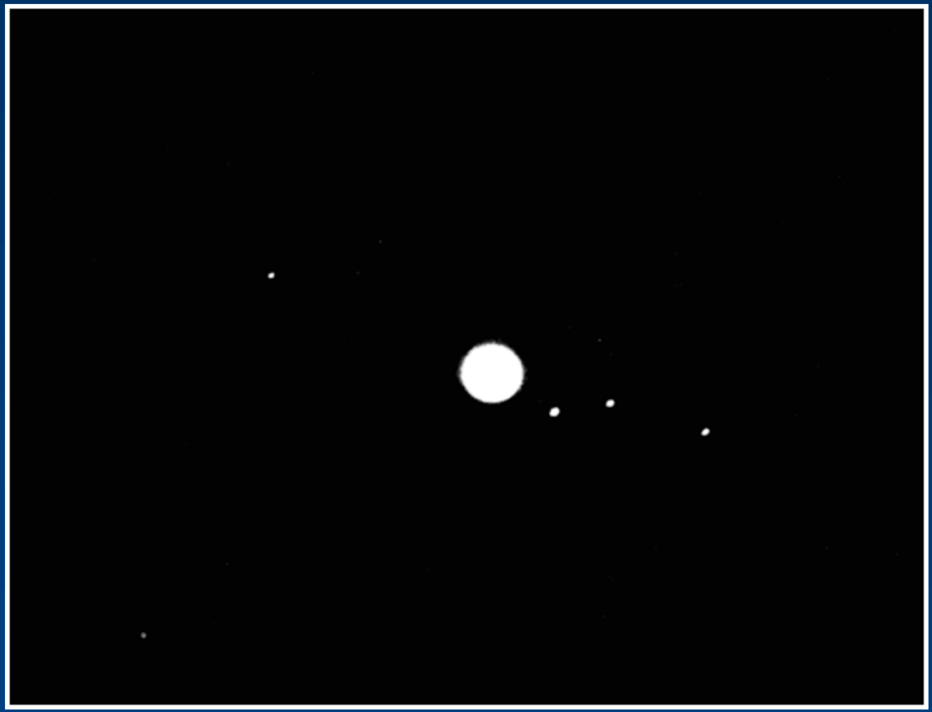
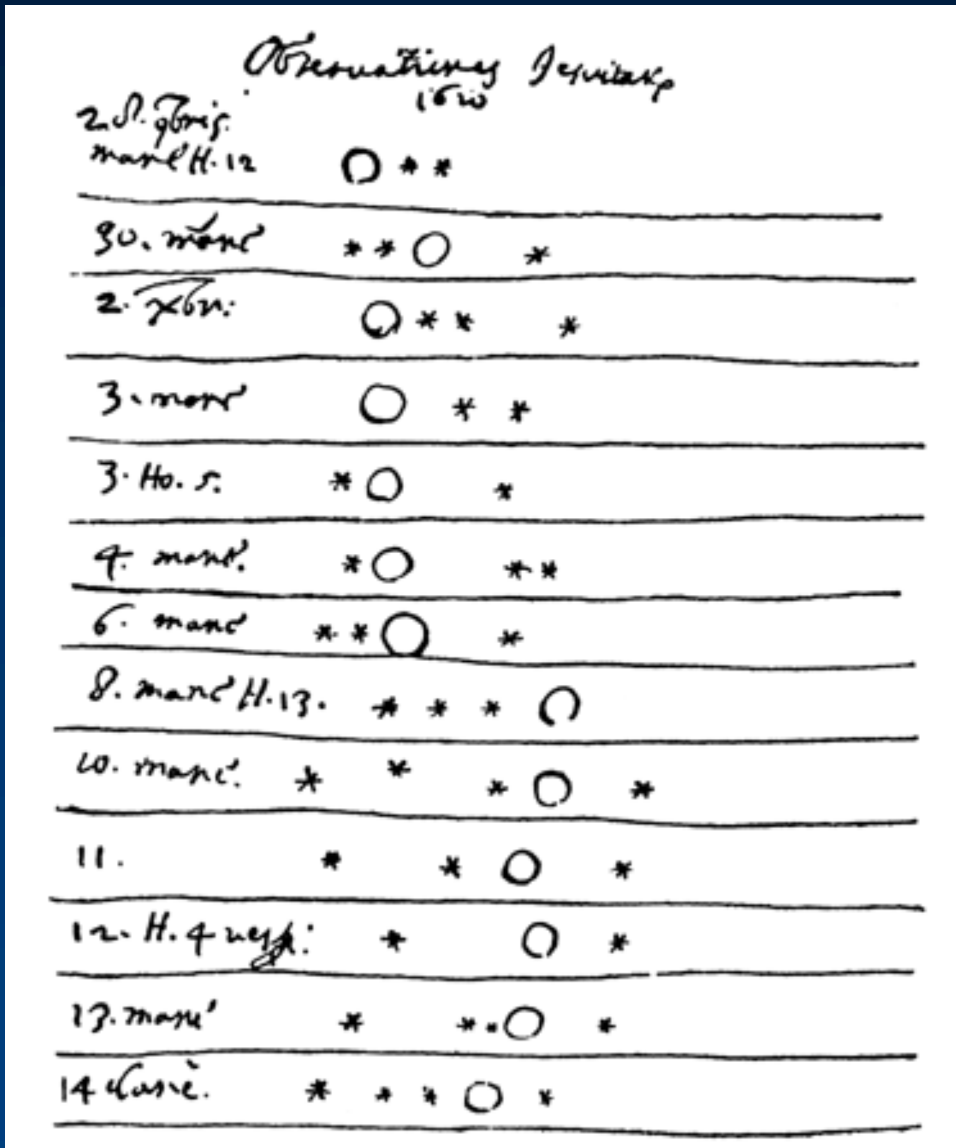
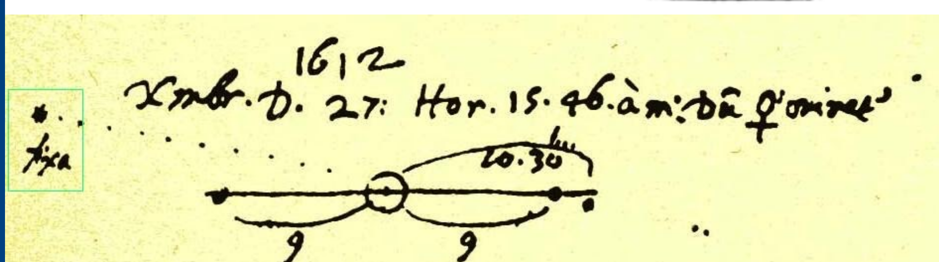
The moons of Jupiter and Saturn

Jupiter's Moons

The discovery of the Galilean satellites was important in the history of science. Galileo found objects *not* orbiting Earth.








Io
Europa
Ganymede
Callisto

Slightly smaller than our Moon

Largest moon in the solar system

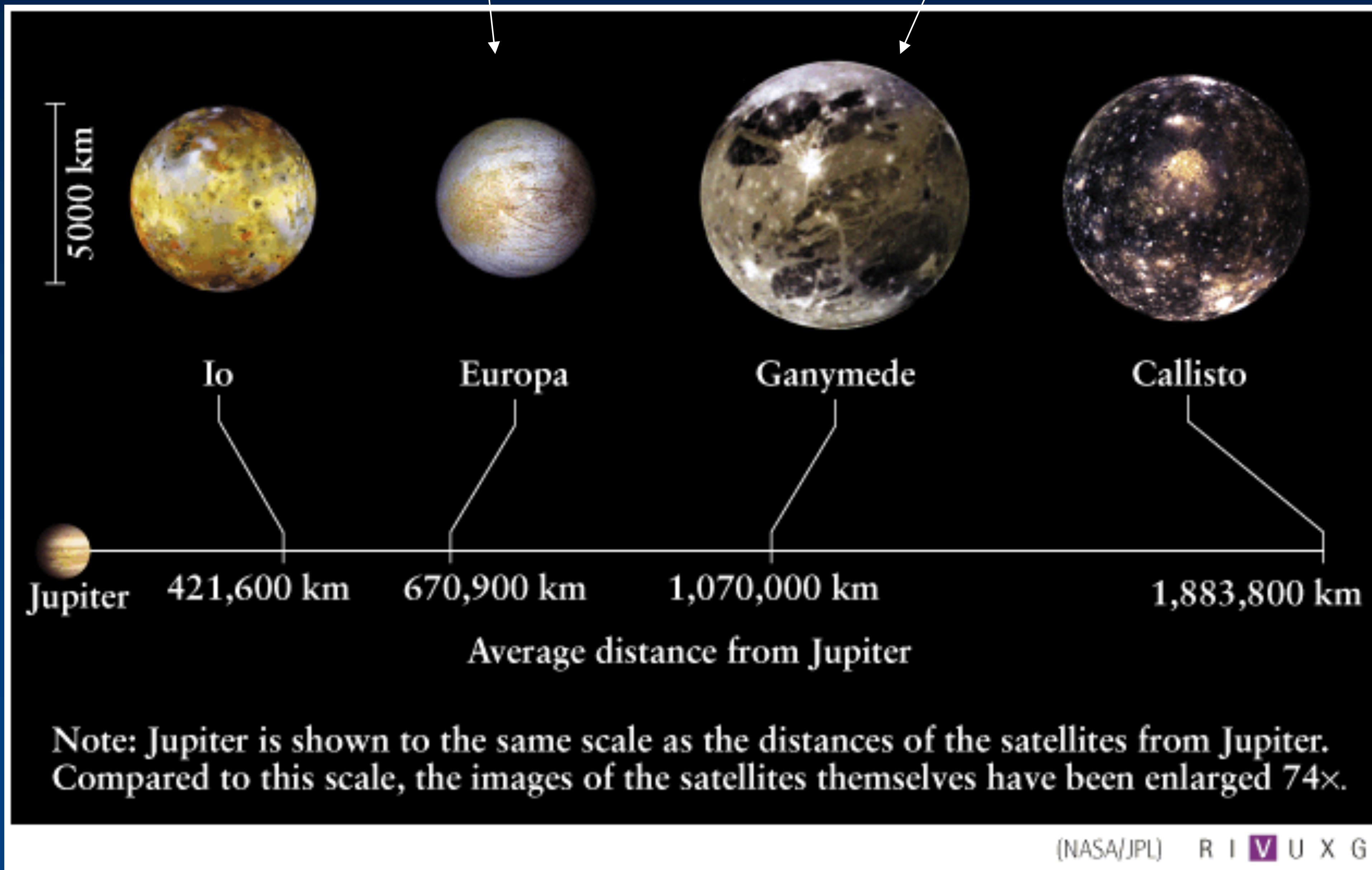


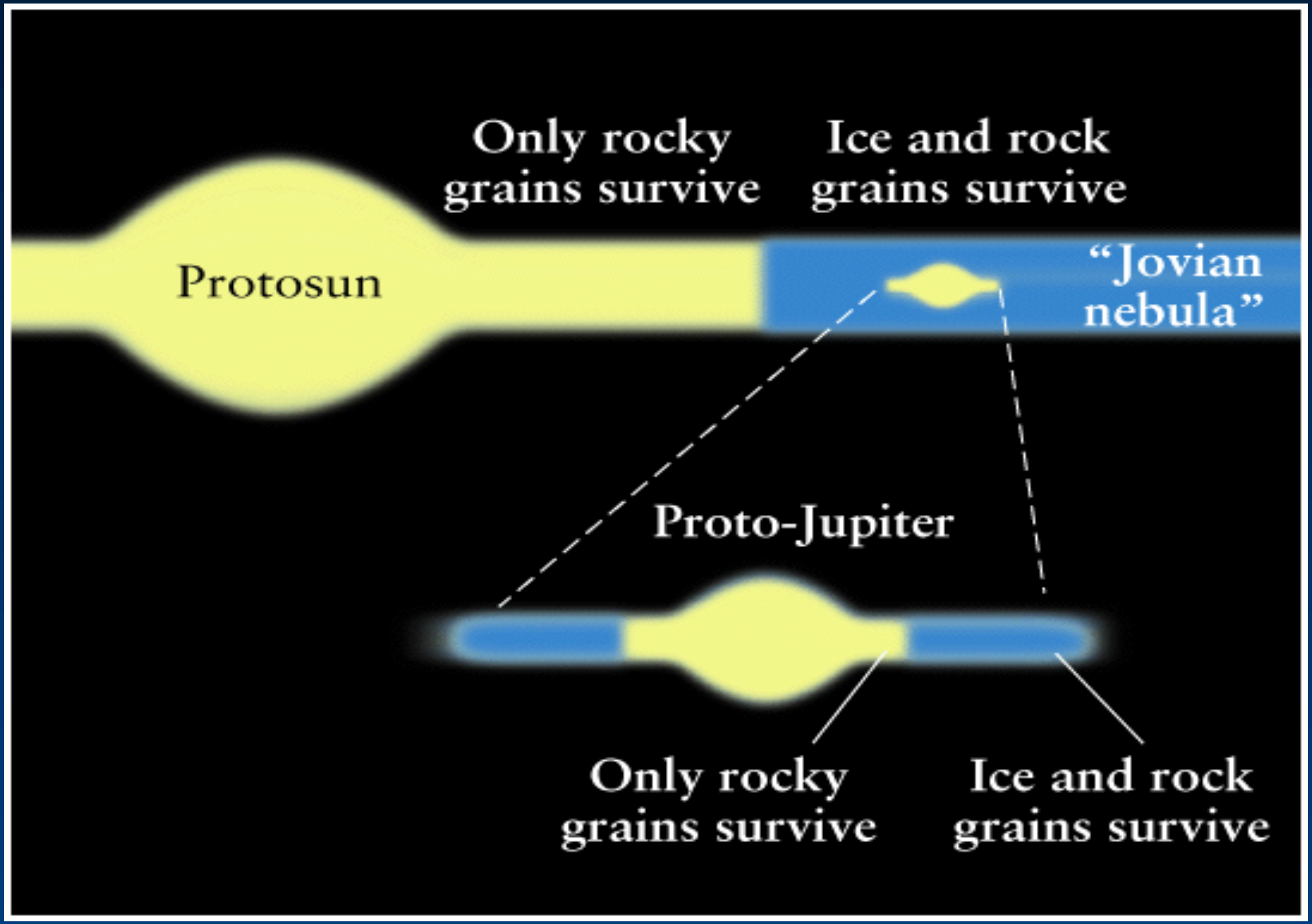
Table 14-1 The Galilean Satellites Compared with the Moon, Mercury, and Mars							
	Average distance from Jupiter (km)	Orbital period (days)	Diameter (km)	Mass (kg)	Mass (Moon = 1)	Average density (kg/m^3)	Albedo
Io	421,600	1.769	3642	8.932×10^{22}	1.22	3529	0.63
Europa	670,900	3.551	3120	4.791×10^{22}	0.65	3018	0.64
Ganymede	1,070,000	7.155	5268	1.482×10^{23}	2.02	1936	0.43
Callisto	1,883,000	16.689	4800	1.077×10^{23}	1.47	1851	0.17
Moon	—	—	3476	7.349×10^{22}	1.00	3344	0.11
Mercury	—	—	4880	3.302×10^{23}	4.49	5430	0.12
Mars	—	—	6794	6.419×10^{23}	8.73	3934	0.15

Rotation: Synchronous, plus periods of rotation of first three in resonances 1:2:4

Densities: Decreases as a function of distance from Jupiter

a higher density implies a higher fraction of rocky material

Formation of Galilean moons mimics formation of Solar System: Jupiter was hot during formation, so rockier moons closer in, icier ones further out. Rocky Io, Europa not typical of outer Solar System! Ganymede bigger than Mercury but less massive

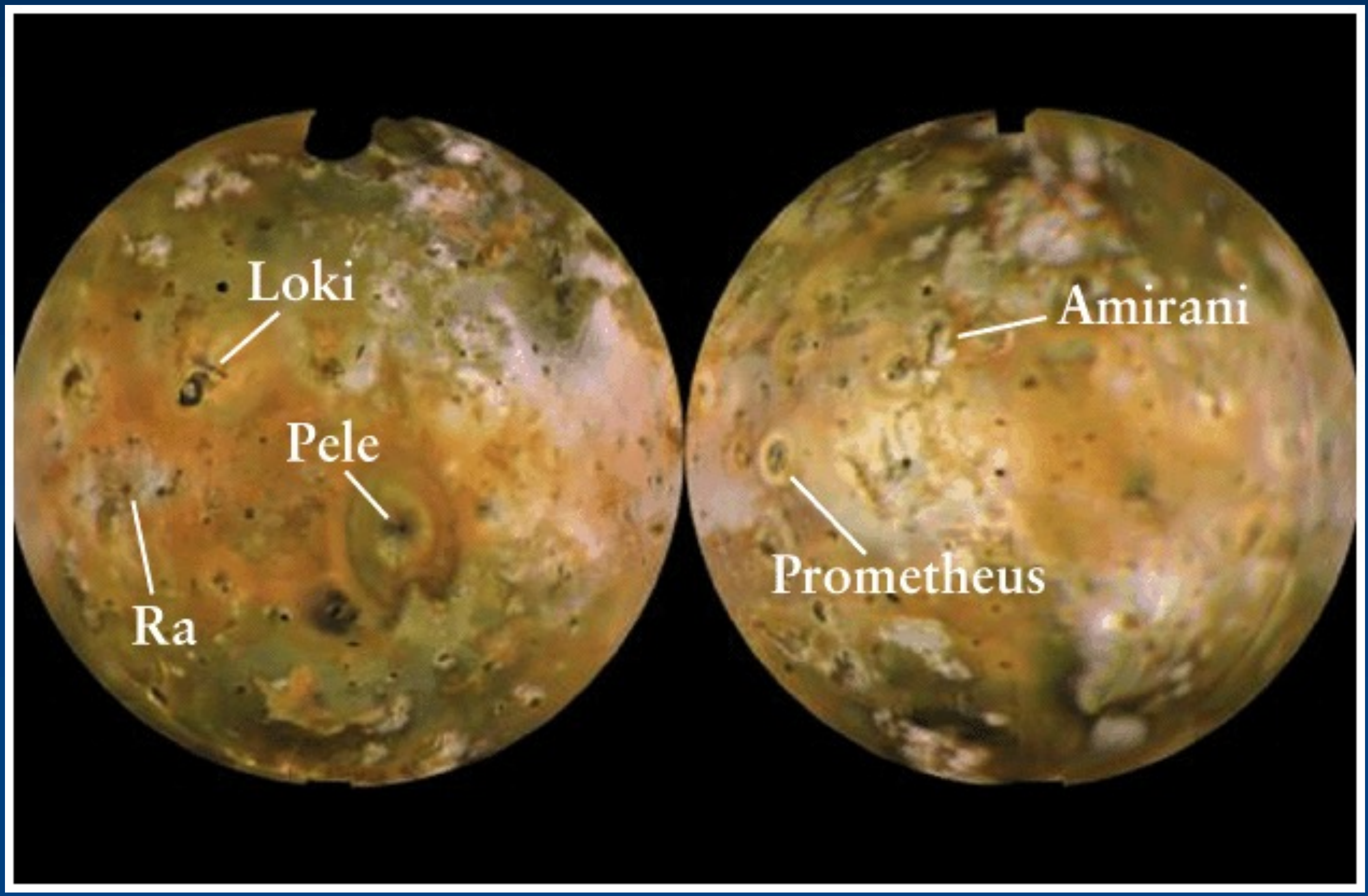


Io and Europa: primarily rocky material.

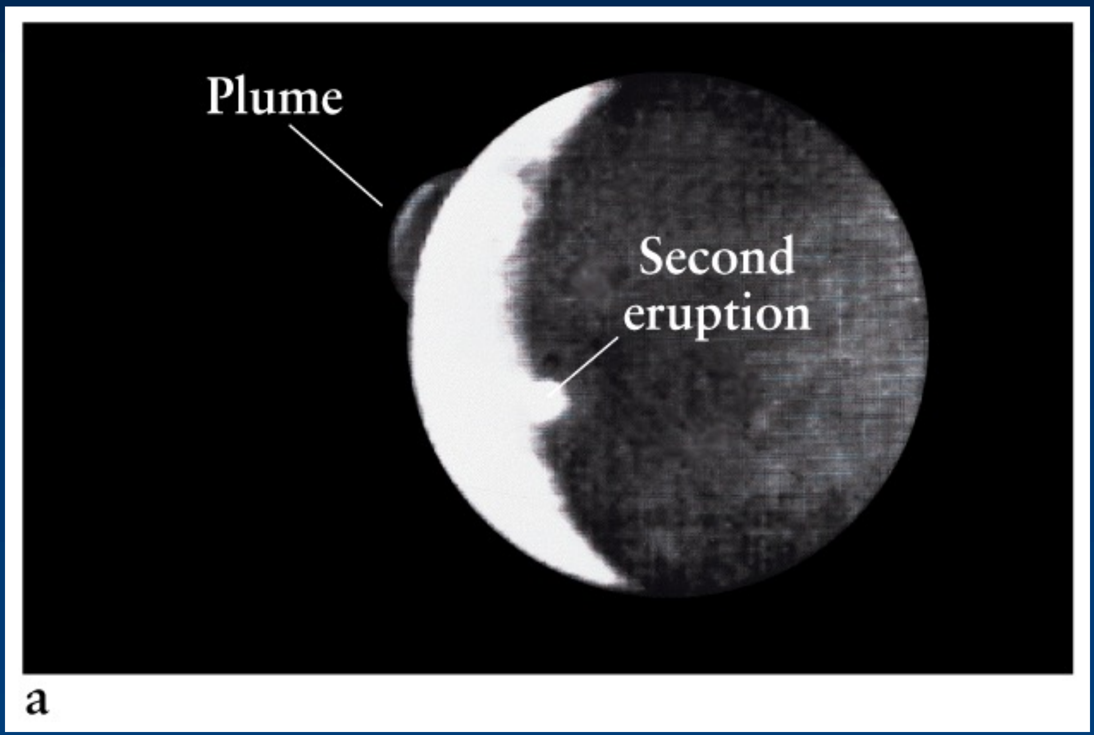
Ganymede and Callisto: roughly equal parts rock and water ice.

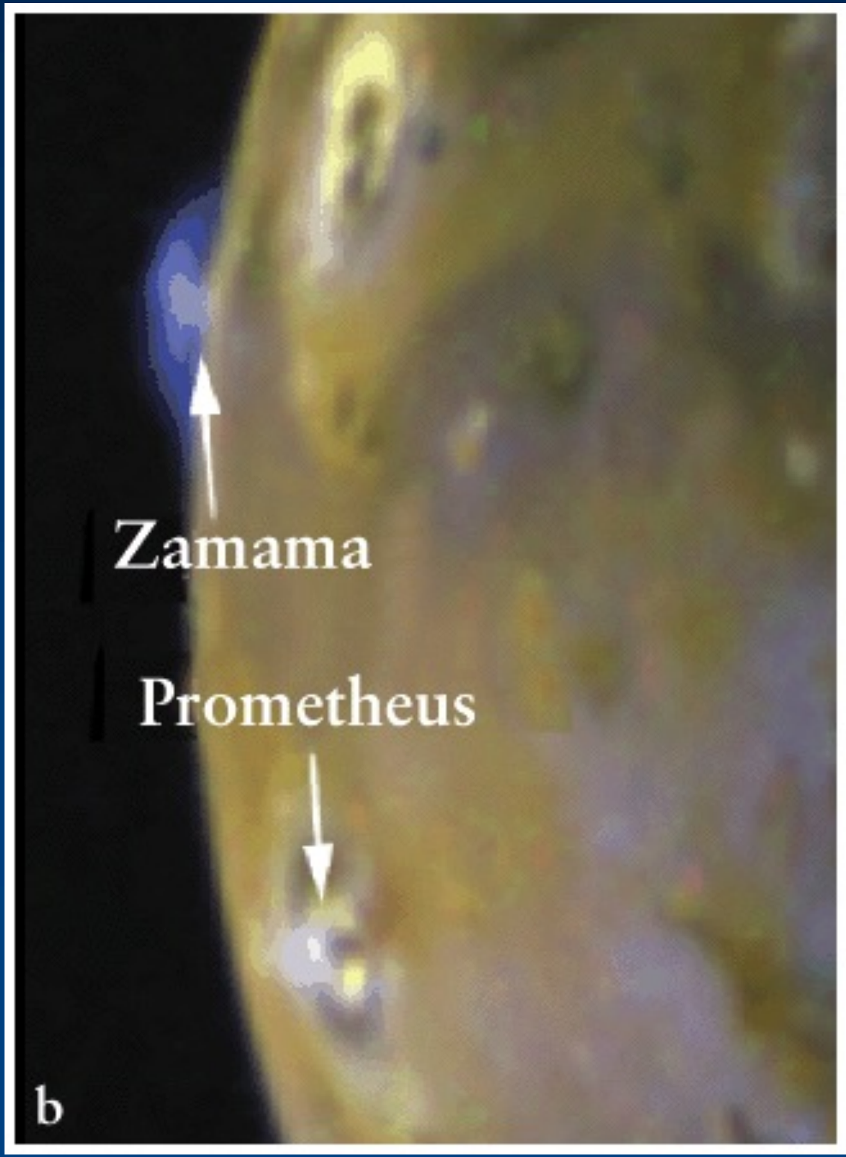
Jupiter's moon Io

- Similar in size and density to our Moon.
- The most geologically active body in the Solar System.



Plume on left rises to 260 km above surface, plume on right 100 km. Blue due to scattered sunlight.

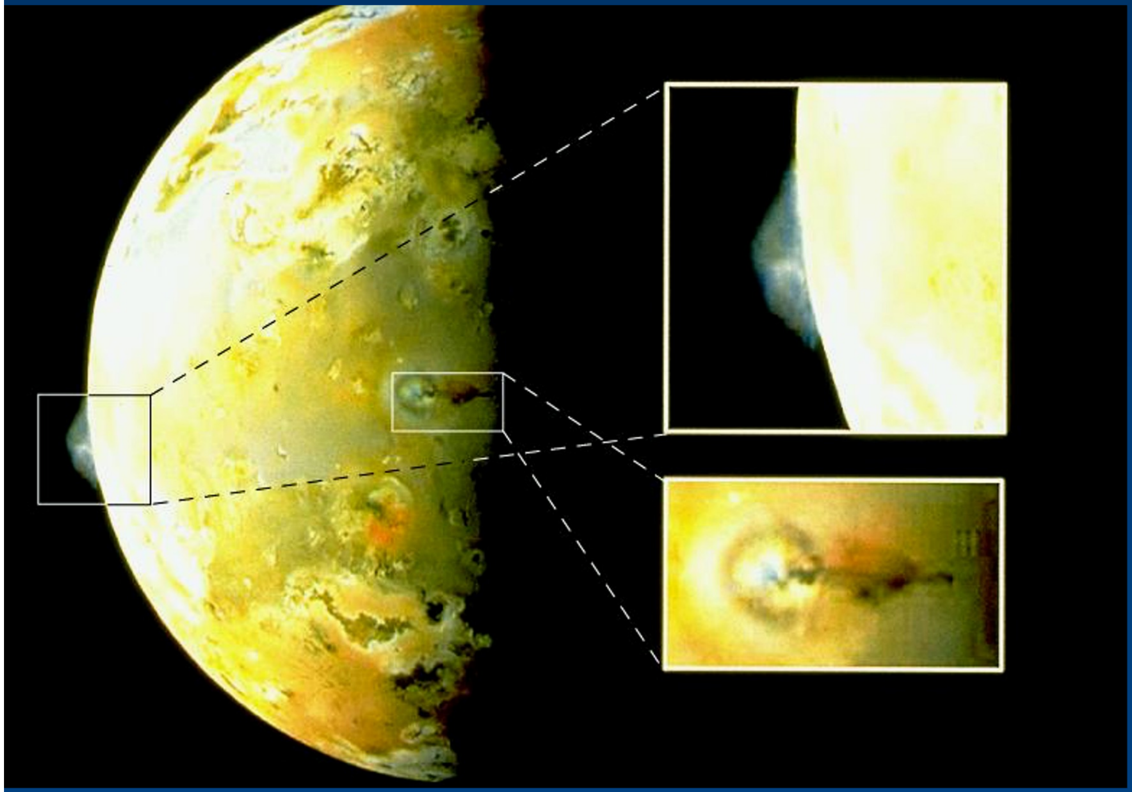


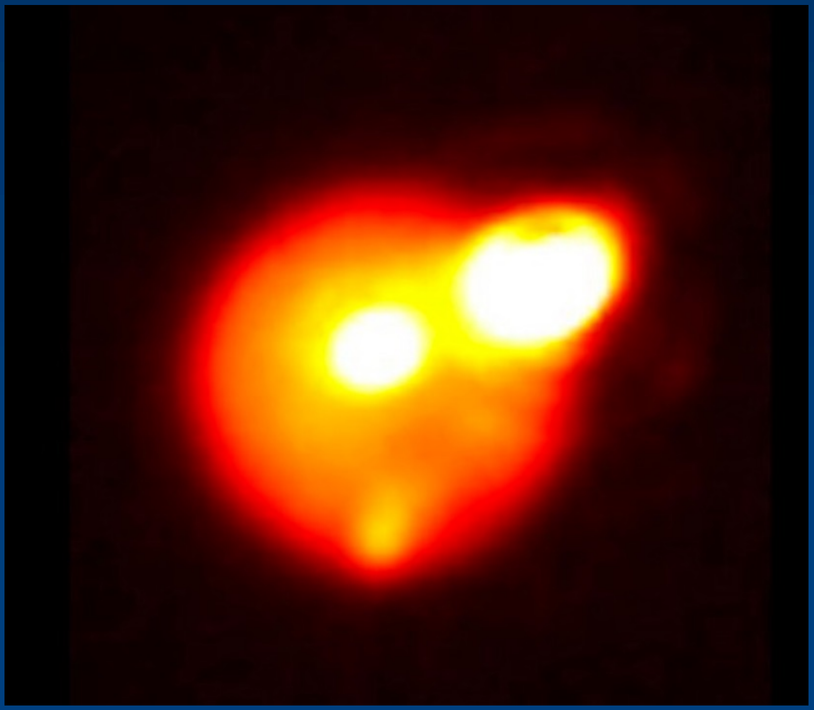


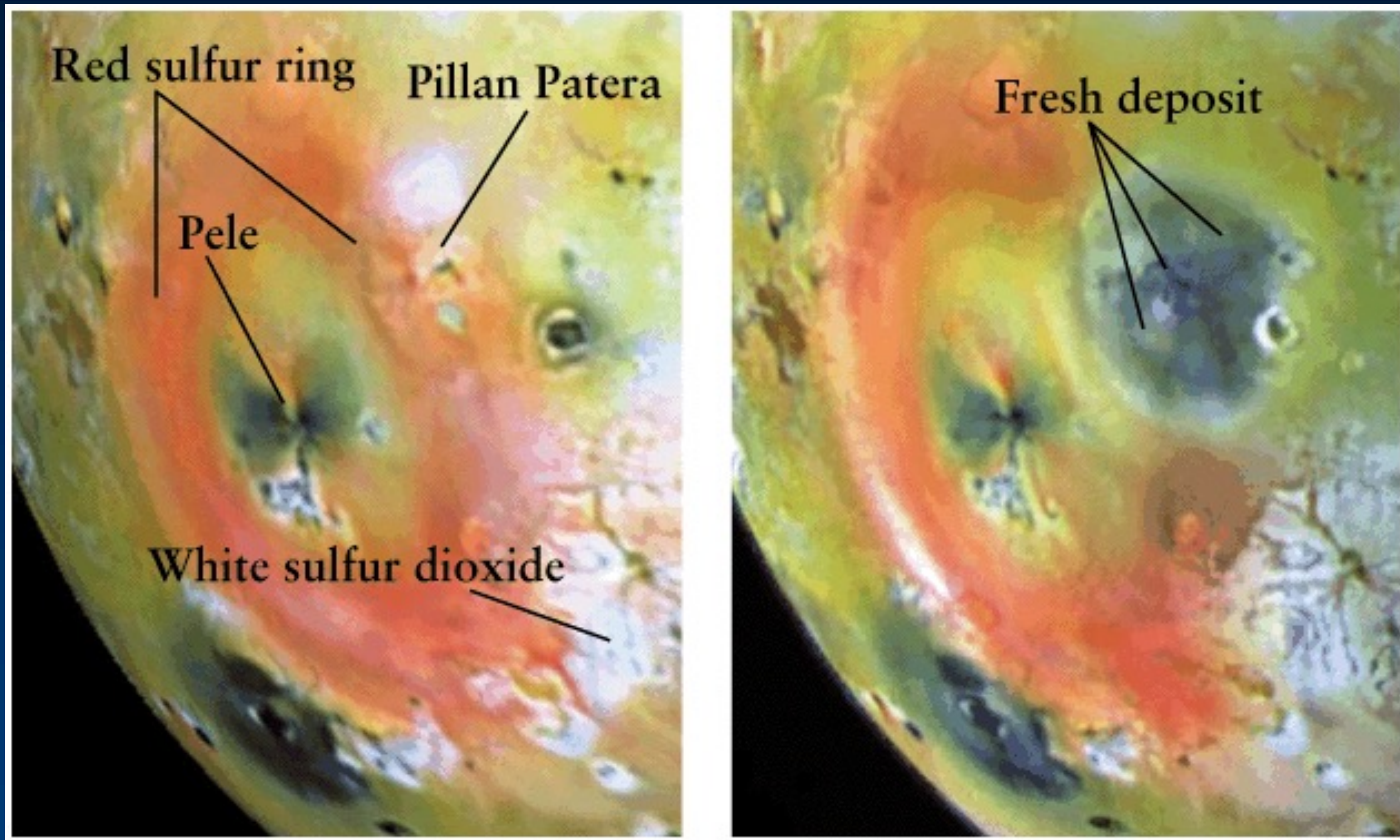
Voyager 1 & Galileo

Active volcanoes

About 300 or so active volcanoes, more like geysers. Can last months or years. Ejecta speeds up to 1000 m/s. Each volcano ejects about 10,000 tons/s. Entire surface covered by 1m of ejecta in 100 years. Also lava flows. Magma layer many 100’s of km thick in interior. Giant eruptions every few years.



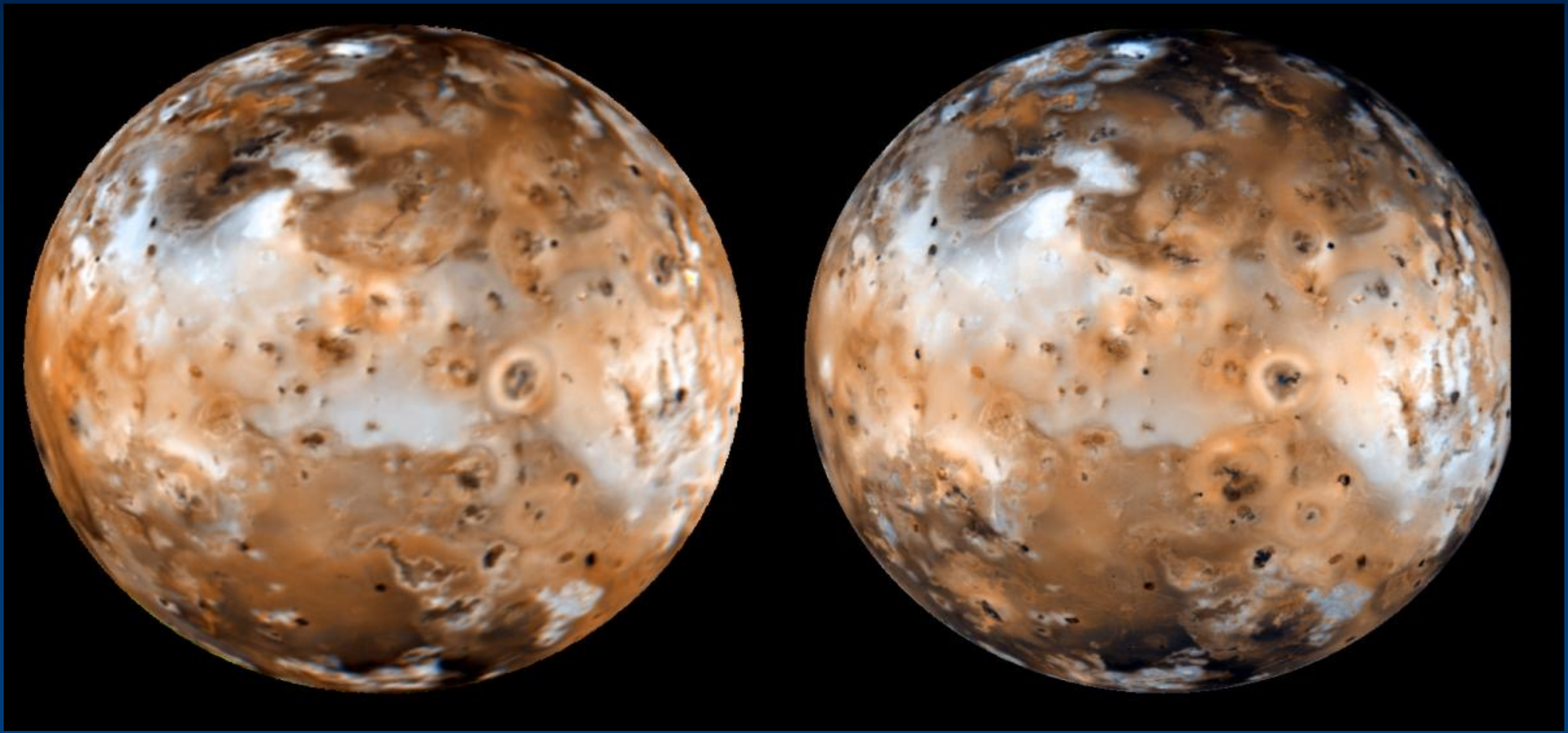




Time between photos: a few months.

Colors from different sulfur compounds (as measured by Voyager's spectrometers), forming at different temperatures: S can be orange, red, black, depending on temperature; frozen SO_2 snowflakes are white.

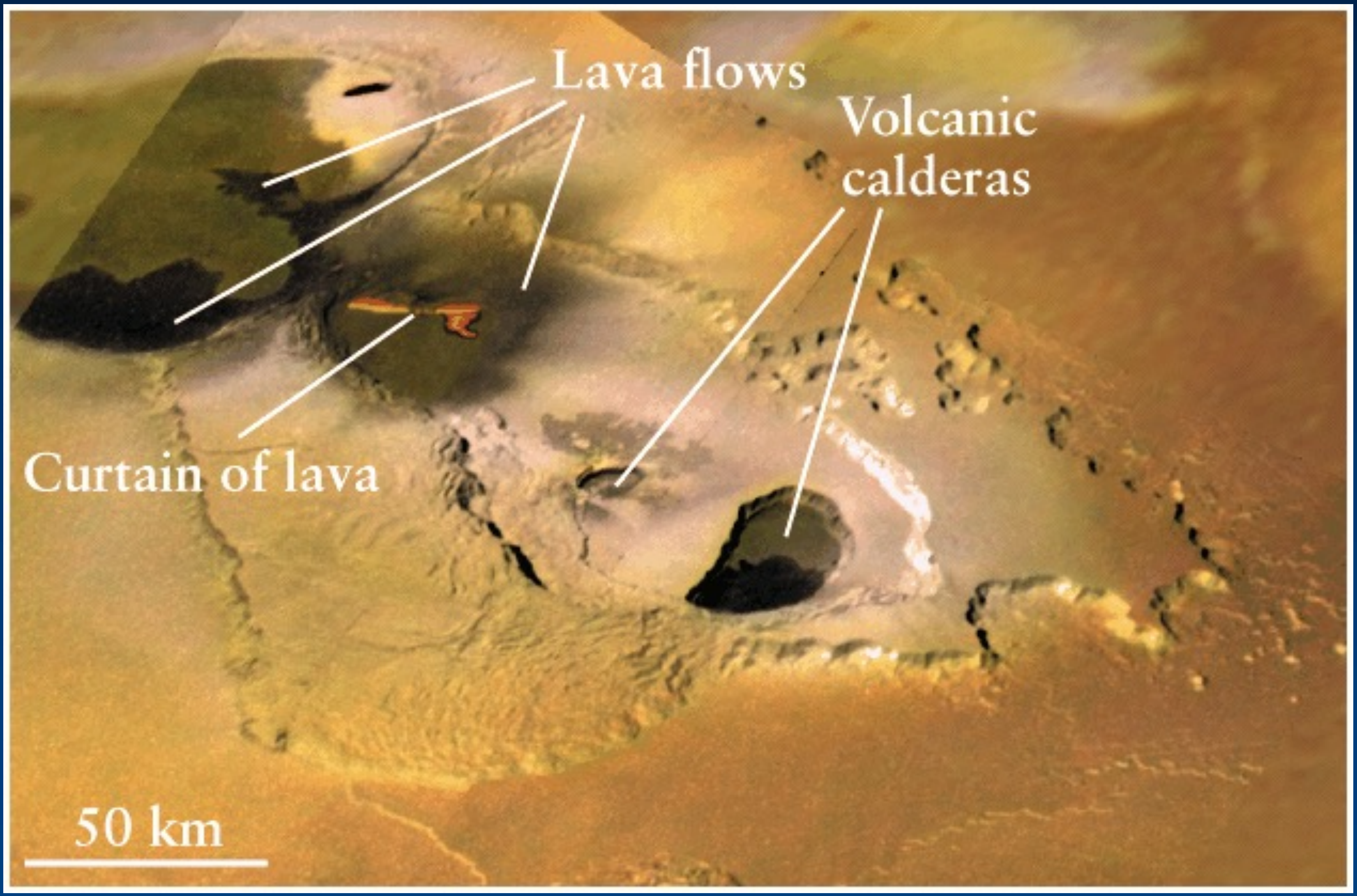
Activity causes surface to change over the years:



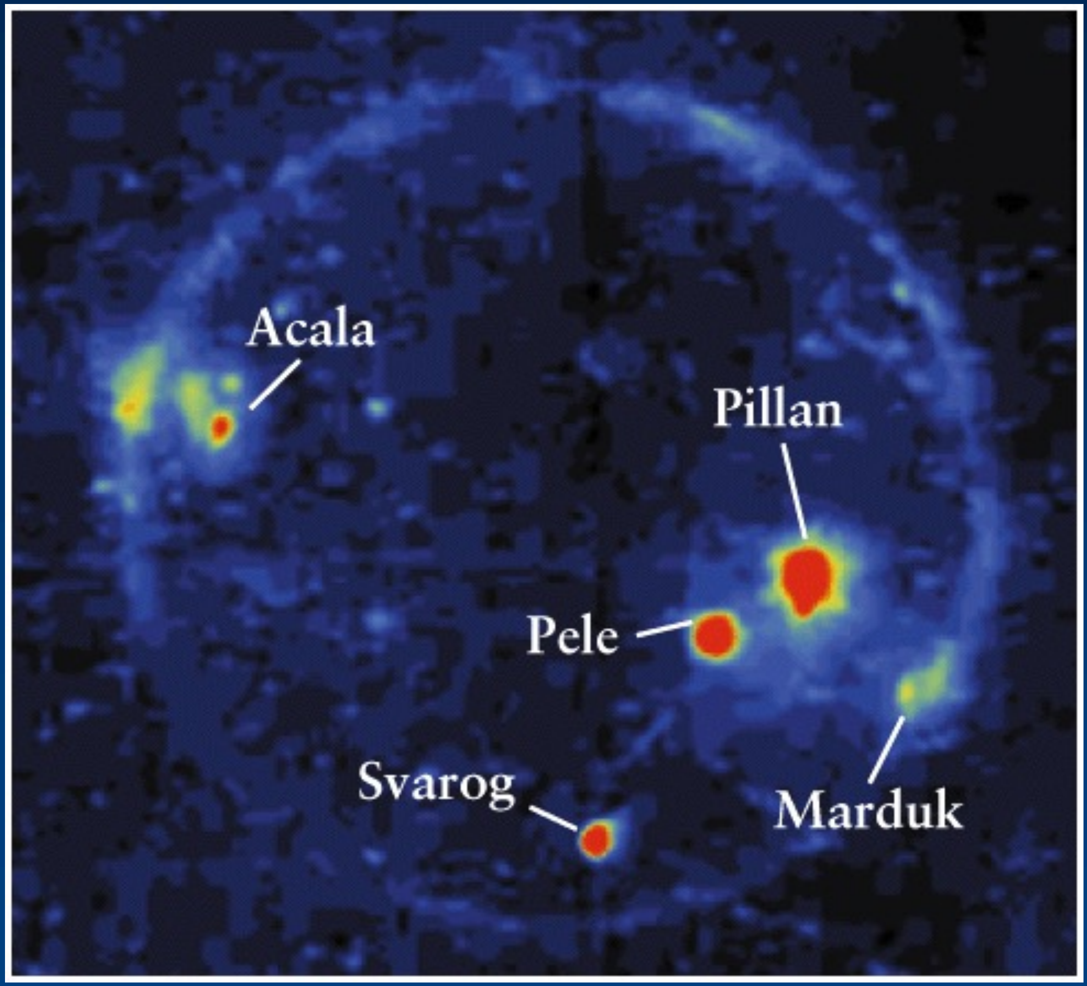
Voyager 2 (1979) Galileo (1996)

Io completely lacks impact craters!

Close up of activity – happening today!



Io night side– volcanoes glow in IR and visible light.



Galileo

Heat source?

- Volcanic activity requires internal heat.
- Io is a small body, and should have been cooled off by now, and be geologically dead.
- What is the energy source on Io?

Tidal Heating

- Tidal force from Jupiter elongates Io.

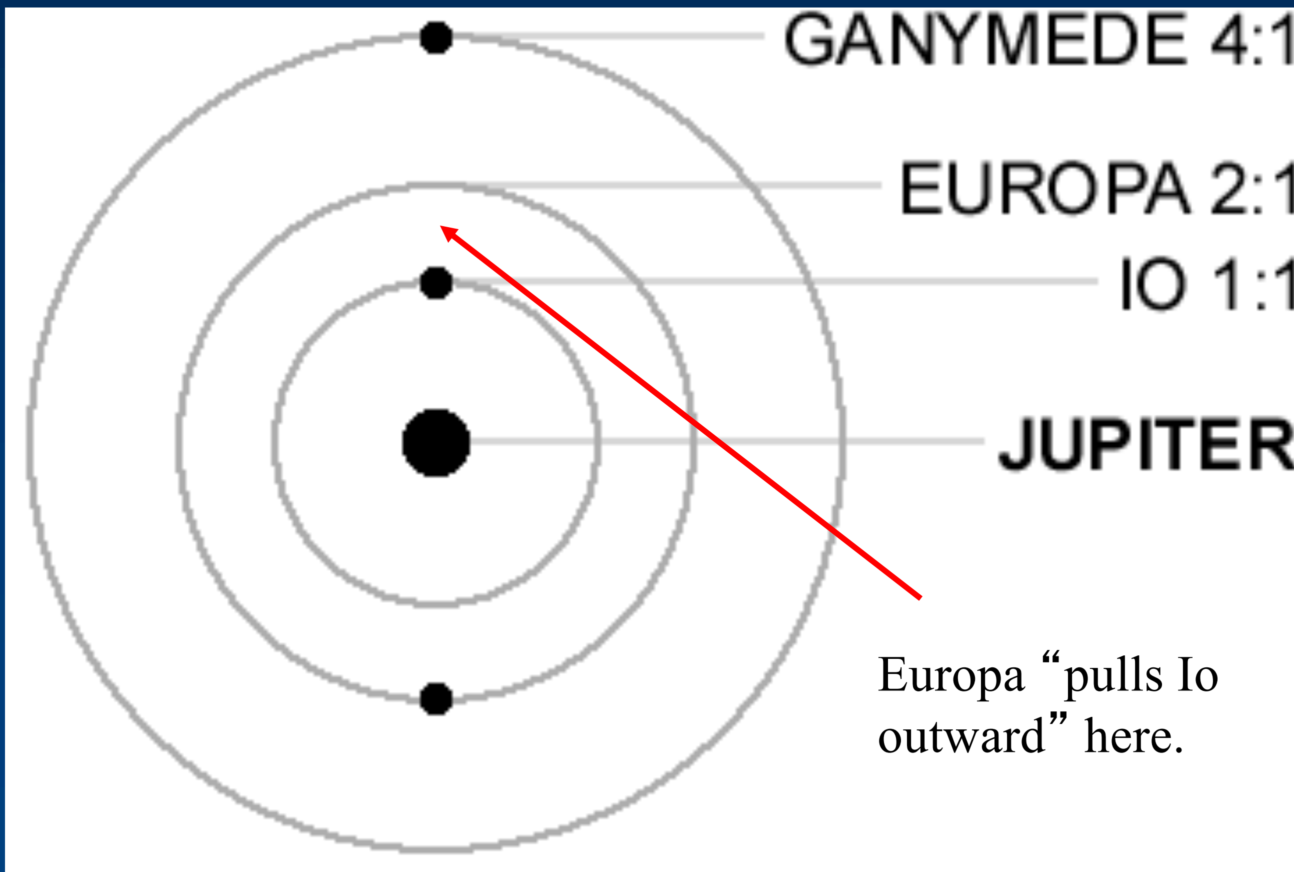
- As Io moves around in orbit, Europa and Ganymede exert gravitational tugs due to the 1:2:4 ratio of orbital periods.

- Io's orbit is distorted into an ellipse
  $\Rightarrow$ variable distance from Jupiter
  $\Rightarrow$ varying strength of tidal force

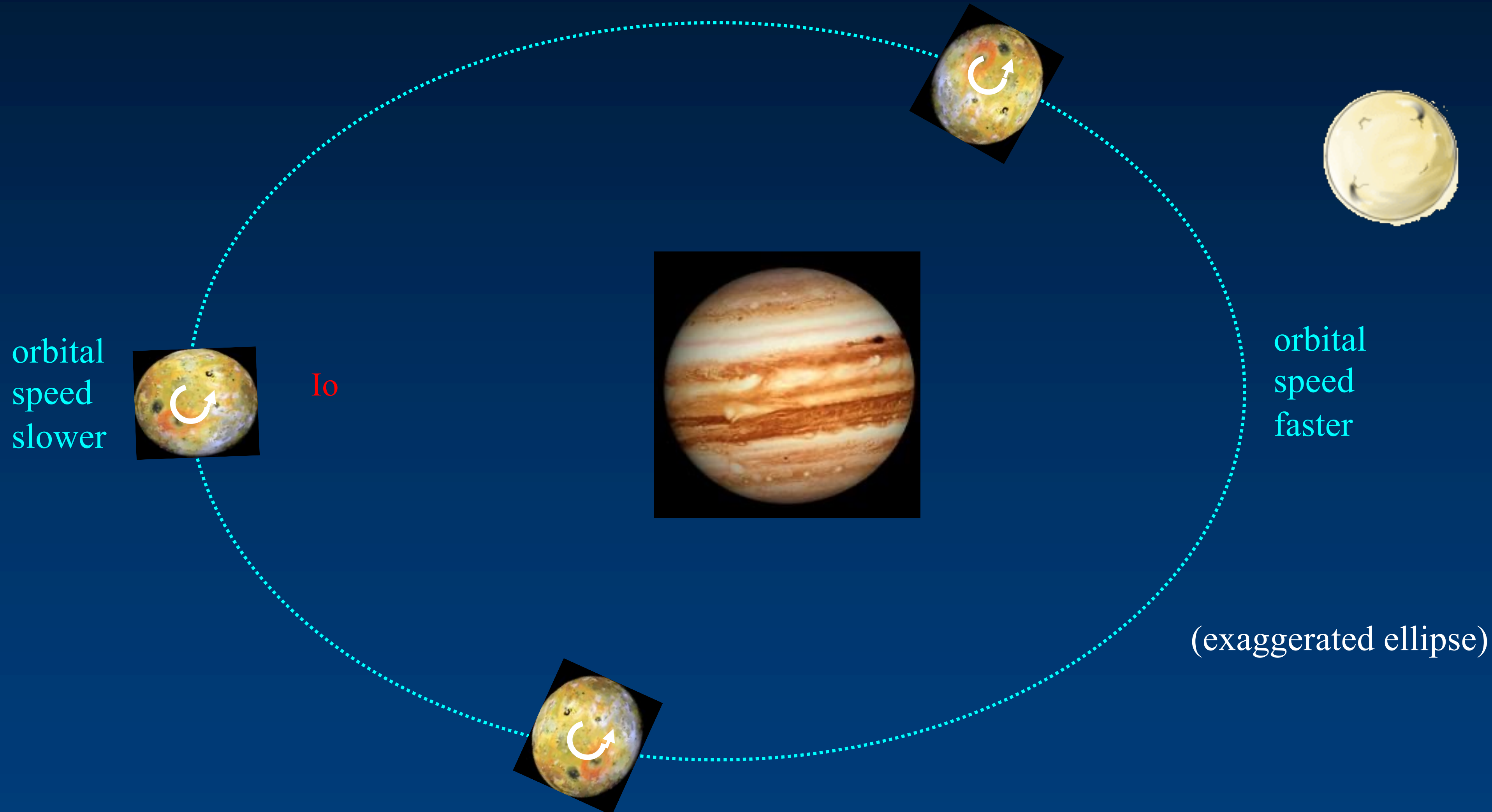
- Io gets squeezed and flexed. Interior is hot!

Tidal Heating

Io and Europa are in a "resonance orbit":

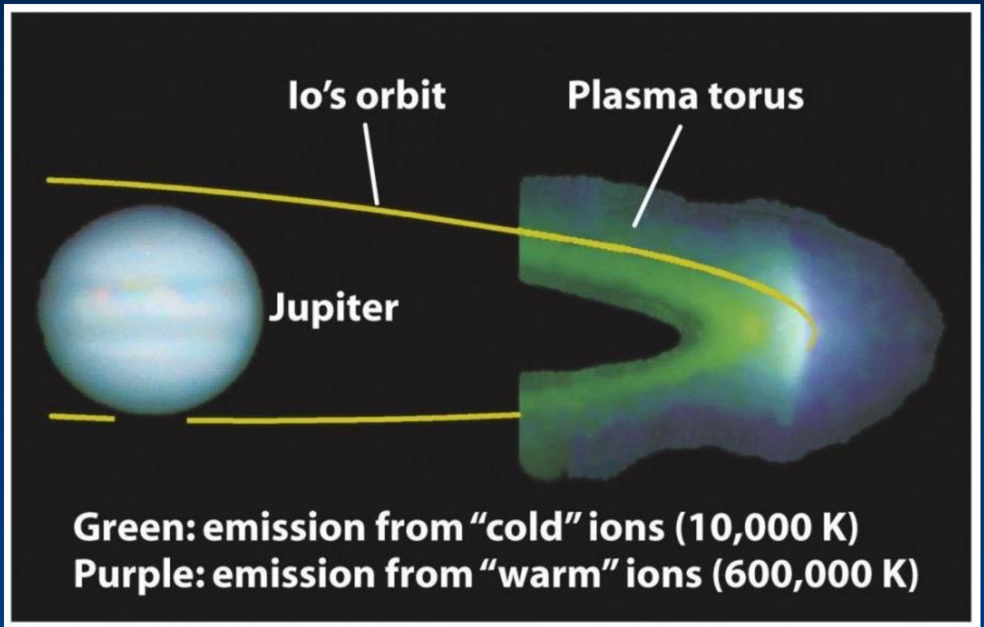


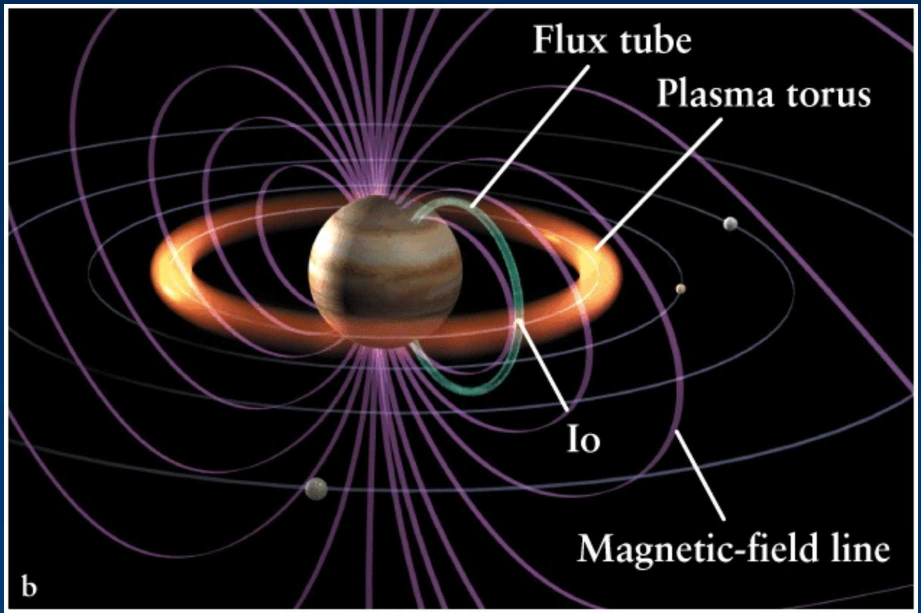
The periodic pull on Io by Europa makes Io's orbit elliptical.



Io "tidally locked" like our Moon. Tidal bulge always points to Jupiter.
So bulge swings around faster when Io is closer to Jupiter.
But Io rotates on its axis at a <u>constant rate</u>, so cannot keep bulge <u>exactly</u> pointed at Jupiter at all times during orbit.
So bulge moves back and forth across surface => stresses => heat => volcanoes

Some plume particles from the geysers leave Io and interact with Jupiter’s magnetic field. Forms a torus of energetic particles.

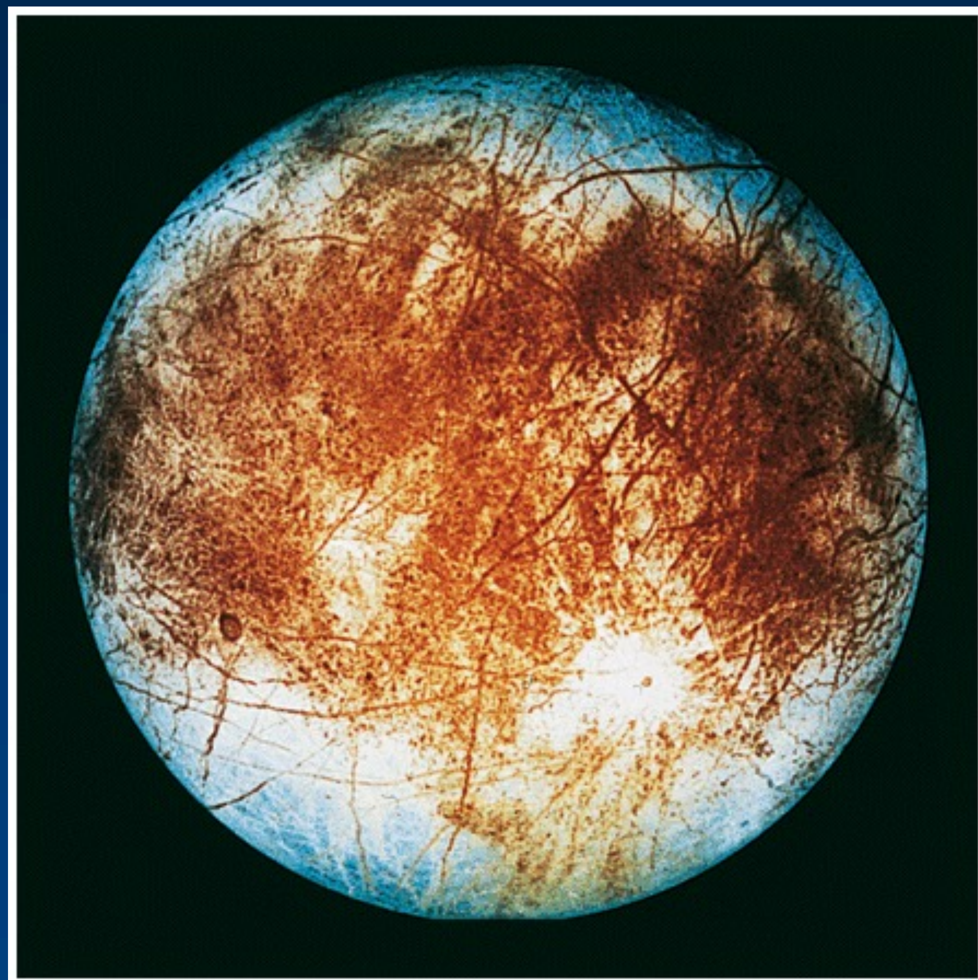




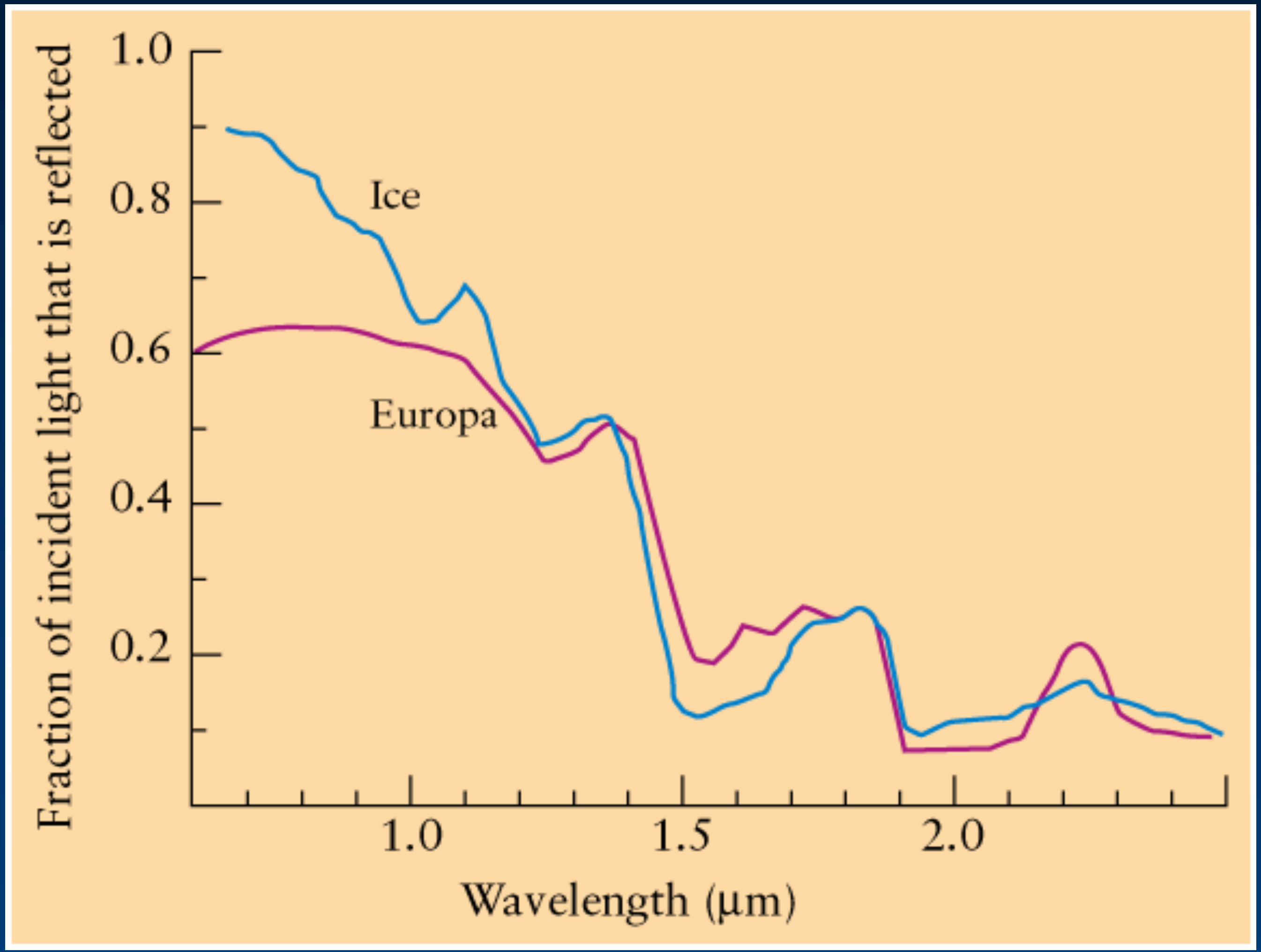
As Io moves, an electric current is set up in a cylinder of concentrated magnetic flux ("Io flux tube").

Electrons spiraling in the magnetic field produce radio emission.

Europa



False-color visible and IR image from Galileo

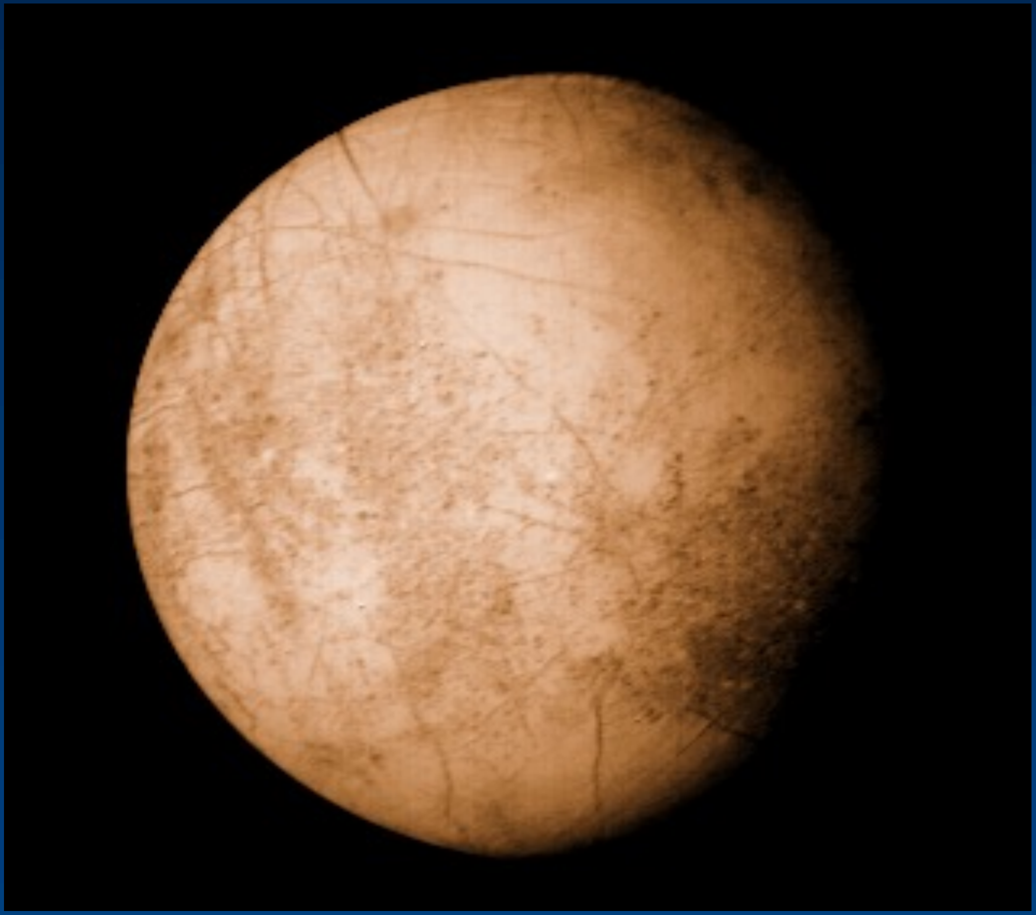


Spectroscopic observations from Earth indicated Europa's surface is almost pure frozen water.

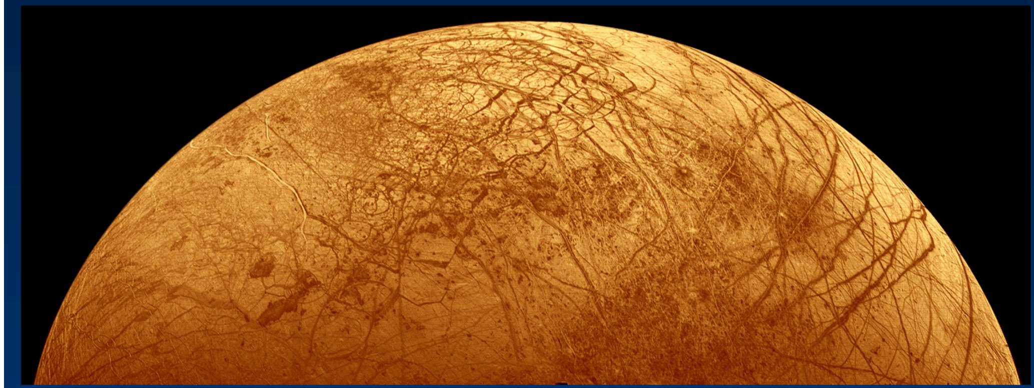
Smooth surface

- Europa is the smoothest body in the Solar system: almost no craters, no mountains

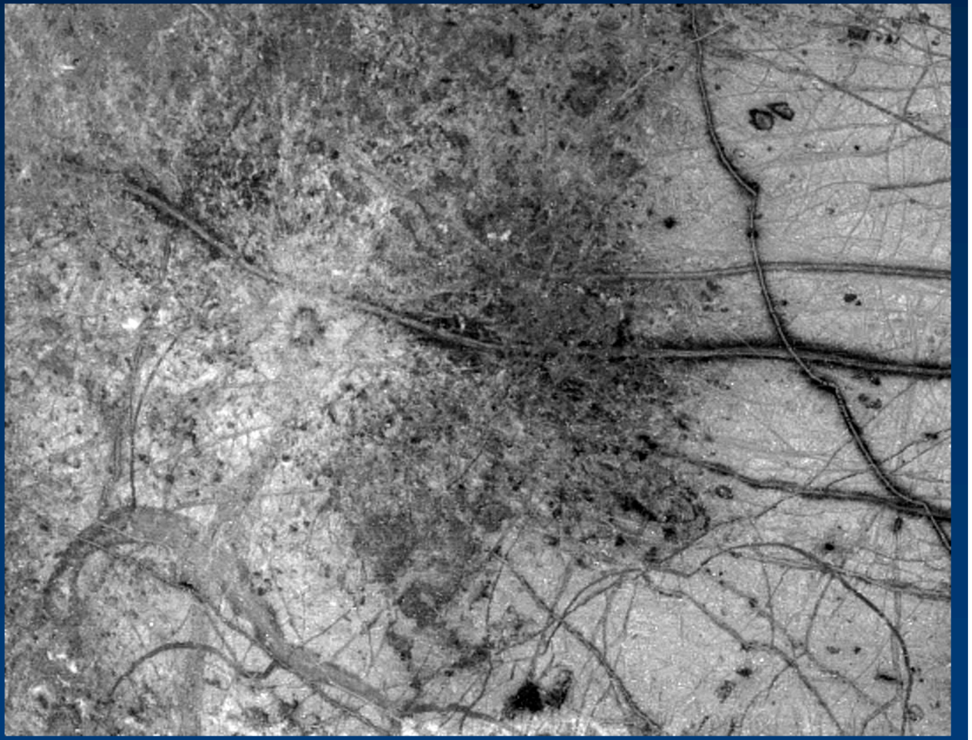
- Young surface reprocessed by geological activity



Europa may have warm water ocean beneath icy surface

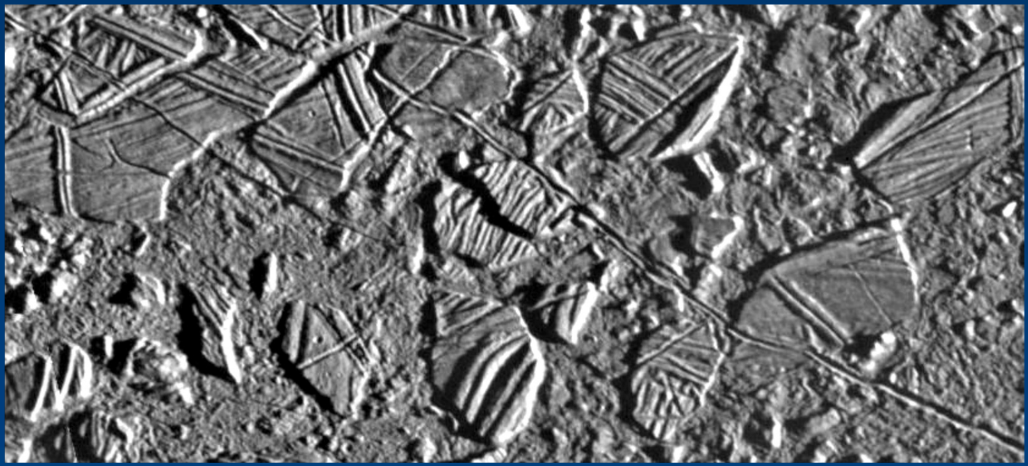


Fissures suggest tidal stresses.



860 km

Dark deposits along cracks suggest eruptions of water with dust/rock mixed in (Europa's density => 90% rock, 10% ice).



42 km

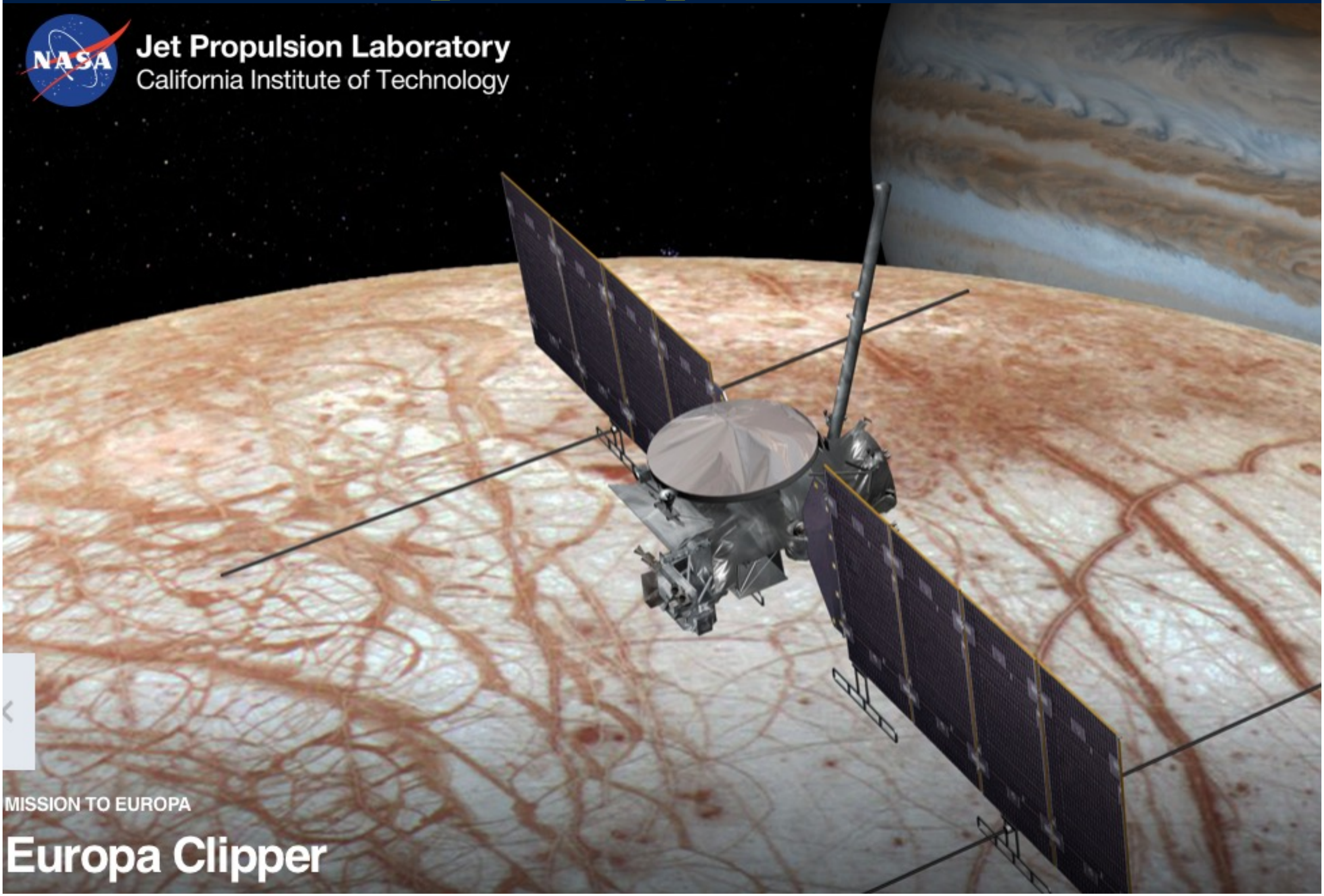
Icebergs or "ice rafts" suggest broken and reassembled chunks.

Interior of Europa

- Surface is water ice, below is presumably a water ocean, down to 100-200 km, but most interior is rock (85%-90% of total mass).
- Warm ocean – possibility of life?

- Internal heat?
  - Too small for retained heat from formation, it must come from *tidal forces* (like Io, but weaker).
  - Resonant orbits with Ganymede and Io make Europa's orbit elliptical => varying tidal stresses from Jupiter => heat.

Europa Clipper Mission



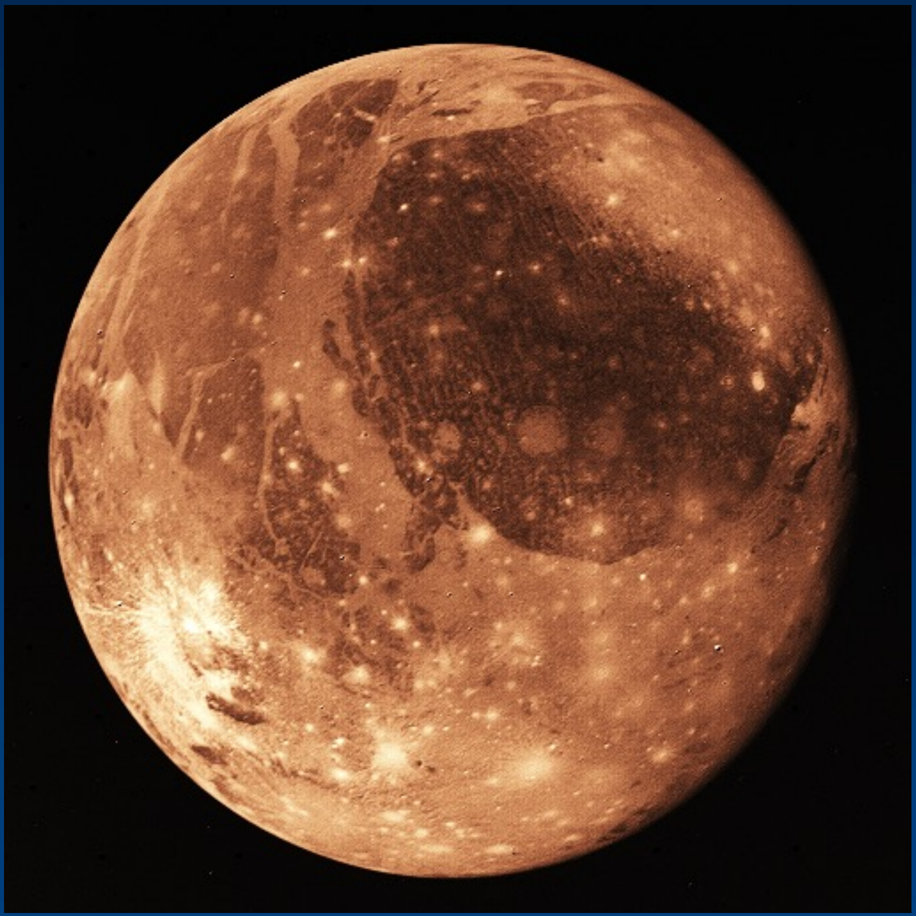
Europa Clipper Mission

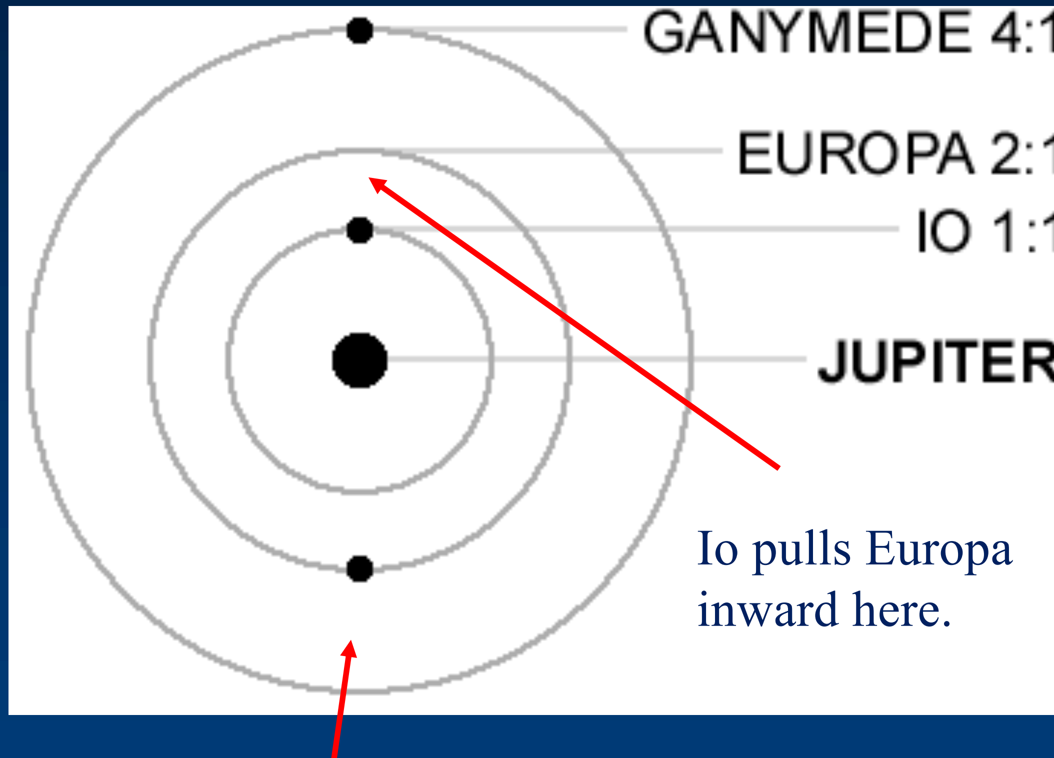
Scientific Instrument(s):

- Plasma Instrument for Magnetic Sounding (PIMS)
- Interior Characterization of Europa using MAGnetometry (ICEMAG)
- Mapping Imaging Spectrometer for Europa (MISE)
- Europa Imaging System (EIS)
- Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)
- Europa THermal Emission Imaging System (E-THEMIS)
- MAss SPectrometer for Planetary EXploration/Europa (MASPEX)
- Ultraviolet Spectrograph/Europa (UVS)
- SUrface Dust Mass Analyzer (SUDA)

Ganymede

- Largest satellite in solar system – larger than Mercury
- Mostly ice
- Magnetic field. Implies electrically-conducting (salty?) liquid layer beneath surface – internal heat still. Calculations show orbit may have been more elliptical in past – tidal heating.

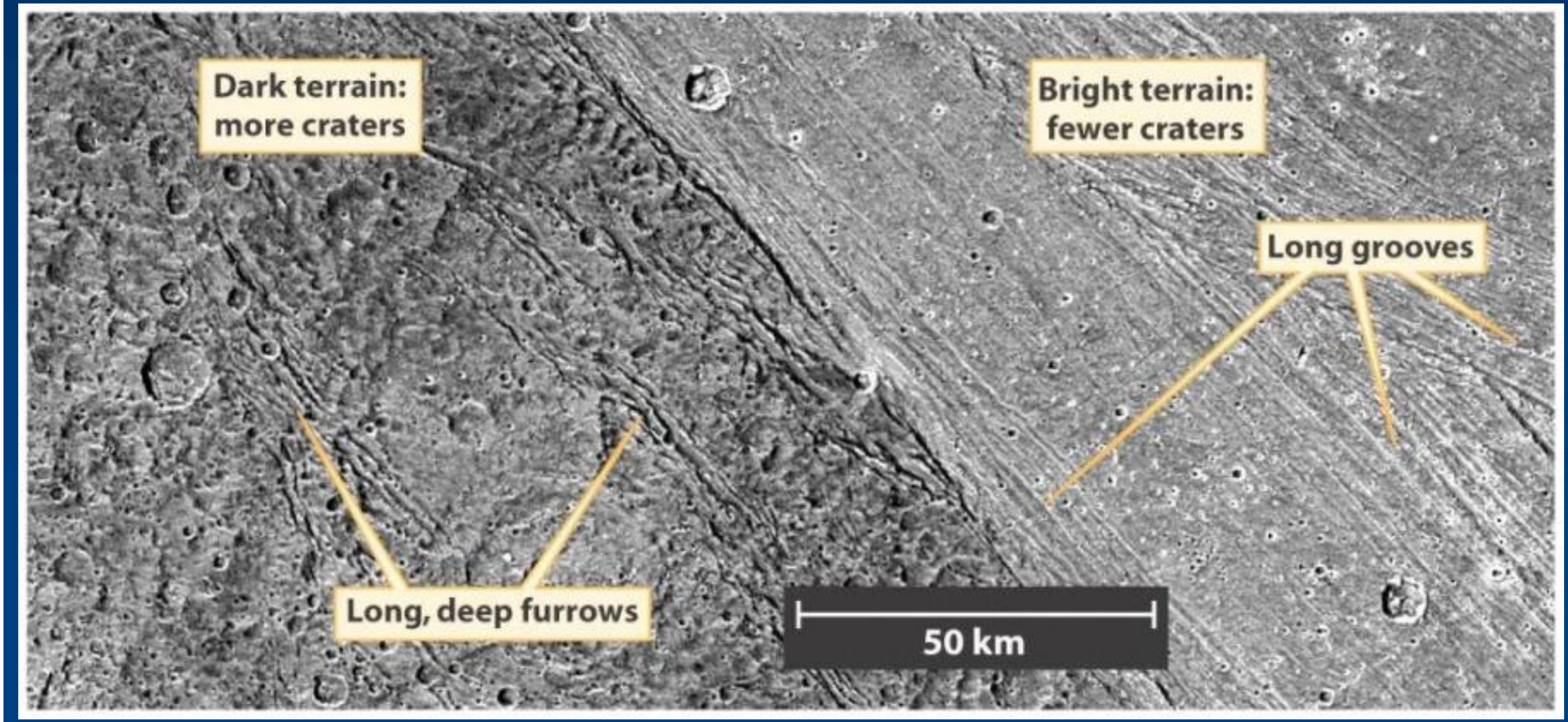




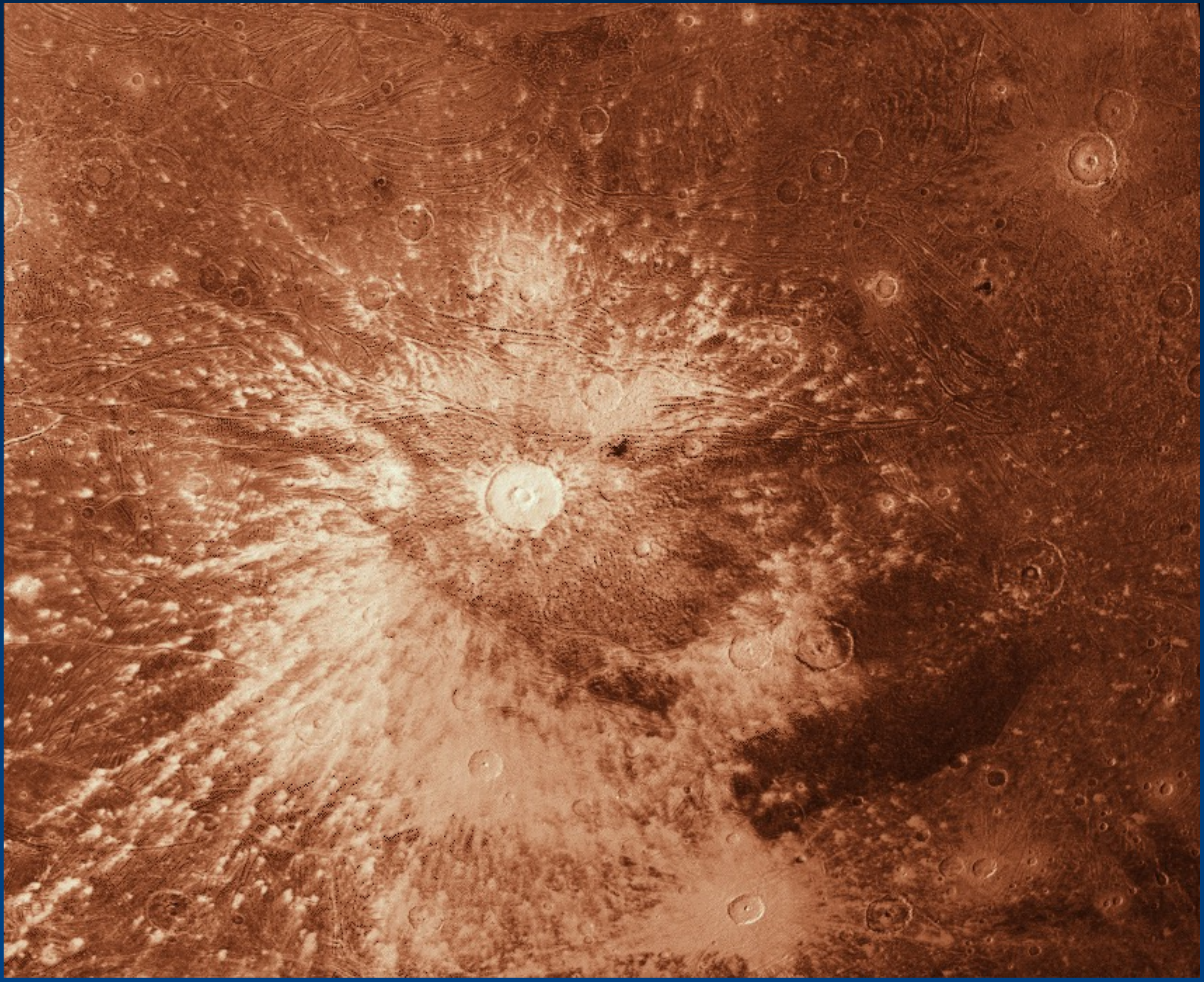
Ganymede pulls
Europa outward here.

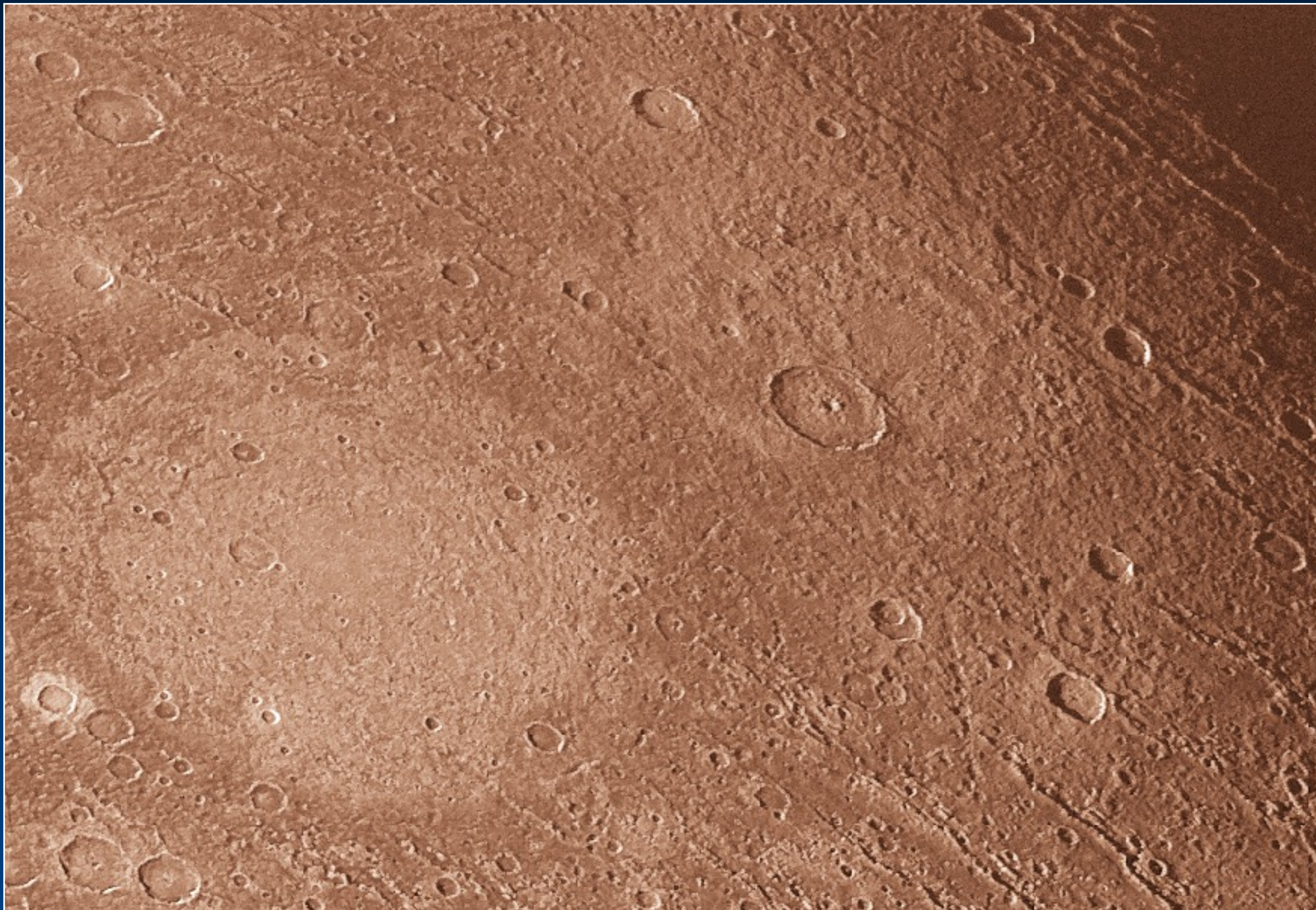
Terrain

- Heavily cratered, but unlike the Moon and Mercury, the craters are made of *ices* and are flatter.
- Bright vs. dark areas: dark areas are very old, more craters.
- Grooves in bright areas due to tectonic stretching. Some areas appear flooded with frozen watery fluid. Age about 1Gyr only.



Younger craters show light-colored rays – freshly exposed ice.

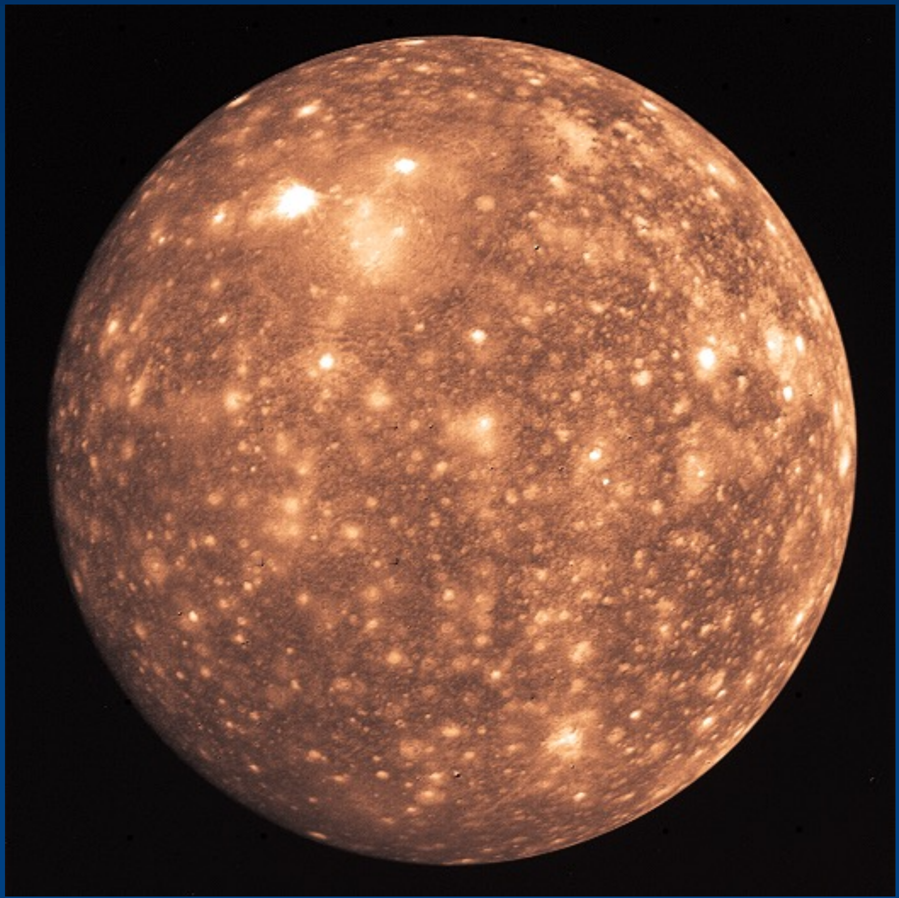




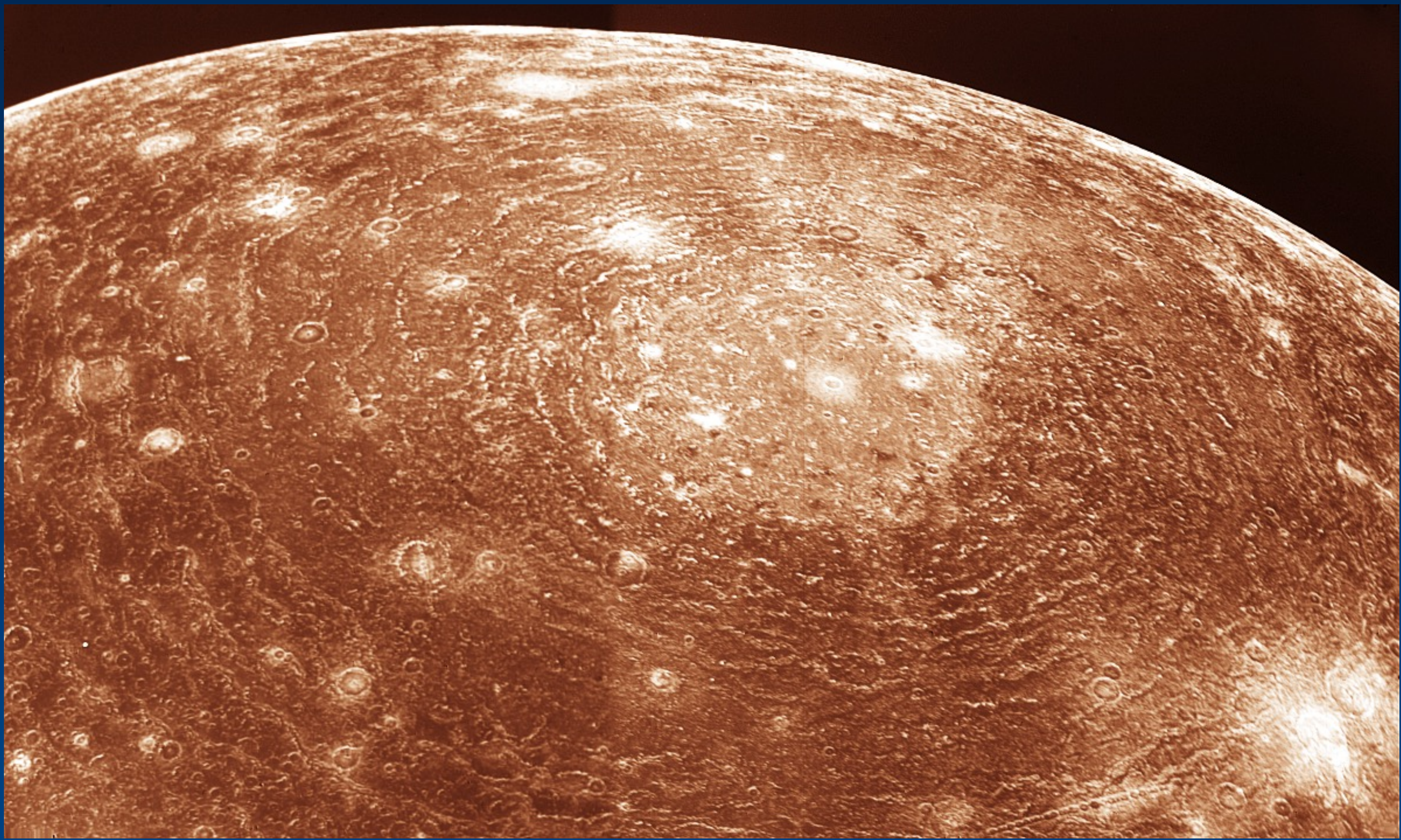
Craters are relatively flat: weak nature of Ganymede's crust allows flow over geological timescale?

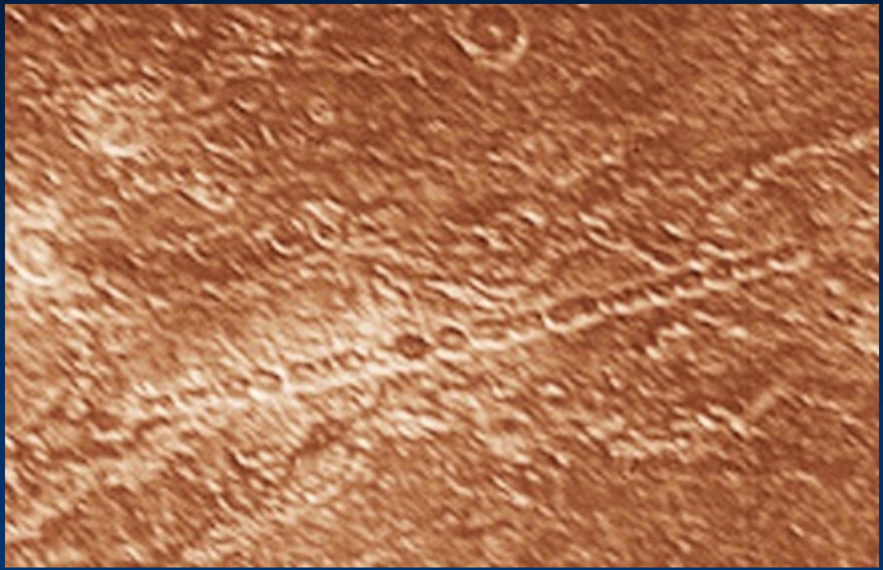
Callisto

- Also covered by frozen water layer
- No evidence for geological activity. Instead, there are a number of major impact features.
- Maximum cratering density
- But no craters < 1km. Eroded away. Why?
- Dark, dusty material covers surface. Origin not clear



Valhalla: huge impact basin. Crater density indicates it is ancient. 3000 km across.





- Series of impact craters: probably from the impact of a comet that was tidally disrupted (like Shoemaker-Levy 9)

Summary: Galilean satellites

- Io & Europa mostly rock (ρ_{avg} = 3.5 & 3.0 g/cm^3)
- Io has rocky crust, molten mantle and active volcanoes
- Europa has icy crust, rocky mantle and core

- Ganymede & Callisto mixed ice & rock (ρ_{avg} = 1.9 & 1.8 g/cm^3)
- Deep ice mantles over rocky/icy cores
- Less geologically active (than Io & Europa)

Many more moons besides Galilean (63+). Small objects, some have highly inclined, or even retrograde orbits

Table 14-2 Jupiter's Family of Satellites

	Average radius of orbit (km)	Average radius of orbit (Jupiter radii)	Orbital period (days)	Year of discovery
Inner satellites:				
Metis	127,960	1.7922	0.2948	1979
Adrastea	128,980	1.8065	0.2983	1979
Amalthea	181,300	2.539	0.4981	1892
Thebe	221,900	3.108	0.6745	1979
Galilean satellites:				
Io	421,600	5.905	1.769	1610
Europa	670,900	9.397	3.551	1610
Ganymede	1,070,000	14.99	7.155	1610
Callisto	1,883,000	26.37	16.689	1610
Outer satellites:				
Leda	11,094,000	155.4	238.72	1974
Himalia	11,480,000	160.8	250.57	1904
Lysithea	11,720,000	164.2	259.22	1938
Elara	11,737,000	164.4	259.65	1905
Ananke	21,200,000	296.9	631^R	1951
Carme	22,600,000	316.5	692^R	1938
Pasiphae	23,500,000	329.1	735^R	1908
Sinope	23,700,000	331.9	758^R	1914
S/1999 J1	24,200,000	338.5	768^R	2000

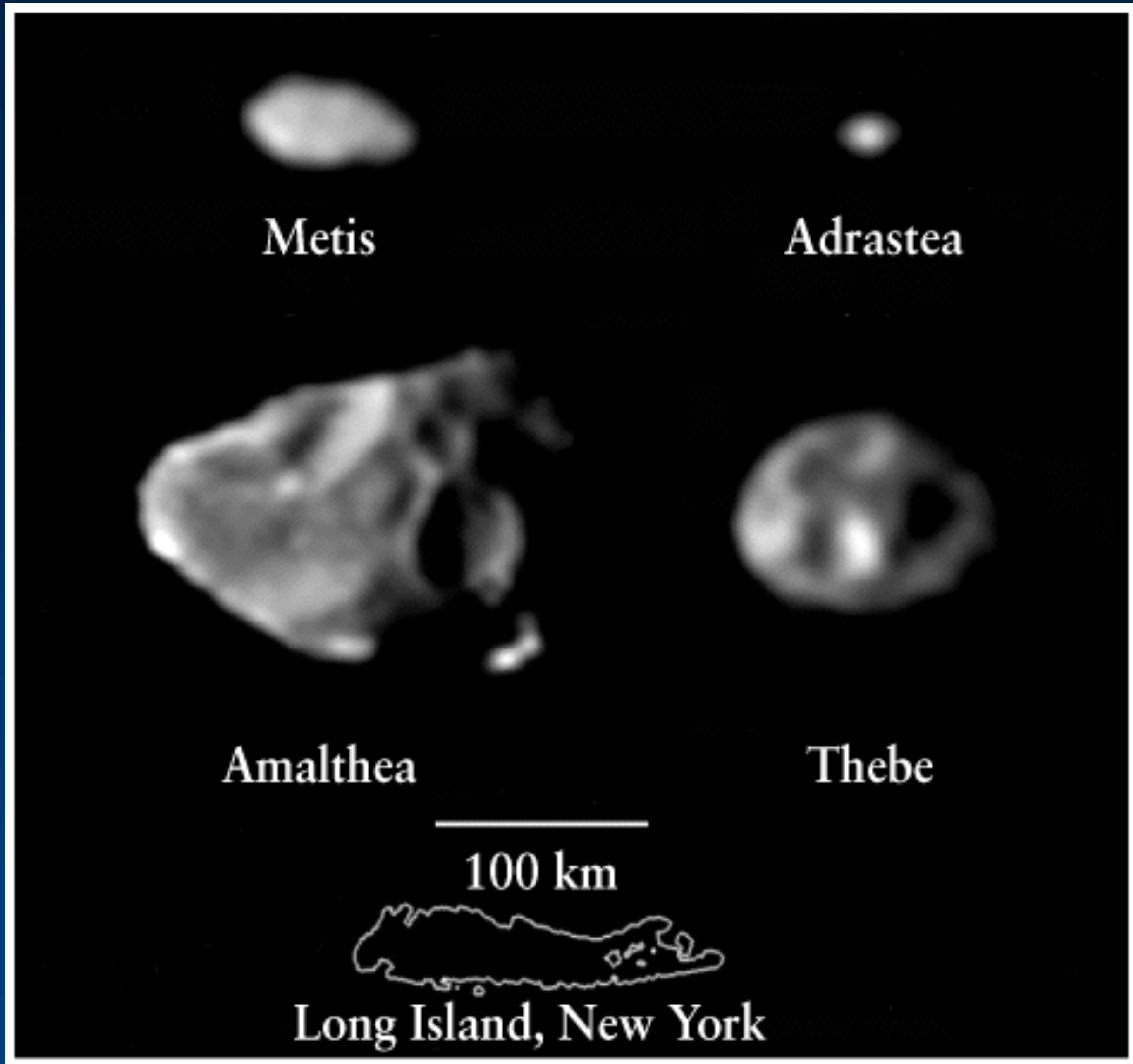
Note: The superscript R on the orbital period of a satellite means that it orbits Jupiter in a retrograde direction. Eleven additional satellites (S/2000 J1 through S/2000 J11) were discovered in 2000. Their average distances from Jupiter range from 7 to 24 million km, and their sizes range from 3 to 8 km. Nine are in retrograde orbits. The discoveries of these satellites had not been confirmed as of this writing (early 2001), so they do not appear in the above table.

- Outer satellites: Most have highly inclined or retrograde orbits: probably captured asteroids

Worksheet #14

- From the orbit of Io, calculate the mass of Jupiter

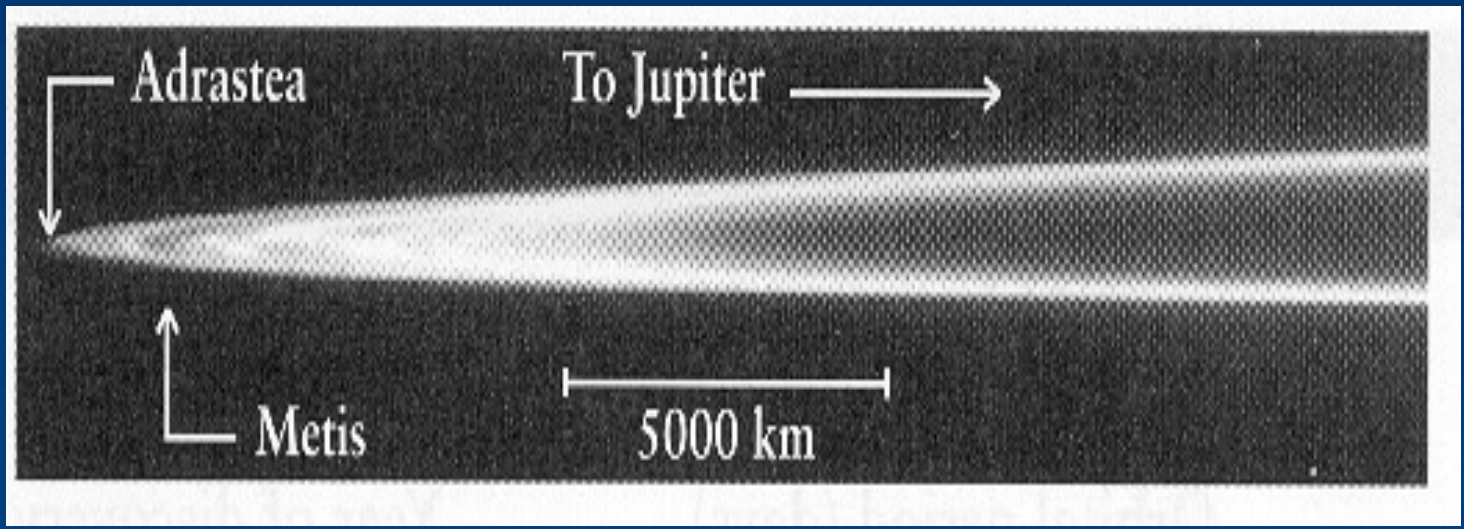
Inner four satellites – inside Io's orbit



Irregular shapes, orbit in Jupiter's equatorial plane. All orbit in same sense as Jupiter rotates ("prograde"). Suggests formed with Jupiter.

Inner satellites probably produce the ring

Not visible from Earth - discovered by Voyager satellites. Faint, particles of rock. Presumably produced by meteorite impacts on inner satellites.



Saturn's Moons

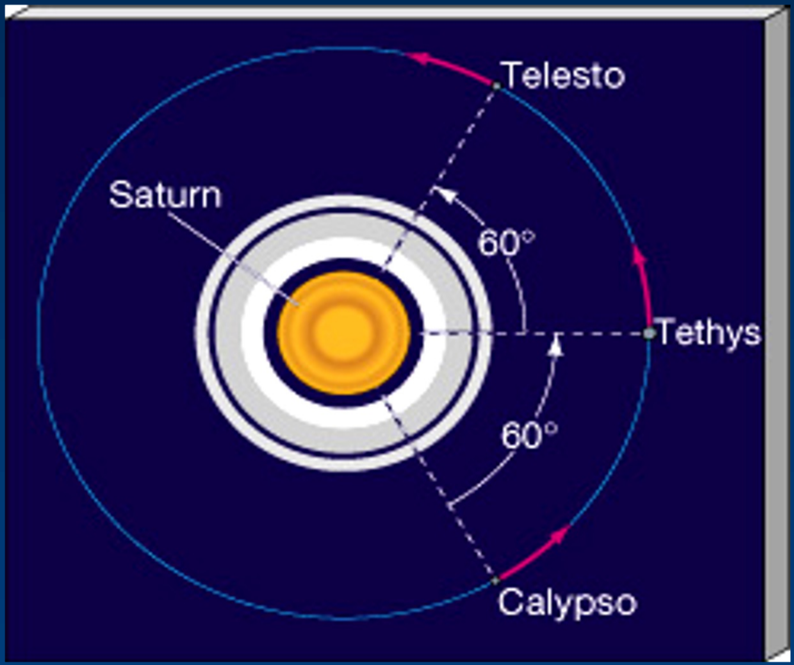
- 1 planet sized: Titan – only Ganymede is larger. Low density ⇒ ice and rock.

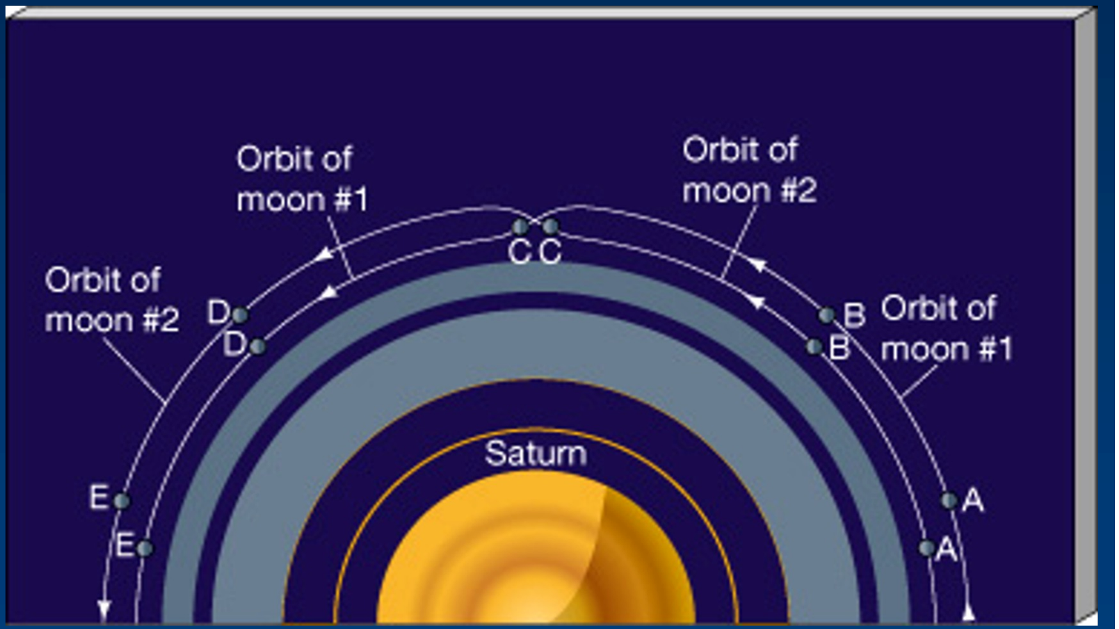
From Cassini-Huygens mission

Bizarre Orbits of some of Saturn's Moons

Tethys

Janus and Epimethius



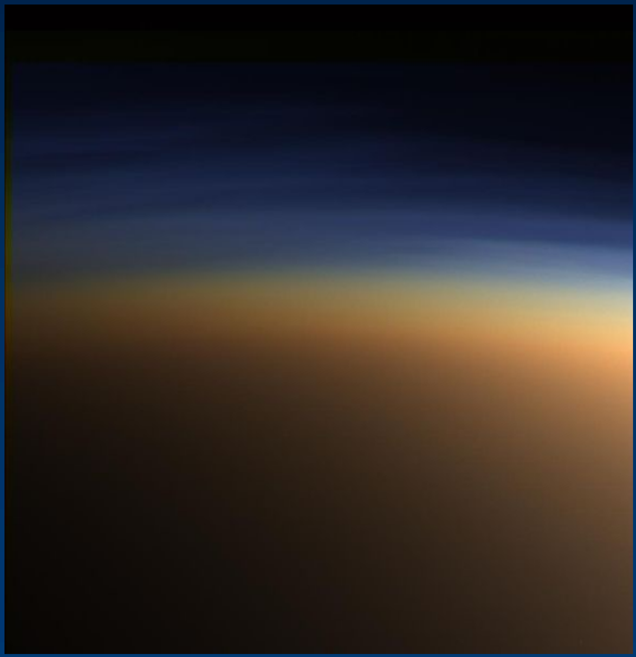


Telesto and Calypso share orbit with Tethys, and are always 60 deg. ahead and behind it! They stay there because of combined gravity of Saturn and Tethys.

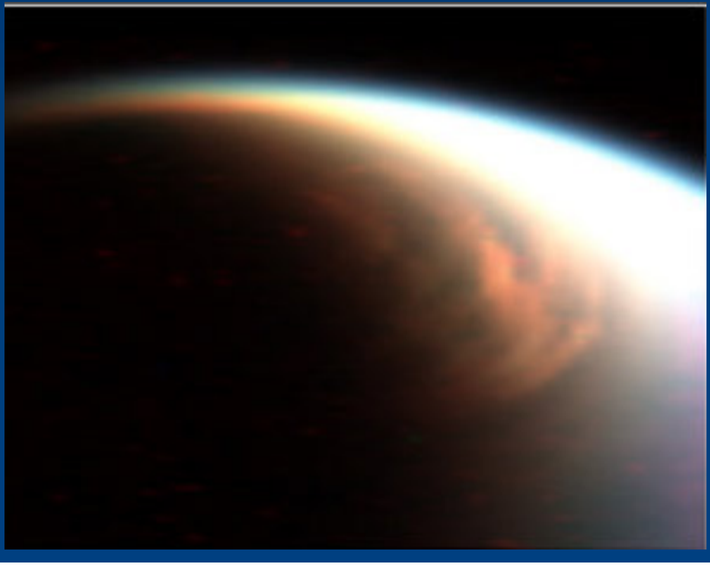
Janus and Epimethius are in close orbits. When the approach each other, they switch orbits!

Titan's atmosphere

Cassini 2005 image



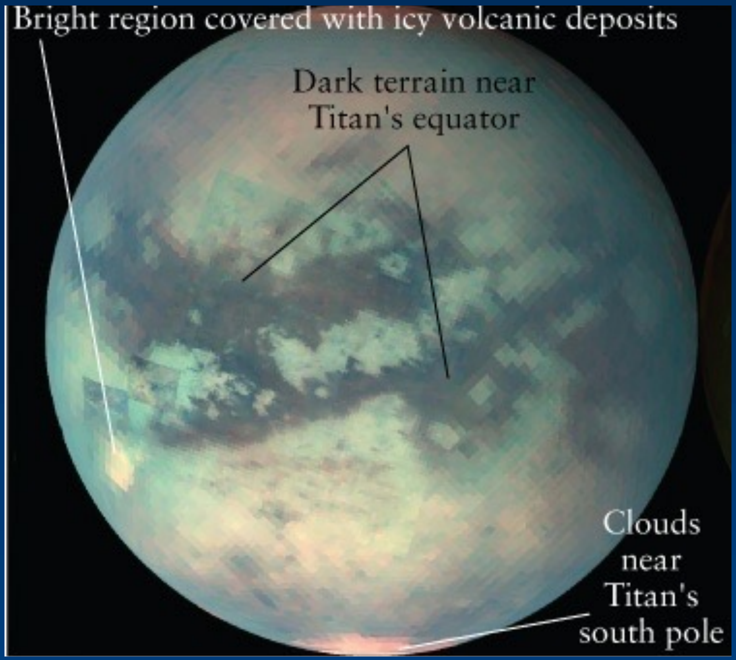
Cloud of methane & ethane confirmed (2006)



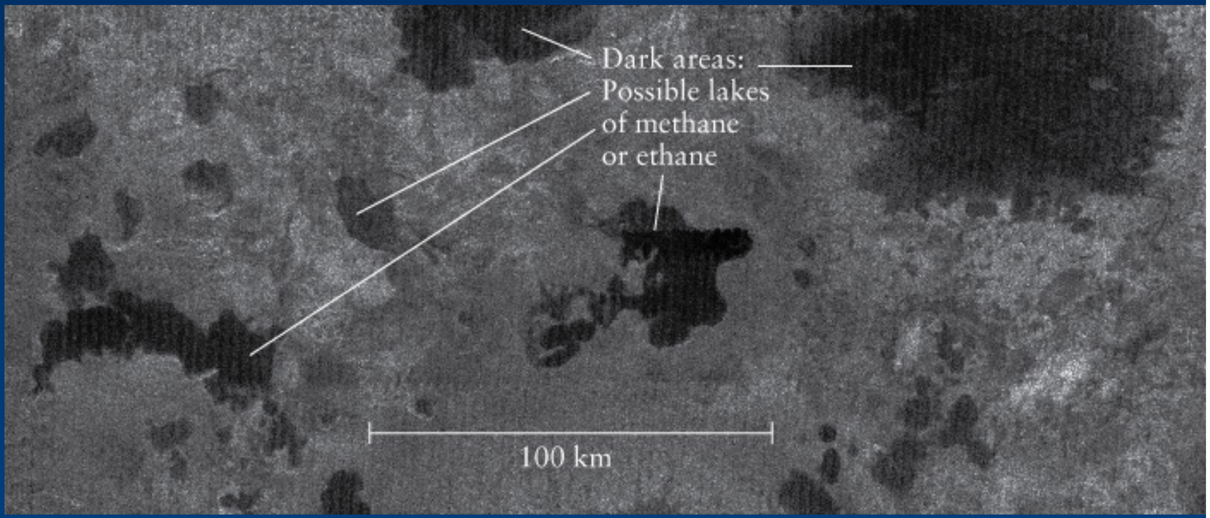
- Cold: Surface temp 95K. Surface pressure 1.6 atm.
- Cold and massive enough to retain atmosphere. Unique among moons in Solar System.
- >95% nitrogen (probably NH_3 broken by solar UV; ~3% methane, other hydrocarbons (like ethane, propane).

Surface of Titan

At this cold temperature, methane and ethane can be ice, liquid or gas! So rain, rivers, lakes possible.



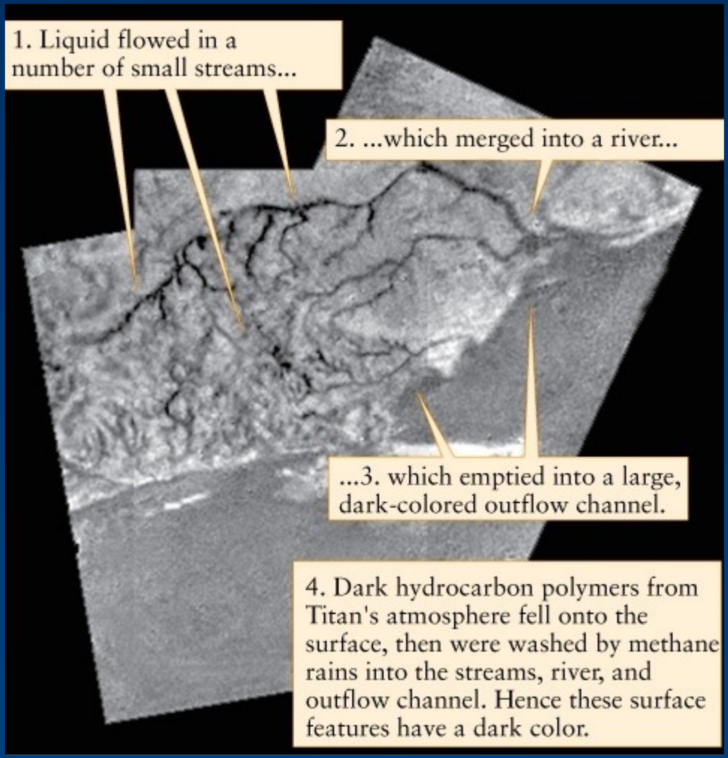
Infrared image from Cassini



Cassini radar image near North Pole – dark regions have no echo, suggesting smooth surface – lakes of methane, ethane?

Cryo-volcanoes would explain methane, which would otherwise be broken by solar UV in 10 million years.

The Huygens probe

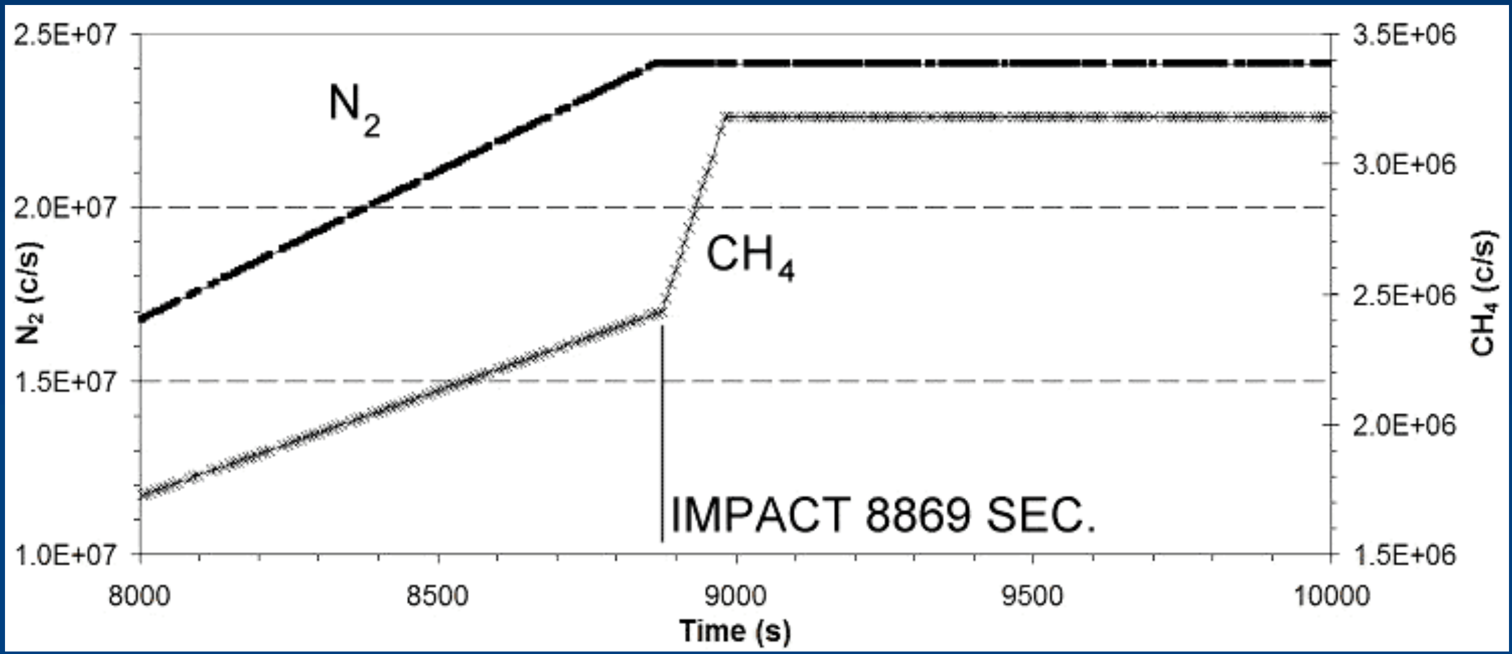


Taken during Huygens' descent (Jan 14, 2005).

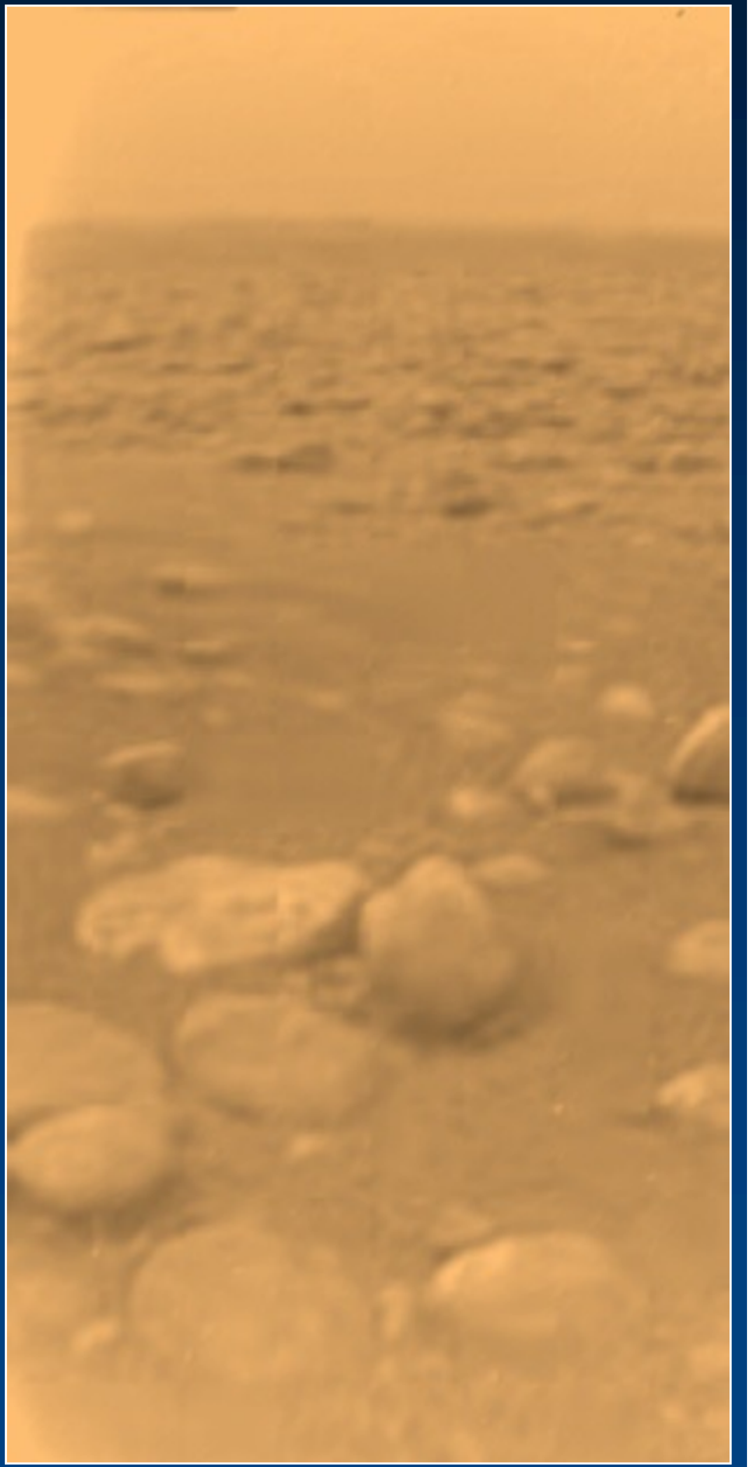
Hills, drainage channels and a shore line.

Huygens on the surface

- Survived for about 70 minutes
- After impact, heat from probe evaporated liquid methane from surface, increase in methane measured. Methane rainfall recent. Estimated 5 cm/yr.



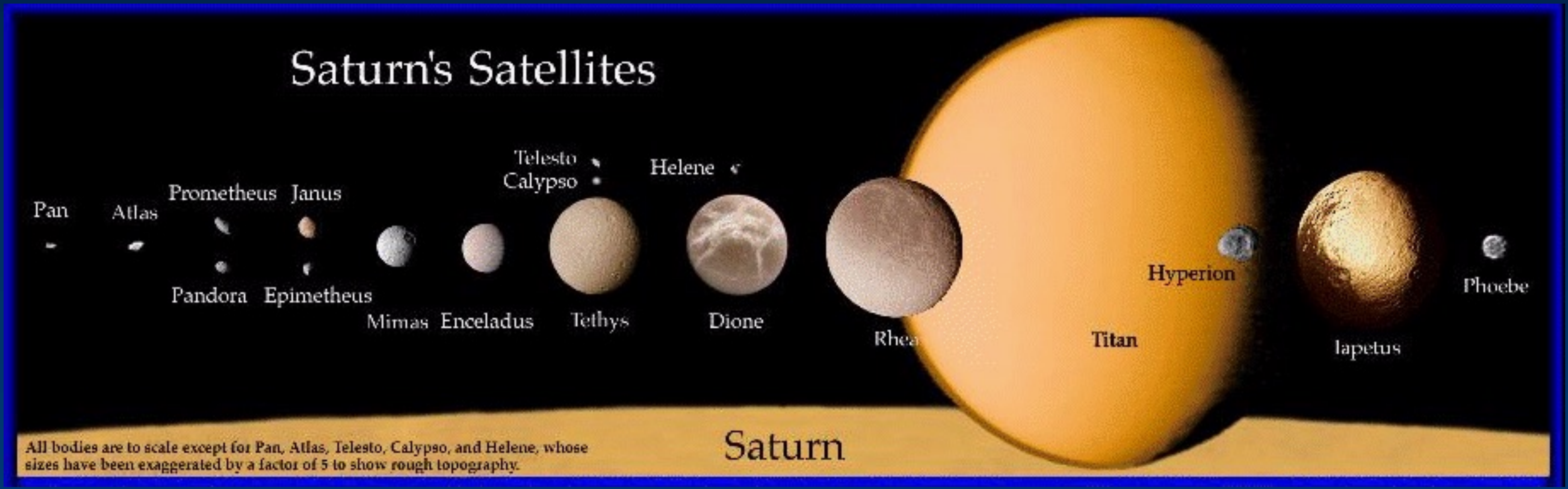
- From the landing: ice rocks, ~15cm across
- Surface darker than expected: mixture of water and hydrocarbon ice
- Evidence of erosion at base of rocks => fluid activity
- Much less methane detected than expected – rivers may date from an earlier period.



Titan's history

- Should have lost its heat of formation long ago. Heat source driving cryo-volcanism may be decay of radioactive elements and tidal heating from Saturn. May have been only a few major periods of cryo-volcanism as moon evolved.
- Has right combination of gravity and temperature to trap atmosphere.

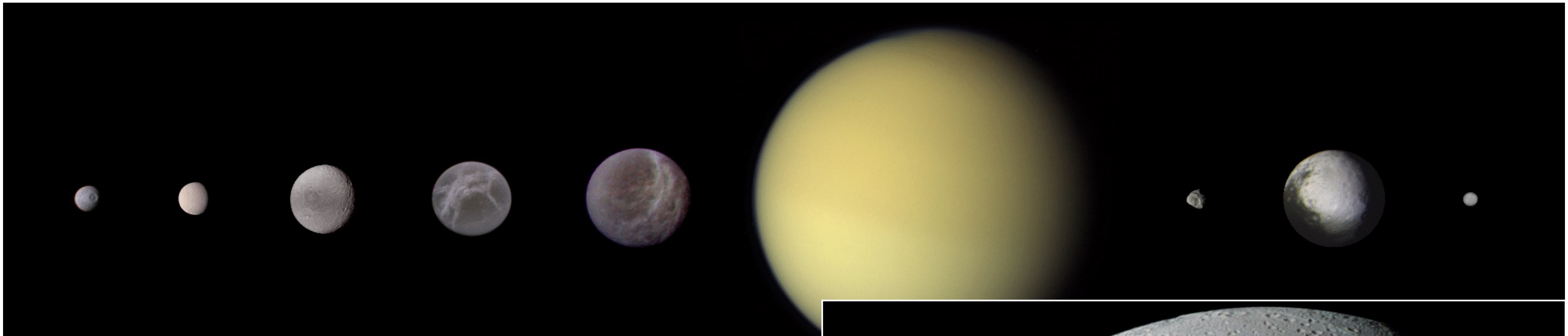
Besides Titan, Saturn has 1 big moon, 6 moderate-sized moons and many other small ones (75!).



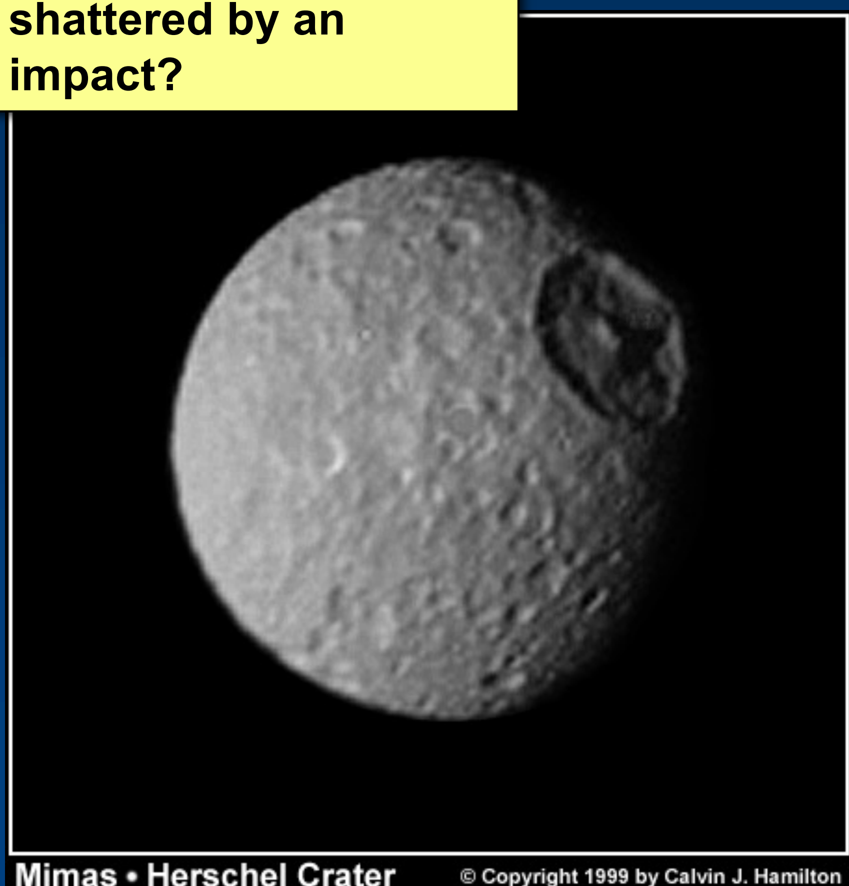
- Range in size from 20 to 1500 km

  >300 km are spherical, < 300 km are irregular.

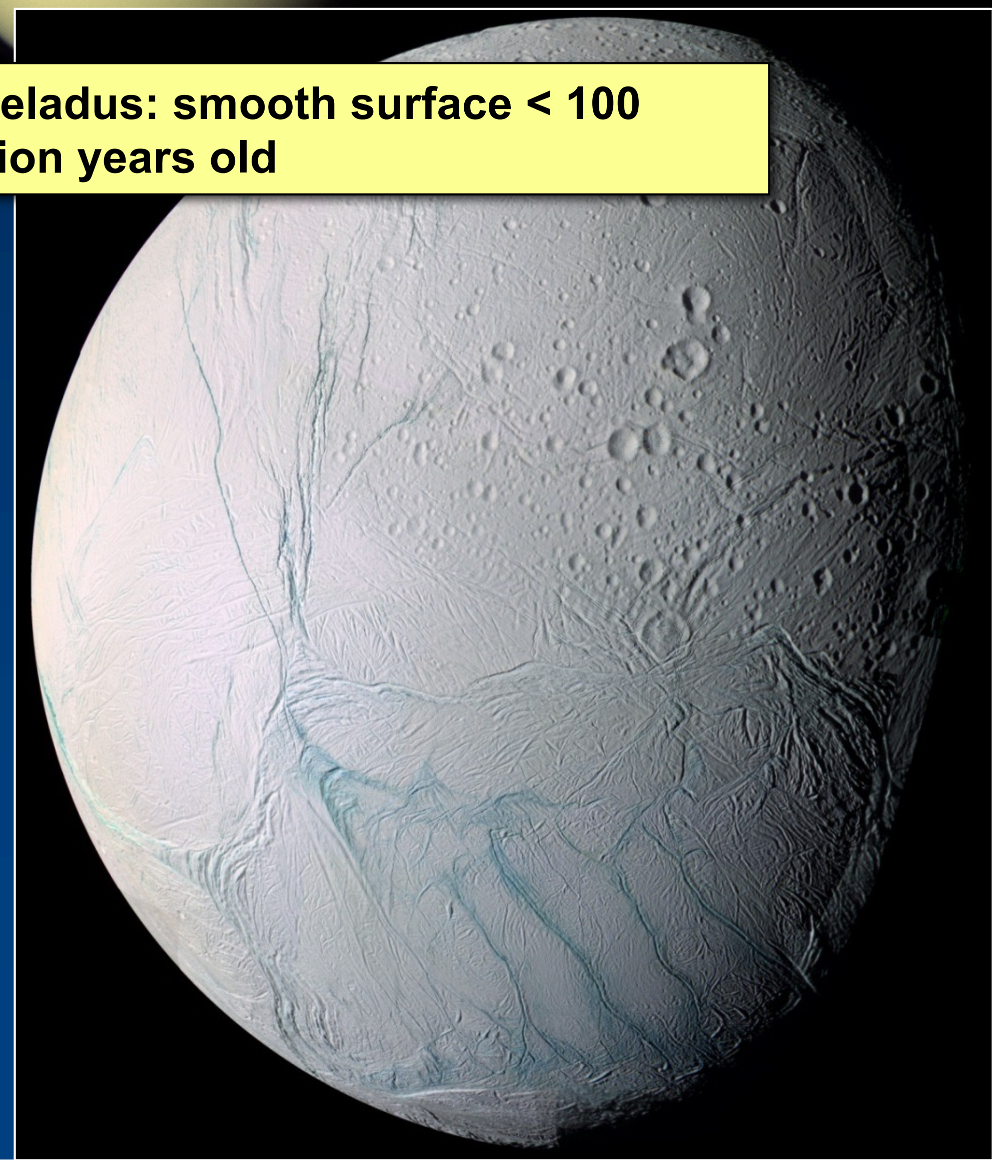
- Mostly icy (water and ammonia), or mixtures of rock & ice, with mean densities of 0.3 g/cm^3 to 1.5 g/cm^3
- Most are heavily cratered



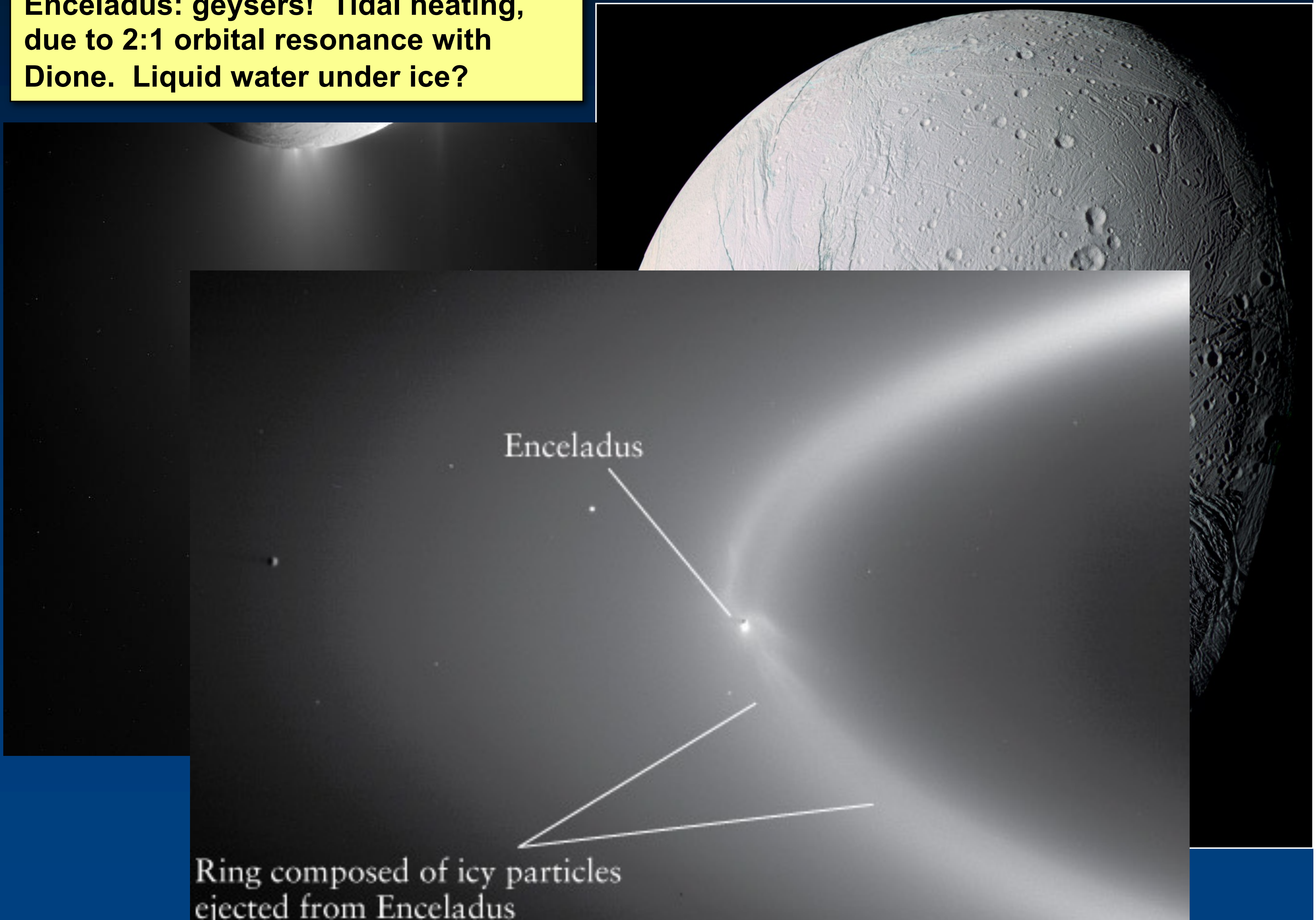
Mimas: Nearly shattered by an impact?

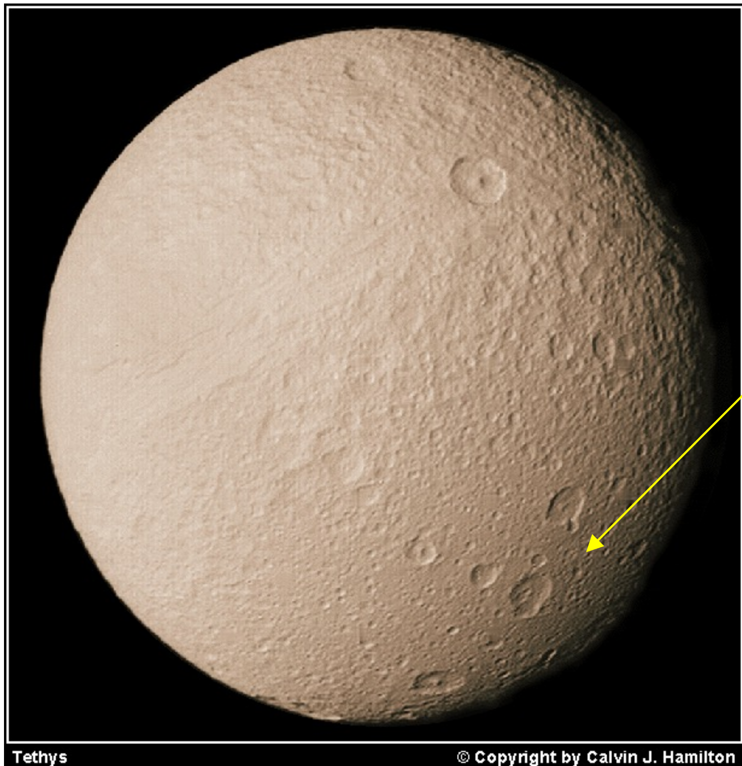


Enceladus: smooth surface < 100 million years old



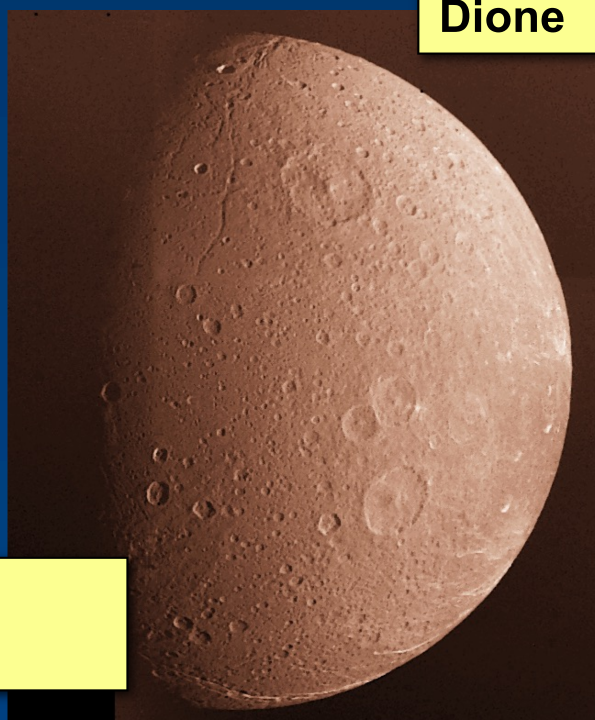
Enceladus: geysers! Tidal heating, due to 2:1 orbital resonance with Dione. Liquid water under ice?



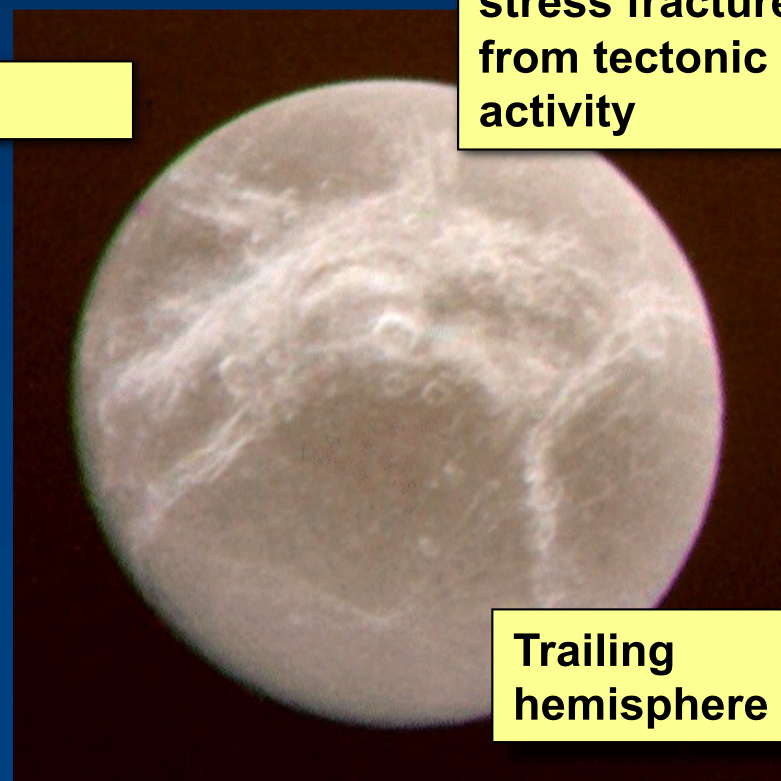


Tethys – region resurfaced by "lavas" of water and ammonia?

Dione



Leading hemisphere

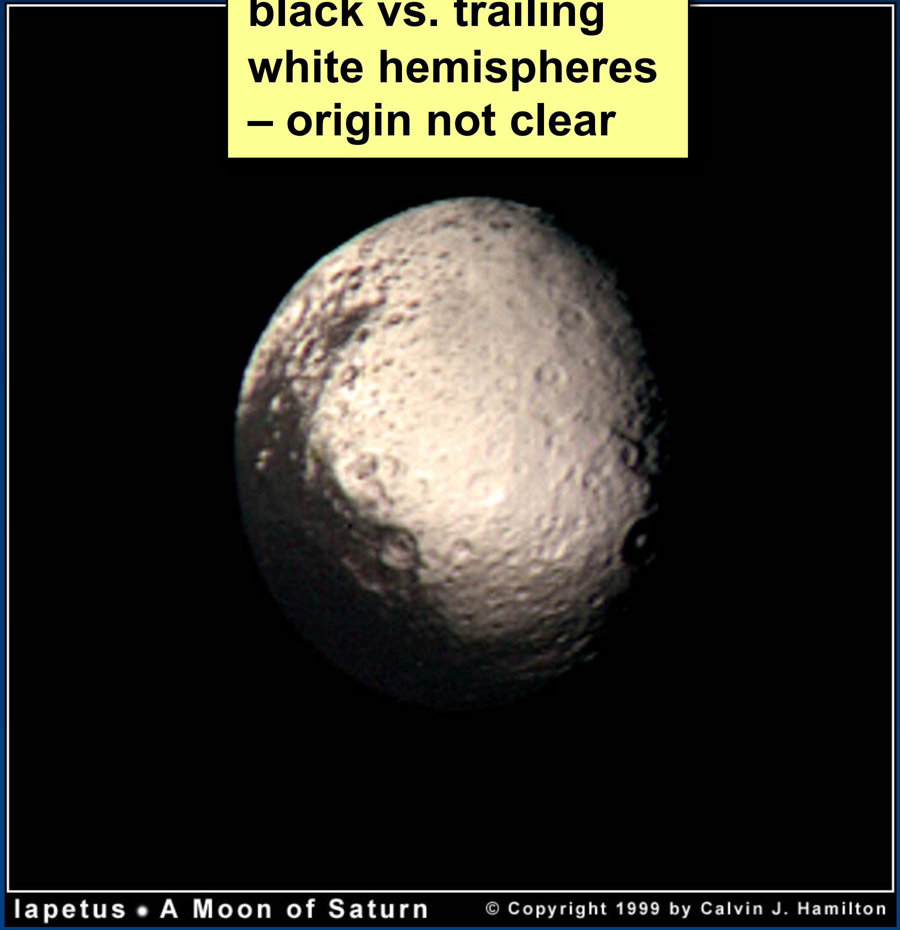


Thought to be stress fractures from tectonic activity

Trailing hemisphere

Rhea – heavily cratered

Iapetus, leading black vs. trailing white hemispheres – origin not clear

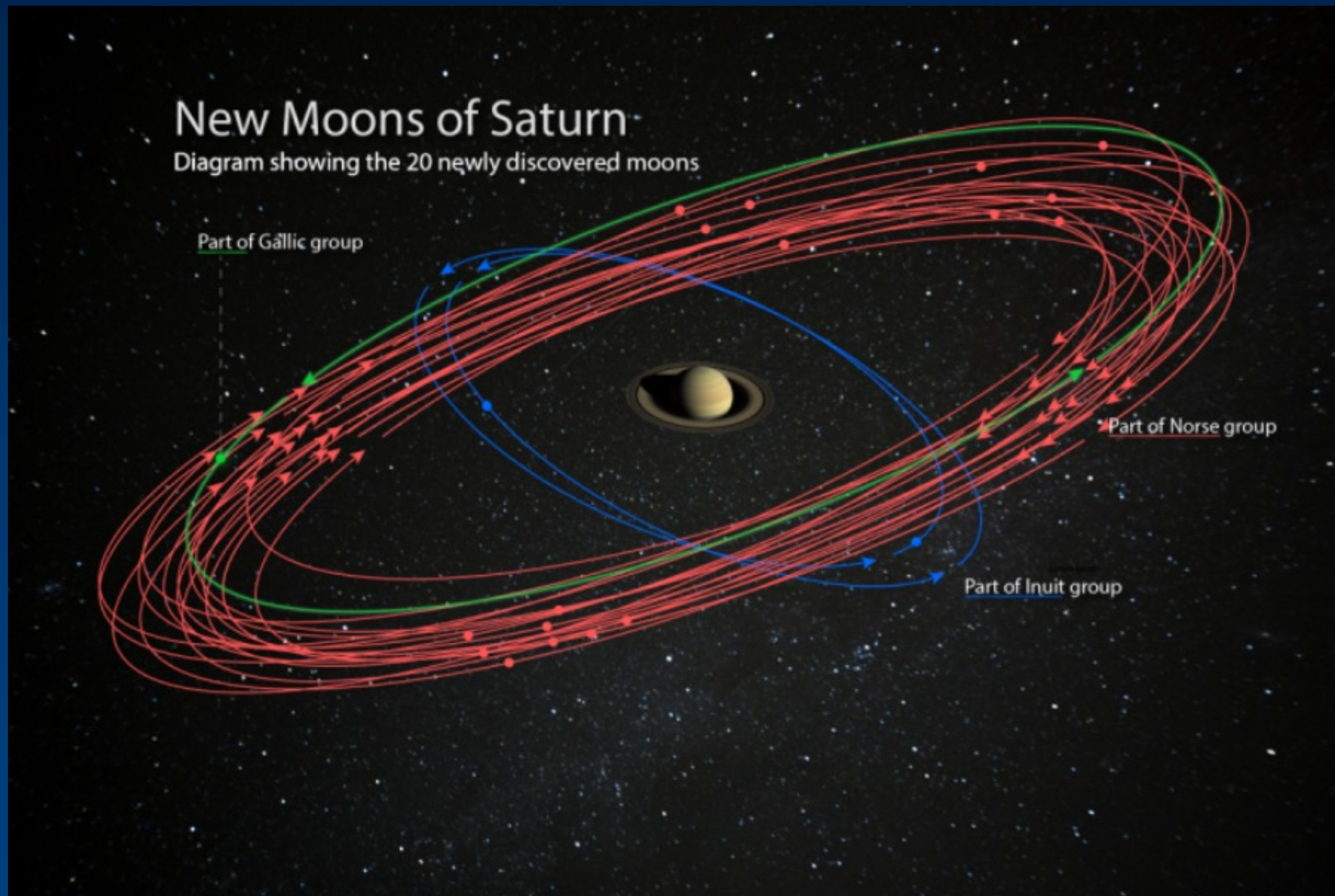


- New moons are still being discovered! 20 new moons in 2019

Small satellites – probably captured asteroids or collision fragments

Saturn: 82

Jupiter: 79



Origin of the rings

Shininess indicates little time (< 100 M years) for dust deposits to accumulate. Results from Cassini indicate recycling of rings (clumping then fragmentation) keeps them shiny. Thus rings probably 4 billion years old, though less massive.

So what is origin?:

- a moon sized object captured/ripped apart?
- asteroid smashed an existing moon?
- Leftover ices from formation?