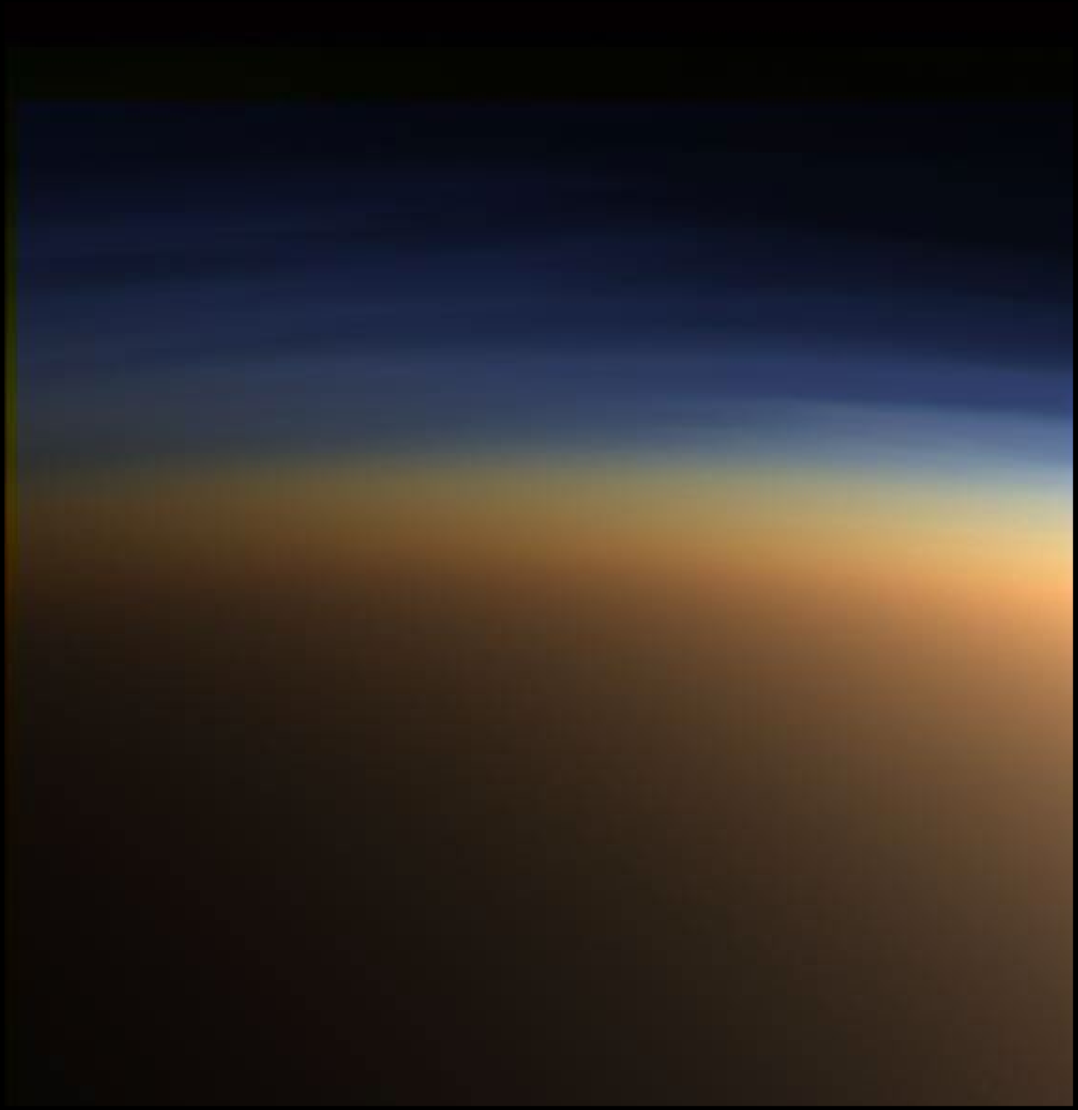
Special moons: Titan

Titan is the second largest moon in the Solar system – slightly smaller than Ganymede – and the first one discovered after the Galilean moons, by Huygens in 1665. It is unusual in many respects:

- It is the only moon in the solar system with a dense atmosphere:
  - Pressure about 1.6 Earth atmospheres at the surface, 95% nitrogen (most of the rest is ammonia) …
  - … so heavily laden with photochemical smog that the surface can't be seen at visible wavelengths.



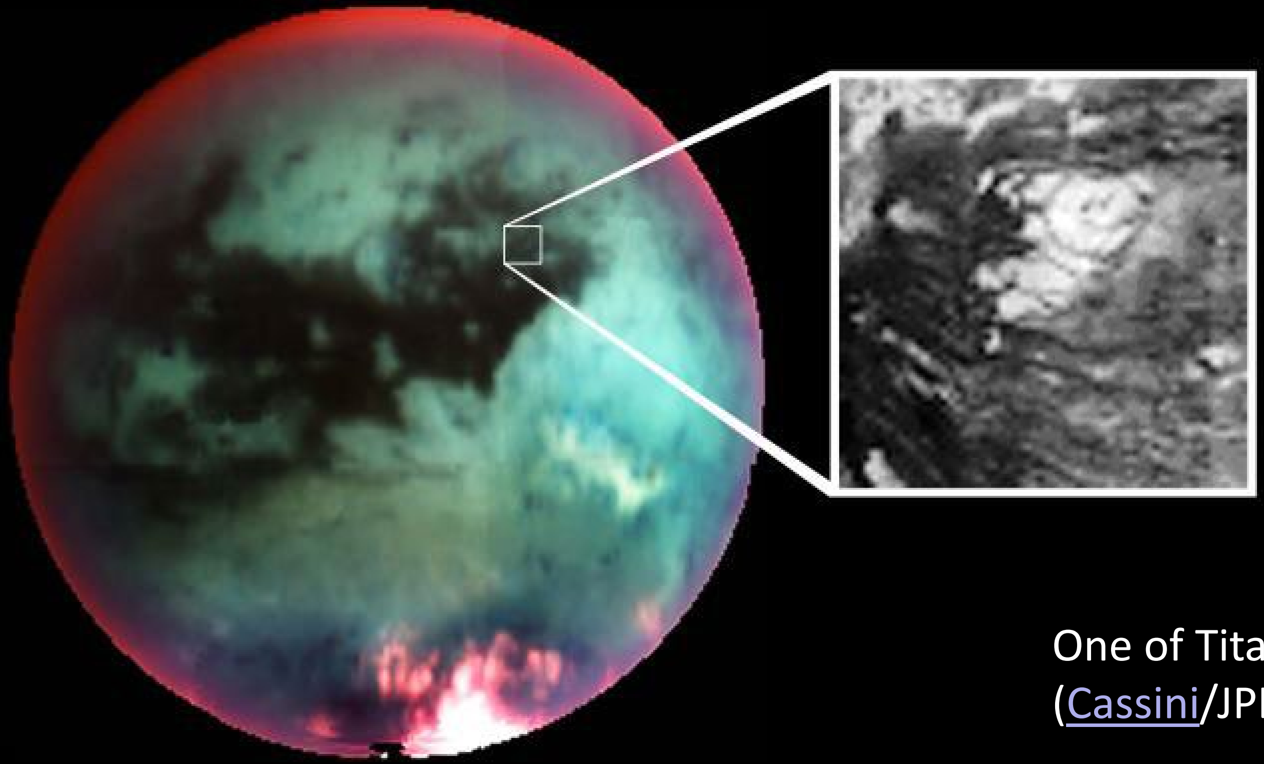
Special moons: Titan (continued)



Haze in Titan’s upper atmosphere, and photochemical smog below (*Cassini/ JPL/ NASA*).

Special moons: Titan (continued)

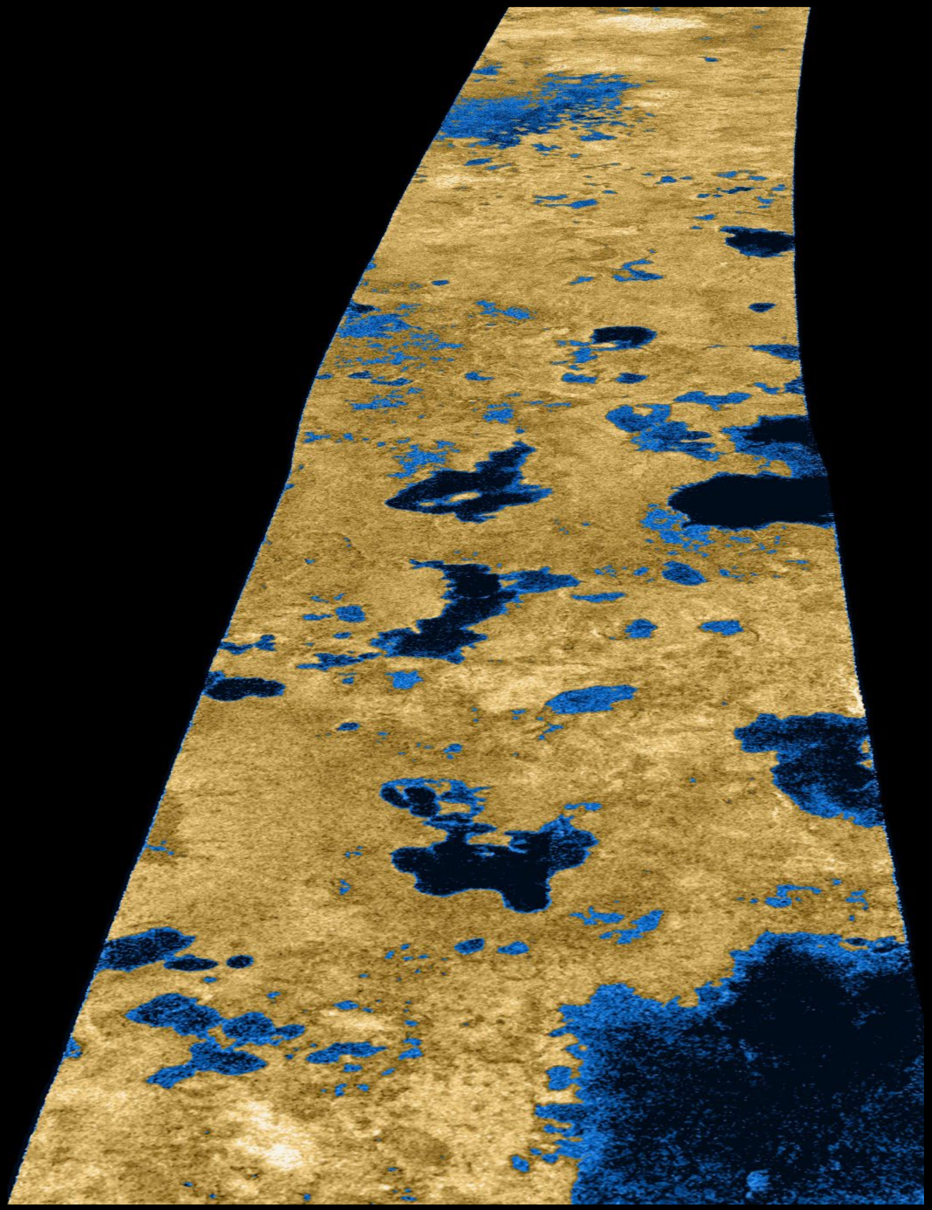
- There are few impact craters apparent in infrared and radar images on the surface of Titan, and much evidence of **cryovolcanism,** involving molten ices instead of molten rock.



One of Titan's cryovolcanoes
(Cassini/JPL/NASA)

Special moons: Titan (continued)

- Titan is the only Solar-system body besides Earth to have liquids permanently resident on its surface.
  - Lakes are all over the place. They are somewhat easier to see near the poles.
    - Best observed by Cassini’s radar: the reflection from a smooth liquid surface is distinctive in radar images, as also is true on Earth.
  - They are full of rather pure liquid ethane and methane …
    - … enabling these contents to be identified unambiguously in multifrequency radar, and
    - also enabling the depth of the lakes to be measured.

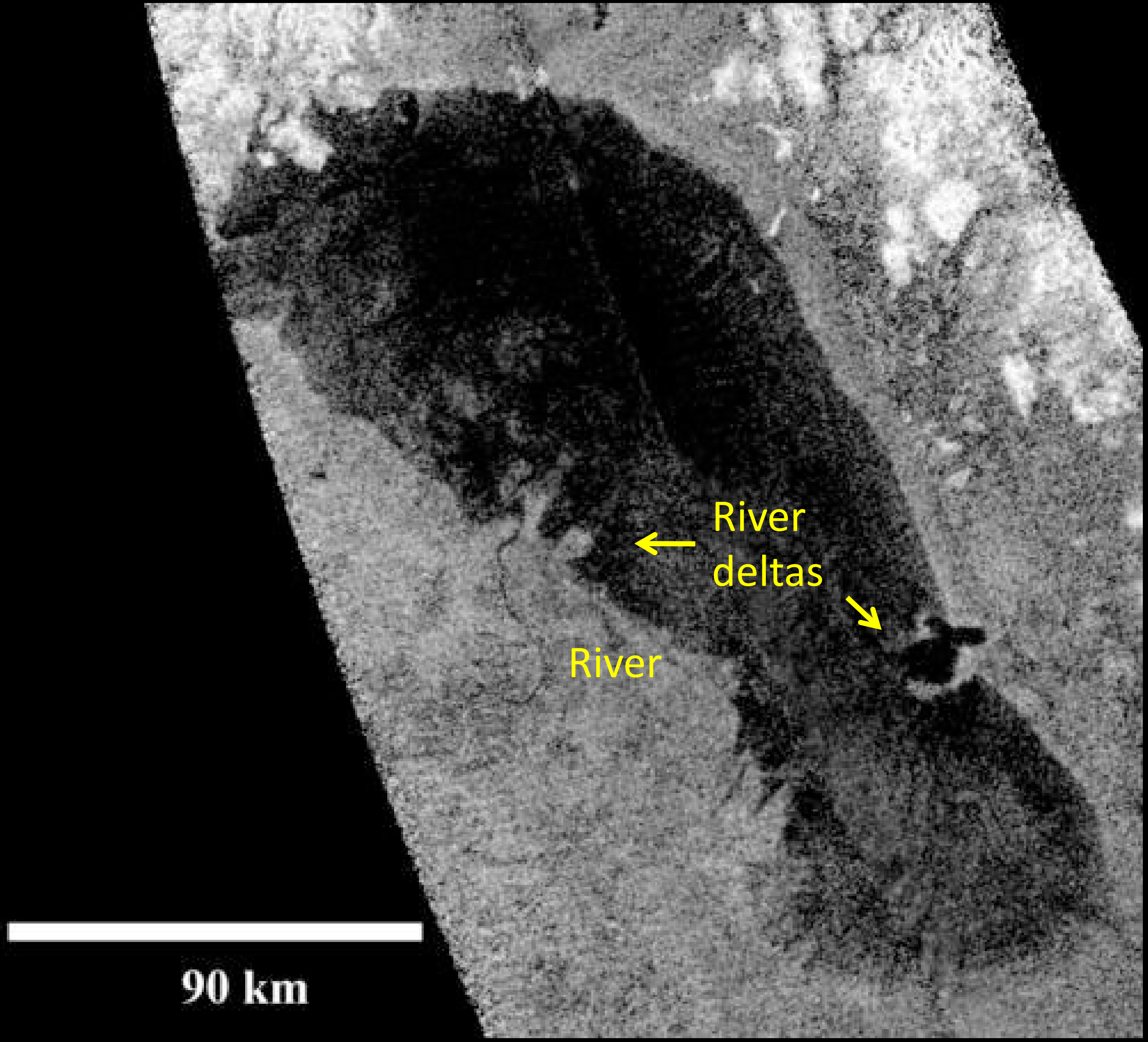


Cassini/JPL/NASA

Special moons: Titan (continued)

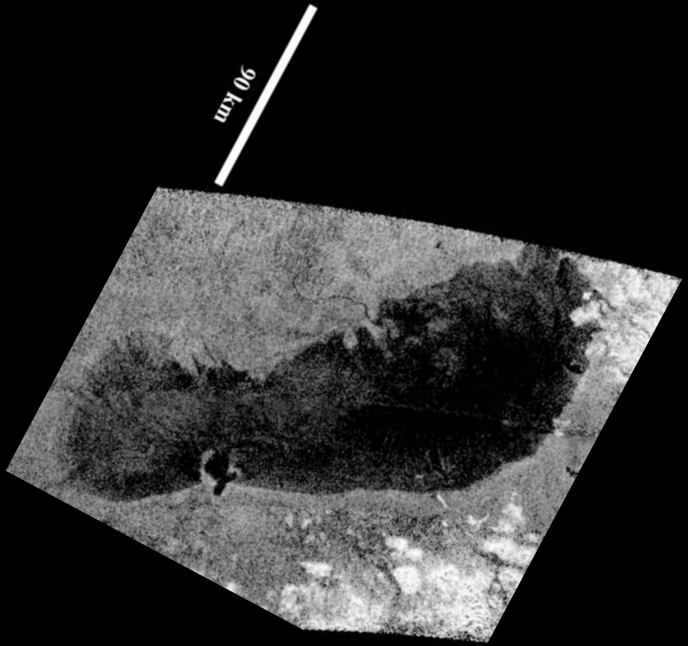
- The lakes change in depth over time.
- They are fed by rivers with deltas.
  - Here for example is Ontario Lacus, near the south pole of Titan.
  - Note the rivers.

    I suppose one of them should be called “Niagara amnis.”



Cassini/JPL/NASA

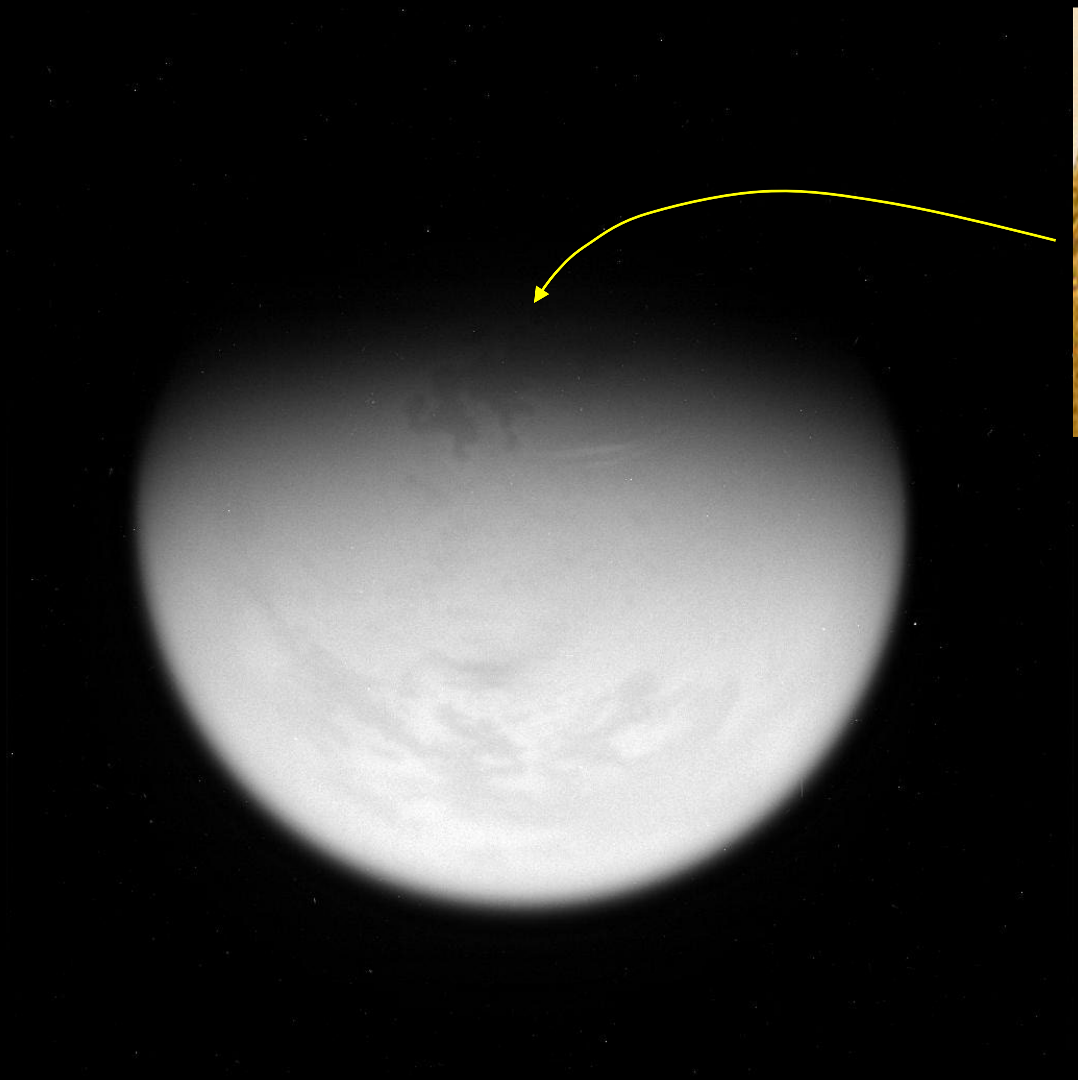
Special moons: Titan (continued)



Ontario Lacus (left) and Lake Ontario (right), shown on the same scale.

Cassini/JPL/NASA

Special moons: Titan (continued)

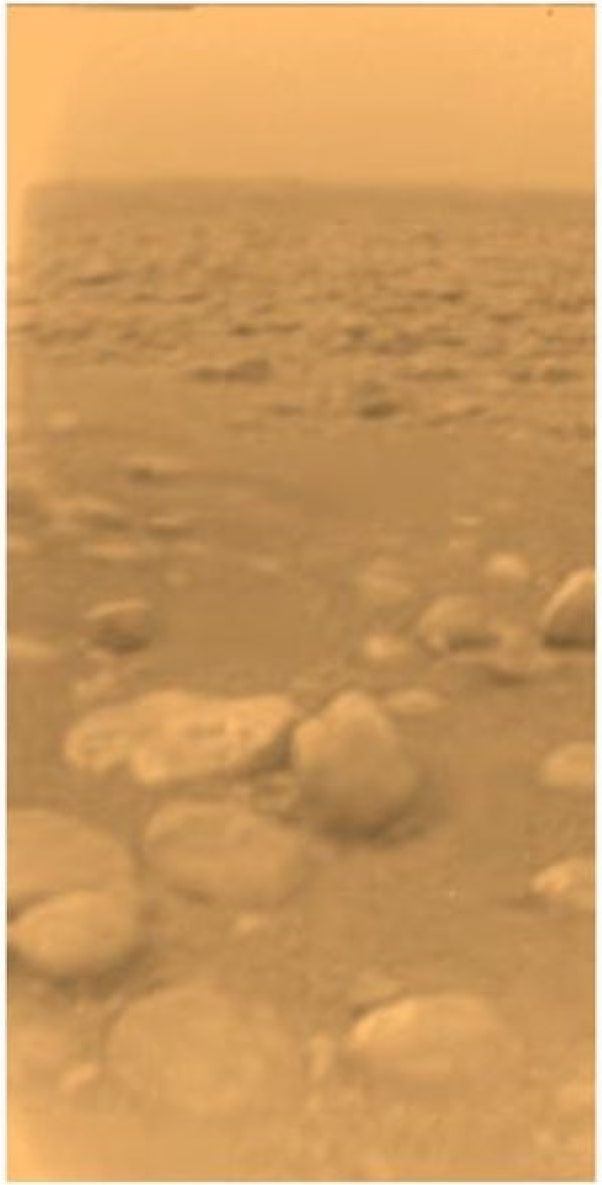


Titan's north-polar great lake Ligeia Mare (Cassini/ JPL/NASA), left, and its northern lobe on the same scale as Lake Superior, above.

Special moons: Titan (continued)

- And we have visited the surface:

  Cassini dropped a lander – named Huygens – which safely penetrated the atmosphere, landed softly, and continued to send back images for hours before it finally froze.



View from Huygens after landing (ESA/ISA/NASA). The bigger rocks in the foreground are about six inches (15 cm) across.

Special moons: Enceladus

Enceladus has the highest albedo in the Solar system, very close to 1.

- So it must be covered in clean water ice, with a smooth surface.
- Indeed, the surface is smooth: not many impact craters, lots of thin cracks and fissures.
- At close range it displays an Arctic pack-ice-like appearance.

Cassini/JPL/NASA

Special moons: Enceladus (continued)

- So the surface of Enceladus is very young. This requires heat sufficient to melt water ice, and a means to distri-bute it over the surface.
- By the E ring's structure and the moon's position within it, Enceladus has also been identified as the major source of this ring's ice particles.
- Precisely how the ring is produced, was obscure until…

Cracked craters on Enceladus (Cassini/JPL/NASA).

Special moons: Enceladus (continued)

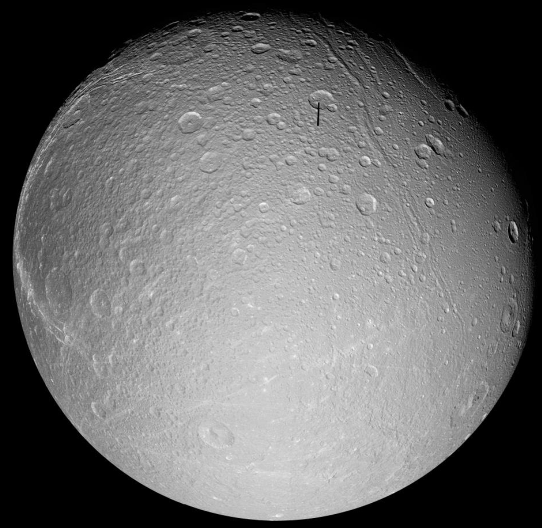
- …the close flybys by *Cassini* in 2005, in which the cryovolcanism that explains both the young surface and the E ring were first seen.
  - The details are still a little obscure, because although Enceladus experiences significant tidal stretching in the Saturn system, it gets tidally stretched only about half as much as Europa, as you will show in Homework #8.

Cassini/JPL/NASA

Special moons: Iapetus

A few of Saturn's moons have broad light or dark streaks across large fractions of their surfaces.

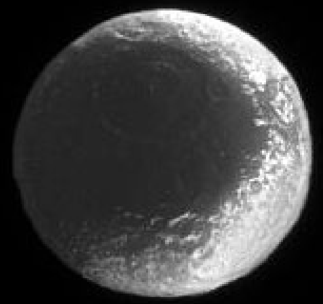
- This is probably from picking up ring or outer-satellite debris, or splashes from surface impacts.
  - At right: the leading (top) and trailing (bottom) hemispheres of Dione (Cassini/JPL/NASA). Tethys and Rhea have similar features
- The most extreme of these is Iapetus.
  - Iapetus is the outermost of Saturn's major satellites, and the one featured in *2001: A Space Odyssey* (the book; it was transplanted to Jupiter for the movie).



Special moons: Iapetus (continued)

Upon discovering the moon we now call Iapetus, Giovanni Cassini remarked that it is only visible when on one side of Saturn.

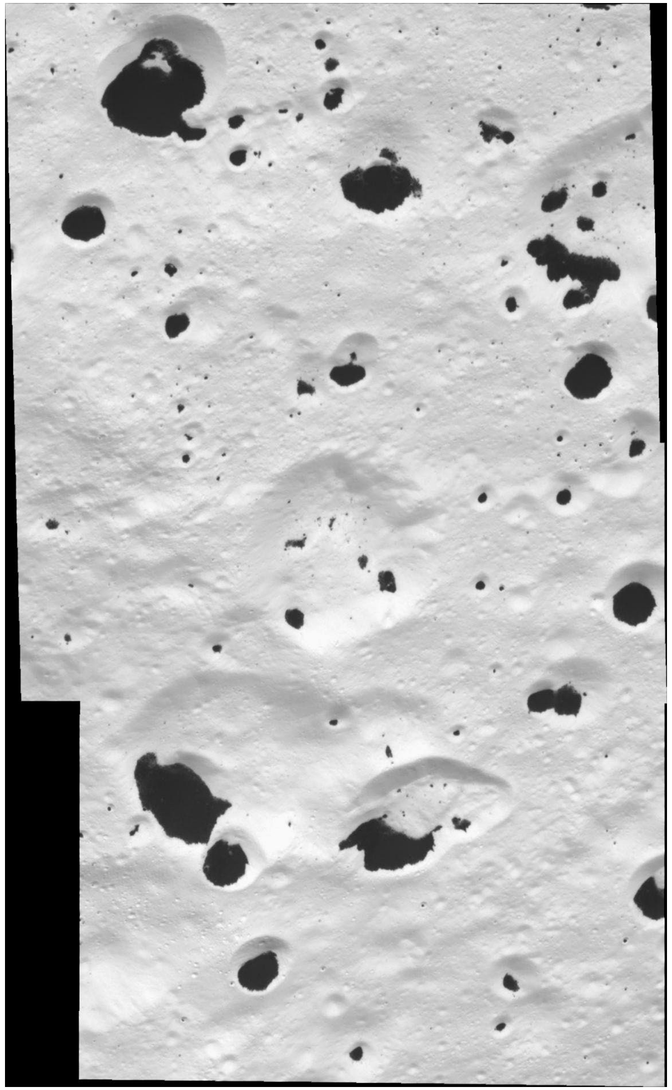
- Thus he reasoned that the moon had one dark hemisphere, and one light-colored hemisphere.
- He turned out to be right. Iapetus's **leading** hemisphere has an albedo of only about 0.05; the **trailing** hemisphere, the usual 0.5 characteristic of ice.
- Infrared spectra show that the dark side is rich in carbonaceous compounds.



Dark (leading) and bright (trailing) hemispheres of Iapetus from Cassini/JPL/NASA

Special moons: Iapetus (continued)

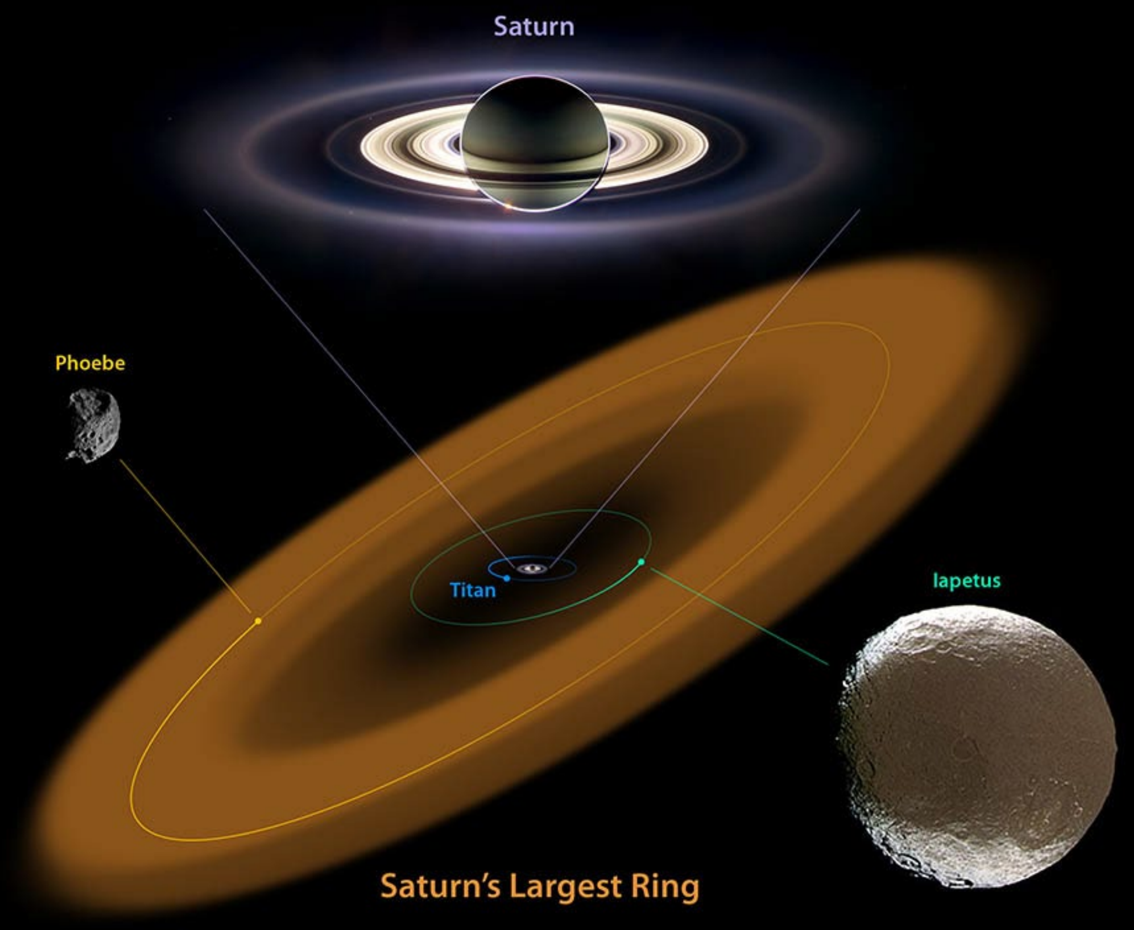
- Images taken in *Cassini* flybys make it clear that the leading hemisphere has a relatively thin coating of dark material that the trailing hemisphere lacks.
  - Near the edge between them, crater floors and slopes facing the dark side show up through the ice as dark patches.
- Is this a thin, loose coating of asteroid-like debris, swept up in orbit?



Cassini/JPL/NASA

Special moons: Iapetus (continued)

- In 2009, the source of the dark material was found: the Phoebe Ring.
  - Iapetus lies near its inner edge.
  - Retrograde Phoebe and its ring particles orbit in the direction opposite prograde Iapetus.
  - Phoebe itself is the source of the ring, and is made of very dark material, as befits a captured asteroid.

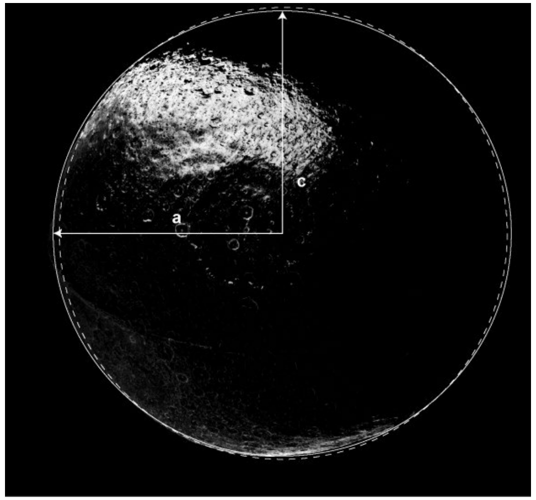


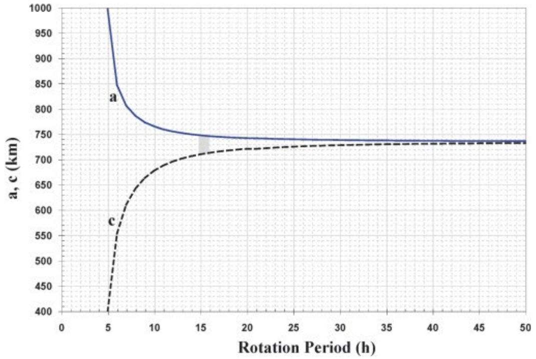
Verbiscer, Skrutskie & Hamilton 2009

Special moons: Iapetus (continued)

But Iapetus's list of distinctive features does not stop there.

- It rotates synchronously– period 79.3 days – but, unlike all of the other regular satellites of Saturn and Jupiter, Iapetus (solid curve) is more oblate than can be consistent with its current rotational period (dashed curve).
    - Oblate = bulging at the equator, flattened at the poles.
- Thus it must have been spinning much faster than synchronously – period 16 hours – when its lithosphere solidified.

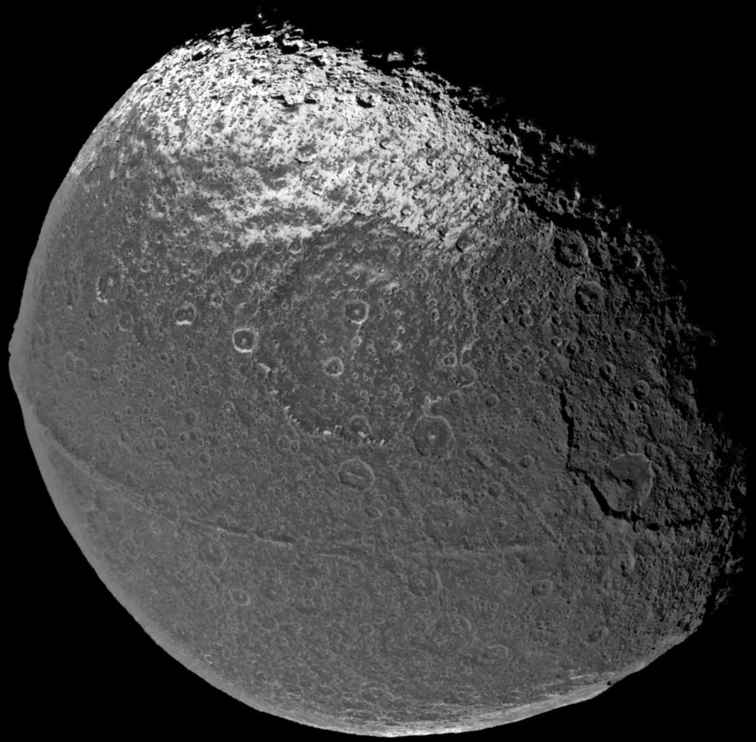


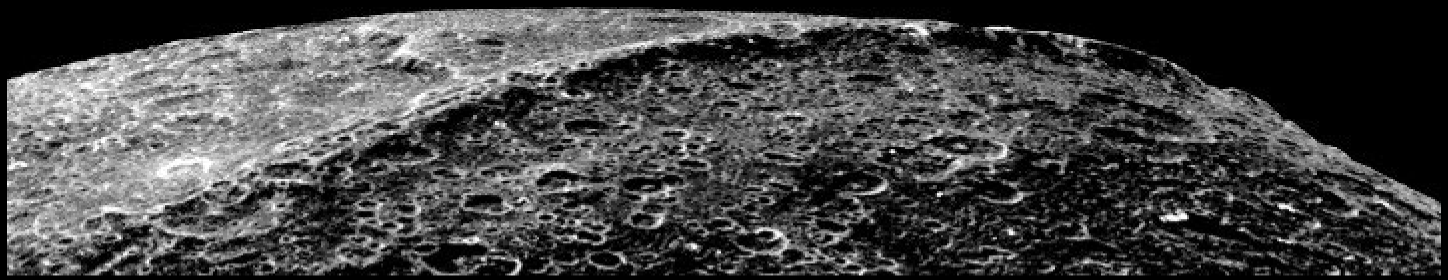


Castillo-Rogez et al. 2007

Special moons: Iapetus (continued)

- It also has a prominent mountain ridge that runs all the way around its equator, making it look something like a walnut.
- In spots this ridge has long parallel, equatorial cracks in it.





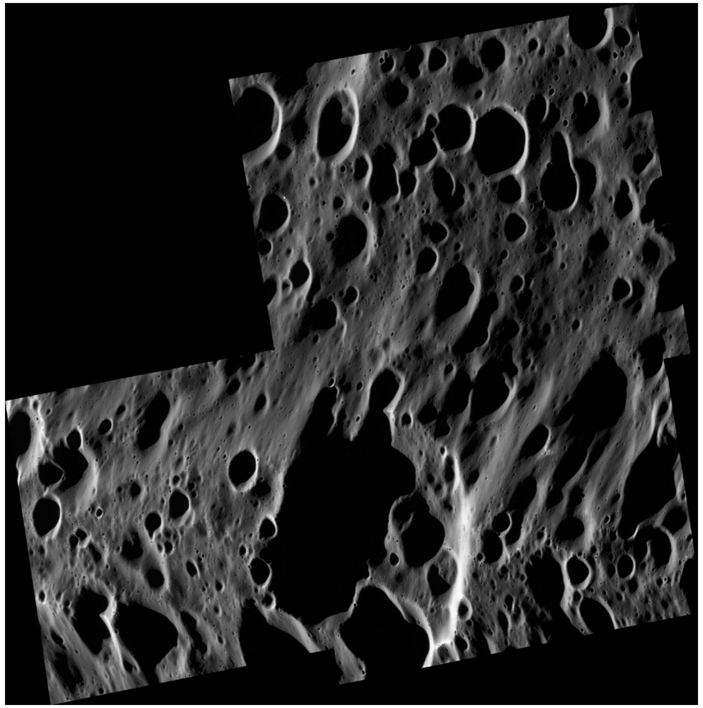
Cassini (above) and Porco et al 2005 (left). See also here for a 3D view.

Special moons: Iapetus (continued)

- A detailed model (Castillo-Rogez et al. 2007) can explain Iapetus's shape and ridge, quantitatively and precisely:
  - The moon forms in orbit around Saturn, in a porous state, by accretion of smaller particles.
  - Radioactivity from short-lived species (^{26}Al, ^{60}Fe) melts ices in the interior.
    - Porosity decreases as gravity compresses the partially-molten interior.
    - Mismatch between new surface area and volume nicely accounted for by that of the ridge. (!!)
  - Melted ices – water with a little ammonia – have very high thermal conductivity by moon-interior standards, causing the outer layers of the moon to cool very rapidly.

Special moons: Iapetus (continued)

- Cooling so rapidly – within about 100 Myr – a thick, strong lithosphere forms.
  - The crust solidifies while the moon is still spinning much faster than it orbits …
  - … both freezing in the rapid-spin oblateness,
  - and comprising a strong, thick place that can preserve heavy cratering from the earliest years of the moon's life.
- Over a much longer time (200-900 Myr), tidal torques spin Iapetus down to its present synchronous rotation.



Cassini/JPL/NASA

Special moons: Iapetus (continued)

- What's interesting in all this is that
  - the successful models **require** that Iapetus formed in orbit around Saturn, and while there were still lots of short-lived radionuclides around.
  - Notably ^{26}Al, which has a halflife of only 0.7 Myr and contributes lots of heat, as we saw in lecture on 17 October 2024.
  - By "lots" is meant that Iapetus has to have formed within 3.5-7 ^{26}Al halflives of the formation of the oldest solid meteoritic particles.
- This in turn requires that **Saturn itself formed between 3 Myr and 5 Myr after the Sun** (Castillo-Rogez et al 2009).
  - Before 2004 it was thought to take much longer than this to form a giant planet, but this time scale is also supported by observations of giant-planet formation in young protoplanetary disks, as we will see.

Special moons: Miranda

Miranda, discovered in 1948 by Gerard Kuiper, is neither very large nor very close to Uranus, but has one of the most geologically-active-looking surfaces in the Solar system, complete with enormous fault scarps, canyons and grabens, mountains and plate boundaries.

- Miranda does turn out to be locked in a 3:1 mean motion resonance, with the (inner) minor satellite Desdemona.

- Even so, it would seem difficult to drive such violent-looking activity with tidal heating, but that is the means most often suggested for the generation of such terrain.

Voyager 2/JPL/NASA

Special moons: Triton

Triton is Neptune's only major moon, 200 times more massive than the sum of the rest, twice the mass of Pluto, and just a little smaller than Europa.

It has four unusual features:

- **Retrograde orbit**. It is very hard to understand how it could have formed near Neptune in this orbit; it must have been captured.
  - Tidal torques will cause the orbit to decay; Triton will hit the Roche limit in about 3.6 Gyr. (See Homework #10.)
- A tenuous **atmosphere** (P = 10^{-6} bar), mostly composed of nitrogen, methane and ammonia.

  This is probably a secondary atmosphere from...

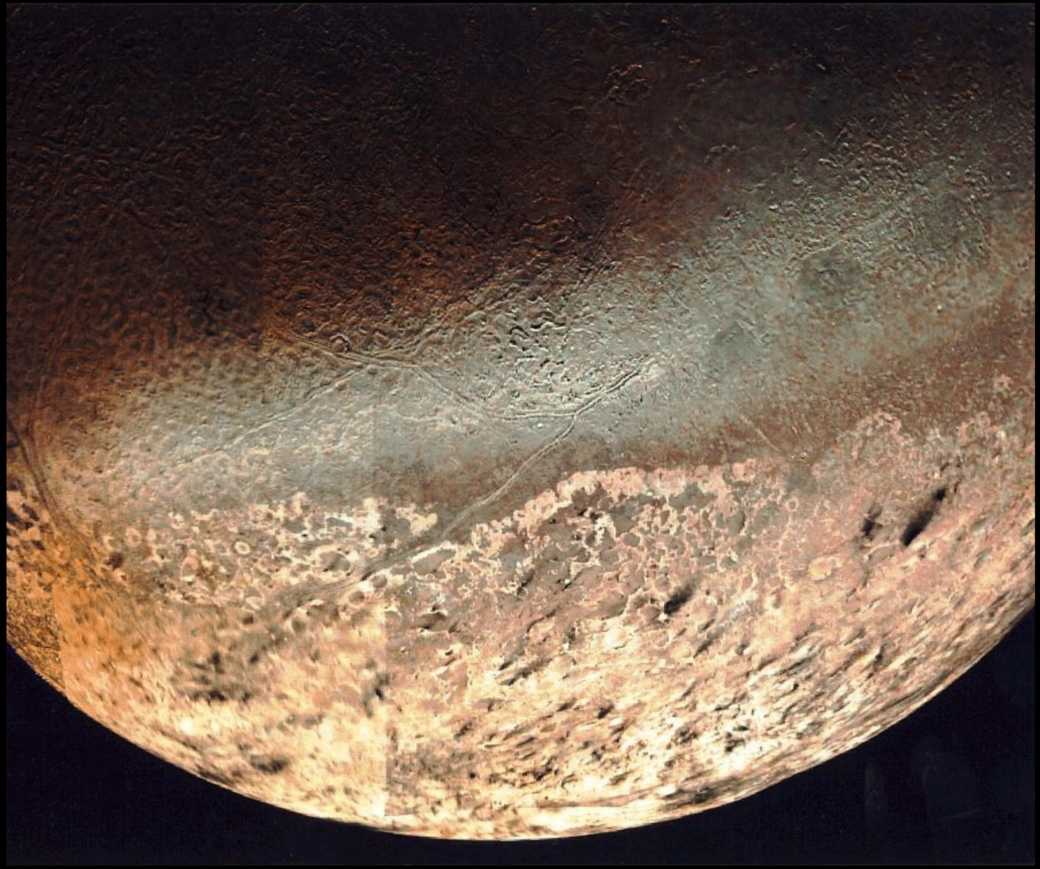
Voyager 2/JPL/NASA

Special moons: Triton (continued)

- **Cryovolcanism**, visible in *Voyager* 2 images as a bunch of dark plumes from the vents, and dark streaks on the surface from the expelled material.

  This is partly responsible for the fact that Triton has a…

- **Very young surface**: not nearly as heavily cratered as the Uranian satellites, perhaps because of filling by cryovolcanic flows and ice-plate "tectonic" activity,



Voyager 2/JPL/NASA