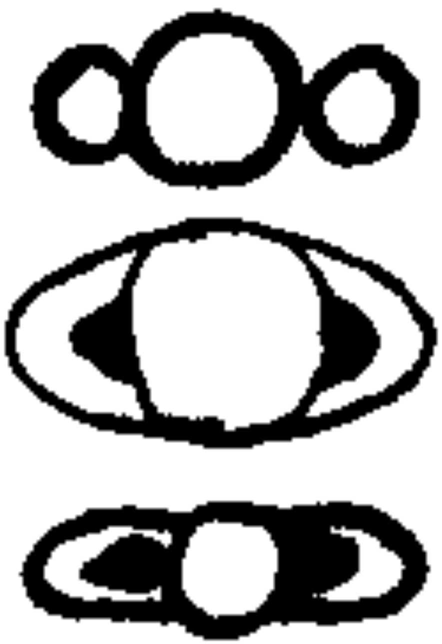
Awesomeness from Mercury

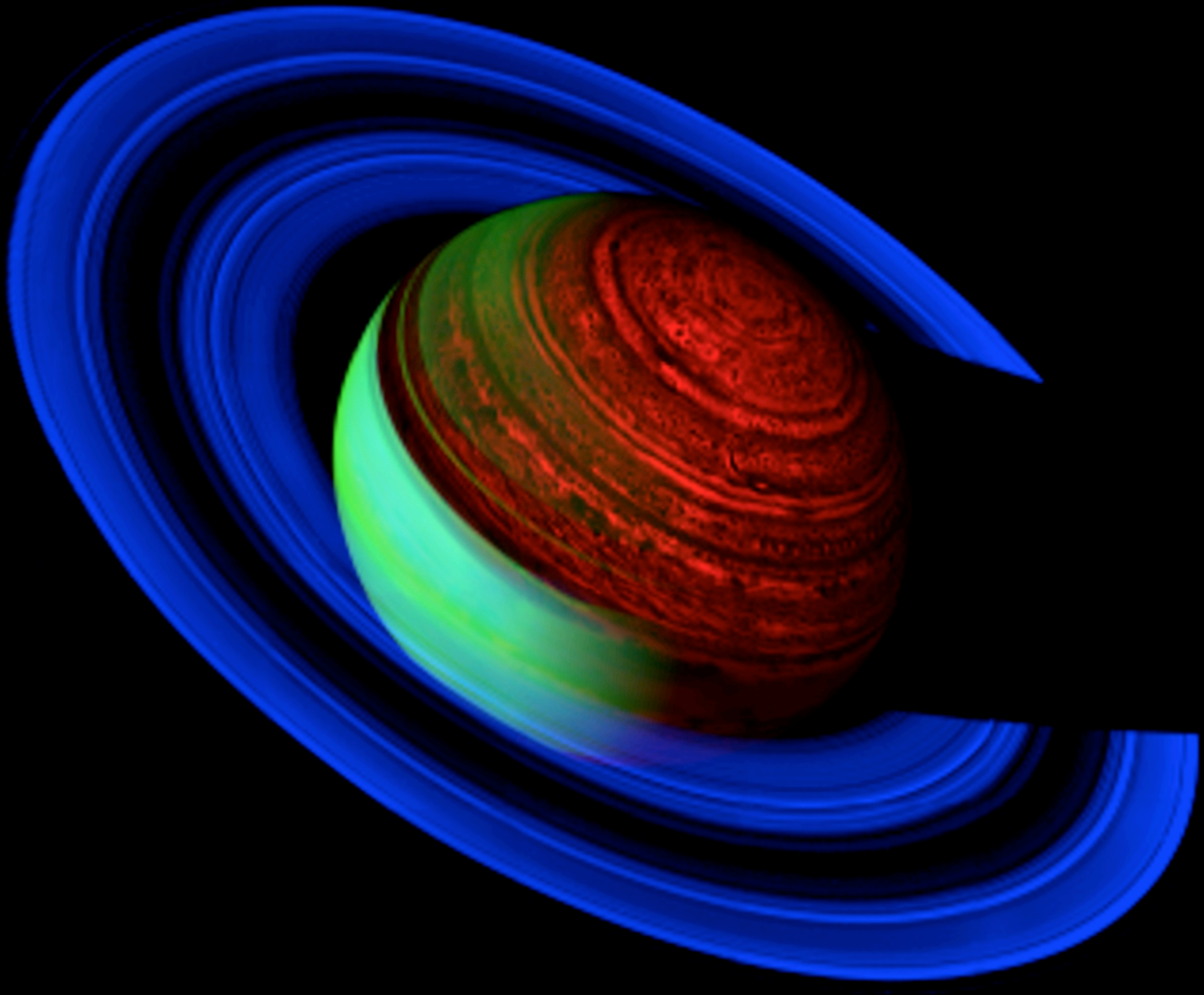
Galileo's Drawings of Saturn



These are sketches of three drawings Galileo made of Saturn through his primitive telescope. ("New Worlds," Couper & Henbest, p.86.)

Huge storms on Saturn

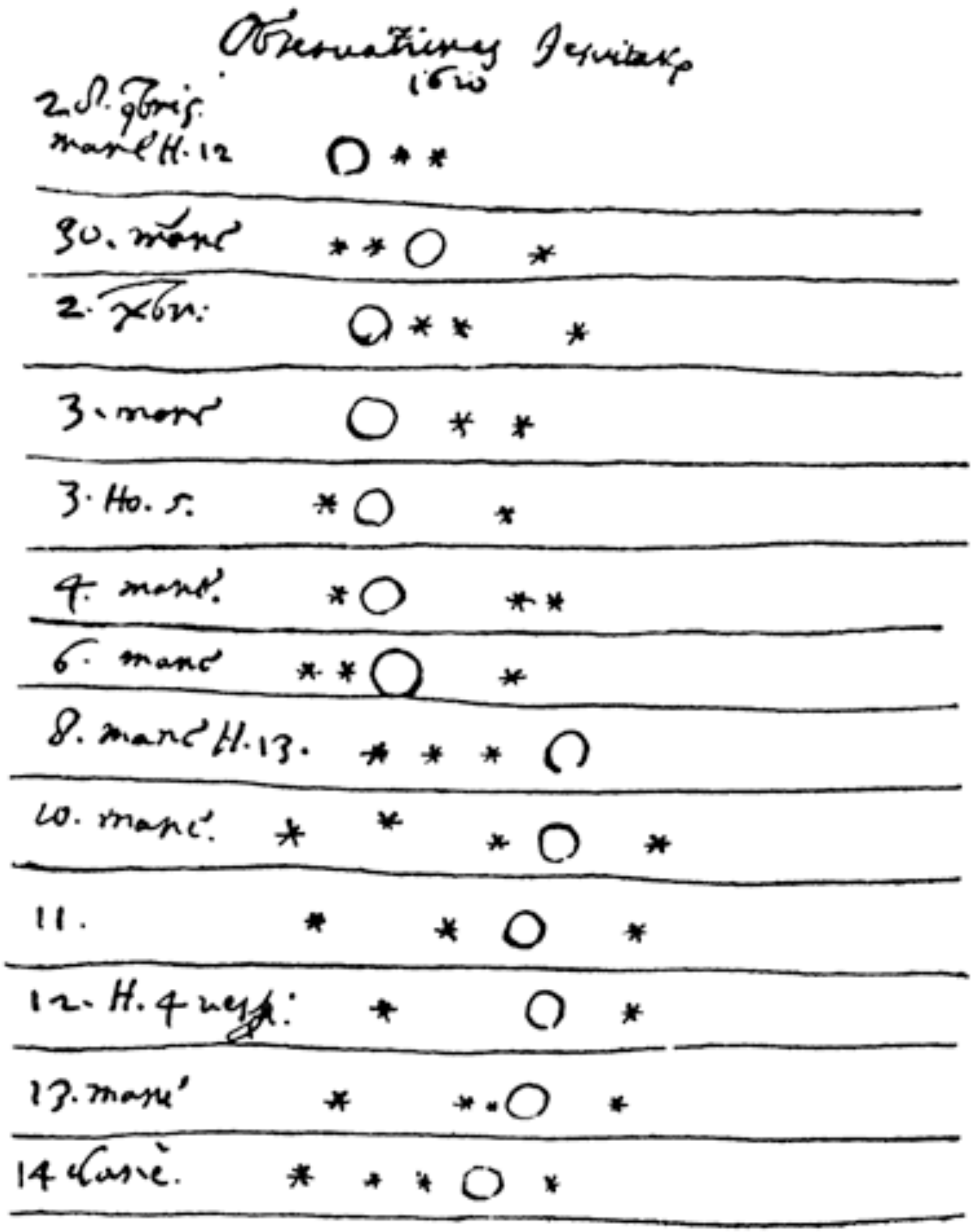
Saturn in the Infrared: 2, 3 and 5 microns



11.2 A Wealth of Worlds: Satellites of Ice and Rock

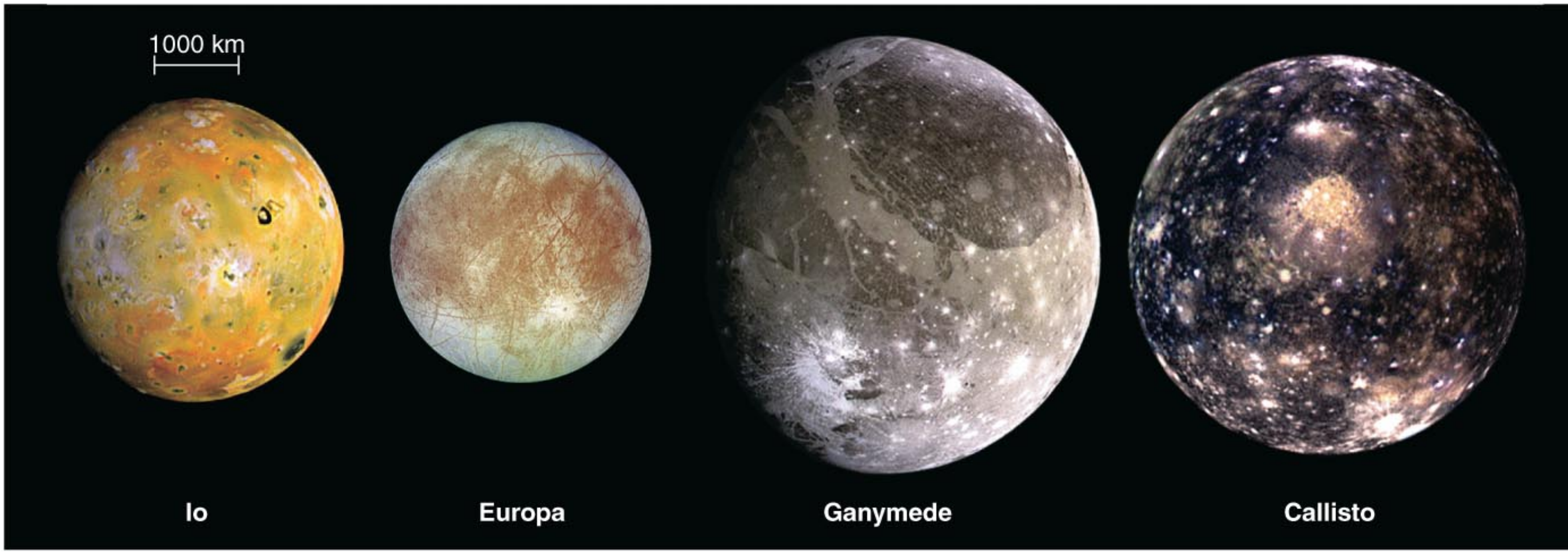
- Our goals for learning:
  - **What kinds of moons orbit the jovian planets?**
  - **Why are Jupiter's Galilean moons so geologically active?**
  - **What is remarkable about Titan and other major moons of the outer solar system?**
  - **Why are small icy moons more geologically active than small rocky planets?**

Galileo's Sketches of Jupiter's Moons



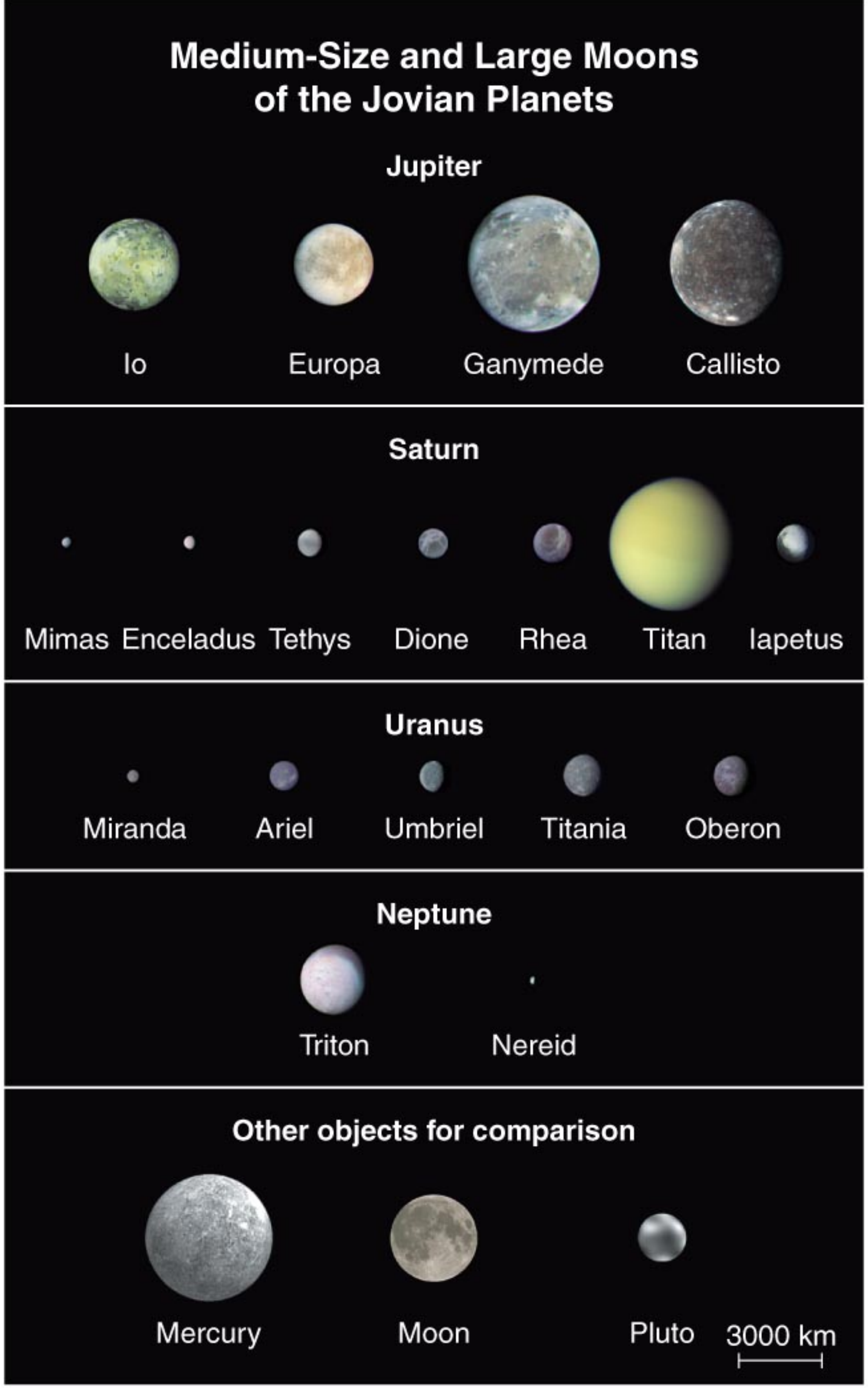
$P^2 \propto a^3$

What kinds of moons orbit the jovian planets?



Sizes of Moons

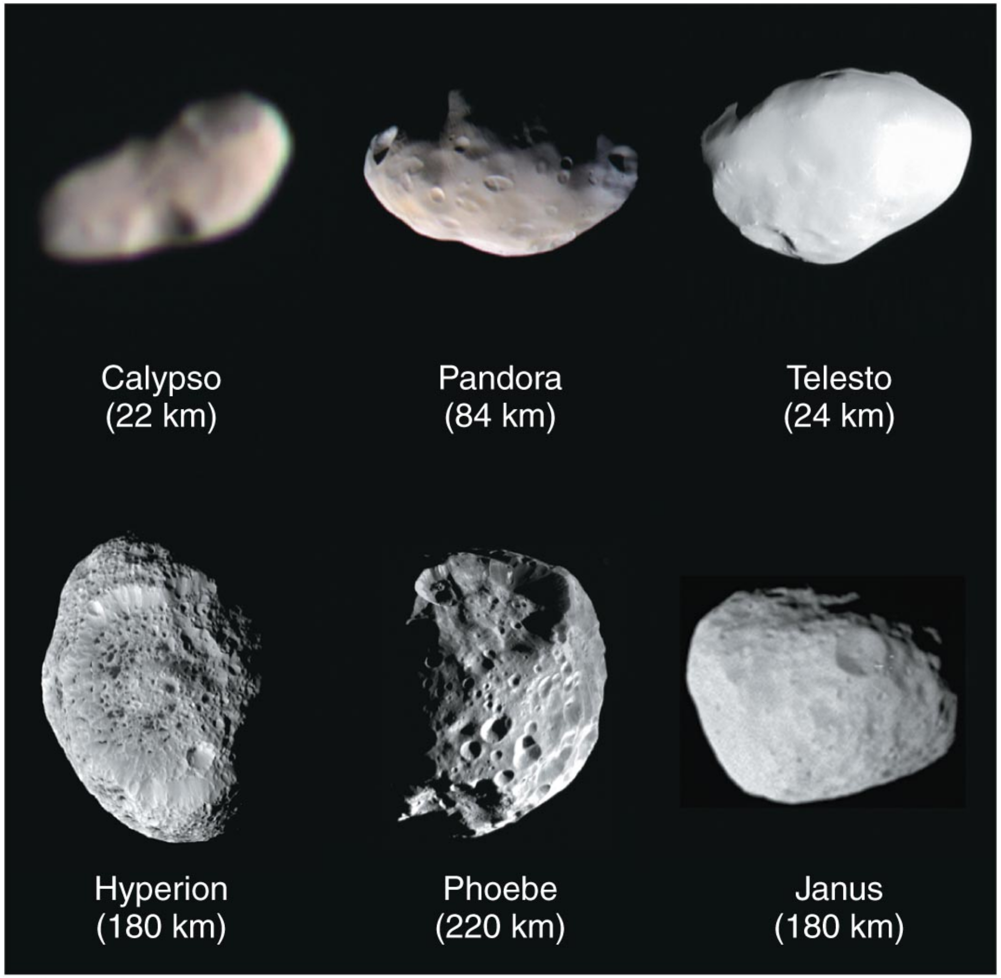
- Small moons (< 300 km)
  - No geological activity
  - Not round!
  - Mostly captured later in life
- Medium-sized moons (300–1500 km)
  - Geological activity in past
  - Round
- Large moons (> 1500 km)
  - Ongoing geological activity



Medium and Large Moons

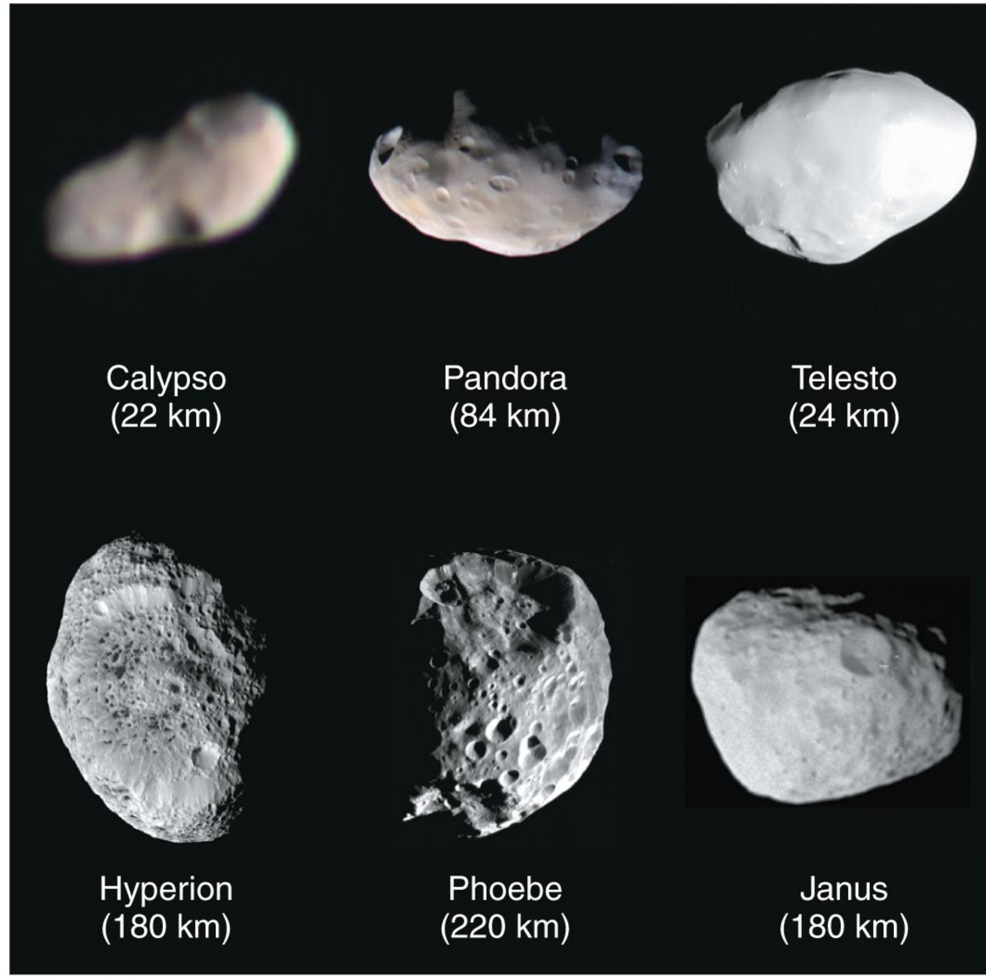
- Enough self-gravity to be spherical
- Have substantial amounts of ice
  - All 4 giant planets are beyond the frost line
- Formed in orbit around jovian planets
- Circular orbits in same direction as planet rotation
- "Mini planetary systems"

Small Moons



- These are far more numerous than the medium and large moons.
- They do not have enough gravity to be spherical: Most are "potato-shaped."

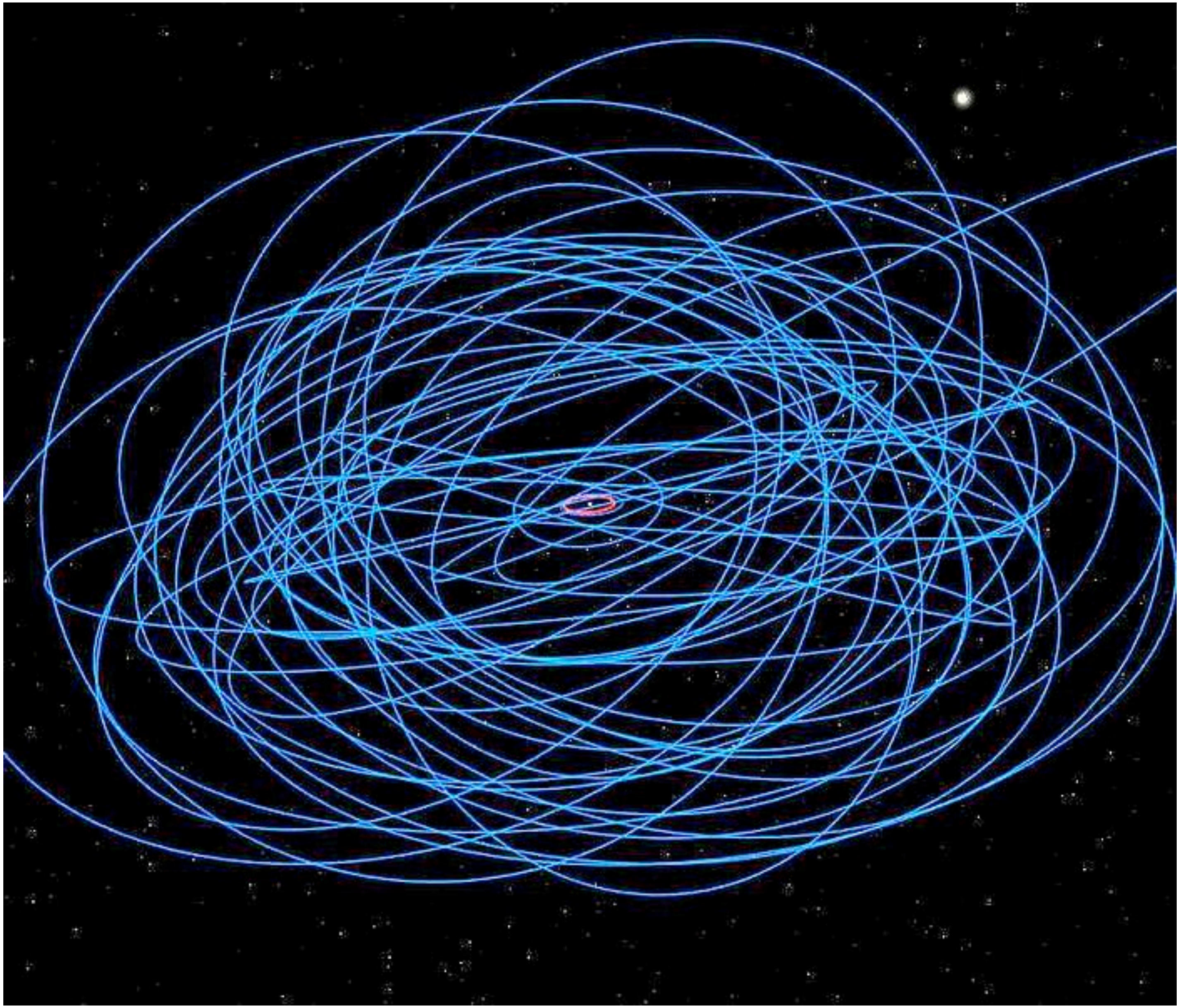
Small Moons



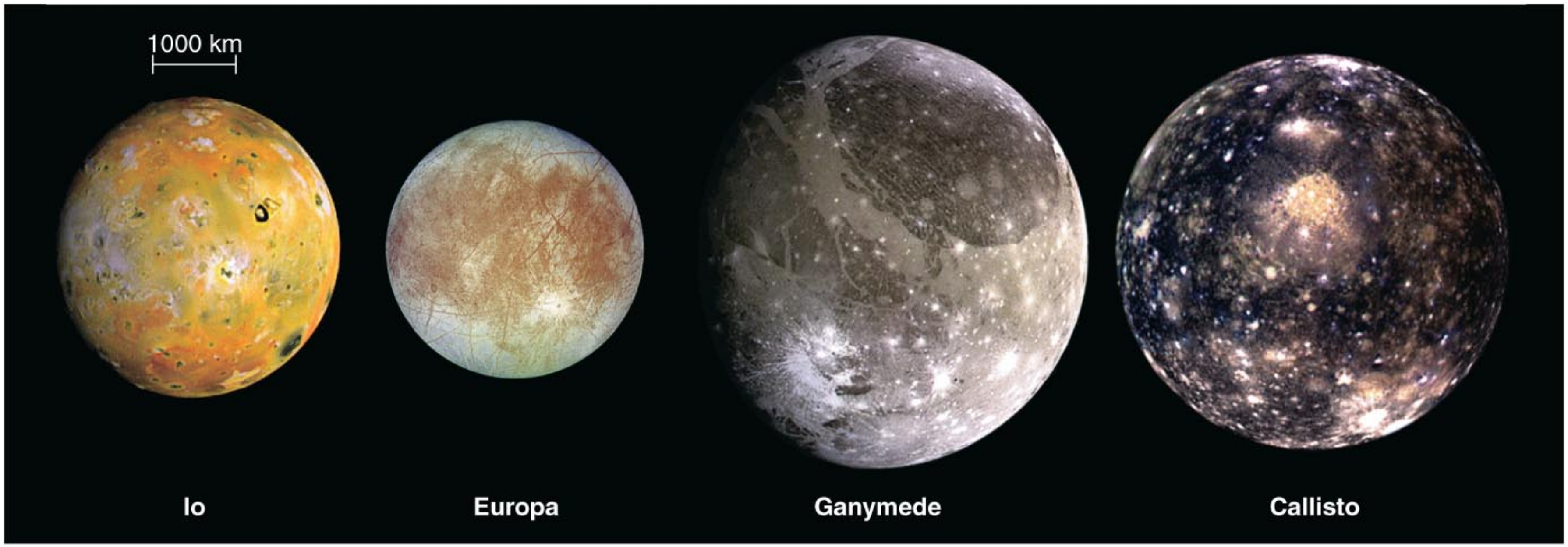
- They are captured asteroids or comets, so their orbits do not follow usual patterns.
- 80% in retrograde orbits

Saturn's Small "Irregular" Moons

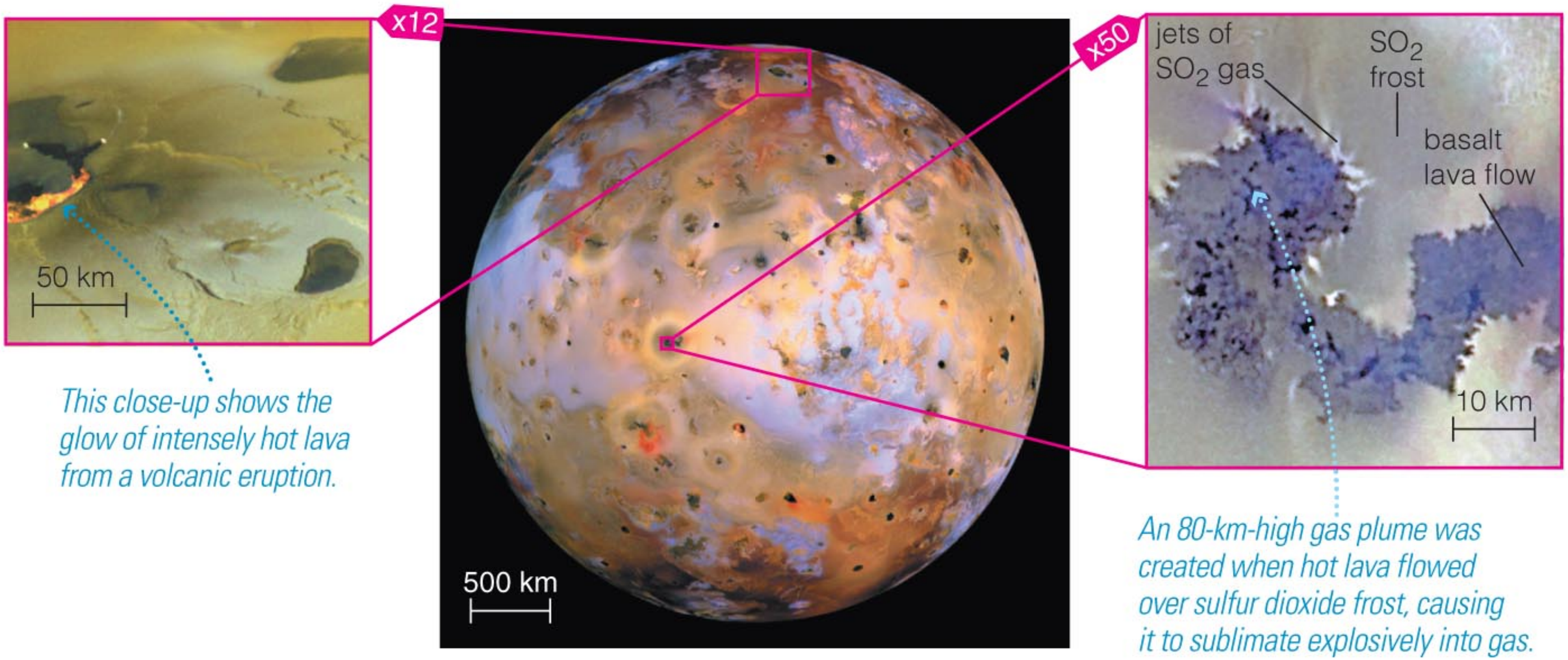
Orbit of Titan shown in red



Why are Jupiter's Galilean moons so geologically active?

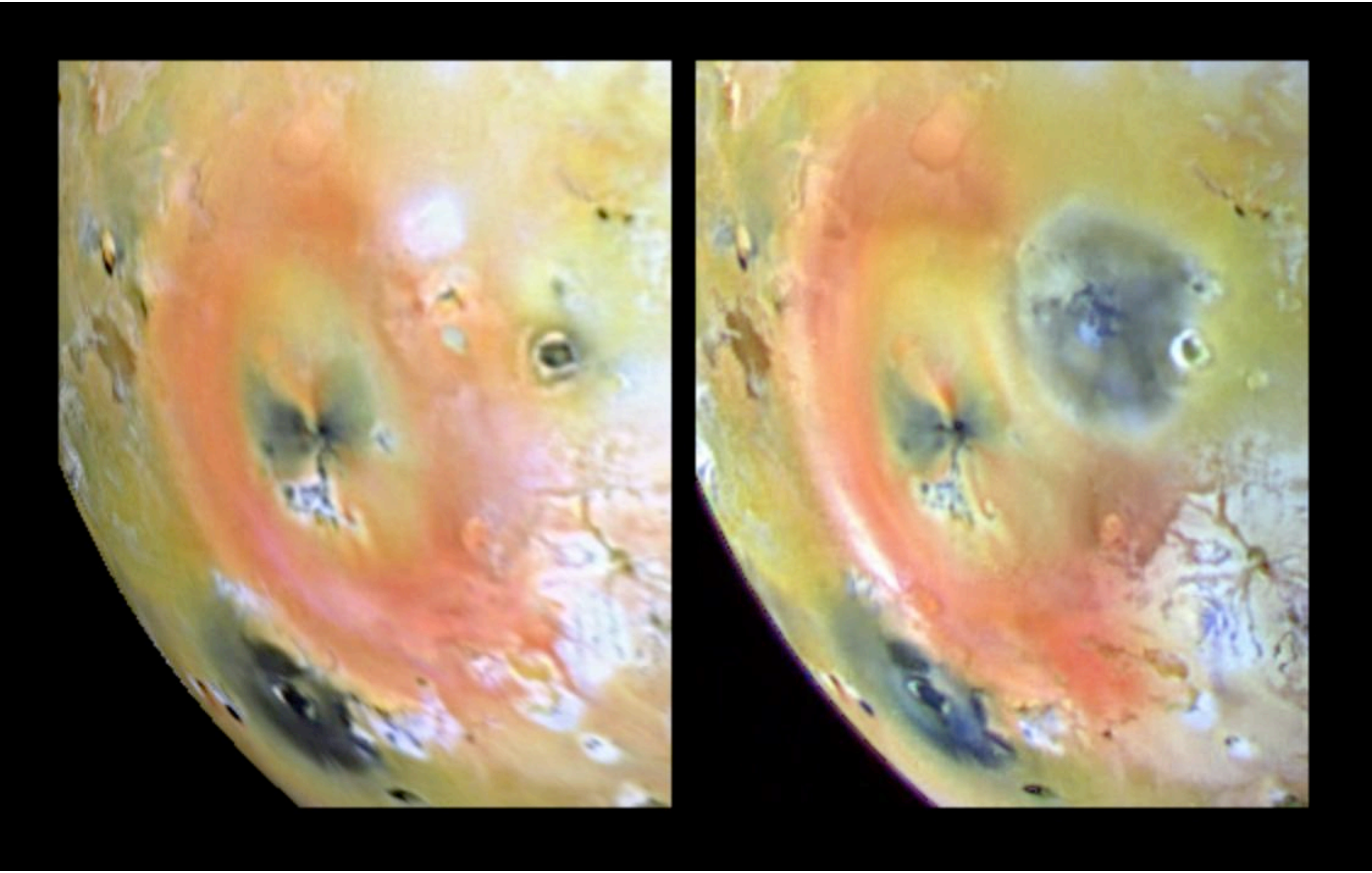


Io's Surface Features

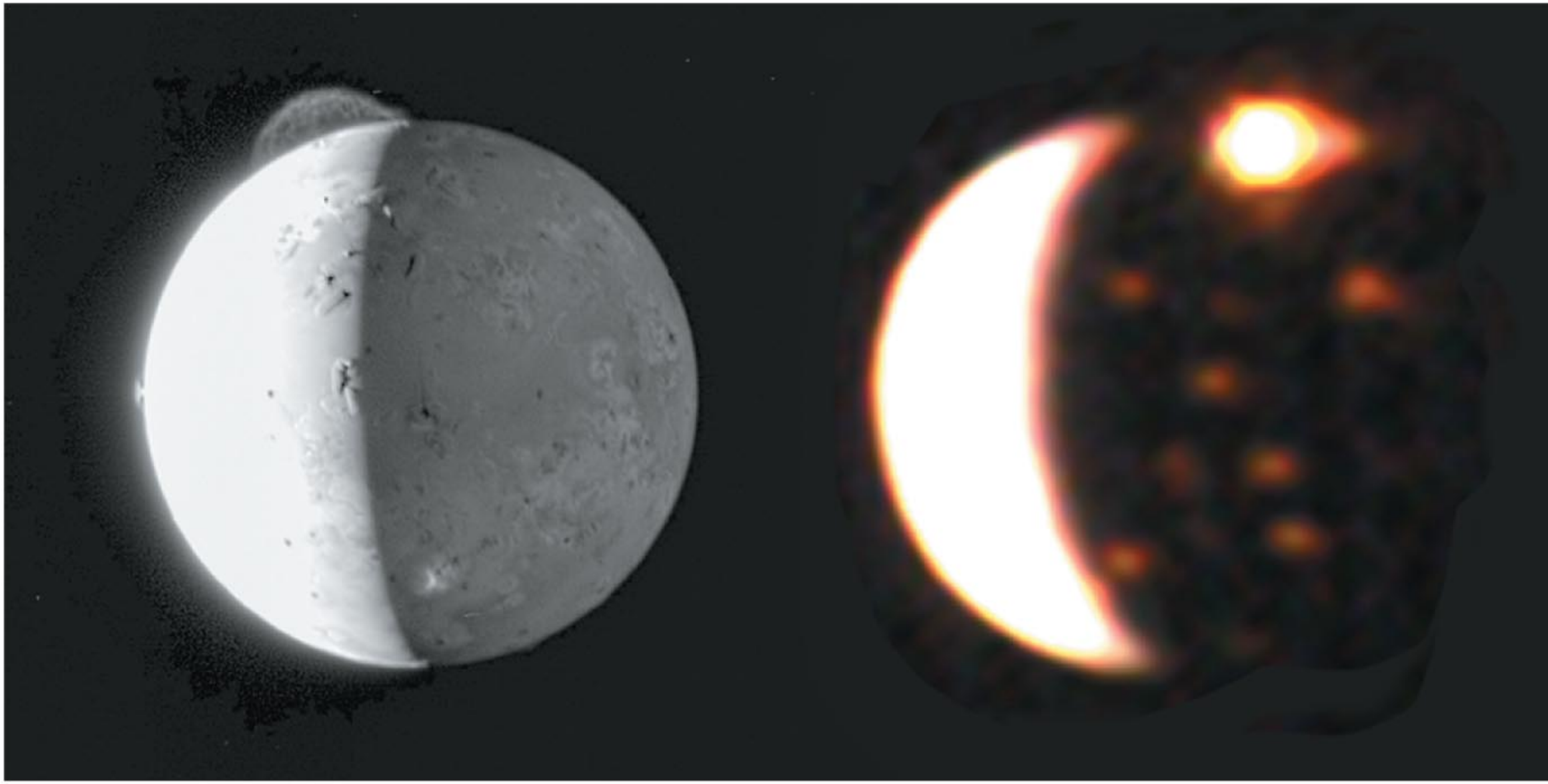


- Io is the most volcanically active body in the solar system, but why?

Io's Surface is Incredibly Dynamic

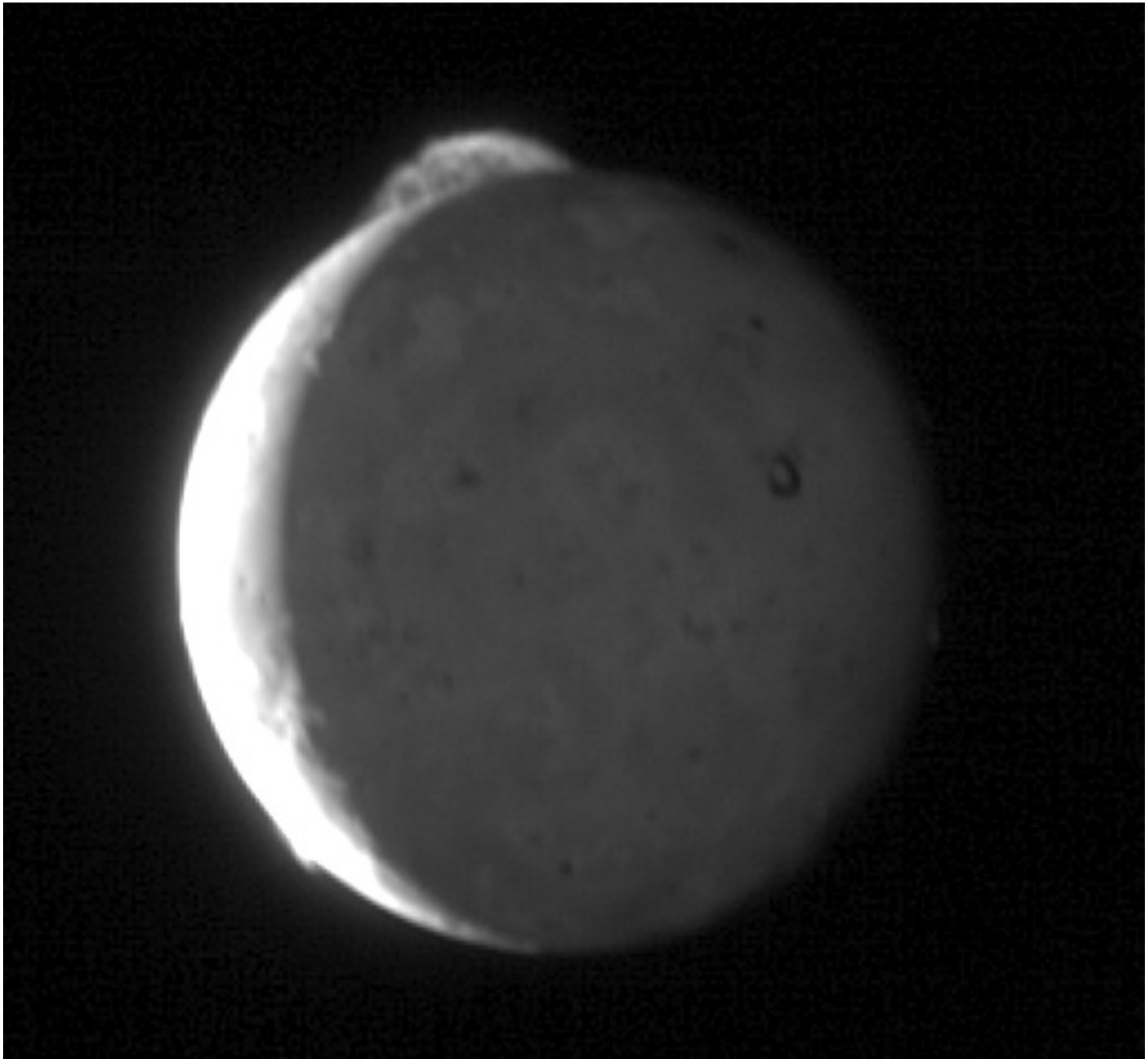


Io's Volcanoes

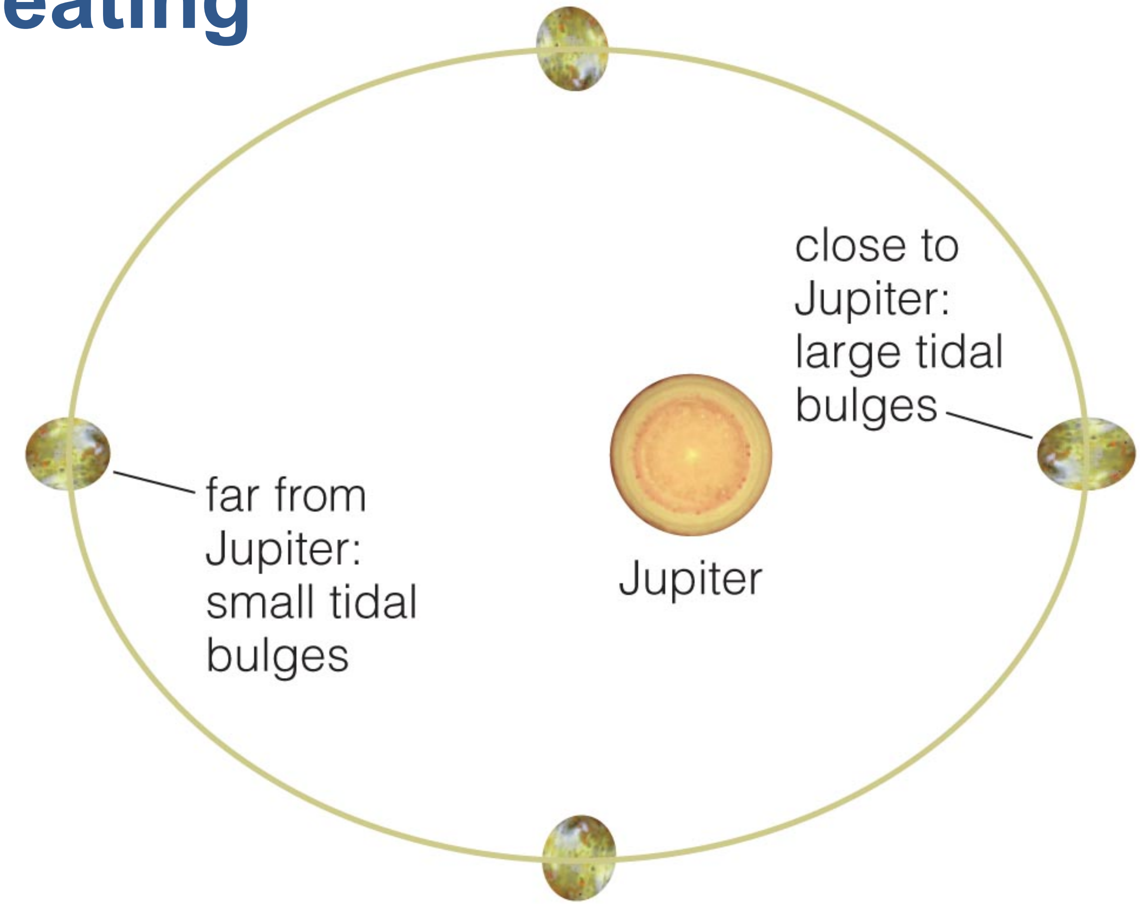


- Volcanic eruptions continue to change Io's surface
- Huge plumes seen in visible light
- "Hot spots" seen in thermal infrared light

Io as seen by New Horizons



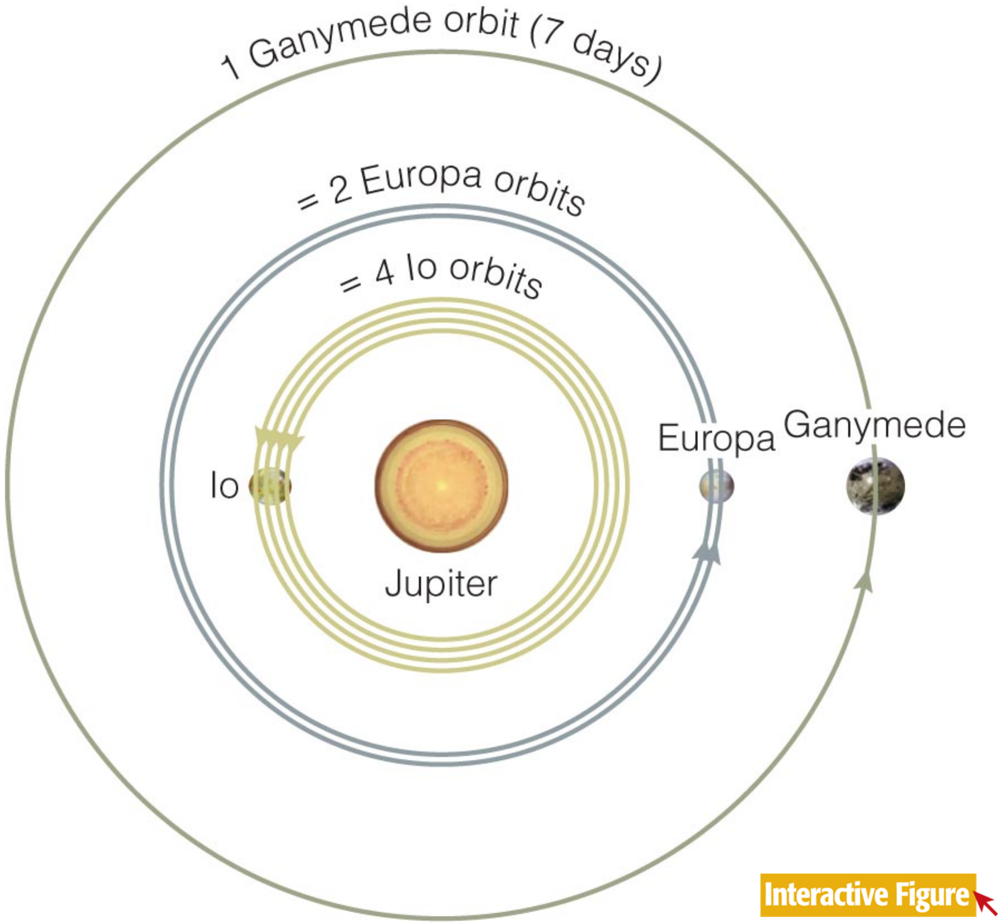
Tidal Heating



Io is squished and stretched as it orbits Jupiter.

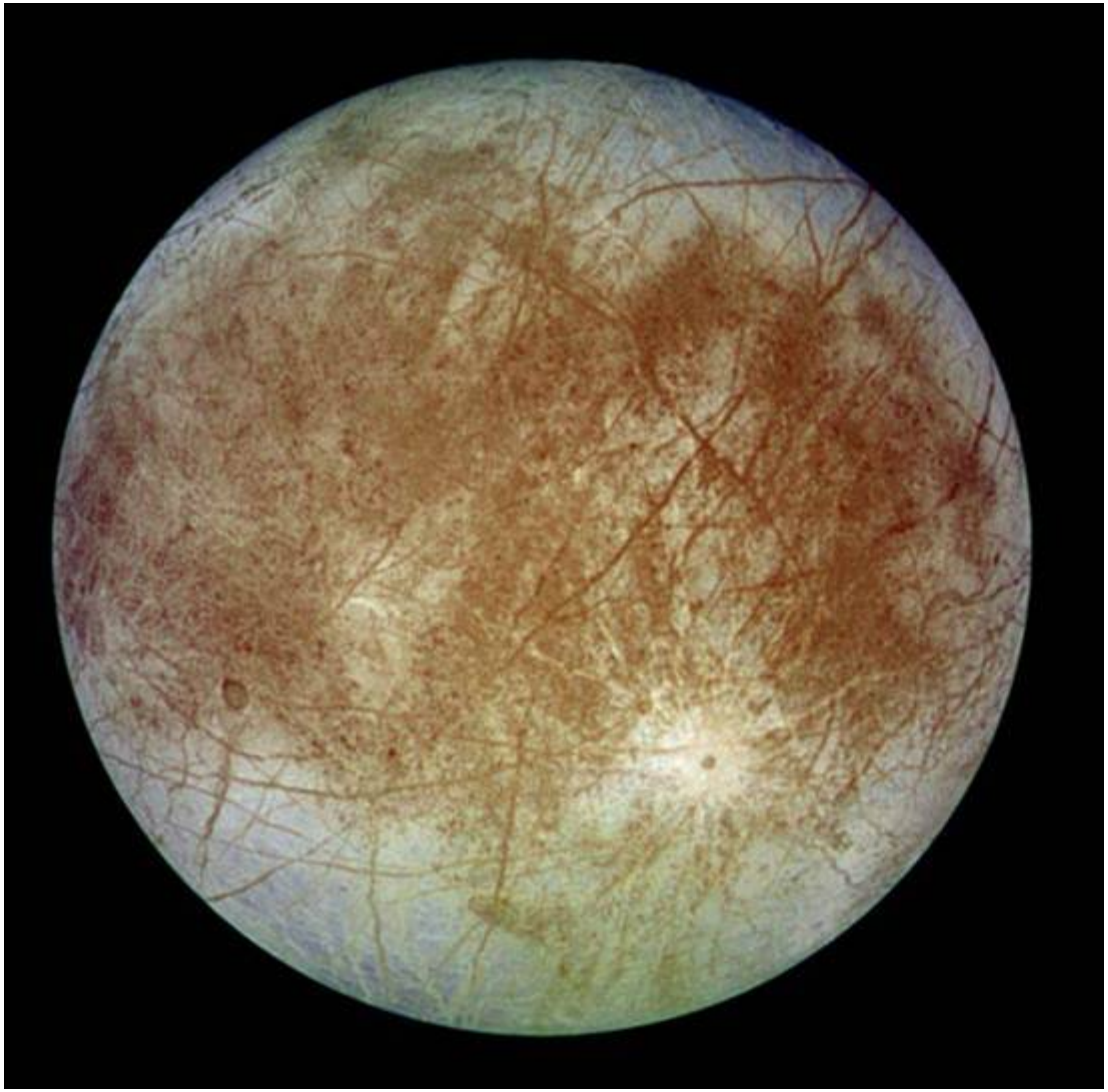
200 times more heating / gram than Earth's radioactivity

Orbital Resonances



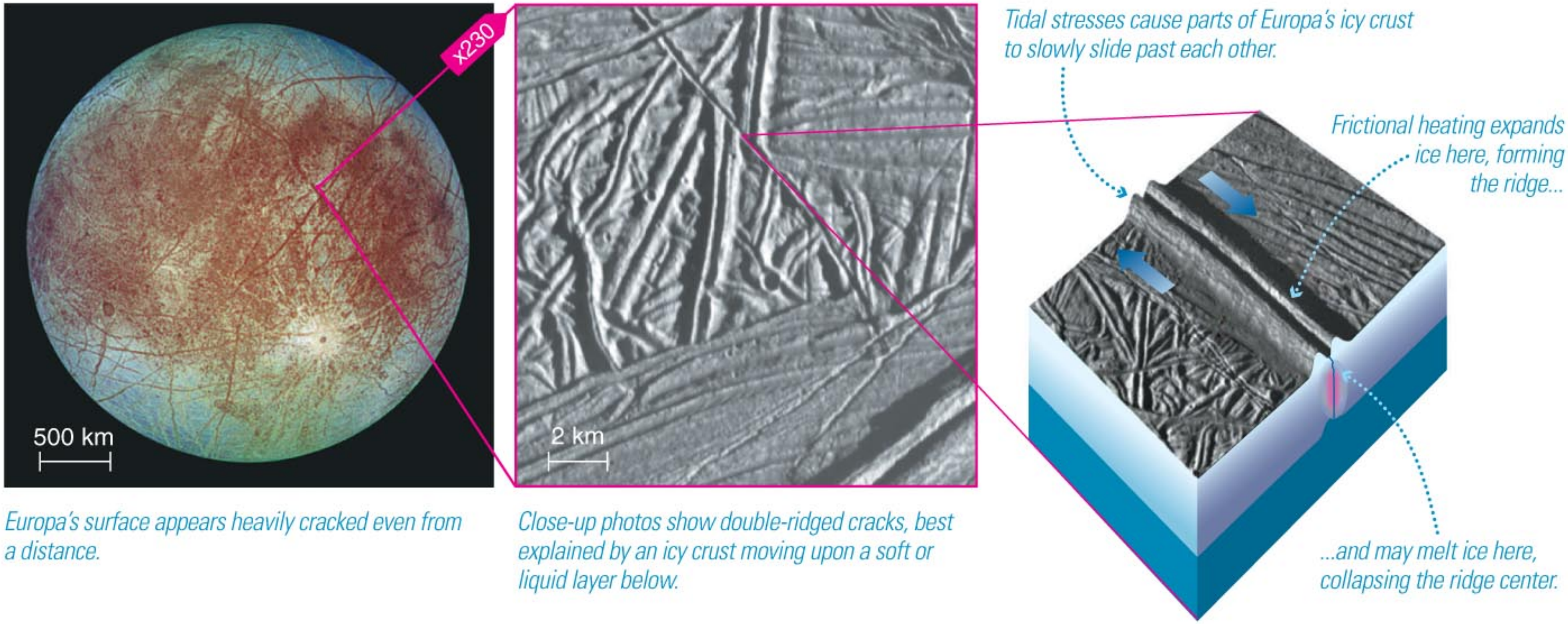
- Every 7 days, these three moons line up.
- The tugs add up over time, making all three orbits elliptical.

Europa's Ocean: Waterworld?



NASA/JPL/DLR

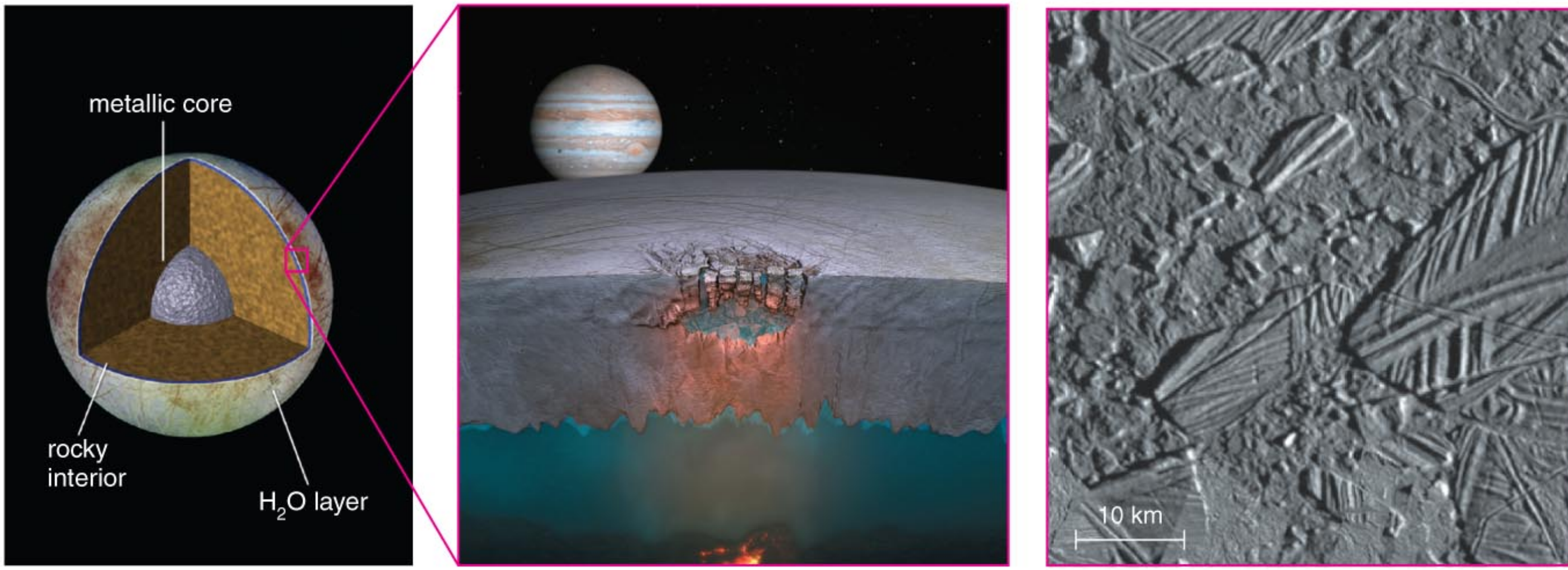
Tidal stresses crack Europa's surface ice.



Europa's surface appears heavily cracked even from a distance.

Close-up photos show double-ridged cracks, best explained by an icy crust moving upon a soft or liquid layer below.

Europa's interior also warmed by tidal heating.

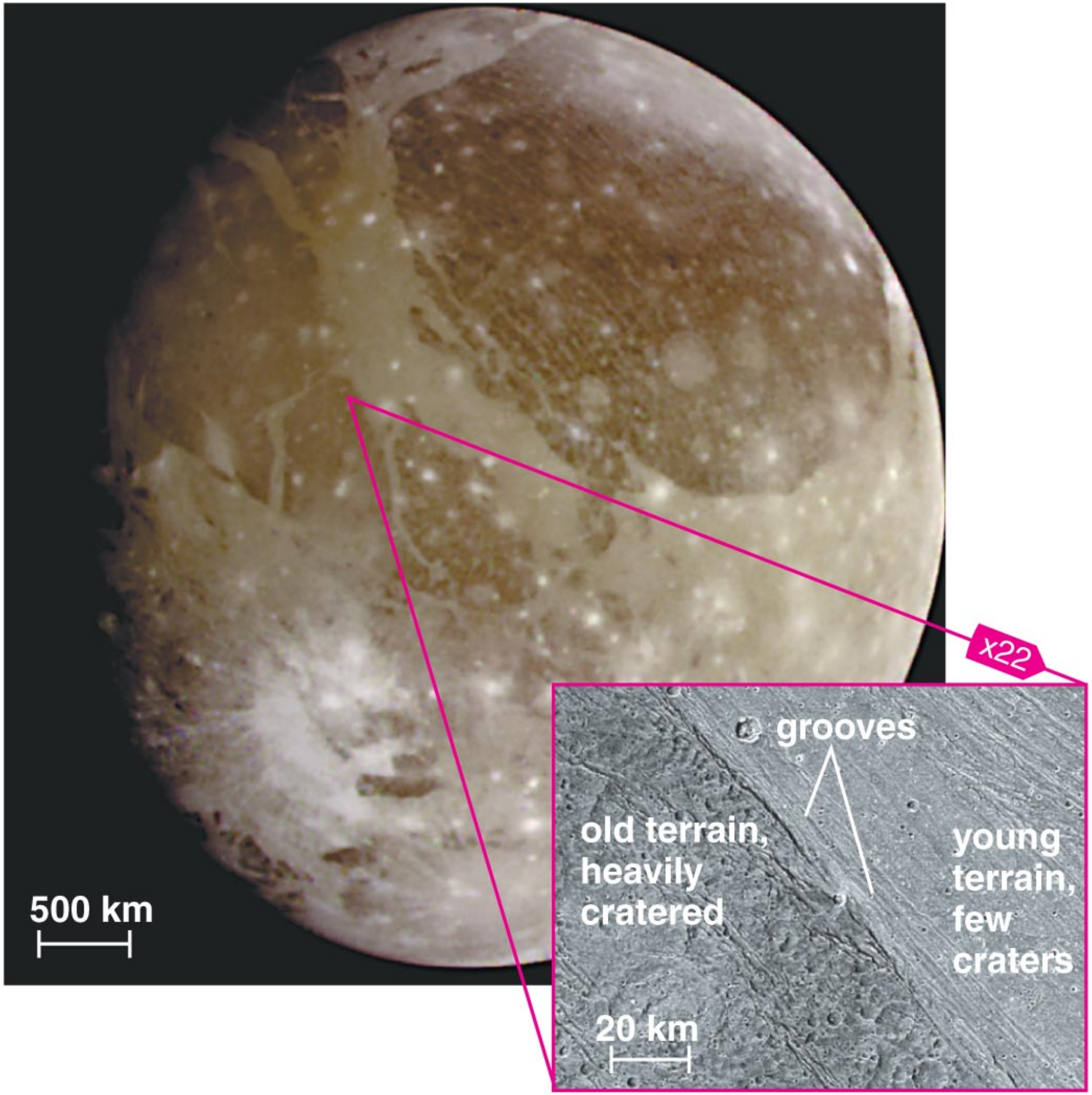


Europa may have a 100-km-thick ocean under an icy crust.

Rising plumes of warm water may sometimes create lakes within the ice, causing the crust above to crack . . .

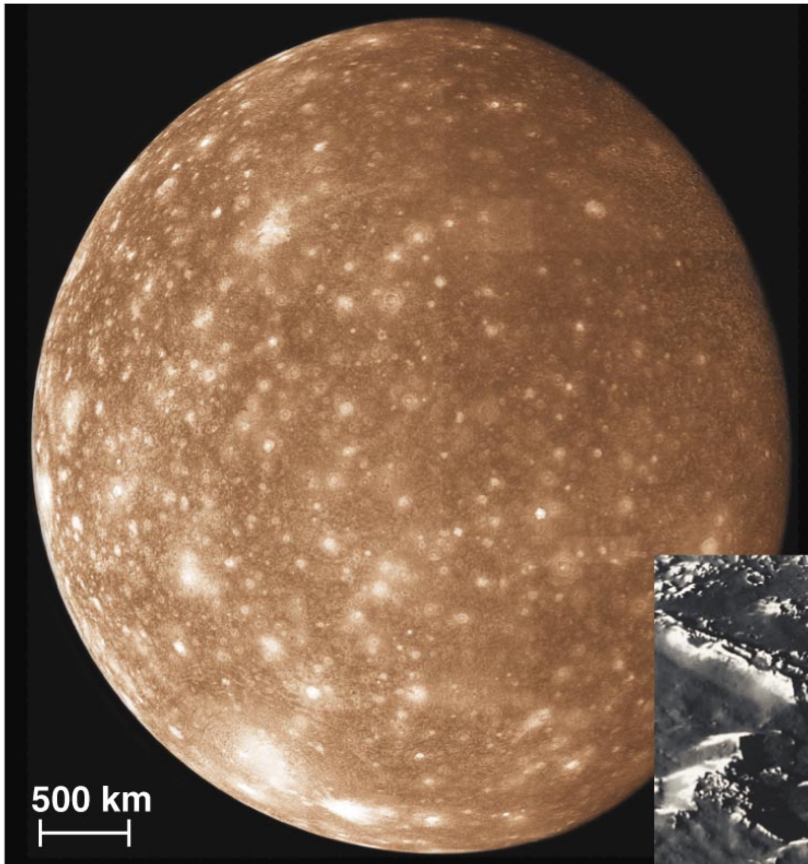
. . . explaining surface terrain that looks like a jumble of icebergs suspended in a place where liquid or slushy water froze.

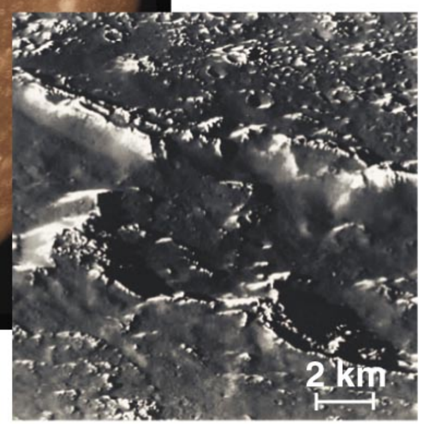
Ganymede



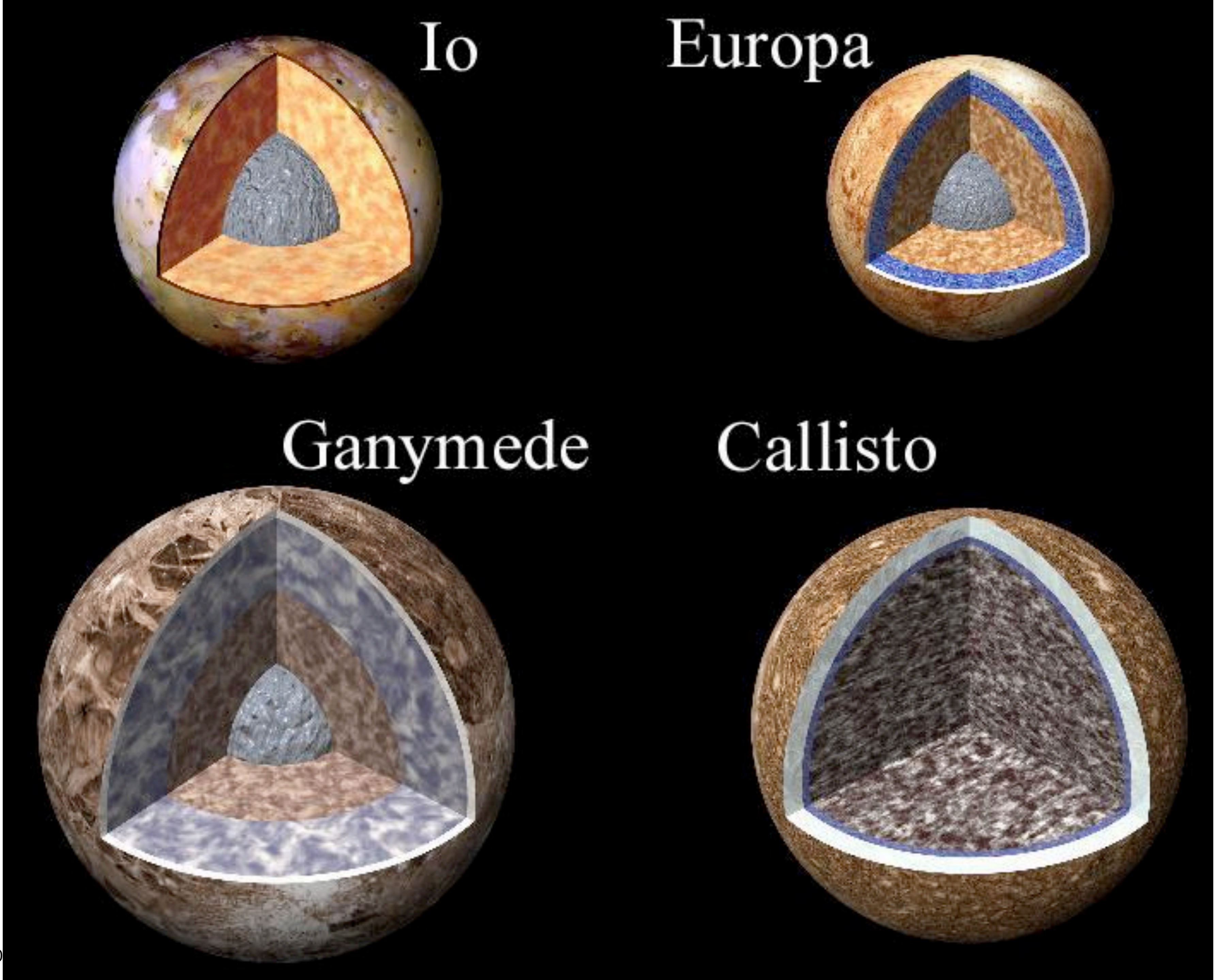
- Largest moon in the solar system
- Clear evidence of geological activity
- Tidal heating plus heat from radio-active decay?
- Has a strong magnetic field, indicating a liquid iron core

Callisto





- "Classic" cratered iceball
- No tidal heating, no orbital resonances
- But it has a magnetic field!?
- Indirect evidence for a salty ionized ocean – Europa and Ganymede too


Io
Europa
Ganymede
Callisto

Clicker Question

How does Io get heated by Jupiter?

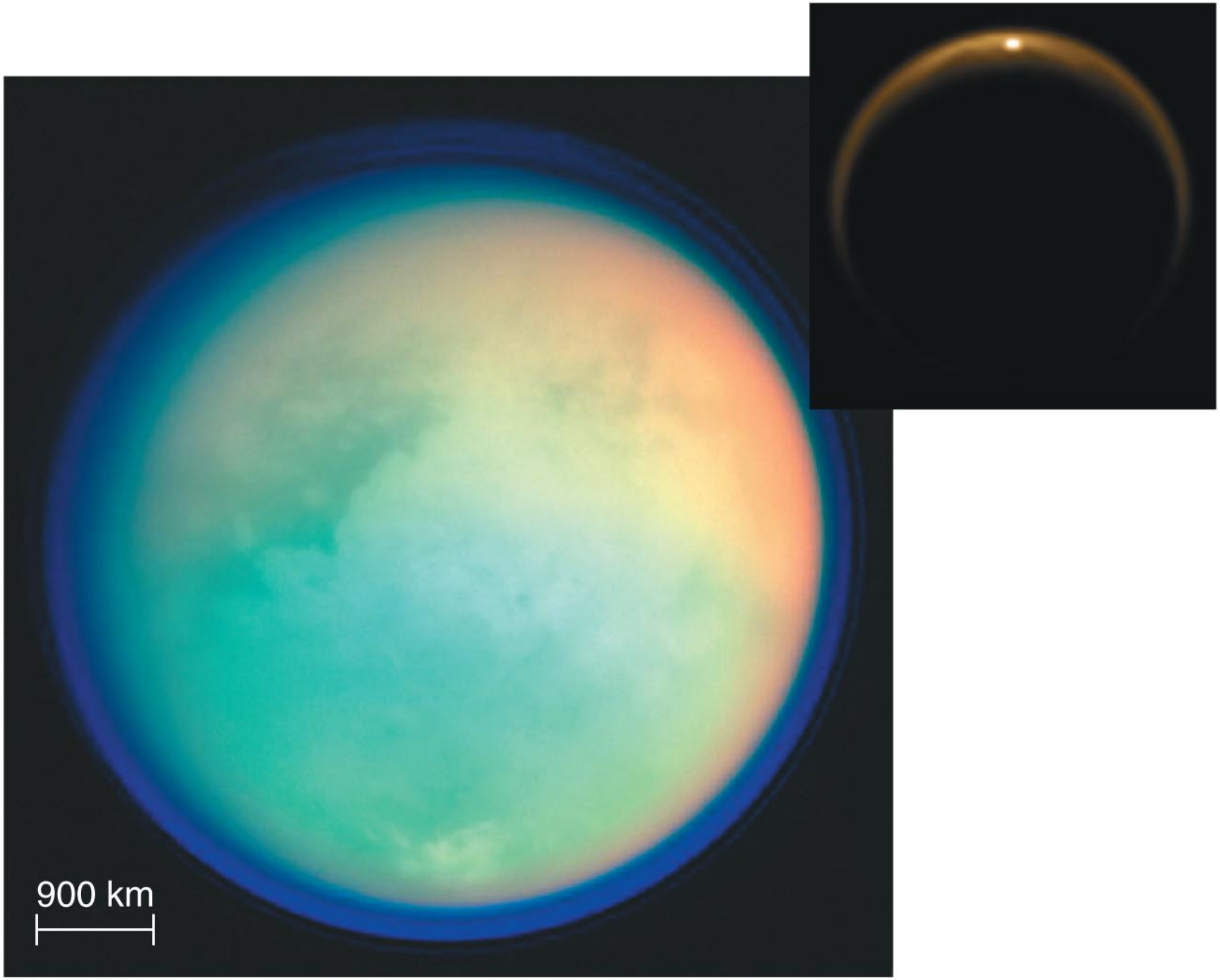
a) auroras
b) infrared light
c) tidal resonance
d) volcanoes

Clicker Question

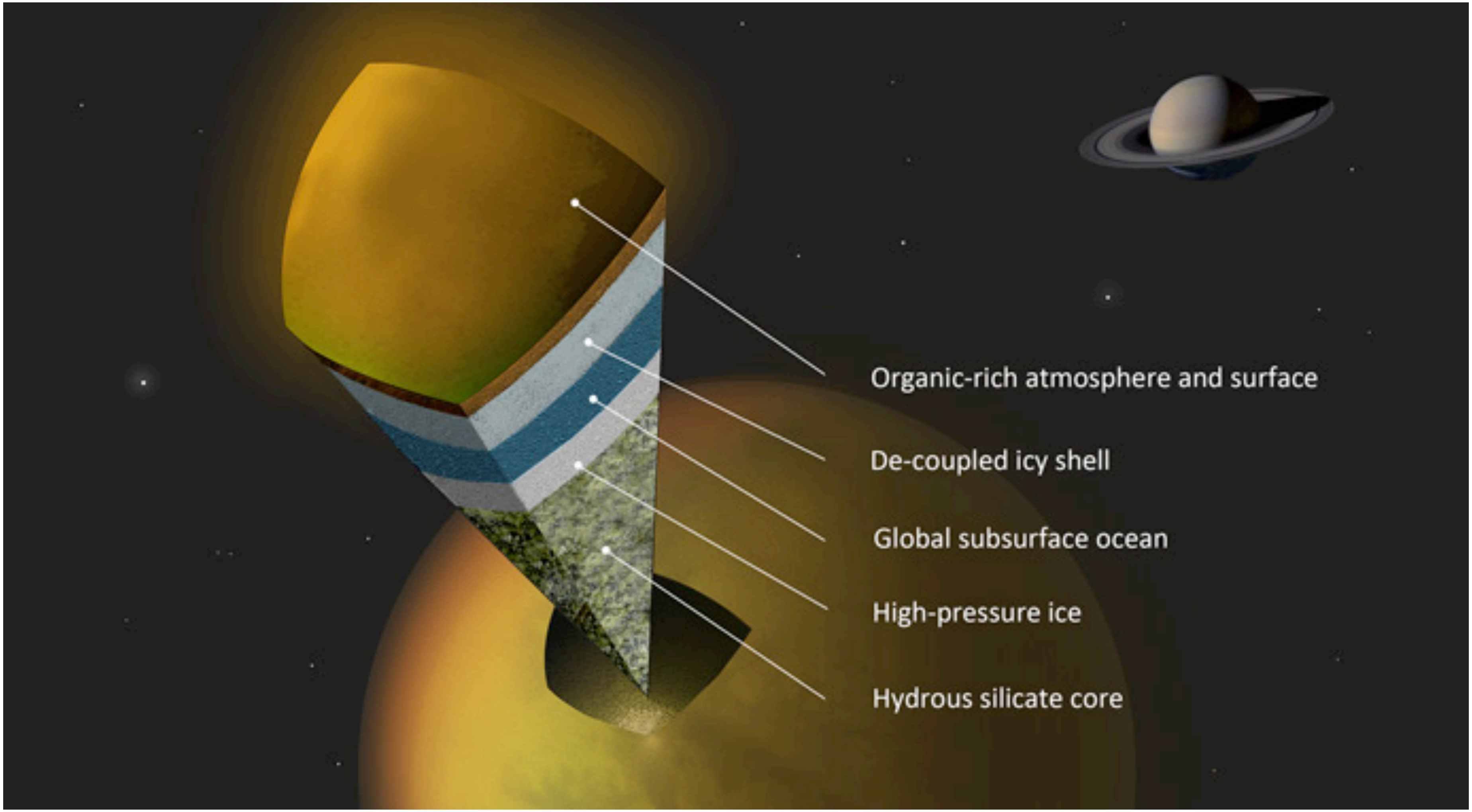
How does Io get heated by Jupiter?

a) auroras
b) infrared light
c) **tidal resonance**
d) volcanoes

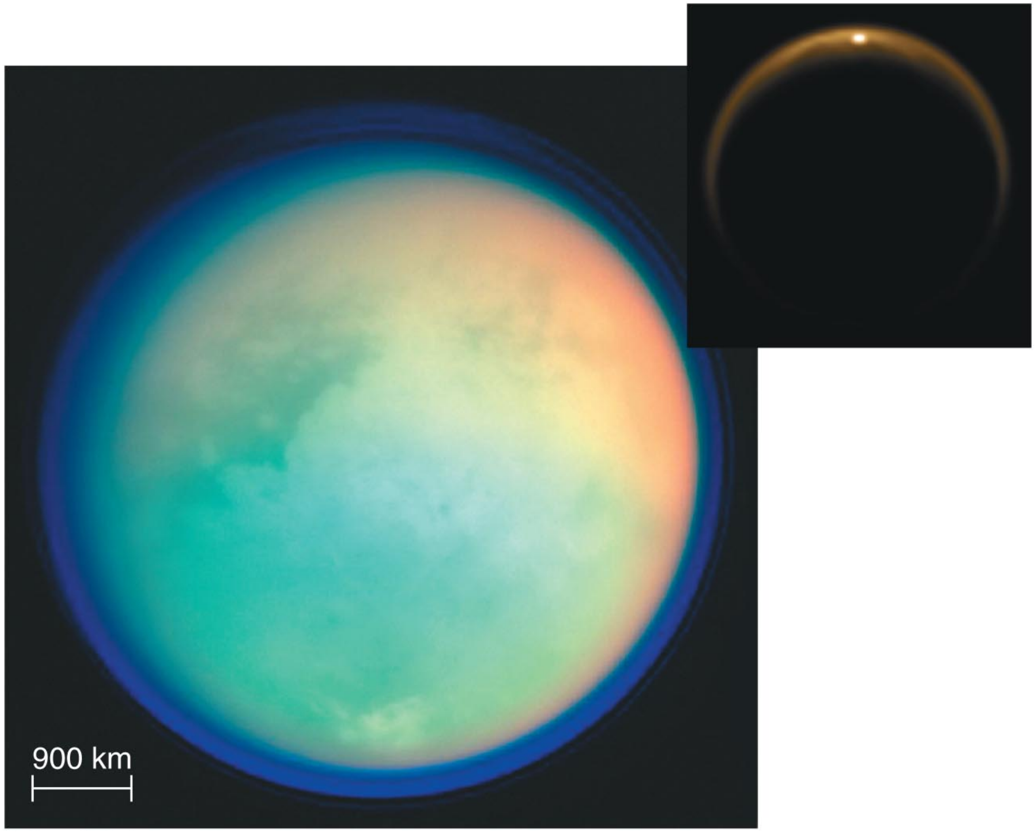
What is remarkable about Titan and other major moons of the outer solar system?



Titan's Interior Structure

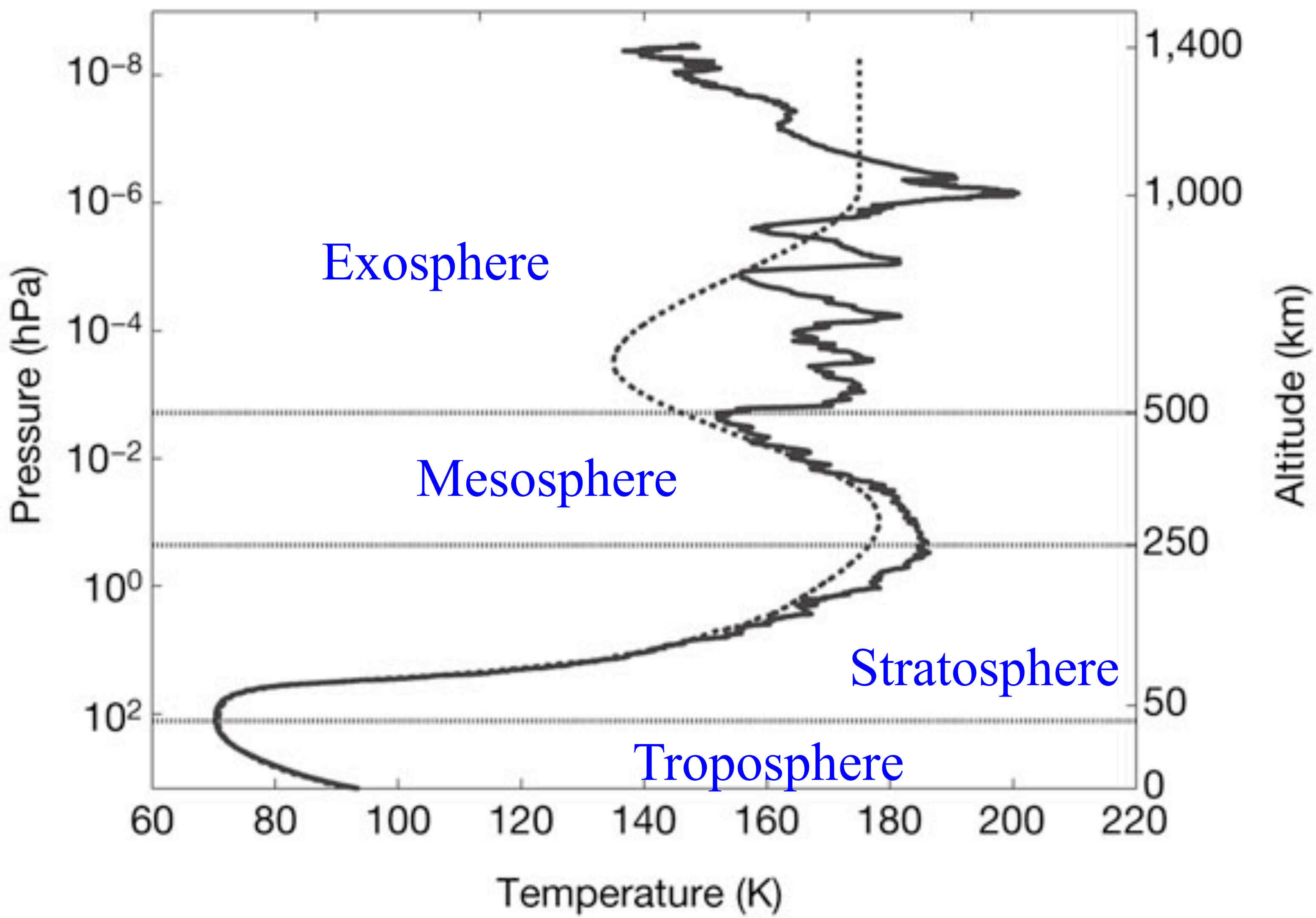


Titan's Atmosphere

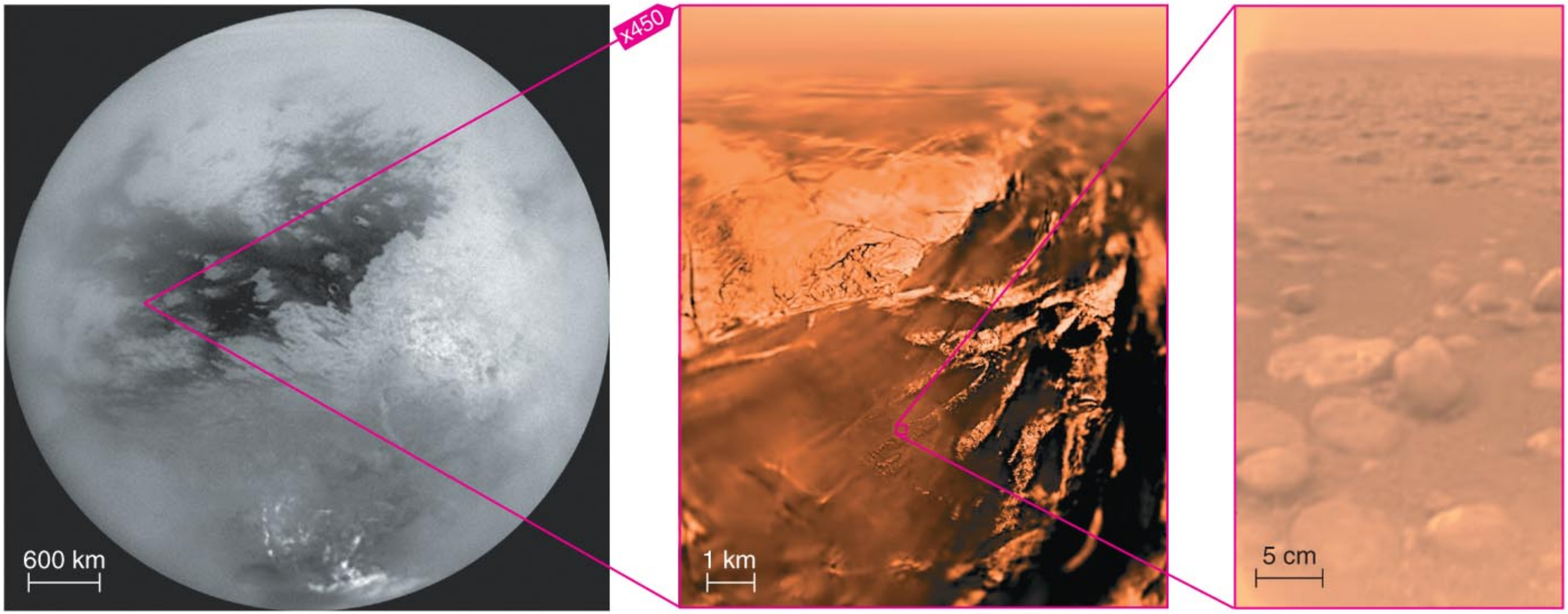


- Titan is the only moon in the solar system to have a thick atmosphere.
- It consists mostly of nitrogen with some argon, methane, and ethane.

Titan’s Atmosphere: Similar to Earth



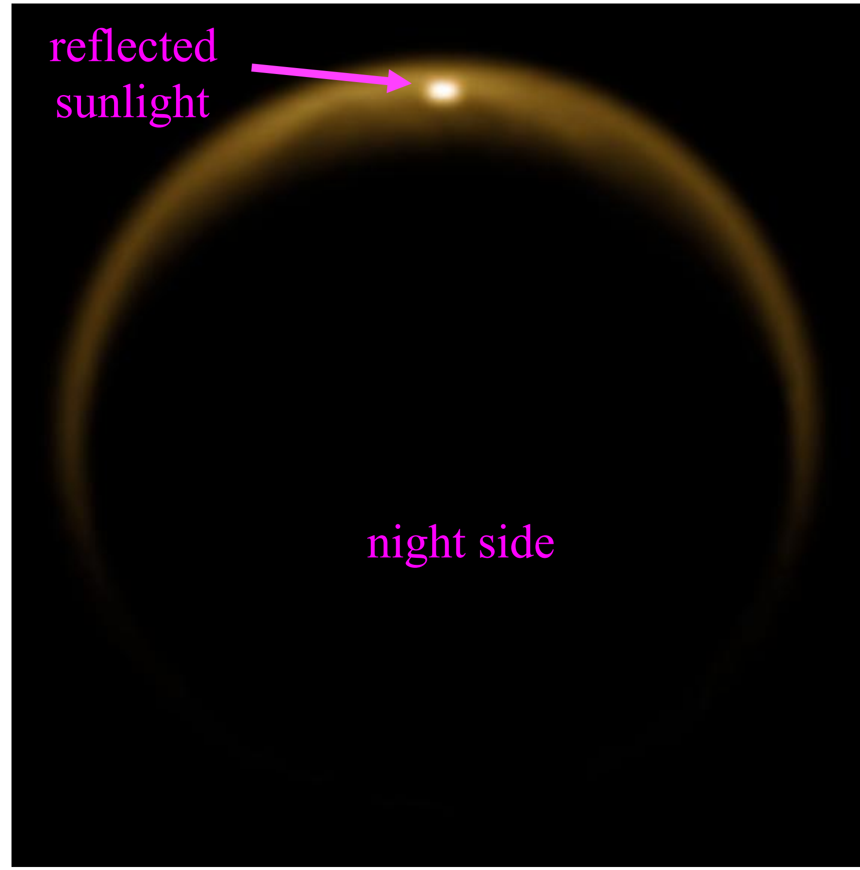
Titan's Surface



- *Huygens* probe provided first look at Titan's surface in early 2005.
- It found liquid methane and "rocks" made of ice.

A Sunlit Lake on Titan

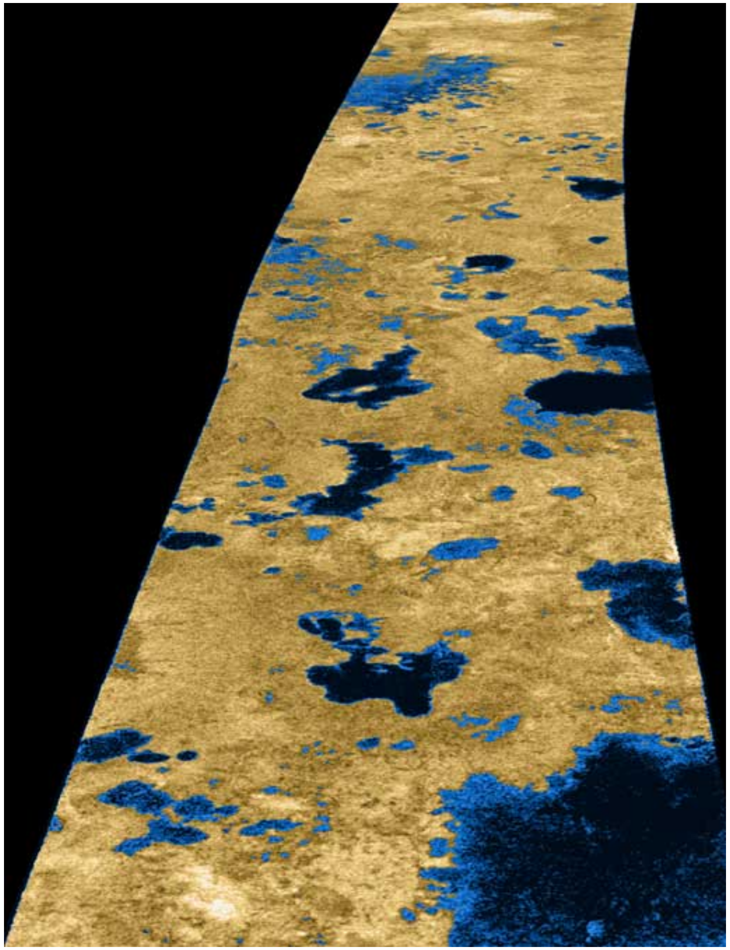
- The Cassini spacecraft recently recorded a flash of sunlight off a region of the northern hemisphere
- Lakes appear mostly at the North and South Poles
- The reflection comes from a dark, smooth region suspected to be a large lake or sea
- Infrared and radar observations previously revealed hundreds of likely lakes near the north pole, and a few lakes near the south pole
- The lakes are filled with ethane, and probably methane



Cassini infrared image of Saturn's moon Titan taken from above the night side of the planet. The bright region in the sunlit northern polar region was predicted, and results from sunlight reflected off a methane lake.

Lakes without Water

- Titan is 94 K - too cold for liquid surface water, but not too cold for liquid methane and ethane
- Sunlight should rapidly convert atmospheric methane to ethane and other species. But methane is abundant, so must be replenished.
- Methane and ethane should be exchanged between the atmosphere and lakes through evaporation and precipitation (similar to water on Earth)
- These processes can help maintain the high atmospheric methane abundance and contribute to observed seasonal variations in the lakes



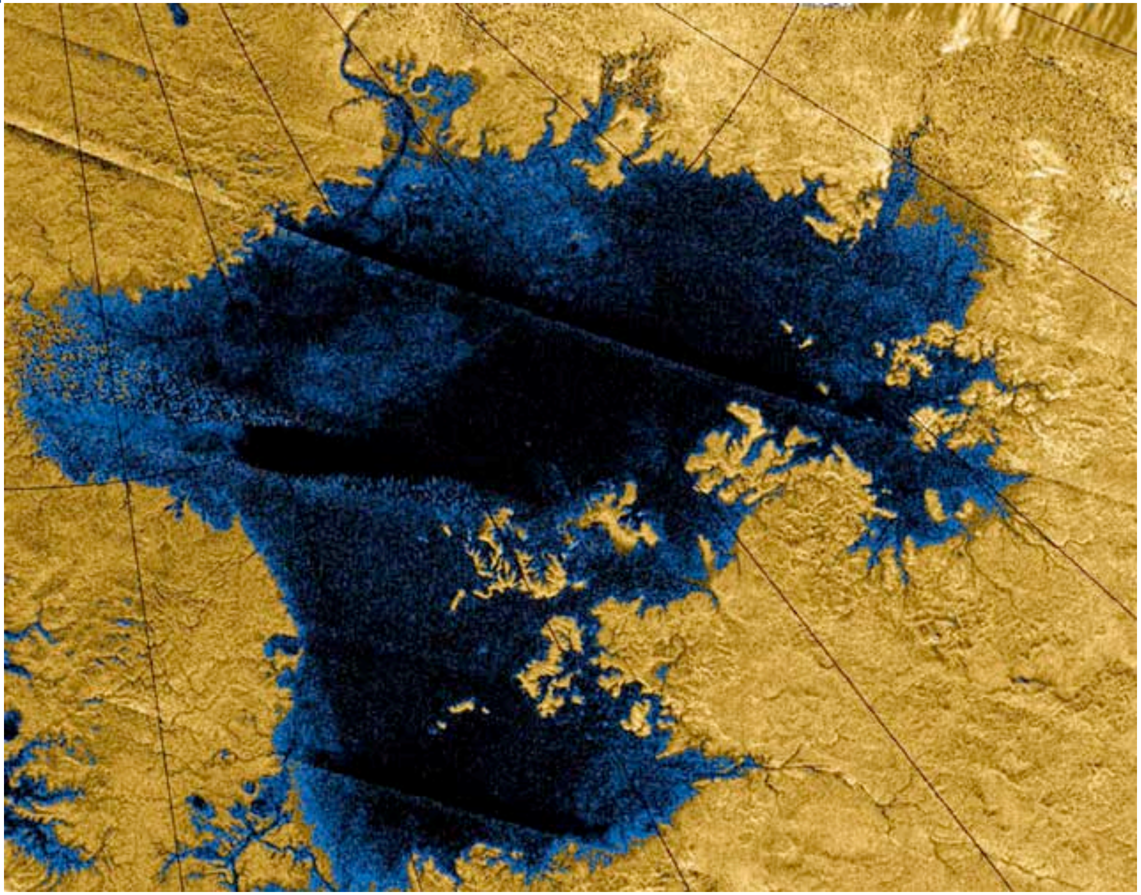
False color Cassini image showing the amount of radar signal reflected from a region of Titan's northern hemisphere. Dark regions are likely lakes.

The Big Picture

- Earth and Titan are the only two objects in the solar system that have stable bodies of liquid at the surface
- Similar processes help maintain surface liquids and atmospheric compositions, despite very different temperatures and materials at each body
- Surface liquids facilitate erosion, and can create 'Earth-like' landscapes (e.g. sedimentary layers, river beds, …)
- Surface liquids may exist on a variety of bodies orbiting other stars, and not be restricted to 'Earth-like' bodies

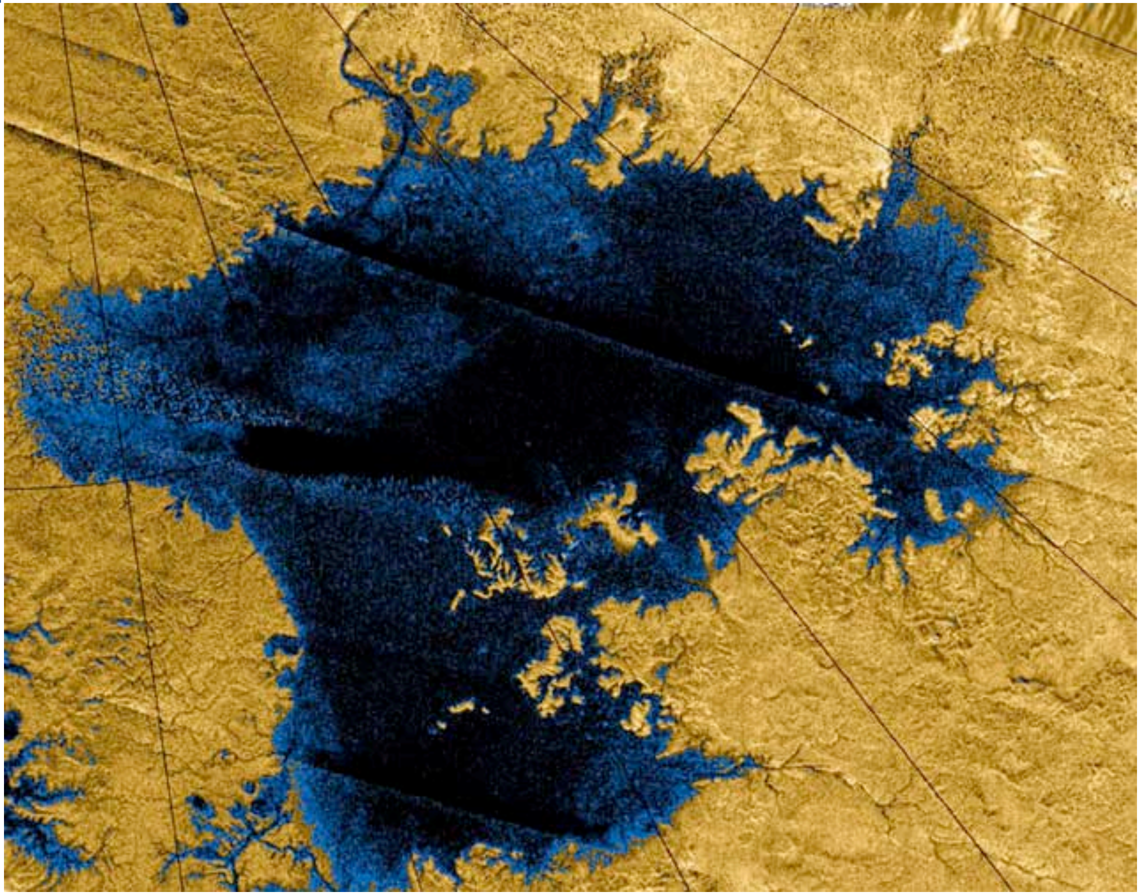
Photograph taken from the space shuttle of glinted sunlight from Earth's oceans.

What is the liquid in Titan's rivers and lakes?



A. water
B. sulfur
C. methane and ethane
D. methane and ammonia
E. sulfur and ammonia

What is the liquid in Titan's rivers and lakes?



A. water
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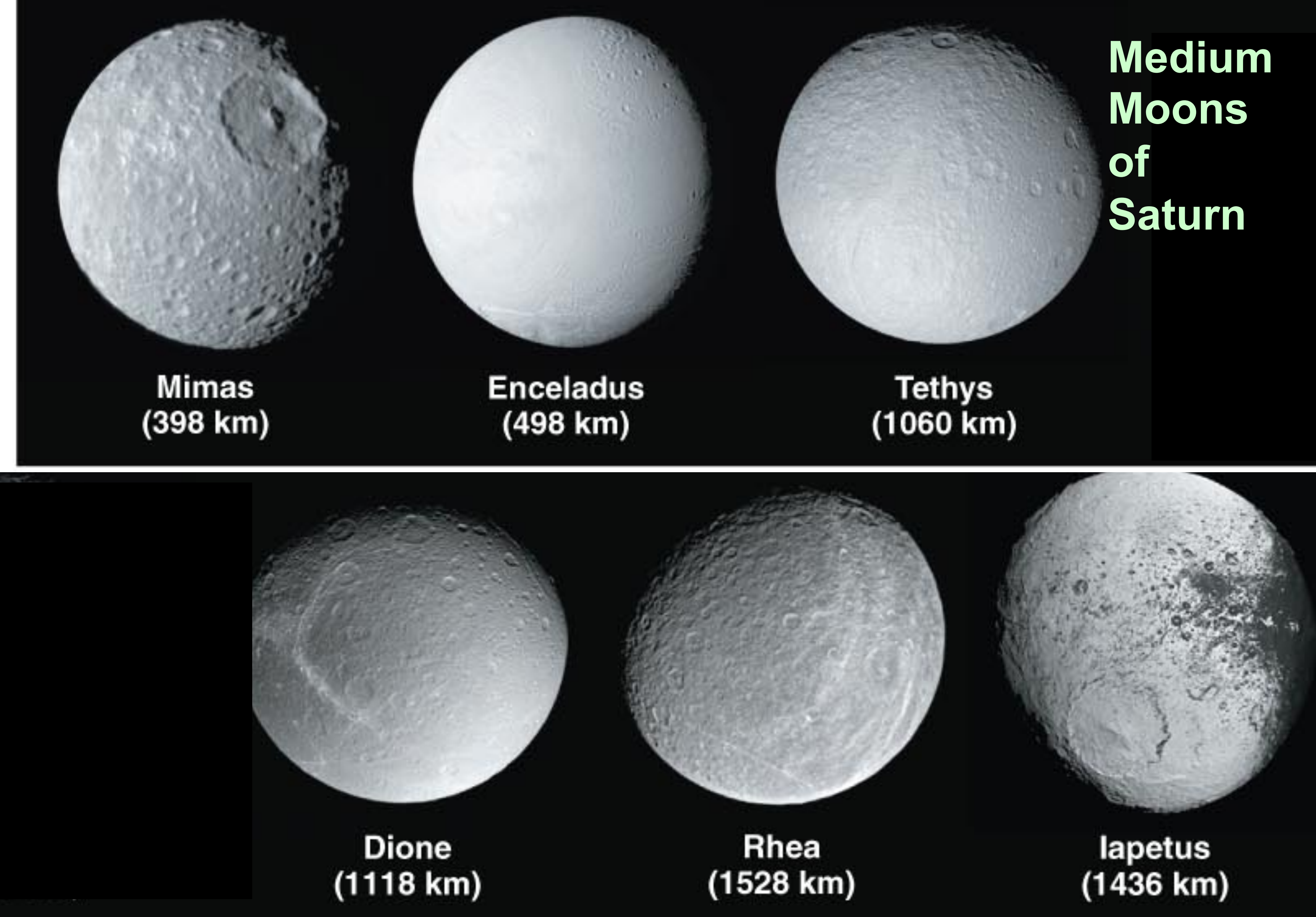
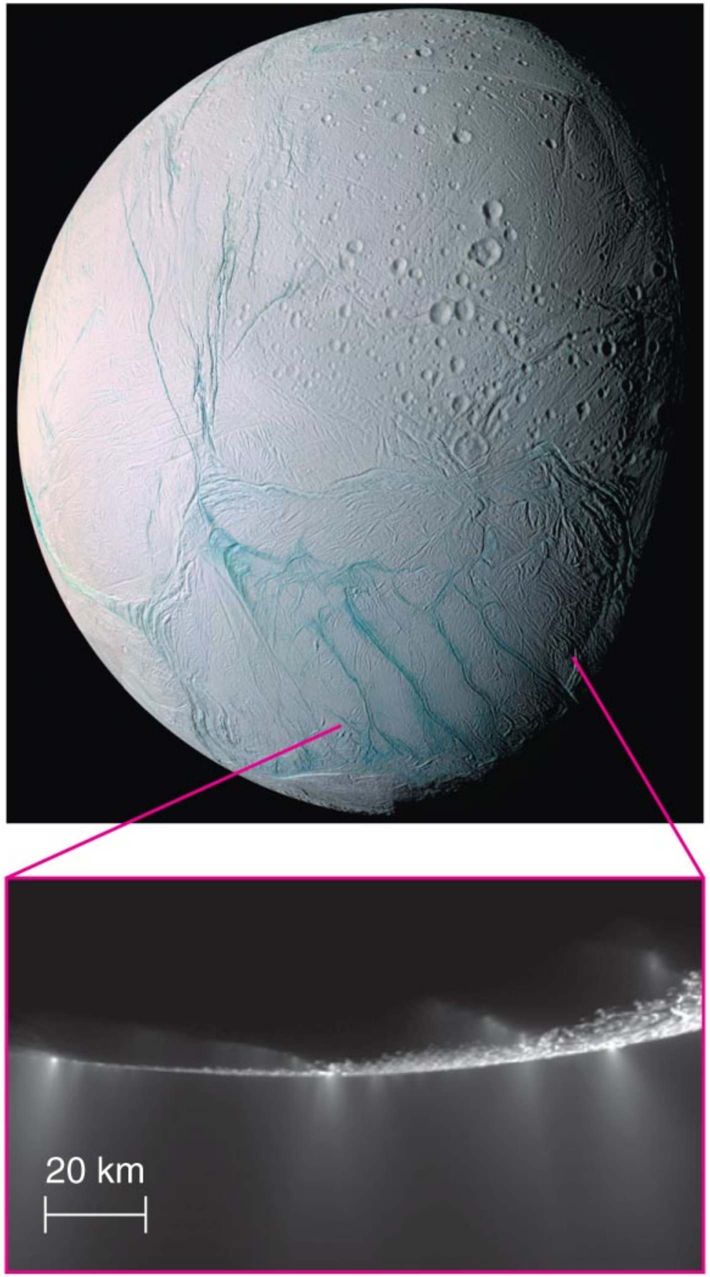
Medium Moons of Saturn



- Almost all of them show evidence of past volcanism and/or tectonics.

Medium Moons of Saturn

- Ice fountains of Enceladus suggest it may have a subsurface ocean
- Aside from Titan science, this is probably the biggest discovery of Cassini about Saturn’s moons



An Ocean Below Enceladus' Icy Crust?

- NASA's Cassini spacecraft has observed plumes of material escaping from Saturn's small icy moon, Enceladus
- The plume is mostly water vapor, with tiny ice particles and other gaseous molecules mixed in (e.g. CO_2, CH_4, C_2H_6)
- The plume supplies ice particles to one of Saturn's rings
- Some ice particles contain salt, which may indicate they originate in an ocean deep below the icy crust

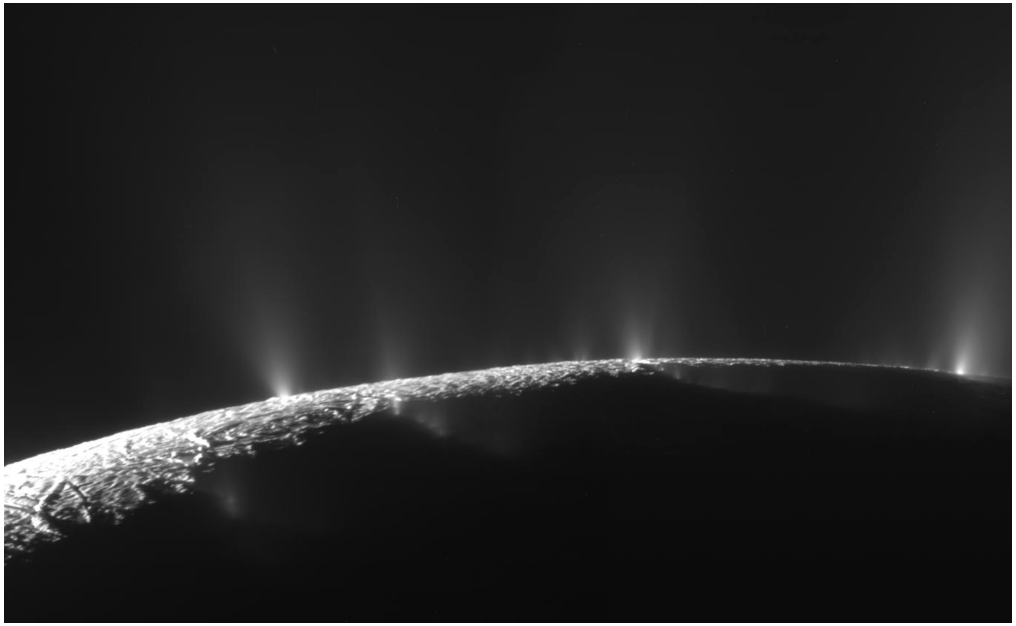
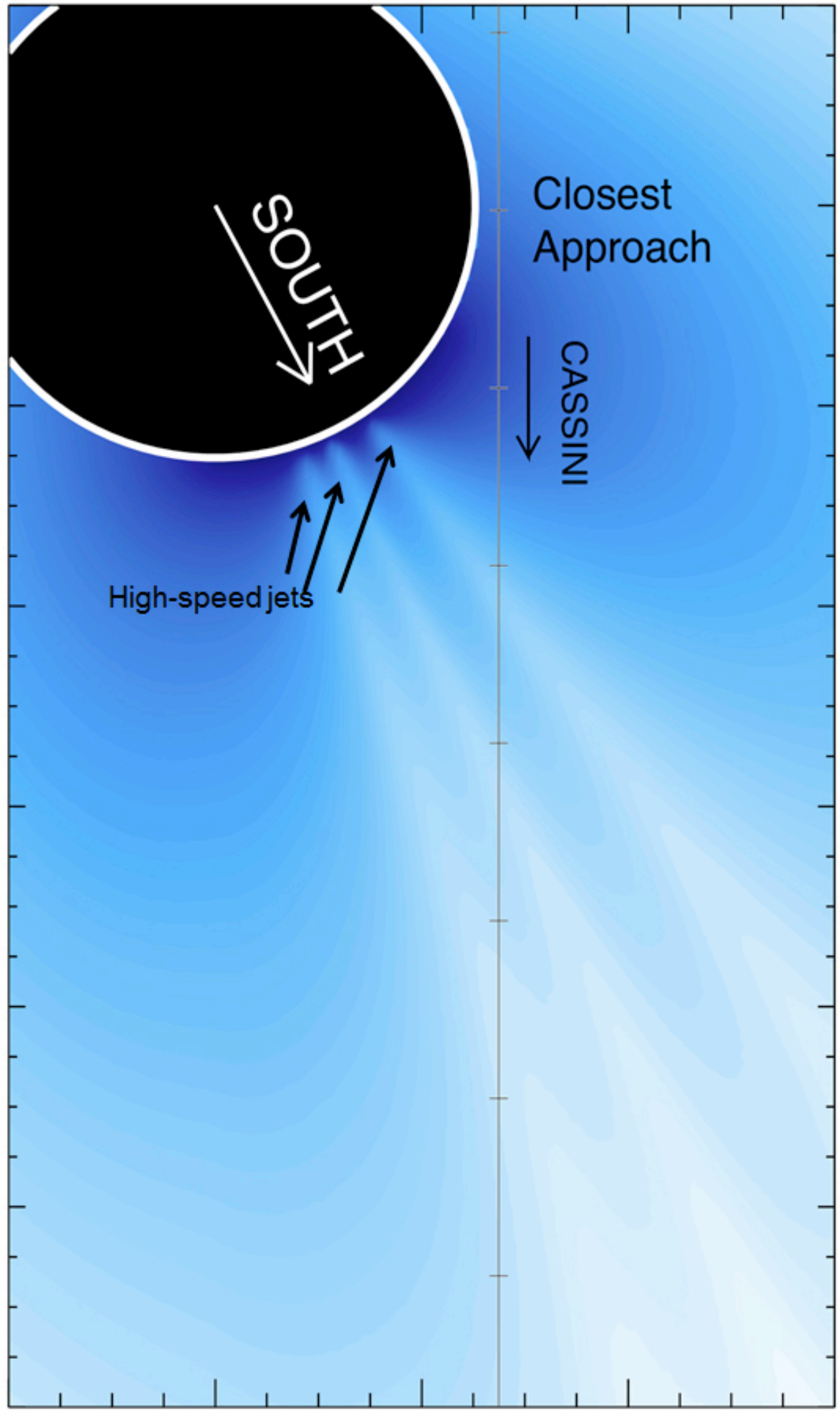


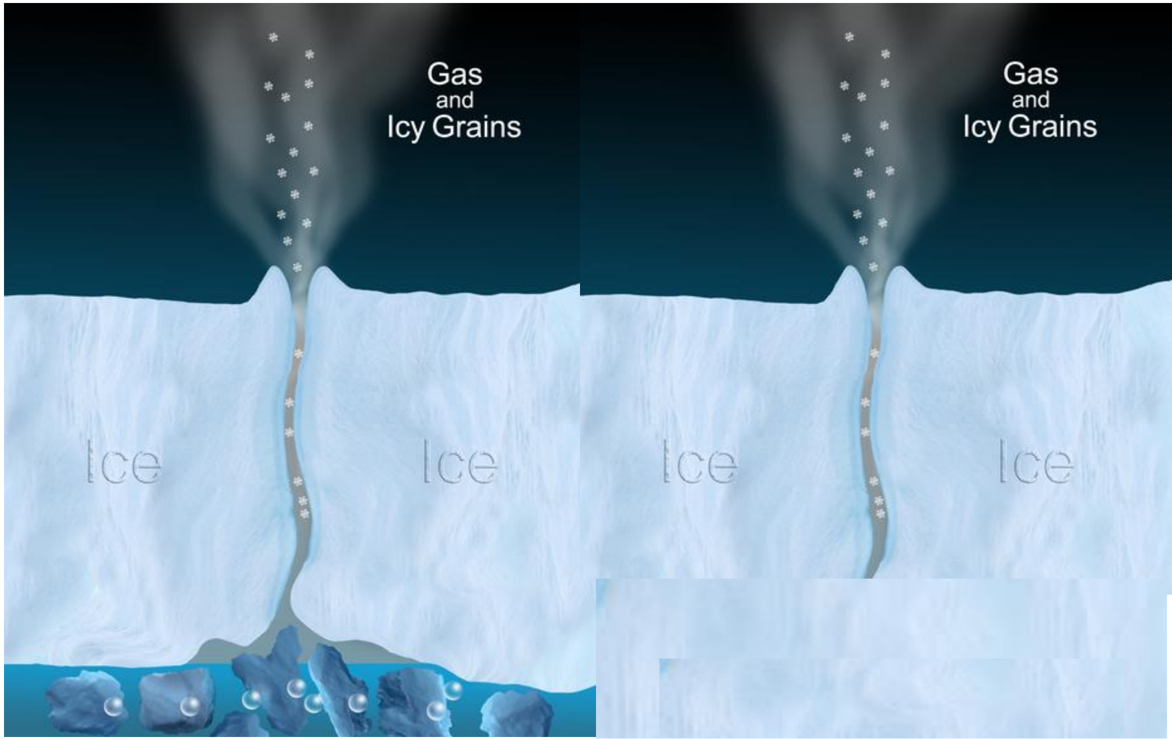
Image mosaic of Enceladus taken by Cassini, showing individual plumes of gas and ice escaping from the surface. The plumes extend 100's of km into space from the ~500 km diameter moon.



SOUTH
Closest
Approach
CASSINI
High-speed jets

What Process Creates the Plume?

- It may be that plumes are escaping through surface cracks from an internal salty ocean or lake
- Alternatively, ice along cracks may sublime or melt, followed by escape of water vapor and icy particles
- Many scientists find the salty ocean model most convincing, but others favor combinations of alternative explanations



Left: Enceladus may have a salty subsurface ocean that releases material to space through cracks in the moon's icy shell. Right: The walls of icy cracks in the surface may melt or sublime, venting gas and icy particles to space.

The Big Picture

- Enceladus is surprisingly active for such a small body - likely a consequence of tidal heating
- Future flybys of Enceladus by Cassini may help to resolve whether Enceladus joins the growing "club" of solar system bodies believed to have oceans
- If Enceladus has an ocean, then it contains all of the 'ingredients' known to be important for life: liquid water, molecular building blocks, and energy

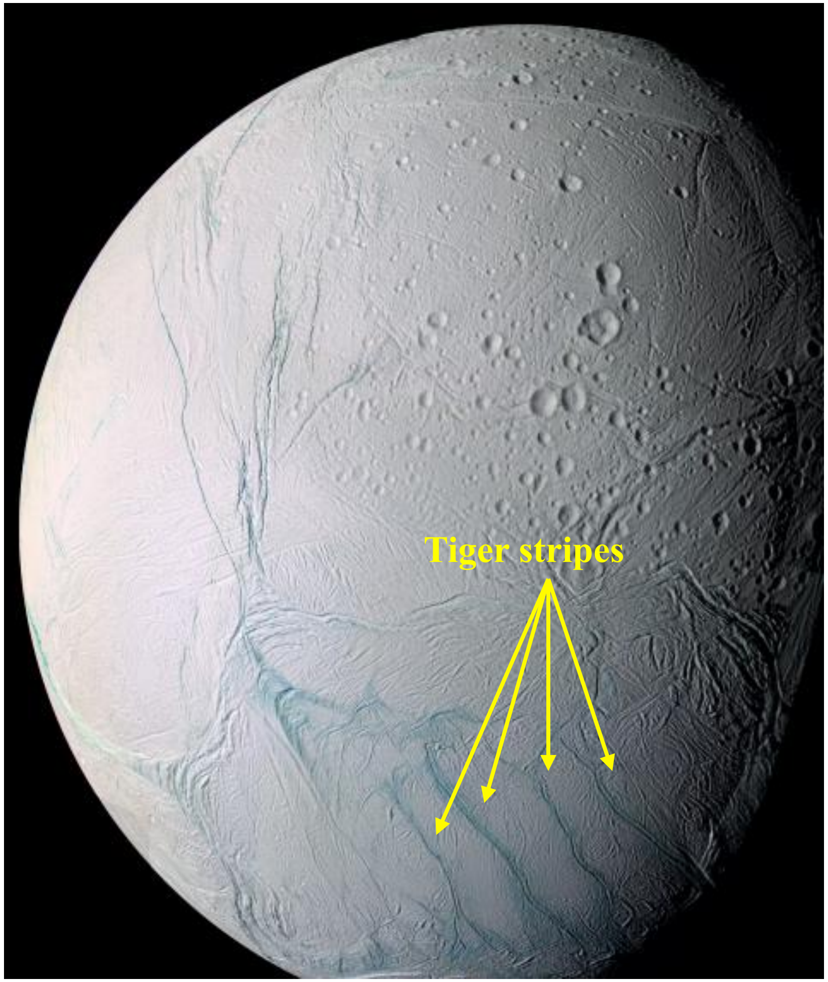


Image of Enceladus showing the 'tiger stripes' region in the southern hemisphere, where the plumes originate

New Science Last Month!

LETTER

doi:10.1038/nature12371

An observed correlation between plume activity and tidal stresses on Enceladus

M. M. Hedman[1], C. M. Gosmeyer[2], P. D. Nicholson[1], C. Sotin[3], R. H. Brown[4], R. N. Clark[5], K. H. Baines[3], B. J. Buratti[3] & M. R. Showalter[6]

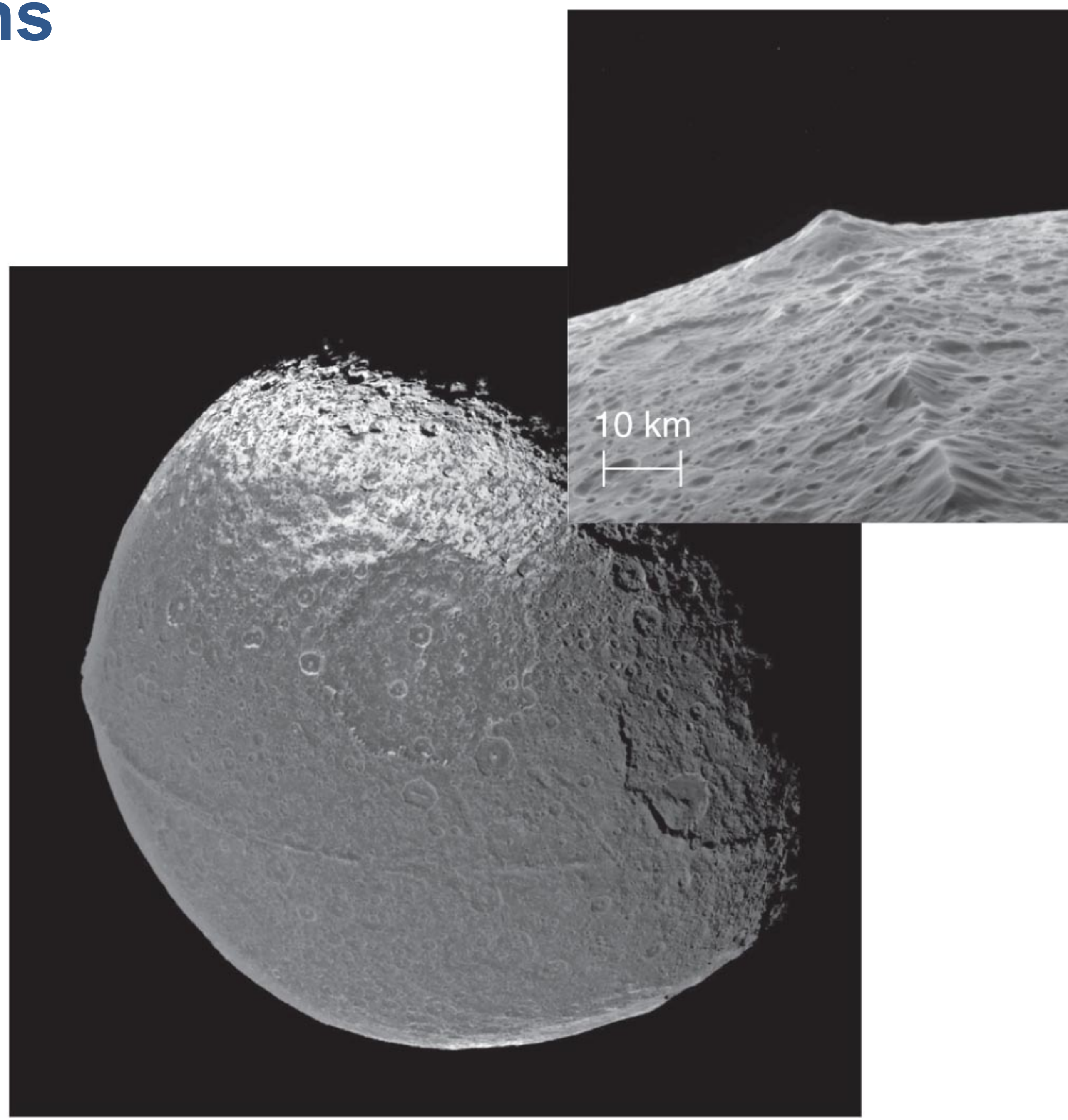
Saturn's moon Enceladus emits a plume of water vapour and micrometre-sized ice particles from a series of warm fissures located near its south pole[1–10]. This geological activity could be powered or controlled by variations in the tidal stresses experienced by Enceladus as it moves around its slightly eccentric orbit. The specific mechanisms by which these varying stresses are converted into heat, however, are still being debated[11–16]. Furthermore, it has proved difficult to find a clear correlation between the predicted tidal forces and measured temporal variations in the plume's gas content[17–19] or the particle flux from individual sources[20,21]. Here we report that the plume's horizontally integrated brightness is several times greater when Enceladus is near the point in its eccentric orbit where it is furthest from Saturn (apocentre) than it is when near the point of closest approach to the planet (pericentre). More material therefore seems to be escaping from beneath Enceladus' surface at times when geophysical models predict its fissures should be under tension[12,15,16] and therefore may be wider open.

Owing to variations in the distance between Cassini and Enceladus, different observations sample the plume's brightness at different altitudes. Hence, in order to derive comparable quantitative estimates of the plume's brightness, we interpolate the brightness data from each observation to a common altitude. Fortunately, the plume's brightness decreases with altitude in a regular manner. Let us define the plume's 'equivalent width' (EW) at a given altitude z above Enceladus' south pole as the total integrated brightness in a horizontal slice through the plume (that is, a fixed z) after removing any background signal from Saturn's E ring (see Supplementary Information). For low-optical-depth systems like the plume, this quantity is insensitive to both the image resolution and the alignment of the fissures, which facilitates comparisons between different observations. Furthermore, as shown in Fig. 2, EW is a nearly linear function of the parameter Z (= $[z/(r_E + z)]^{1/2}$, where $r_E = 250$ km is the radius of Enceladus). This trend is not only a useful empirical fit to the data, it can also be physically justified on the basis of considerations of the velocity dis-

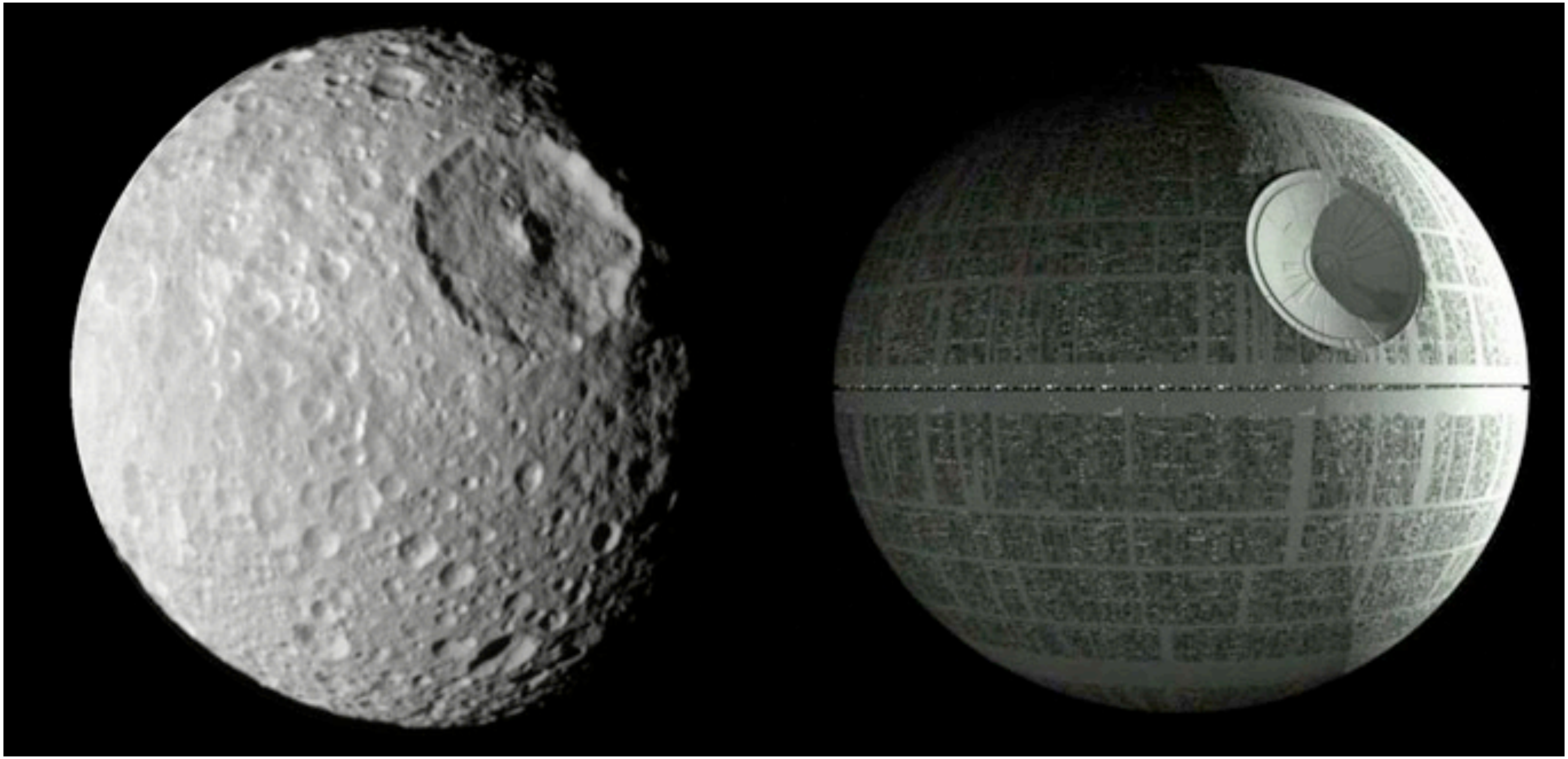
- On it's slightly eccentric orbit, the plumes are brightest when Enceladus is being squished the most

Medium Moons of Saturn

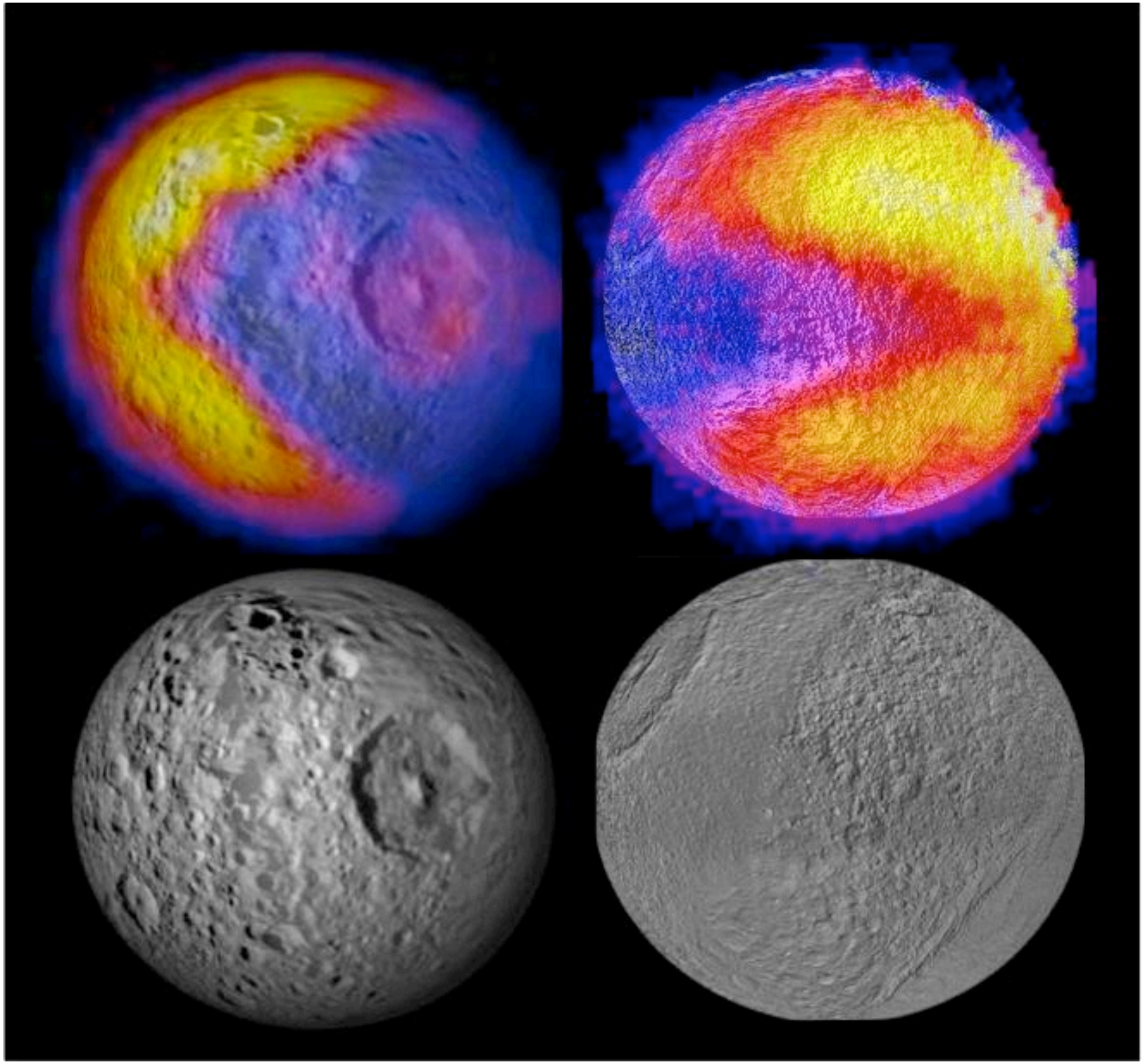
- Iapetus has a curious ridge around much of its equator
- 10 km high
- Likely the result of some kind of tectonic activity
- Weird light/ dark dichotomy



Mimas is Awesome

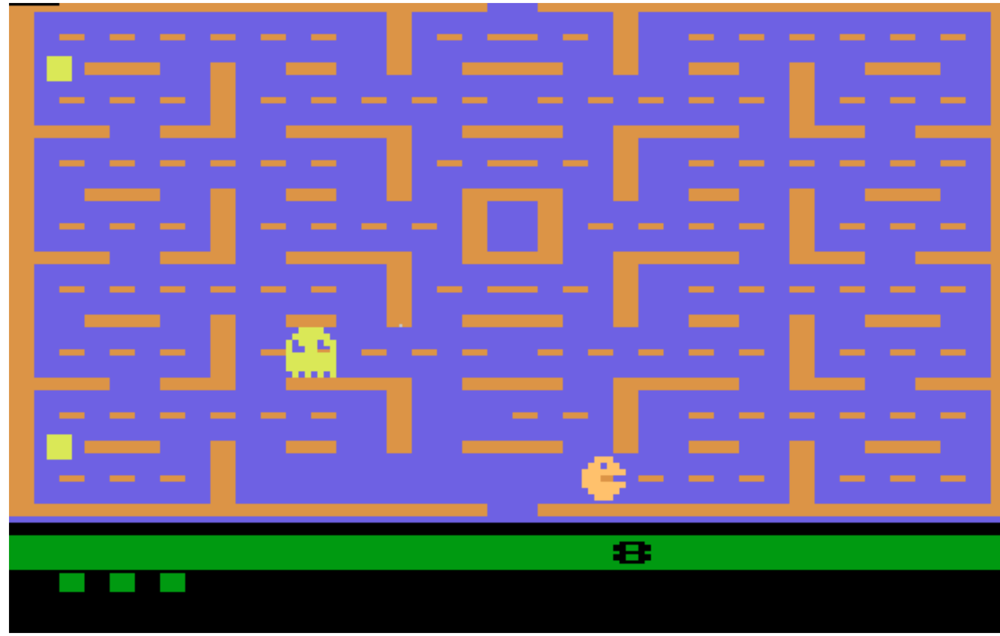


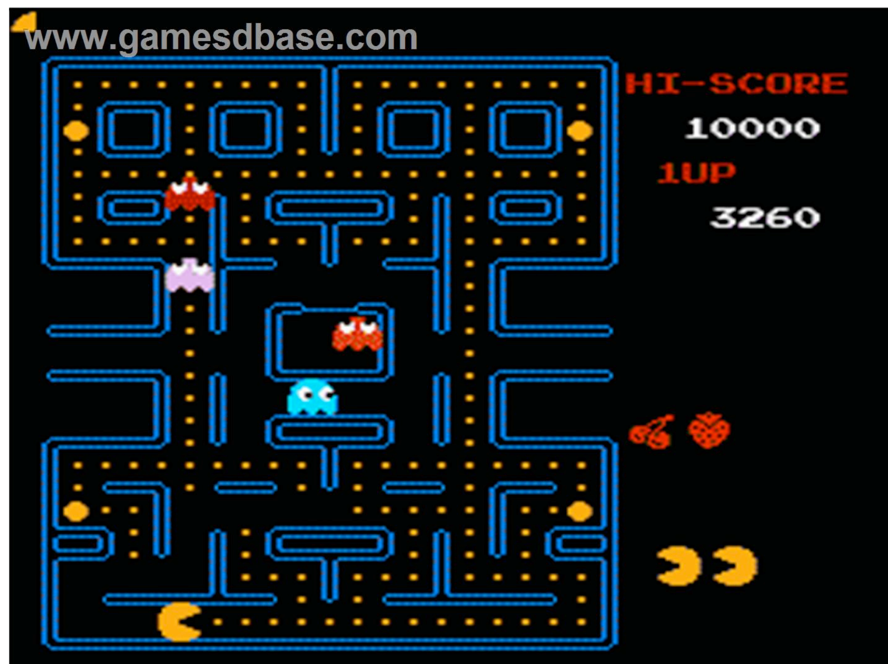
Albedo and Wien’s Law at Work on Mimas



Pac-man, 1980


game program™
PAC-MAN
Use with Joystick Controllers
ATARI®
CX2646
Label, Program & Audiovisual © 1981 ATARI, INC
PAC-MAN is licensed by Namco America, Inc

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READY PLAYER ONE
ERNEST CLINE
A NOVEL

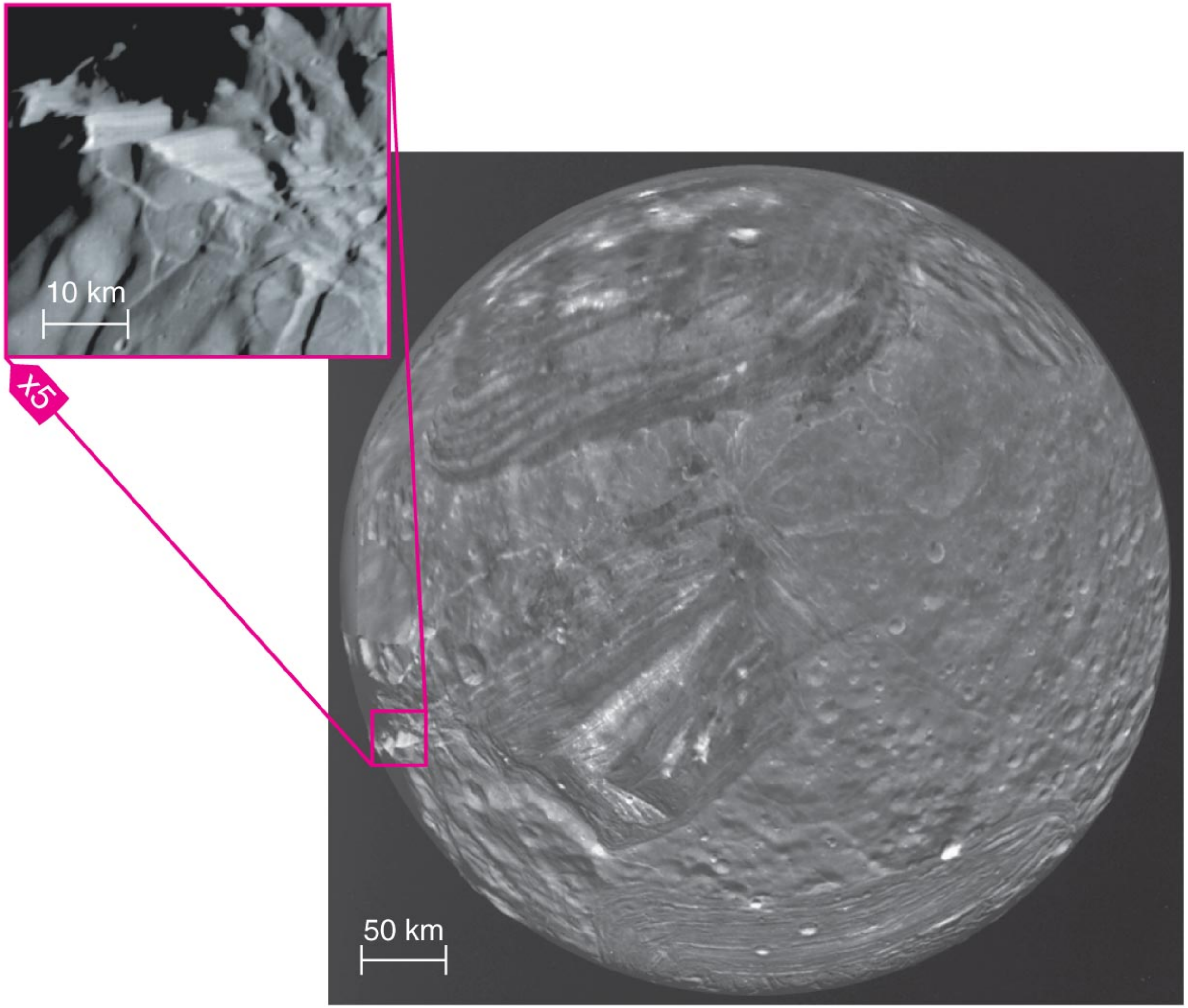
Clicker Question 3

- How does Ms. Pac-Man (1982) differ from Pac-Man (1980)?

  In Ms. Pac-Man:

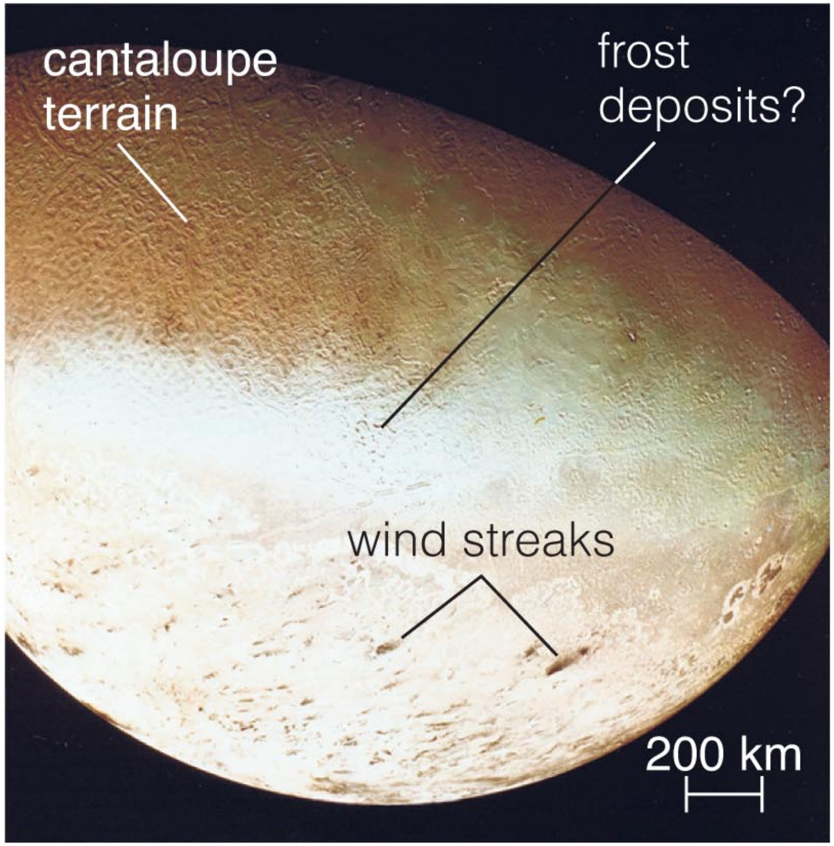
A. The Pac-Man moves faster
B. The ghost motions are randomized
C. There are multiple mazes instead of one
D. The orange ghost is named Sue, rather than Clyde
E. All of the above

Medium Moons of Uranus

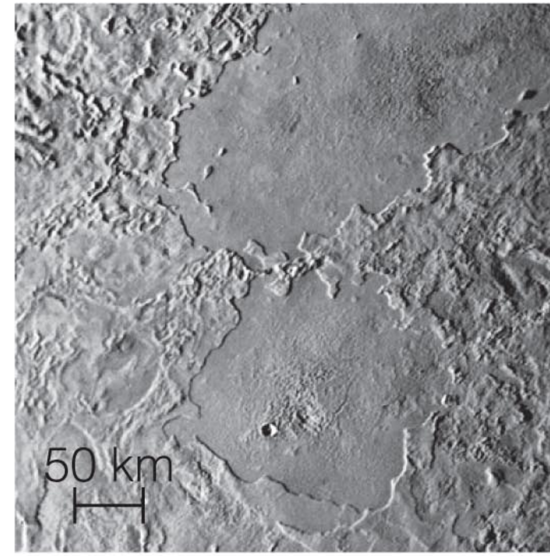


- They have varying amounts of geological activity.
- Miranda has large tectonic features and few craters (possibly indicating an episode of tidal heating in past).

Neptune's Moon Triton



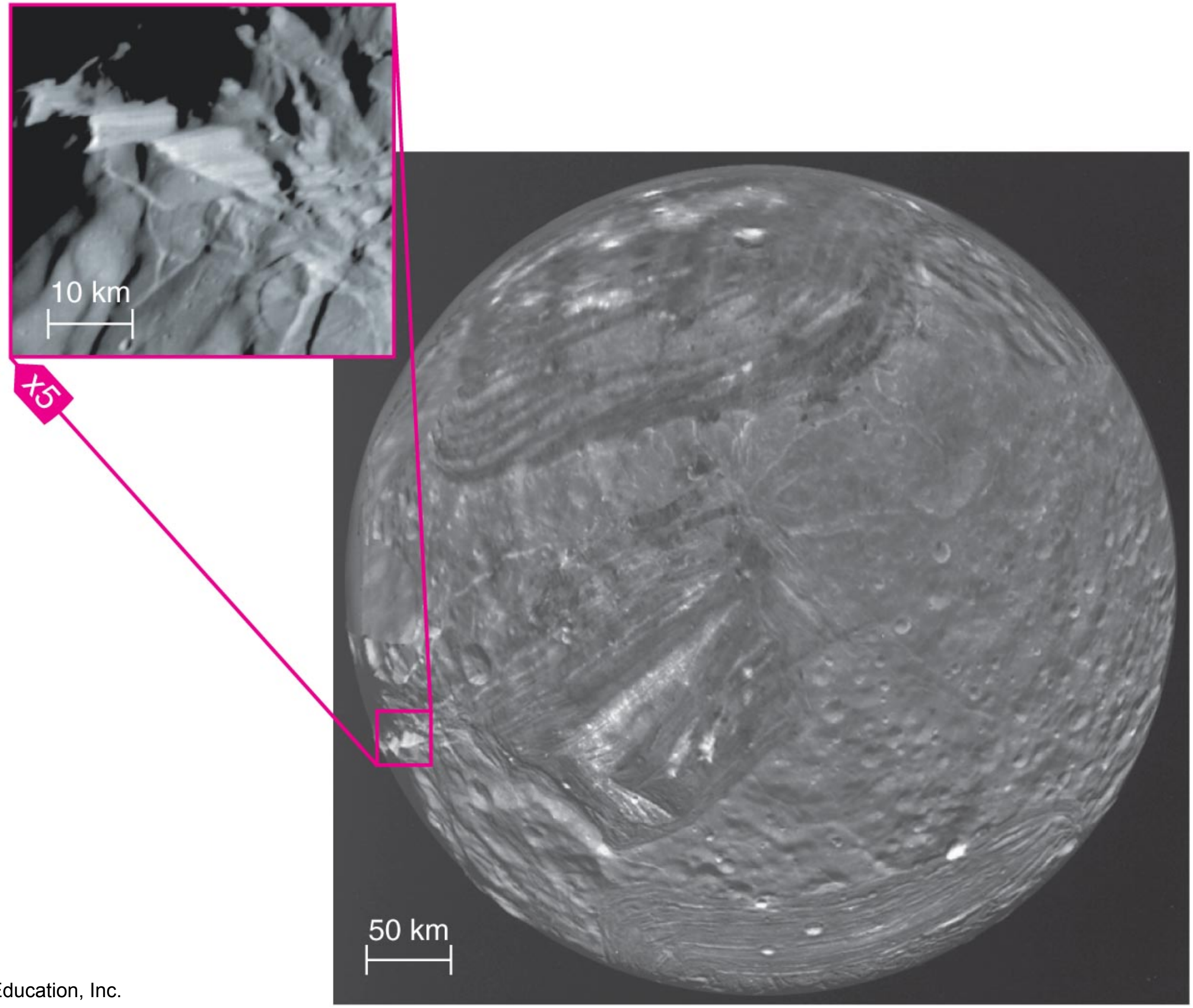
Triton's southern hemisphere as seen by *Voyager 2*.



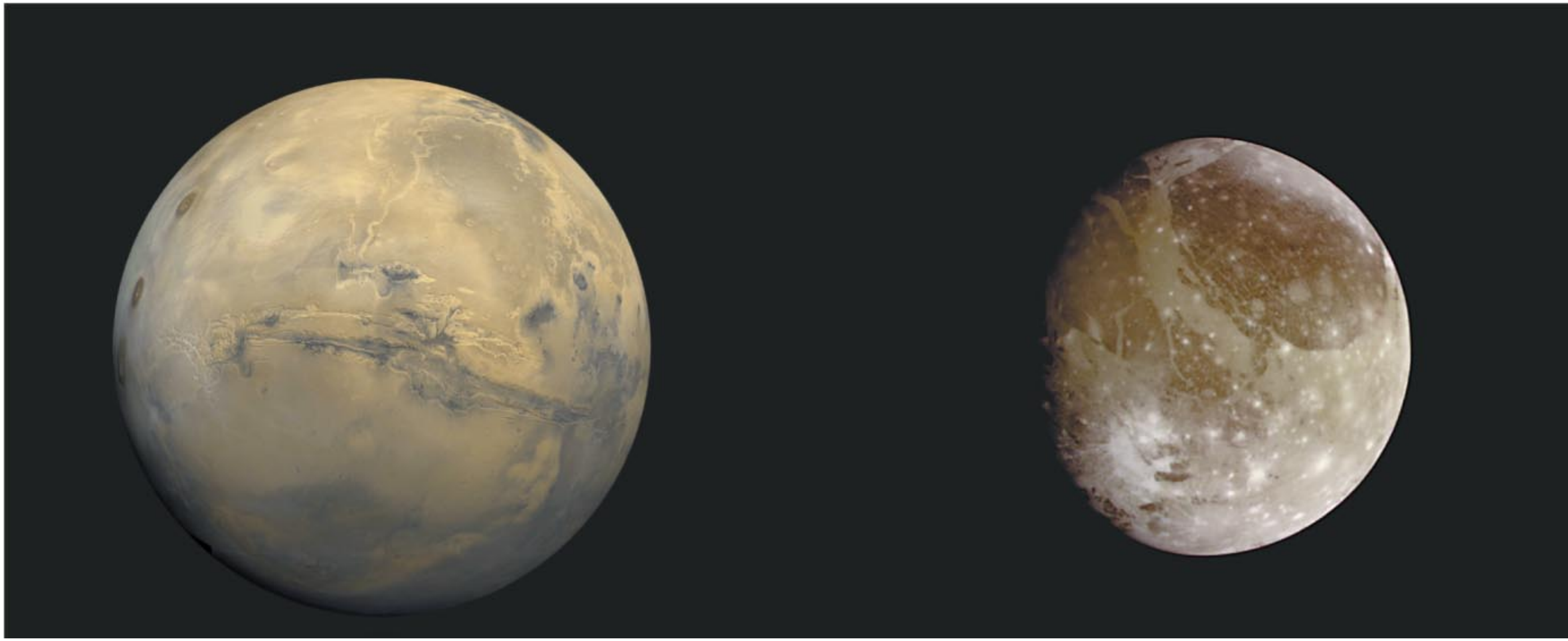
This close-up shows lava-filled impact basins similar to the lunar maria, but the lava was water or slush rather than molten rock.

- Similar to Pluto, but larger
- Evidence of past geological activity
- Orbits *retrograde* and inclined. It's capture likely wiped out the the original satellite system
- Probably had intense tidal heating after capture

Why are small icy moons more geologically active than small rocky planets?



Rocky Planets versus Icy Moons: even small icy moons are not "dead"



- Rock melts at higher temperatures.
- Only large rocky planets have enough heat for activity.

- Ice melts at lower temperatures.
- Tidal heating can melt internal ice, driving activity.

What have we learned?

- **What kinds of moons orbit the jovian planets?**
  - Moons come in many sizes.
  - The level of geological activity depends on a moon's size.
- **Why are Jupiter's Galilean moons so geologically active?**
  - Tidal heating drives geological activity, leading to Io's volcanoes and ice geology on other moons.

What have we learned?

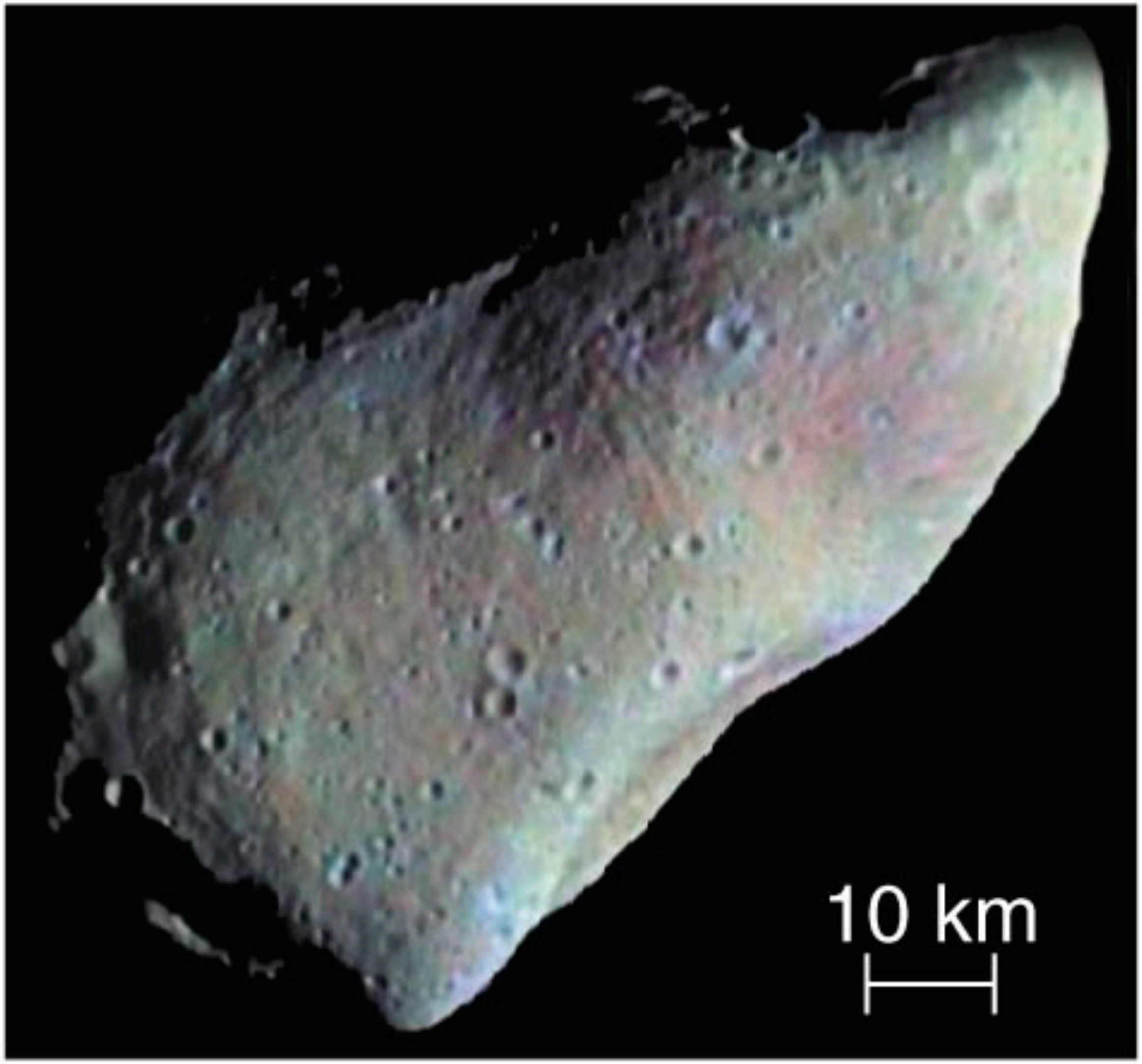
- **What is special about Titan and other major moons of the solar system?**
  – Titan is only moon with thick atmosphere.
  – Many other major moons show signs of geological activity.
- **Why are small icy moons more geologically active than small rocky planets?**
  – Ice melts and deforms at lower temperatures, enabling tidal heating to drive activity.

12.1 Asteroids and Meteorites

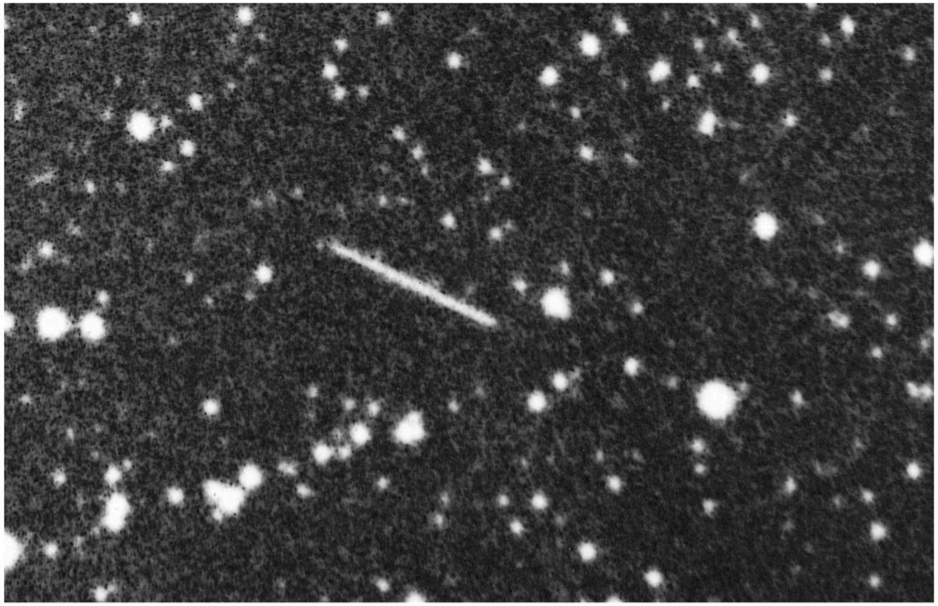
Our goals for learning:

- What are asteroids like?
- Why is there an asteroid belt?
- Where do meteorites come from?

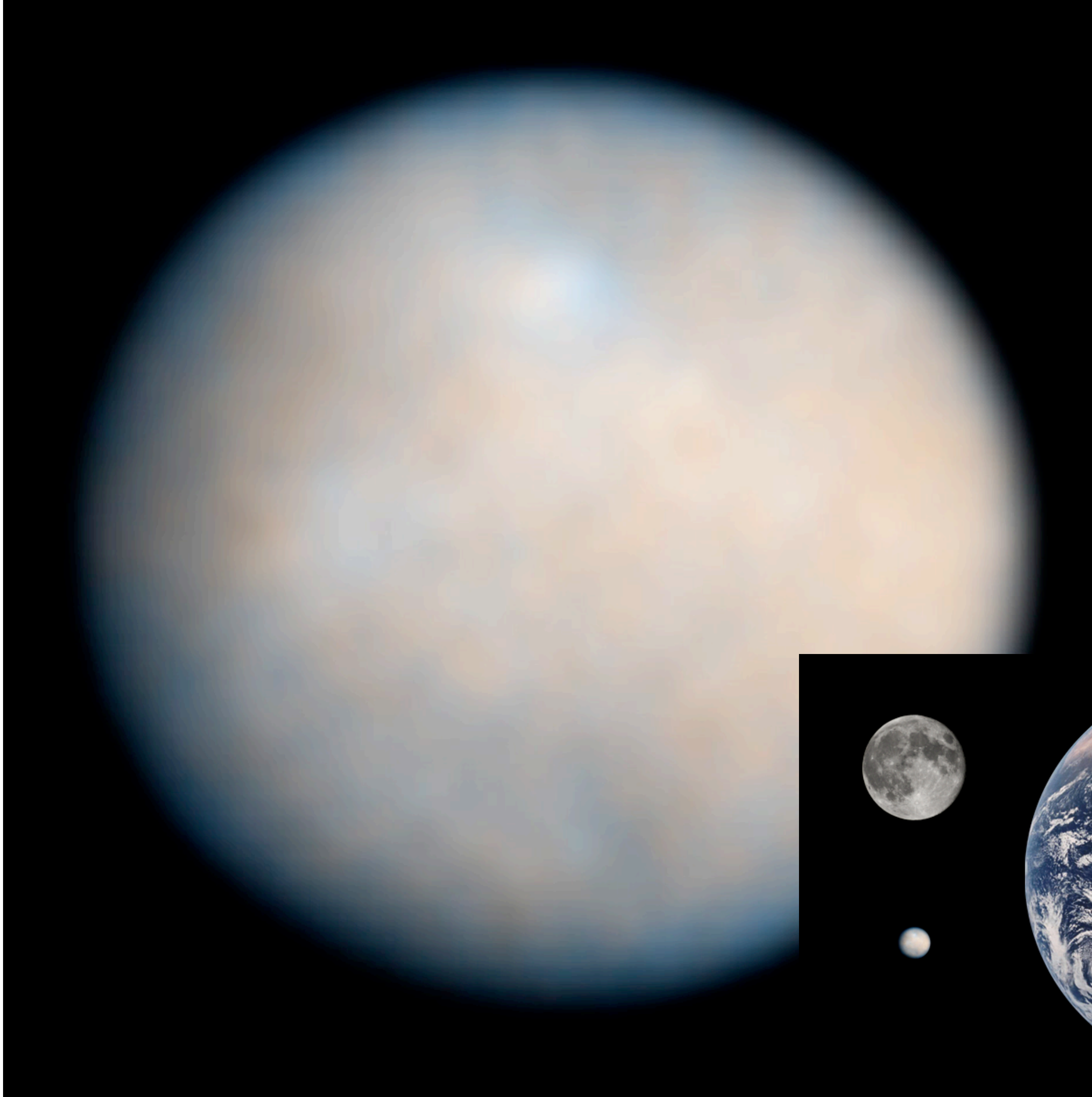
What are asteroids like?



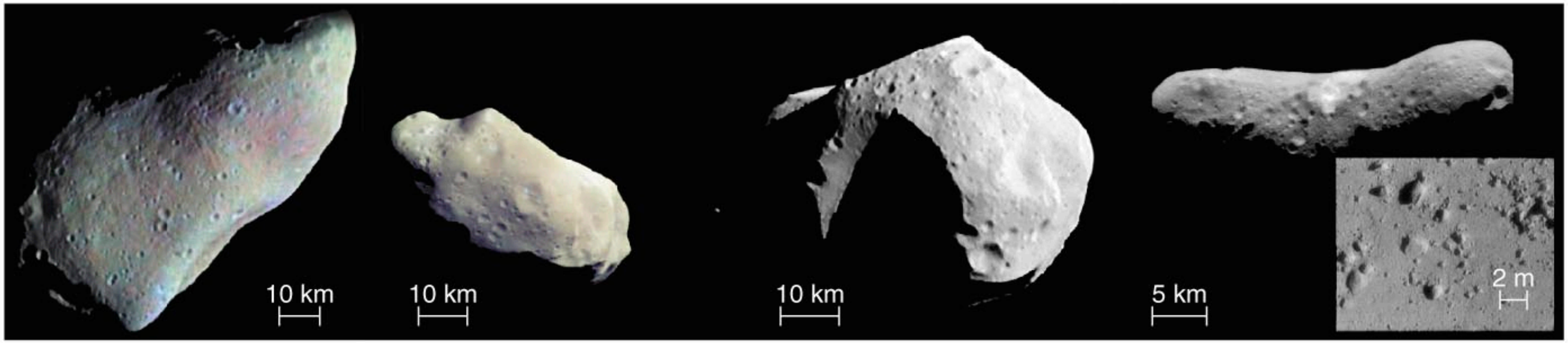
Asteroid Facts



- Asteroids are rocky leftovers of planet formation.
- The largest is Ceres, diameter ~1000 kilometers.
- 150,000 in catalogs, and probably over a million with diameter >1 kilometer.
- Small asteroids are more common than large asteroids.
- All the asteroids in the solar system wouldn't add up to even a small terrestrial planet.



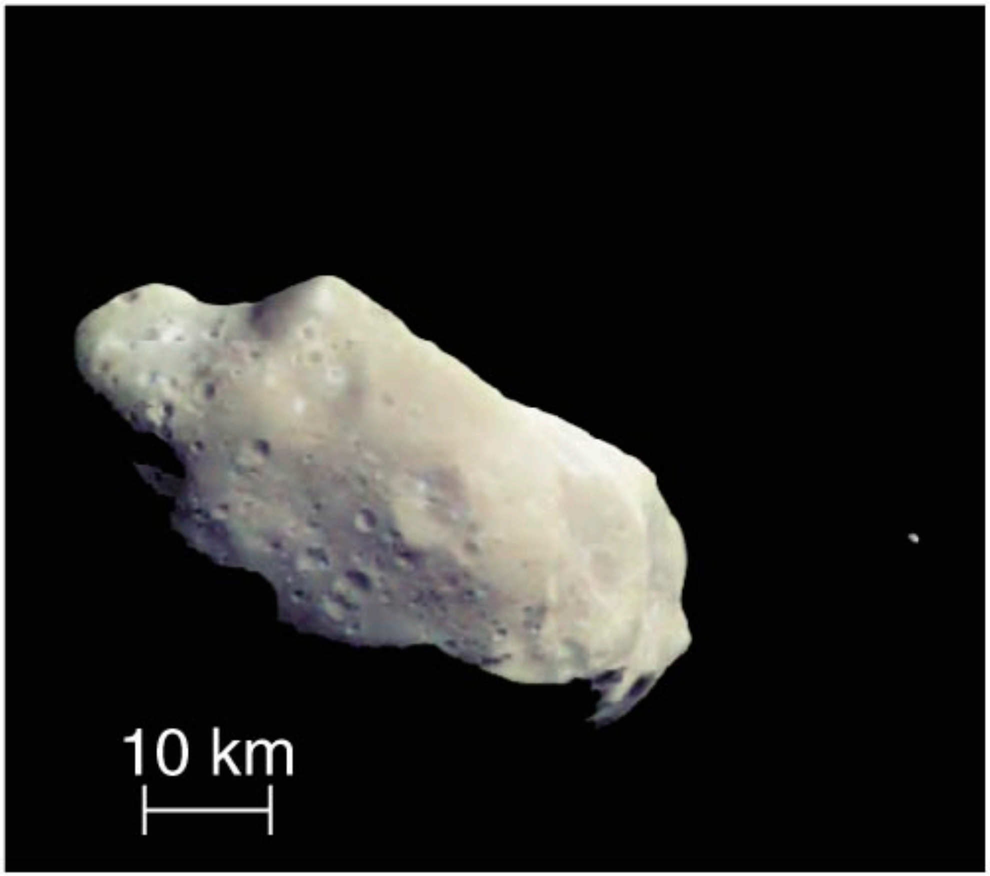
Ceres:
A "planet" for about 30 years in the mid 1800s



Asteroids are cratered and not round

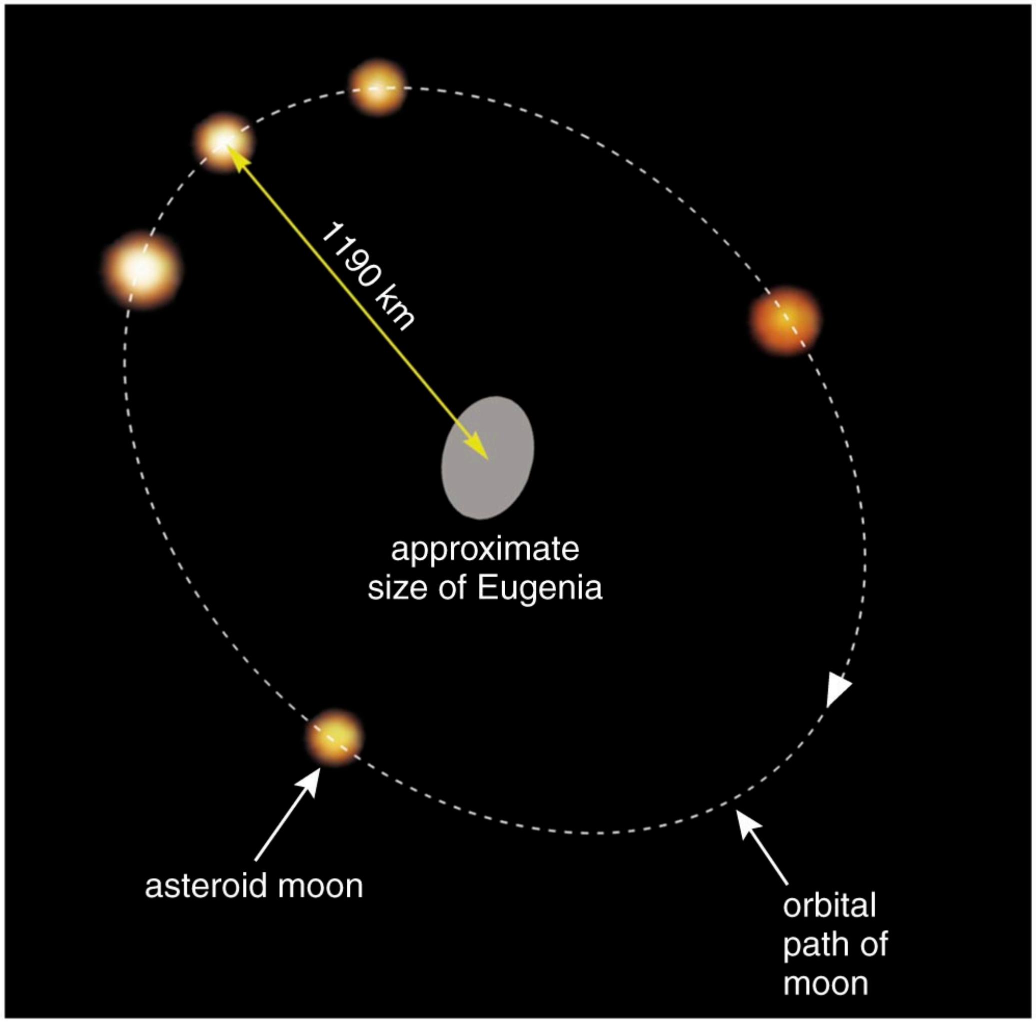
Gravity is not strong enough to overcome strength of rock and internal friction

Asteroids with Moons



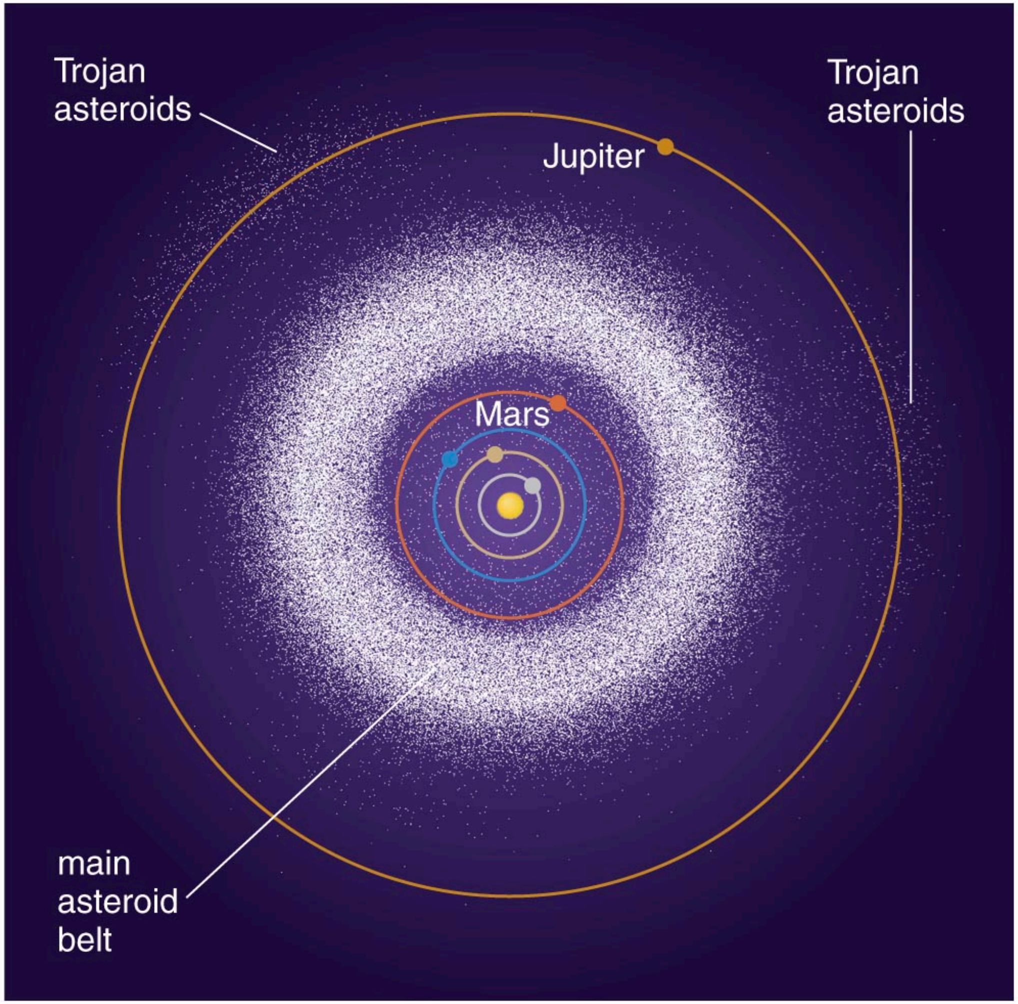
- Some large asteroids have their own moon
  - Newton's verions of Kepler's 3rd law gives masses
- Asteroid Ida has a tiny moon named Dactyl.

Density of Asteroids



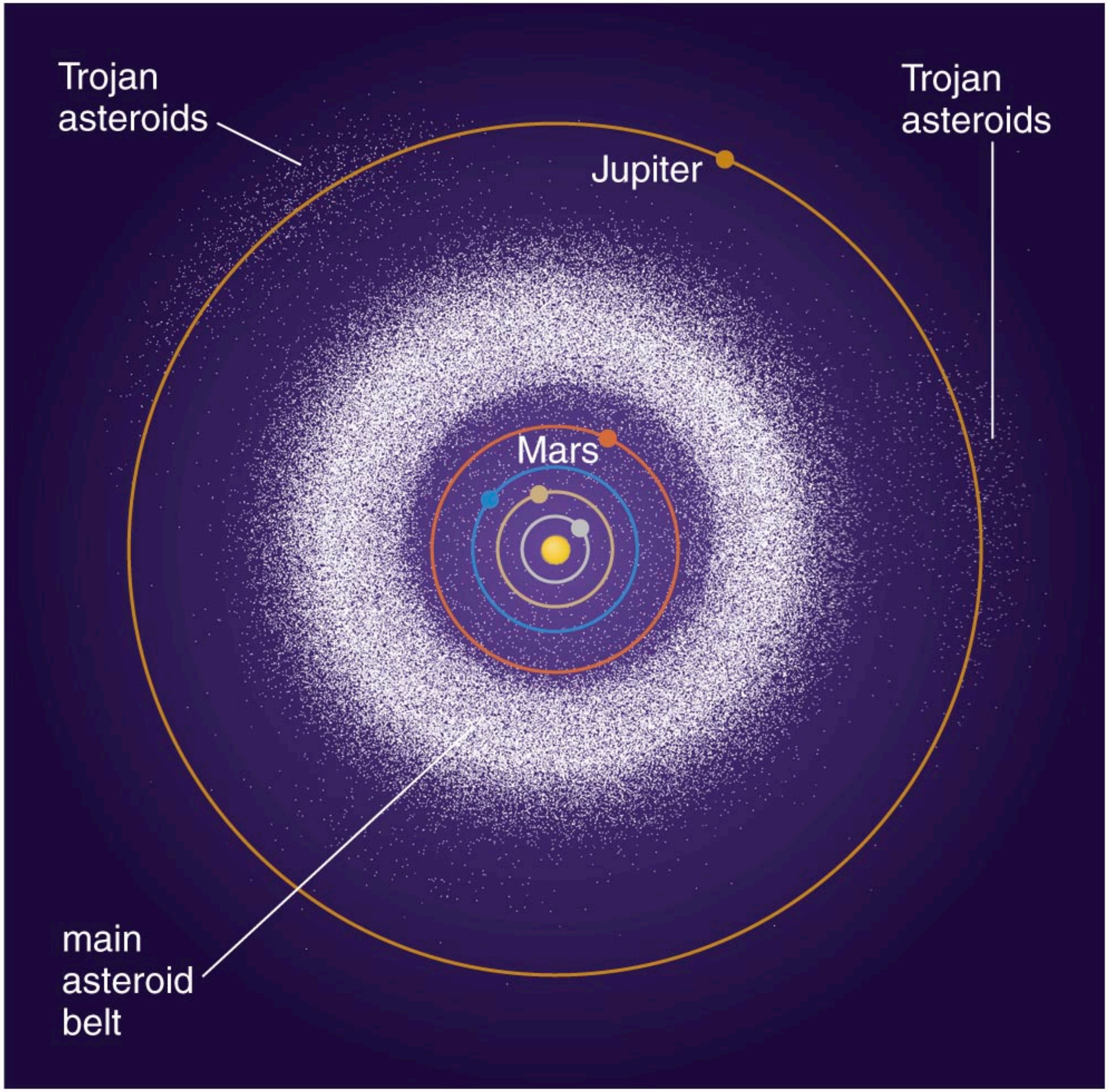
- Measuring the orbit of asteroid's moon tells us an asteroid's mass.
- Mass and size tell us an asteroid's density.
- Some asteroids are solid rock; others are just piles of rubble.

Asteroid Orbits

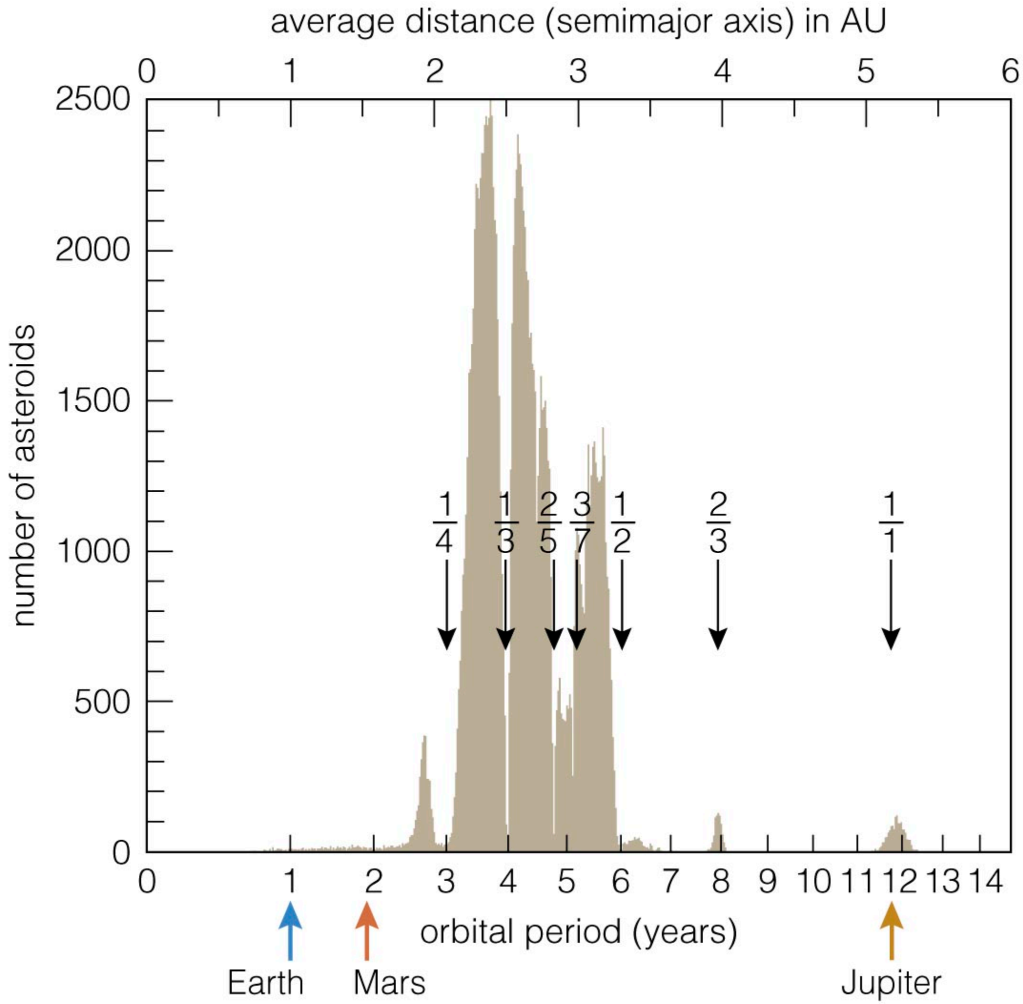


- Most asteroids orbit in the *asteroid belt* between Mars and Jupiter.
- *Trojan asteroids* follow Jupiter's orbit.
- Orbits of *near-Earth asteroids* cross Earth's orbit.

Why is there an asteroid belt?



Orbital Resonances



- Asteroids in orbital resonance with Jupiter experience periodic nudges.

- Eventually, those nudges move asteroids out of resonant orbits, leaving gaps in the asteroid belt.