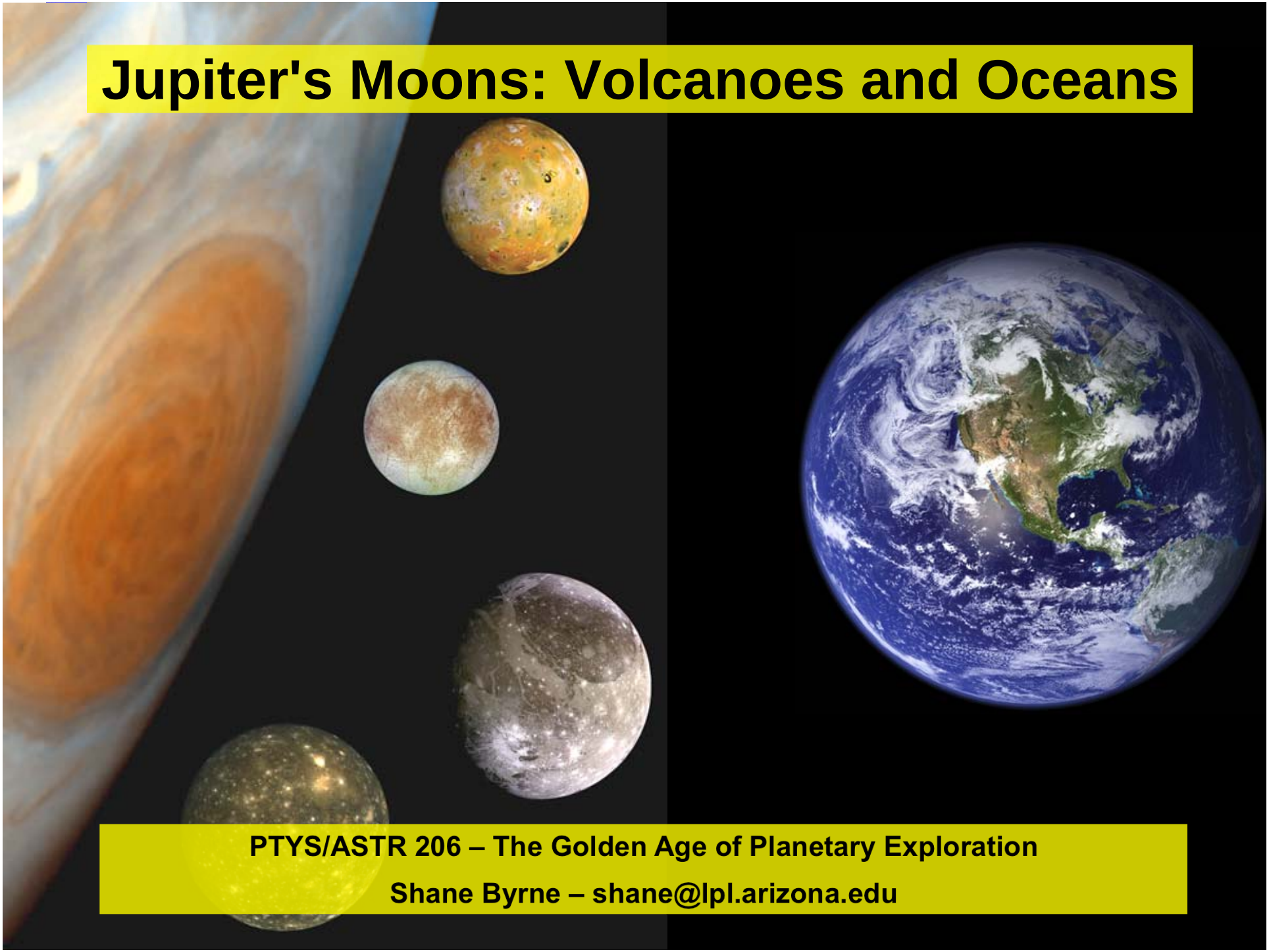
- **Announcements**
  - **HW 4 due now for 50% credit**
  - **Mid-term #2**
    - **Coming up on Thursday**
    - **Material includes everything since the last Mid-term**
    - **Same format**
      - **5-option multiple-choice questions**
      - **1 hour – so don't be late**

Jupiter's Moons: Volcanoes and Oceans



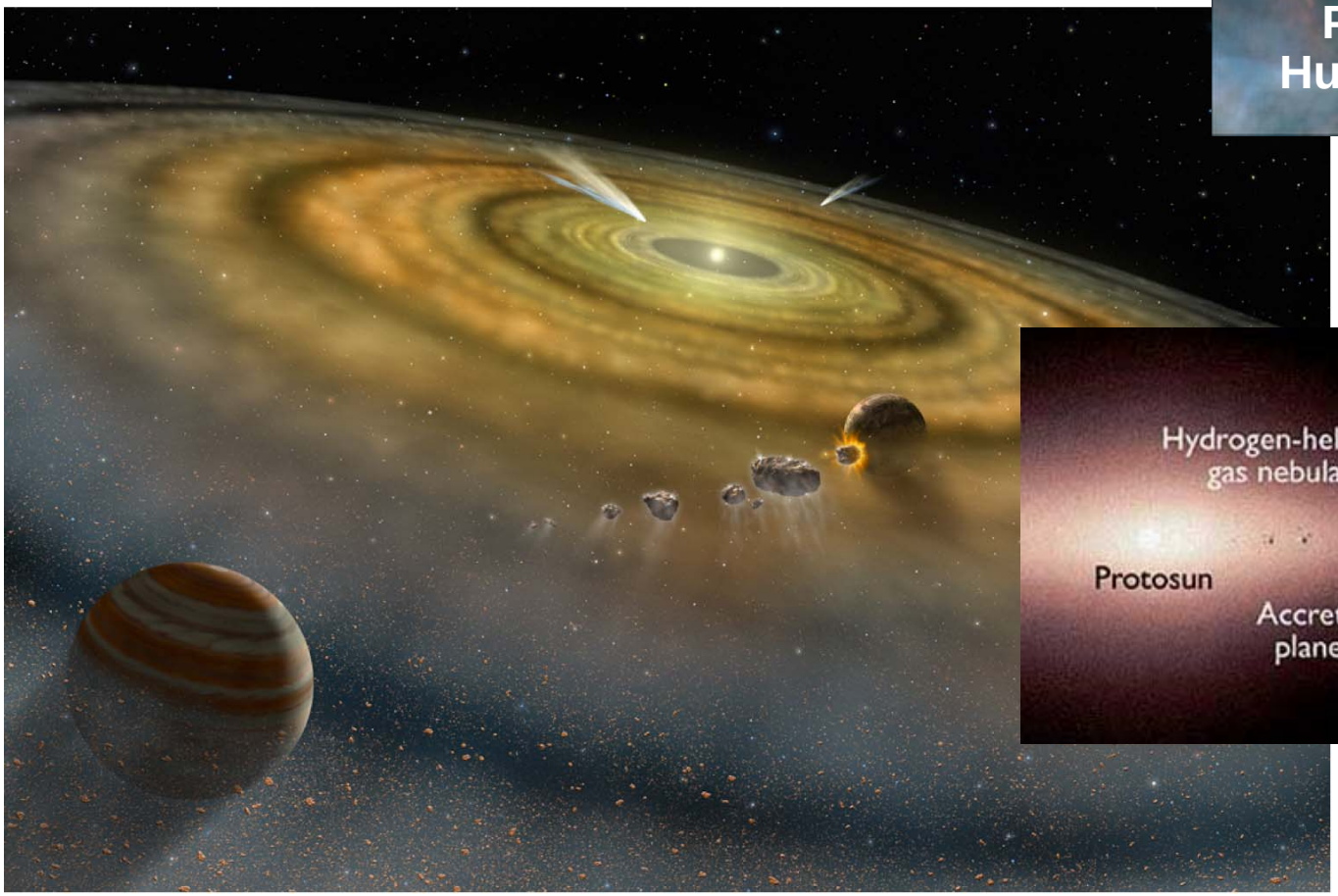
PTYS/ASTR 206 – The Golden Age of Planetary Exploration

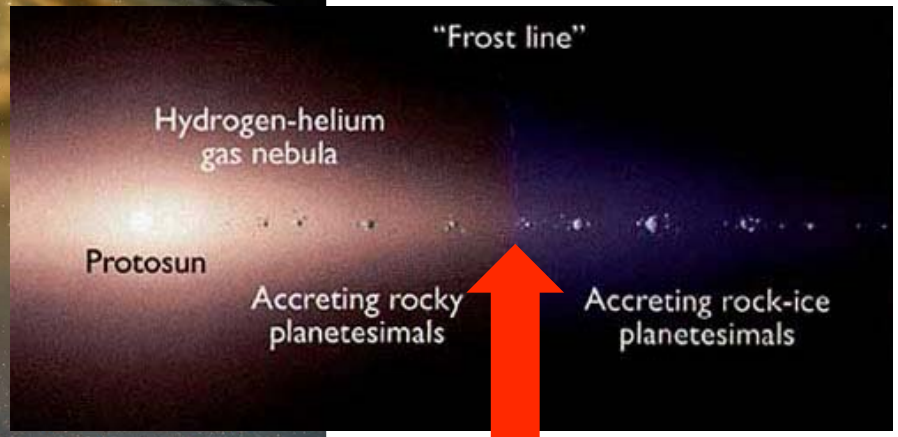
Shane Byrne – shane@lpl.arizona.edu

In this lecture…

- The frost line revisited
  - Jupiter's mini-system
- Jupiter's Rings and small moons
- Galilean Moons
  - Io
    - Volcanoes
    - Tidal heating
  - Europa
    - Ocean
    - Tectonics
  - Callisto
    - A homogeneous world inside and out
  - Ganymede
    - Part Europa – part Callisto
    - Magnetic fields

- **Solar system formation**
  - **A disk dominated by hydrogen and helium**
  - **Warmer closer to the center**
    - **Inner planets iron rich and rocky**
    - **Outer planets get bulked up with water ice**





Transition in the asteroid belt

- **Jupiter forms like a mini solar system**
  - **Rocky bodies close in**
  - **Icy bodies further out**

	Distance (R_J)	Density Kg m^{-3}
Io	5.9	3530
Europa	9.4	3020
Ganymede	15	1940
Callisto	26.4	1850

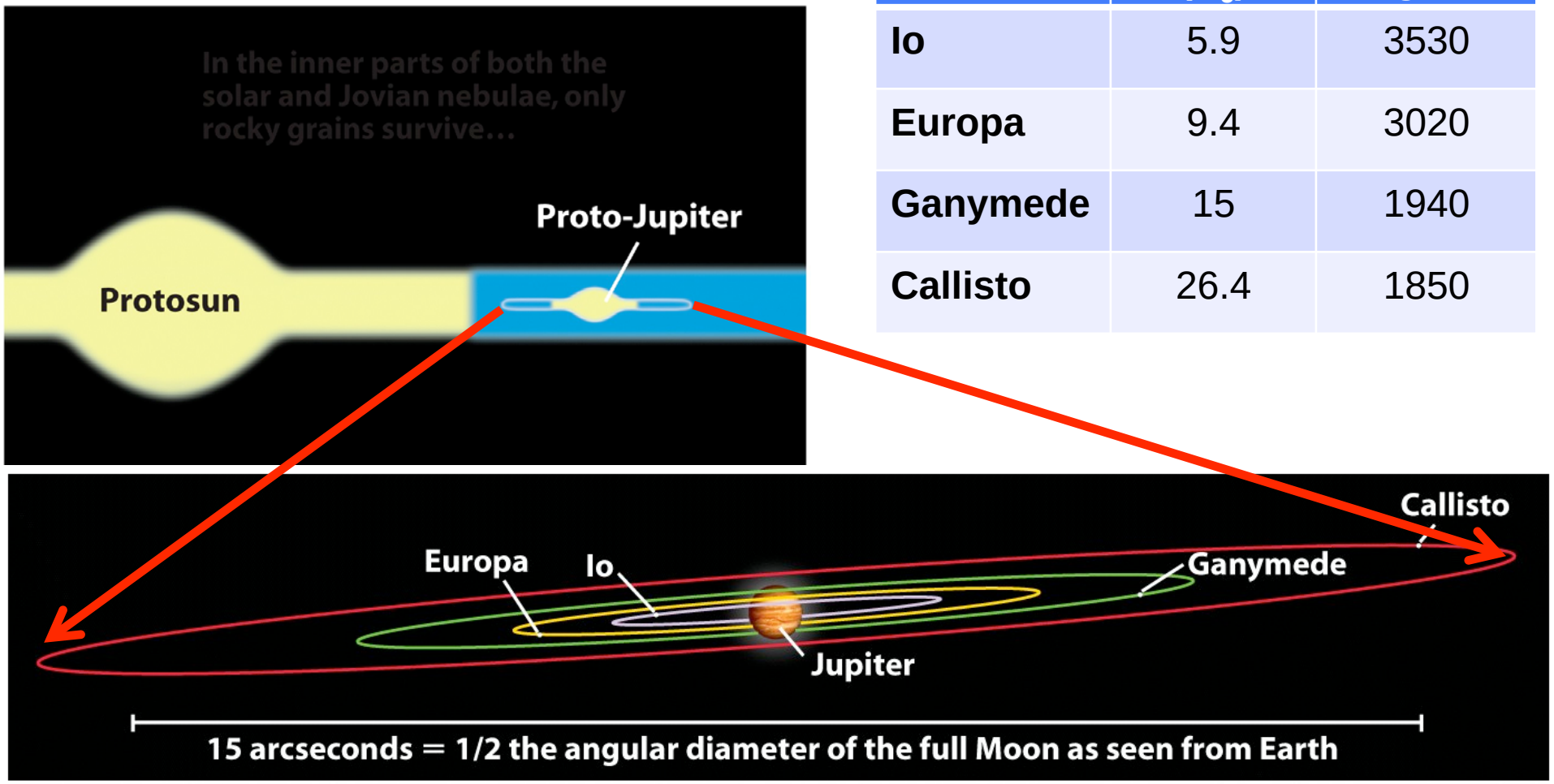


Figure 13-1
Universe, Eighth Edition

- **With increasing distance from Jupiter**
  - **Iron cores get smaller (as a fraction of bodies size)**
  - **Oceans get bigger**
  - **Ice shells get thicker**

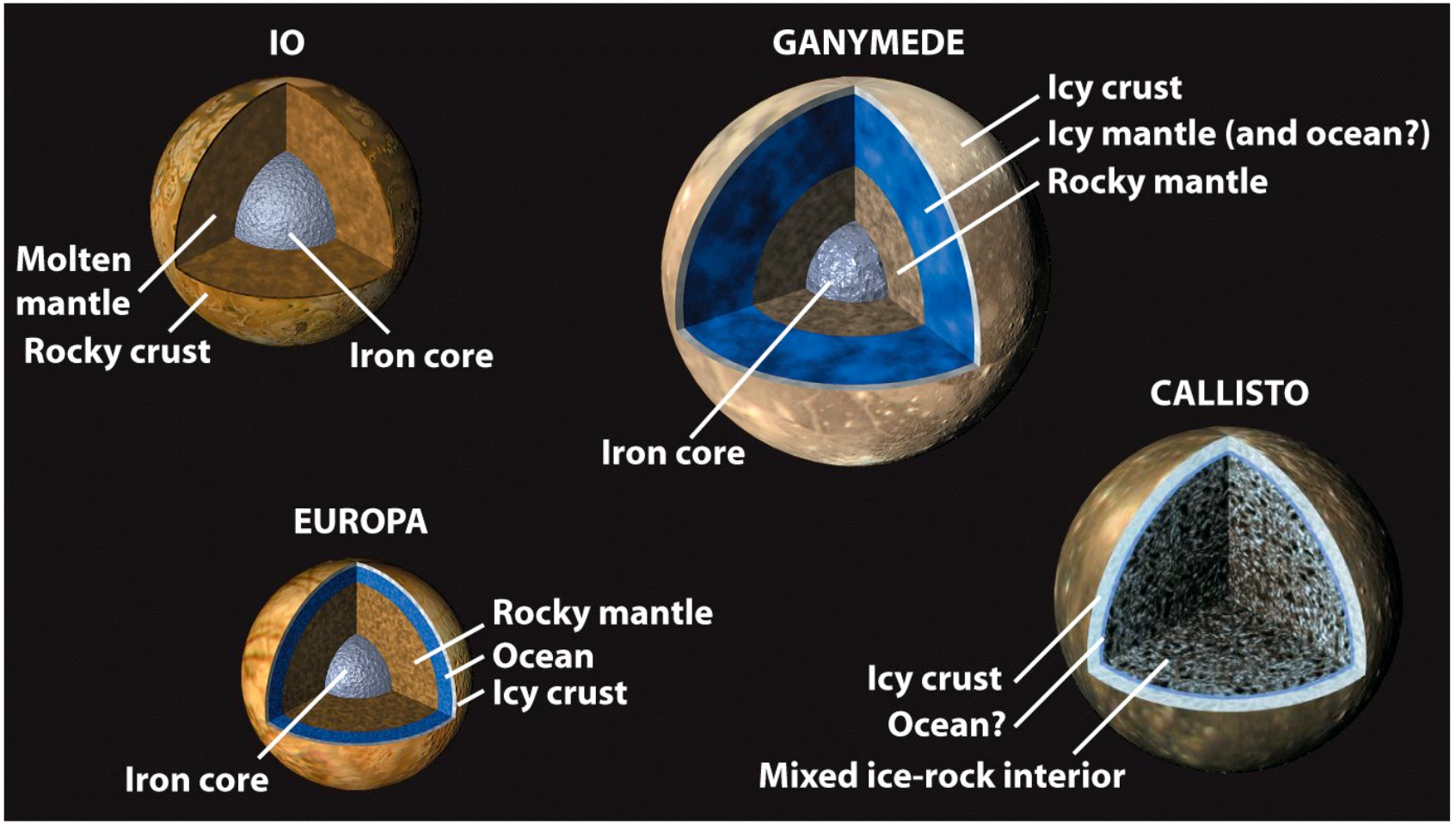
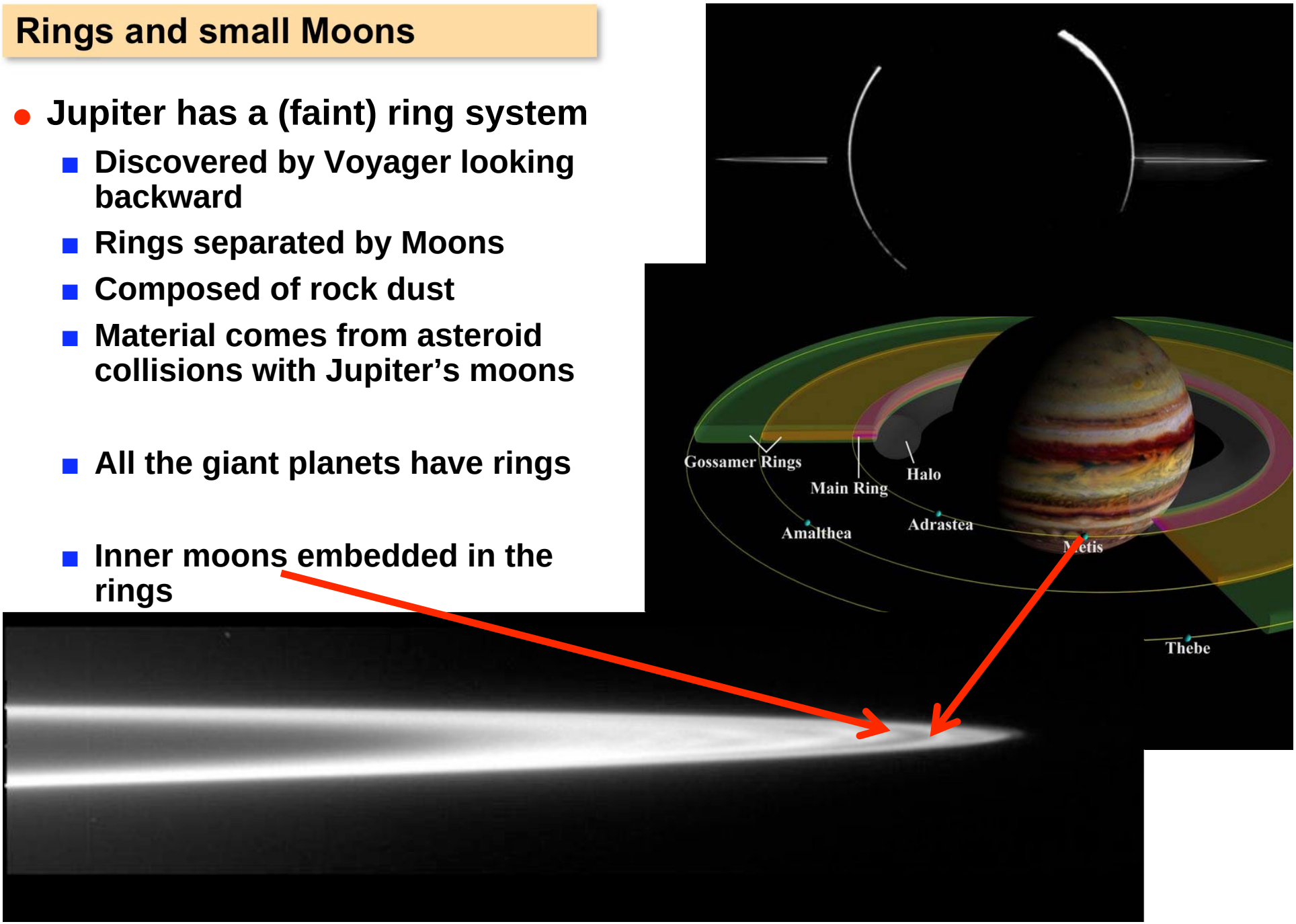


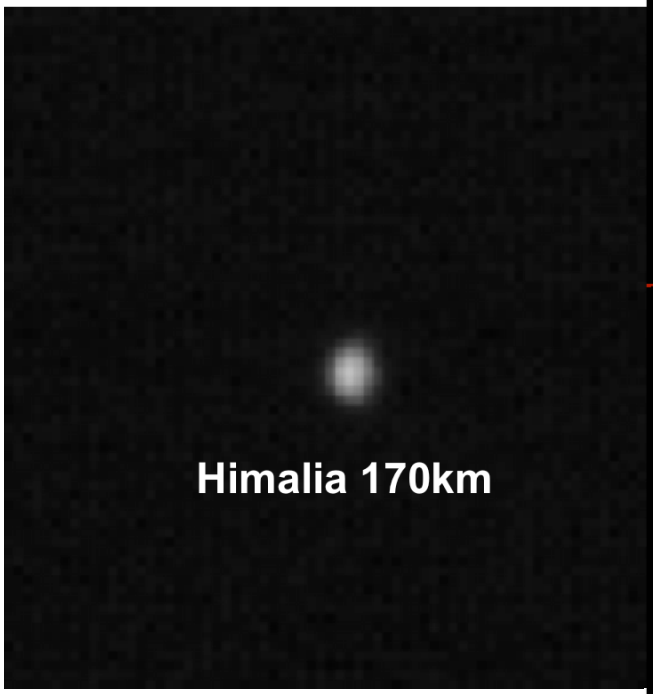
Figure 13-17
Universe, Eighth Edition

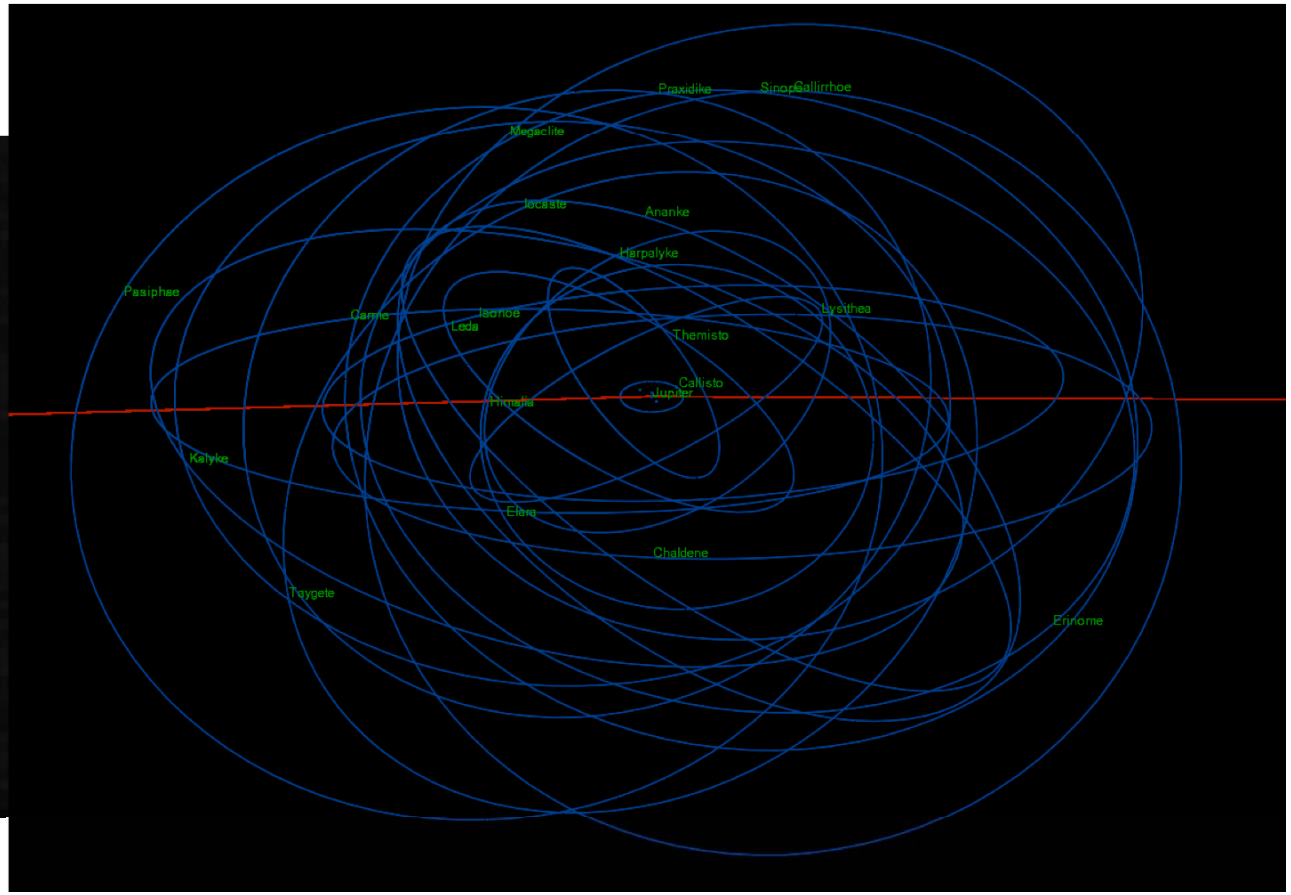
Rings and small Moons

- Jupiter has a (faint) ring system
  - Discovered by Voyager looking backward
  - Rings separated by Moons
  - Composed of rock dust
  - Material comes from asteroid collisions with Jupiter's moons
  - All the giant planets have rings
  - Inner moons embedded in the rings



- **Irregular satellites (~55)**
  - **Distant asteroid fragments, 100-450 R_J**
  - **Small, 2-170 km in size**
  - **Himalia group**
    - **Inclined - Prograde**
  - **Carme, Ananke and Pasiphae groups**
    - **Inclined - Retrograde**





- **Regular Satellites**
  - **Inner Moons (4)**
    - Low-inclination
    - Circular orbits
    - 20-250 km in size
    - Orbit within 1-3 R_J
  - **Galilean Satellites (4)**
    - Io – 3660 km
    - Europa – 3120 km
    - Ganymede – 5260 km
    - Callisto – 4820 km

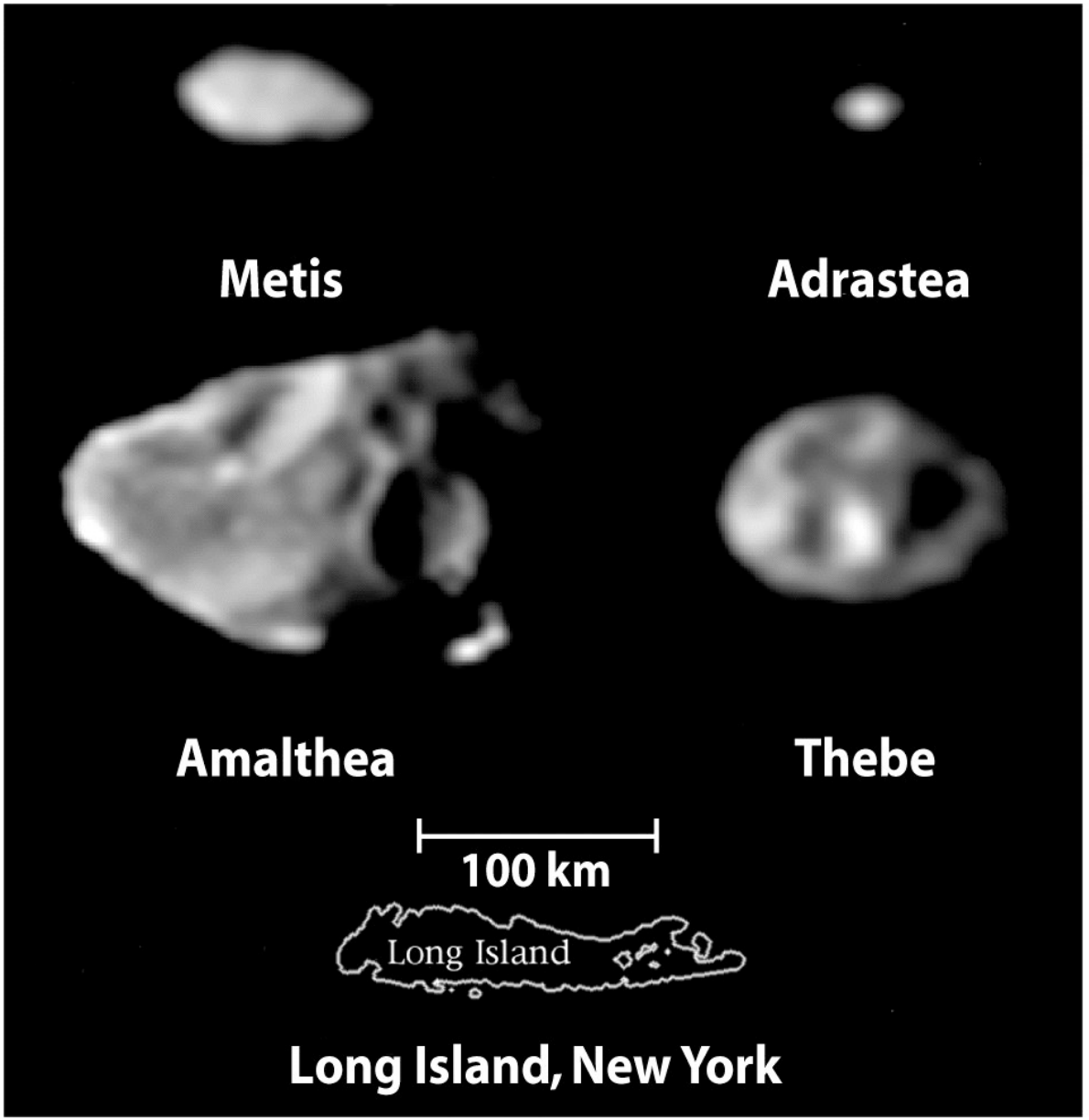
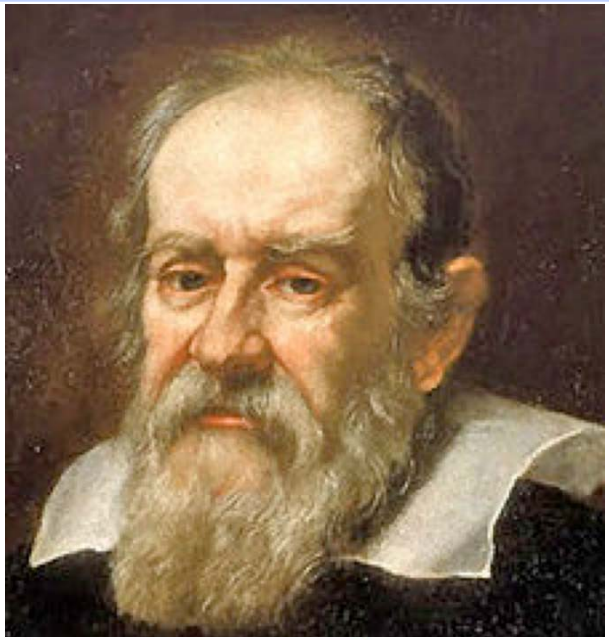


Figure 13-21
Universe, Eighth Edition

Galilean Satellites

- Discovered by Galileo
  - In 1610
  - Using new telescope



- Reformed astronomical thinking
  - Geocentric to heliocentric switch

- Used to measure the speed of light
  - Romer in 1676
  - Timing of Io's eclipses
  - Delay caused by increase in Earth's distance from Jupiter

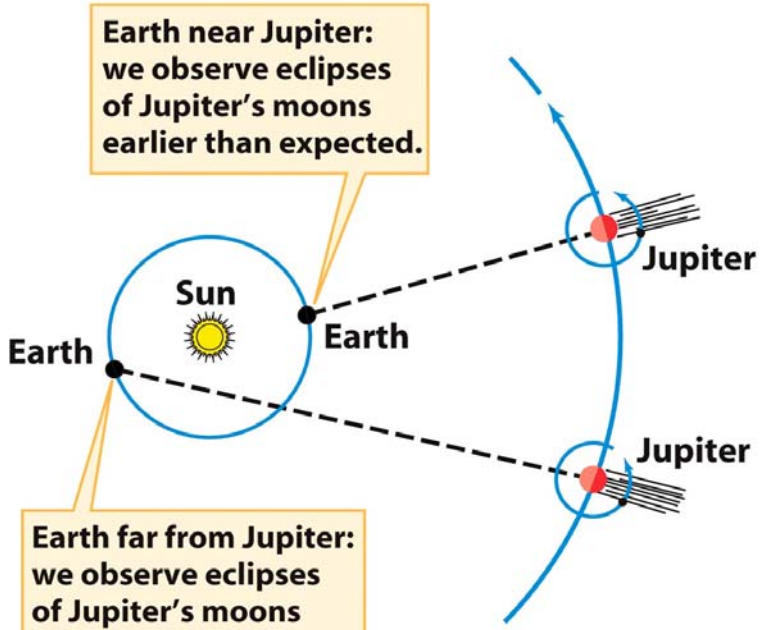


Figure 5-1
Universe, Eighth Edition

Table 13-1 Jupiter's Galilean Satellites Compared with the Moon, Mercury, and Mars

	Average distance from Jupiter (km)	Orbital period (days)	Diameter (km)	Mass		Average density	
				(kg)	(Moon = 1)	(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

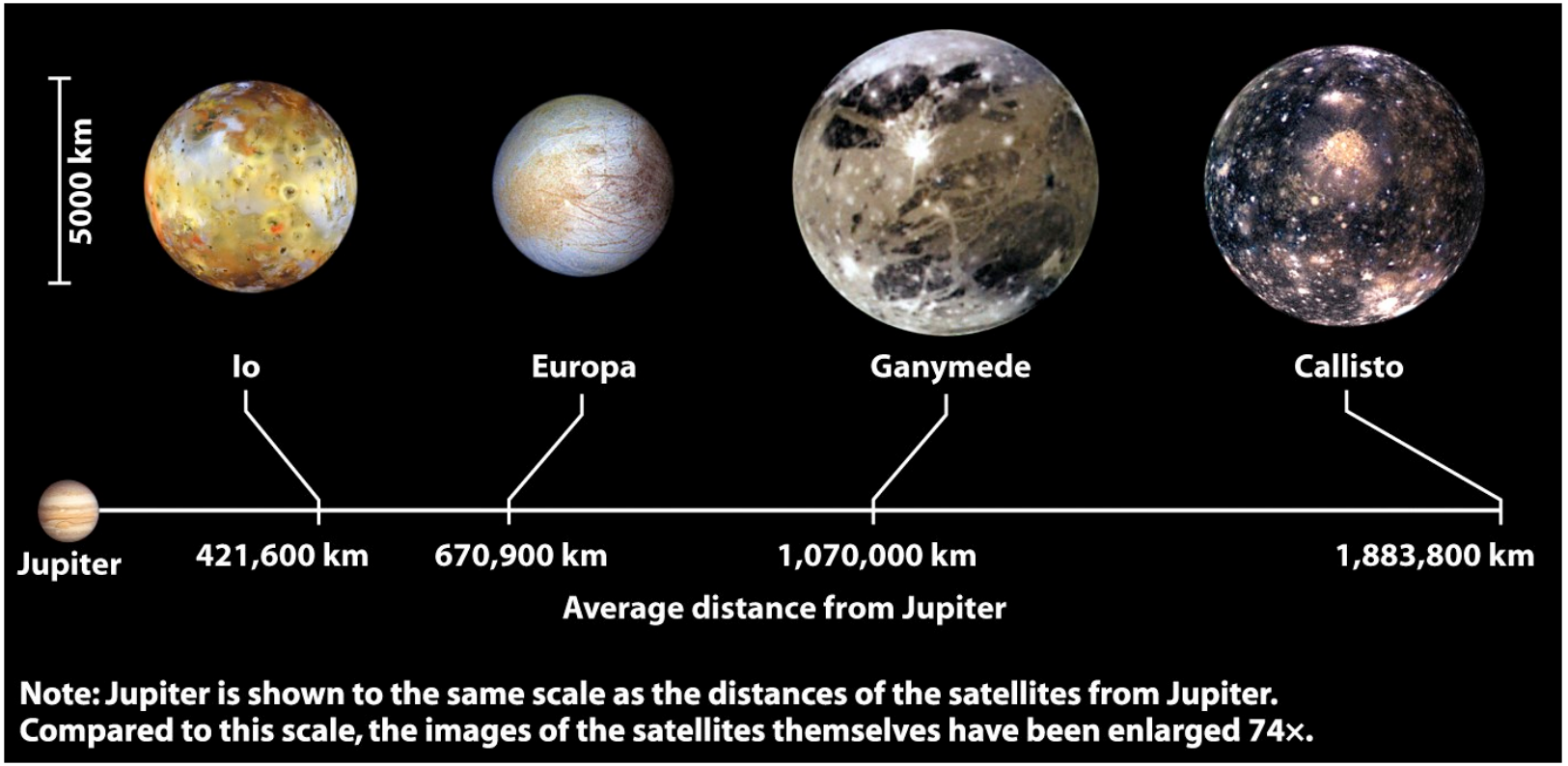
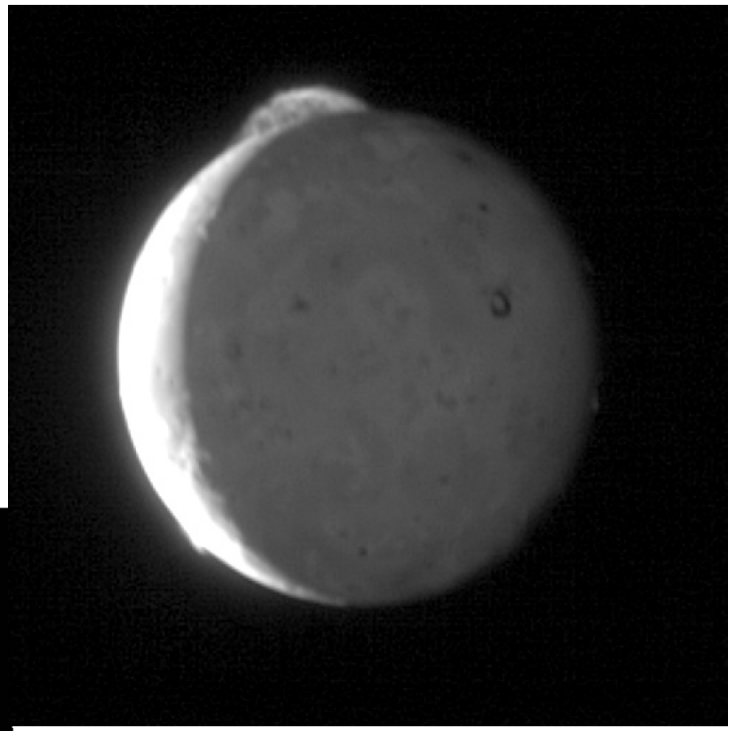


Table 13-1 (inset)
Universe, Eighth Edition

Io

- The most volcanically active body in the solar system
- Volcanoes resurface Io with 1 cm of new material every year



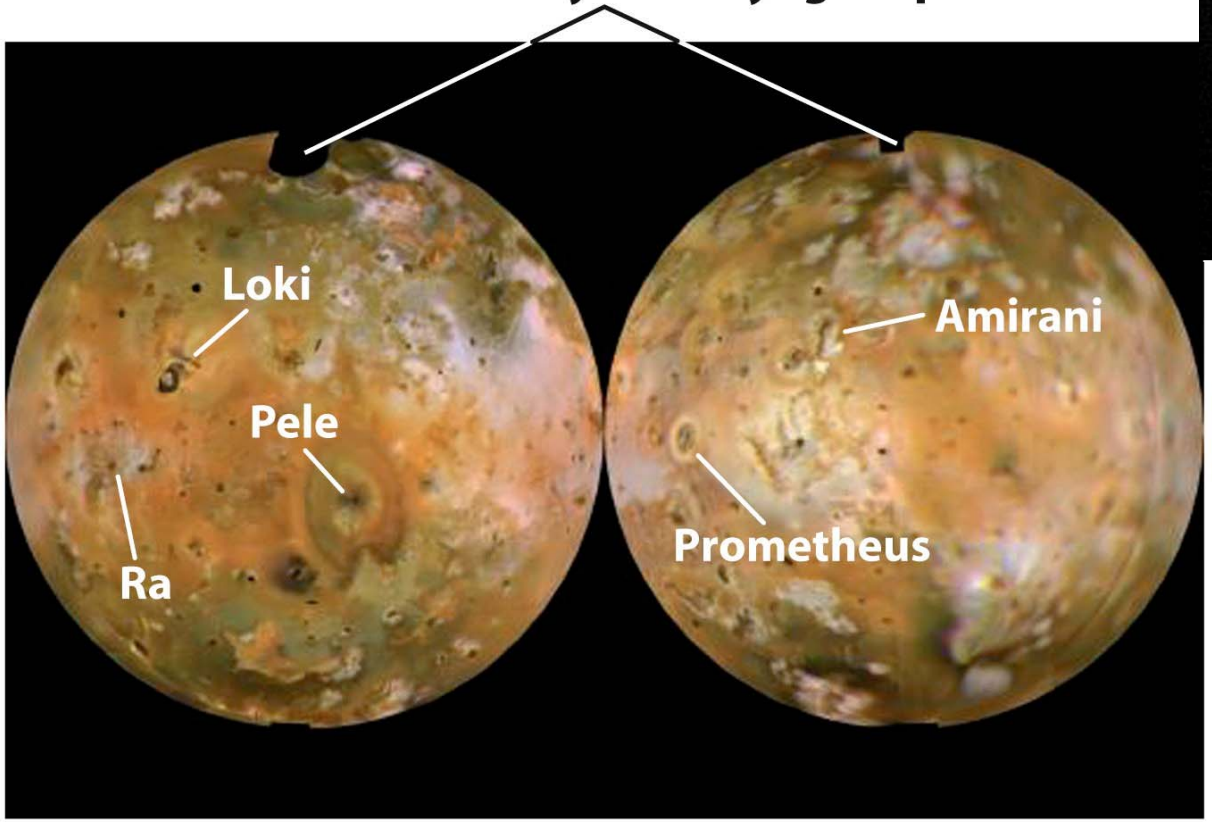
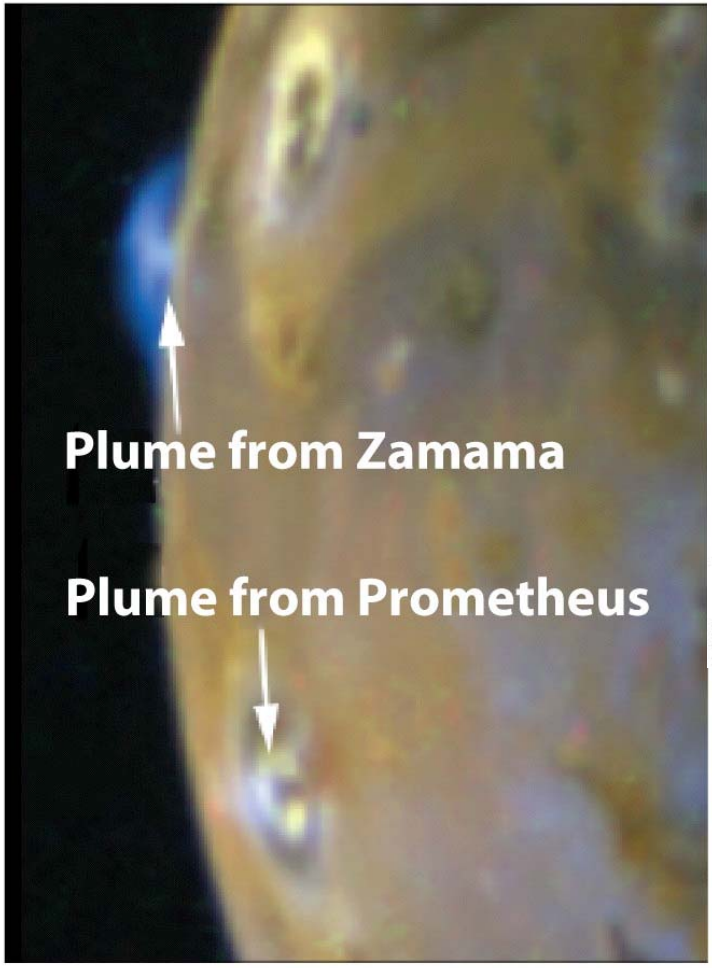


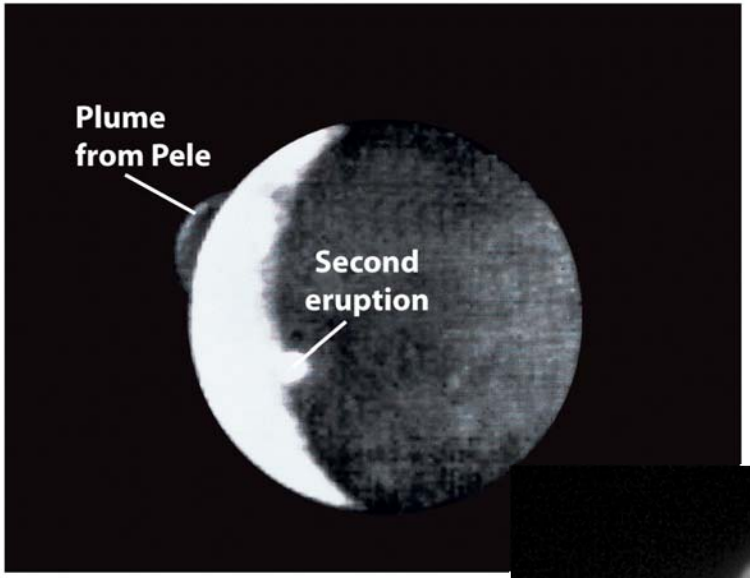
Figure 13-4
Universe, Eighth Edition

- **Constant activity**
  - **Several eruptions in progress at any point in time**



Galileo, November 1997

Figure 13-5b
Universe, Eighth Edition



Voyager 1, March 1979

Figure 13-5a
Universe, Eighth Edition

- **Galileo spacecraft saw the results of several eruptions**
  - **Overlapping deposits show the sequence of eruptions**

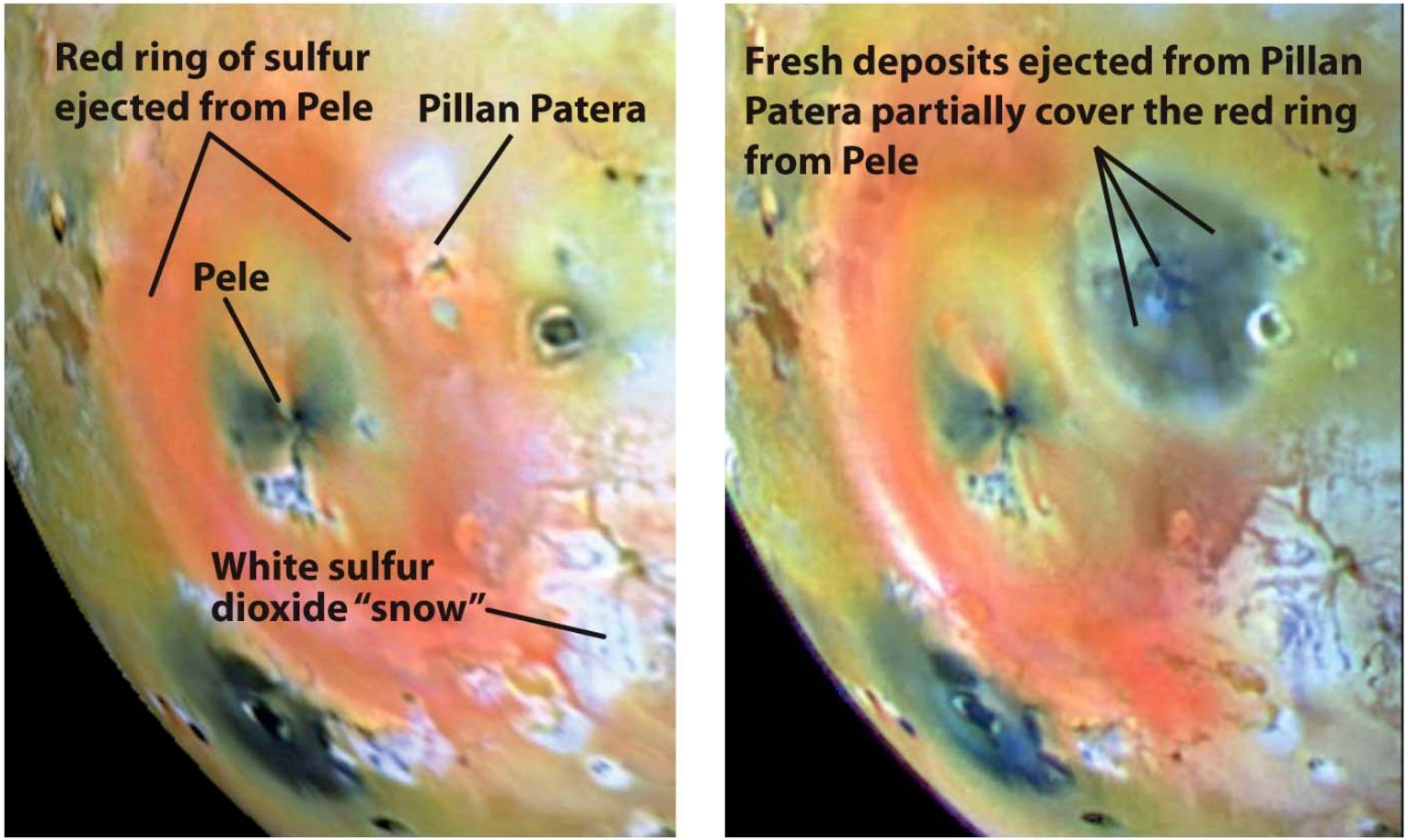


Figure 13-6
Universe, Eighth Edition

- **Active eruptions**
  - **Infrared views from the Earth**
  - **Close ups from spacecraft show erupting lava curtains**

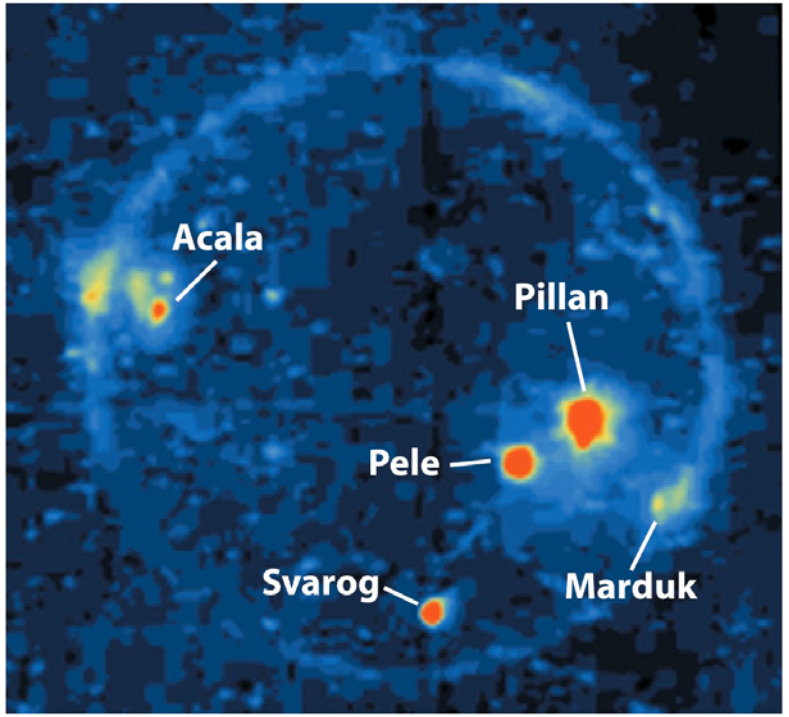


Figure 13-8
Universe, Eighth Edition

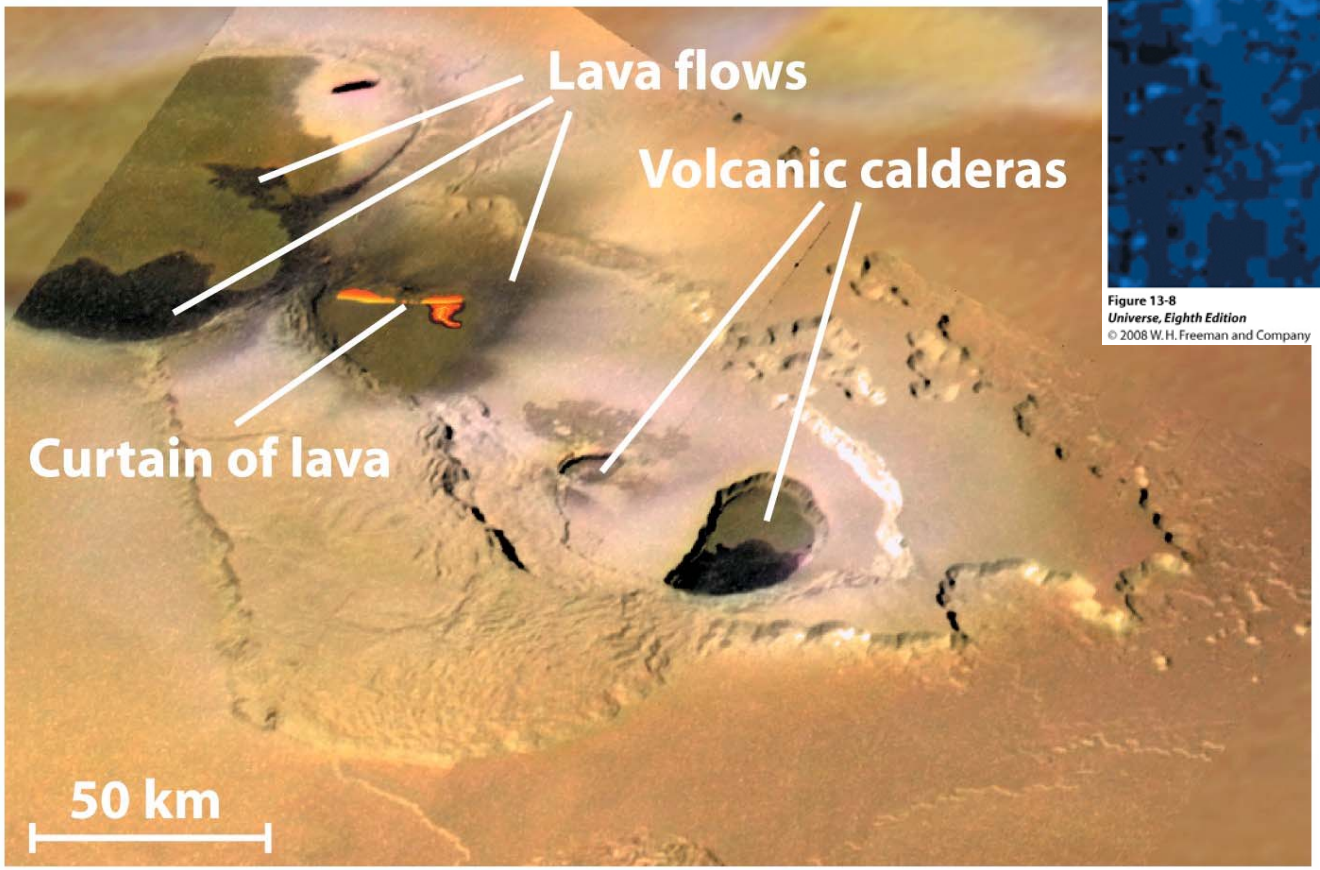
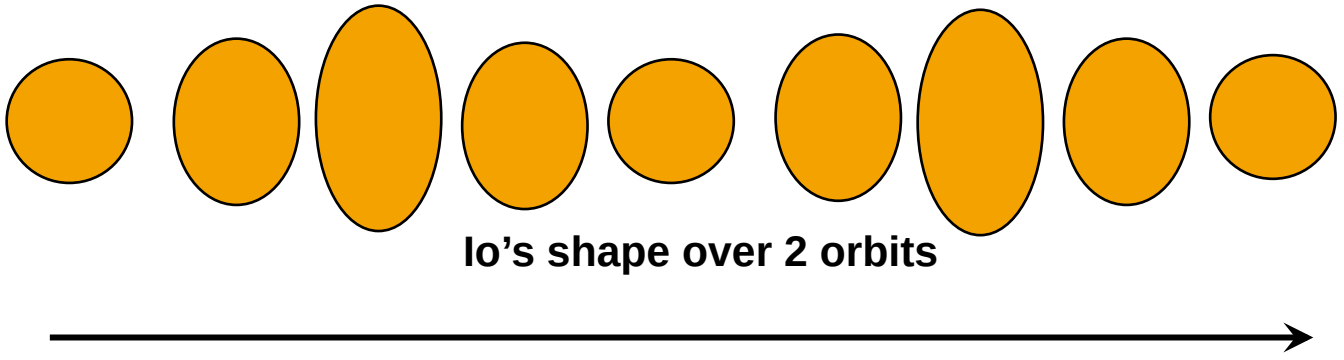


Figure 13-7
Universe, Eighth Edition

- What's going on? – Where's all this energy coming from

- Io is heated by extreme tides
- The Moon raises small tides on the Earth
- Jupiter raises HUGE tides on Io

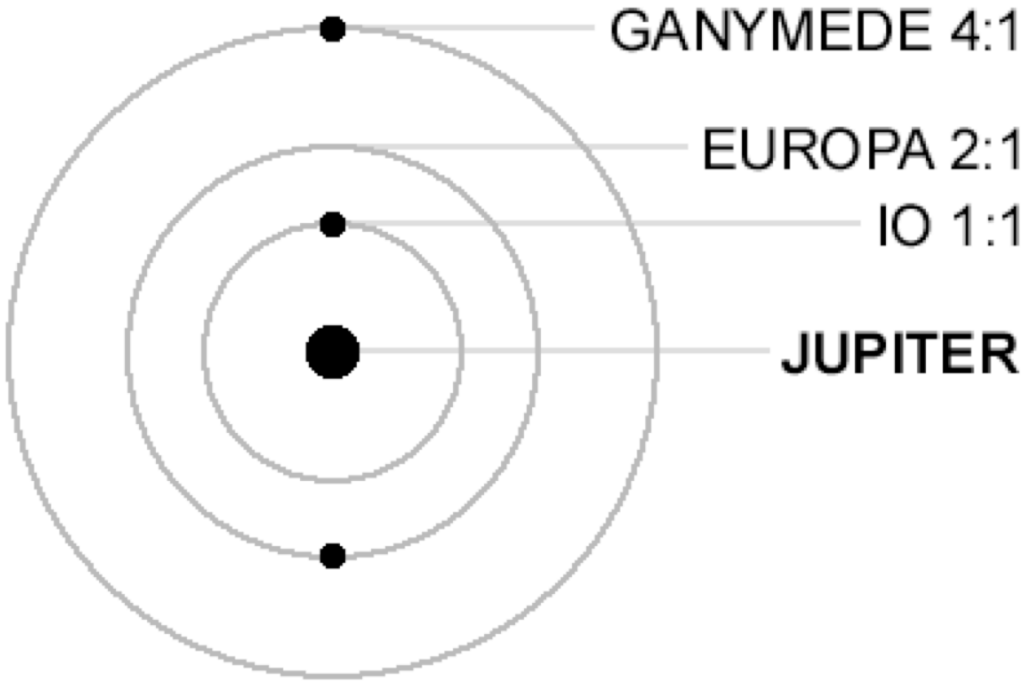
- Io's orbit is a little eccentric
  - Sometimes it's closer to Jupiter than others
  - Tidal effect waxes and wanes



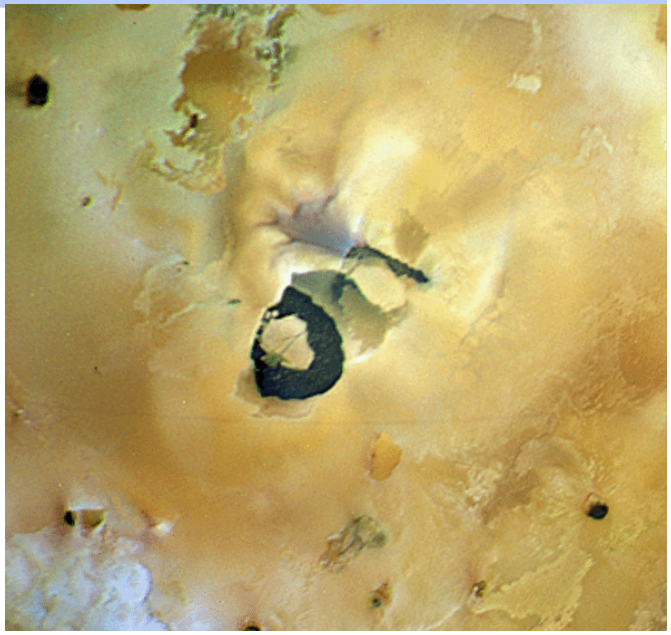
  - Constant flexing of Io creates a lot of internal heat

- Why doesn't this go away?
- Energy is lost by this heating
  - Io's orbital eccentricity should drop to zero

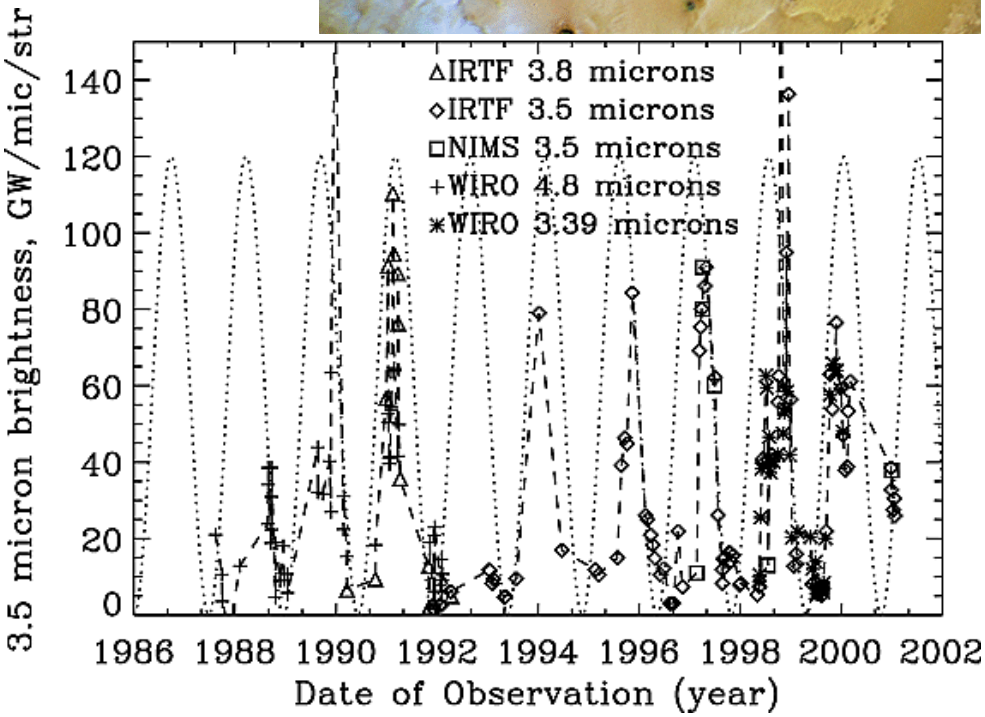
- Io is in a 2:1 resonance with Europa
- Europa is in a 2:1 resonance with Ganymede
- These resonances can transfer orbital energy into Io's orbit
  - Keeps Io's orbit eccentric
  - Keeps the volcanoes running



- **Io's heat flux estimated at 2500 mW m^{-2}**
  - **Earth's average ~ 60-70 mW m^{-2}**
  - **Mostly concentrated at hot-spots**
    - **Plains are cool (surface Temp ~90 K)**
    - **Resurfacing rate of 1cm/yr**
    - **Hot material can be buried**
  - **Loki dominates heat flow**
    - **200km lava lake that periodically (~540 days) overturns**
    - **Solar system's most powerful volcano**

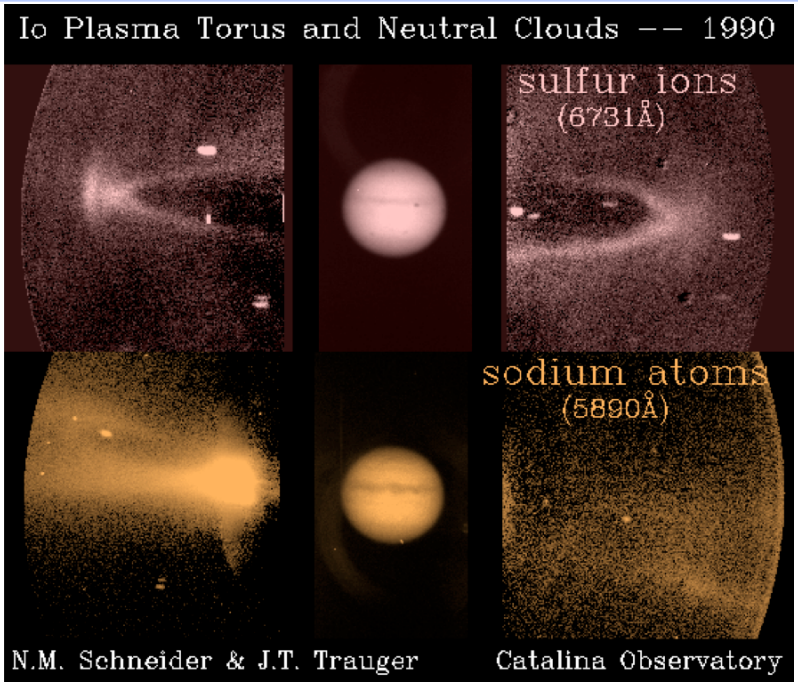


Nyiragongo, Zaire
A terrestrial analogue for Loki?



Rathburn et al., 2004

- **Where does this volcanic material go?**
  - **Charged particles around Jupiter knock sulfur off Io and its plumes**
  - **This collects in a doughnut shaped ring**
  - **Io's plasma torus can be seen from the Earth with filters designer to look for sulfur emission**



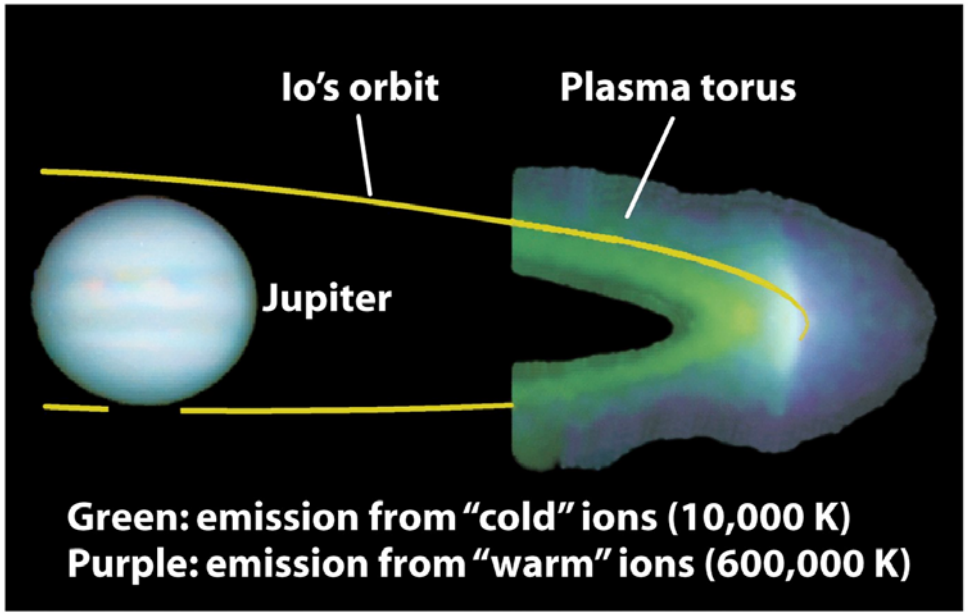
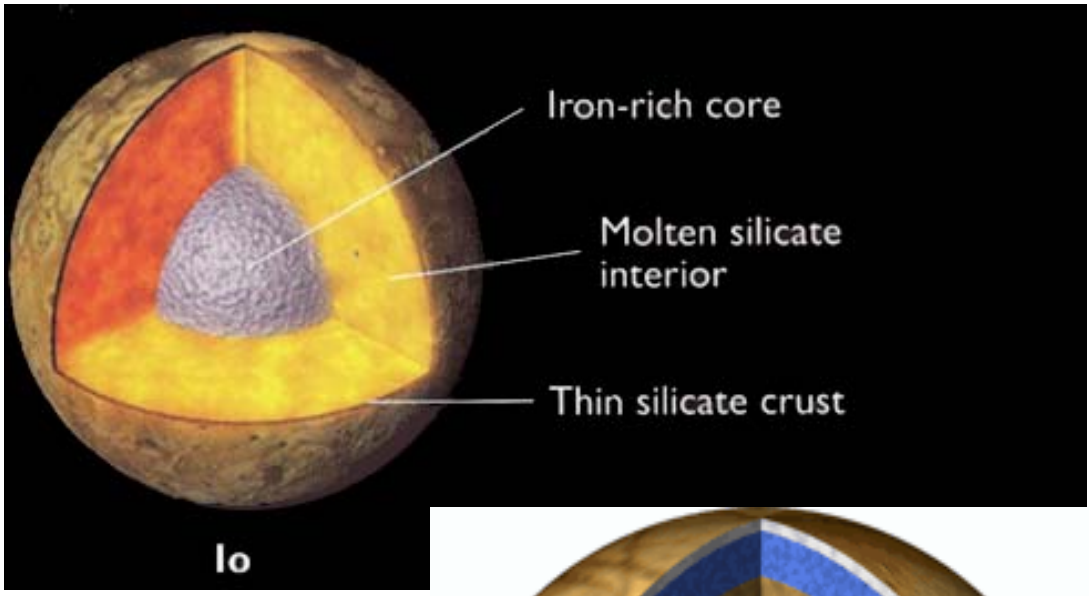


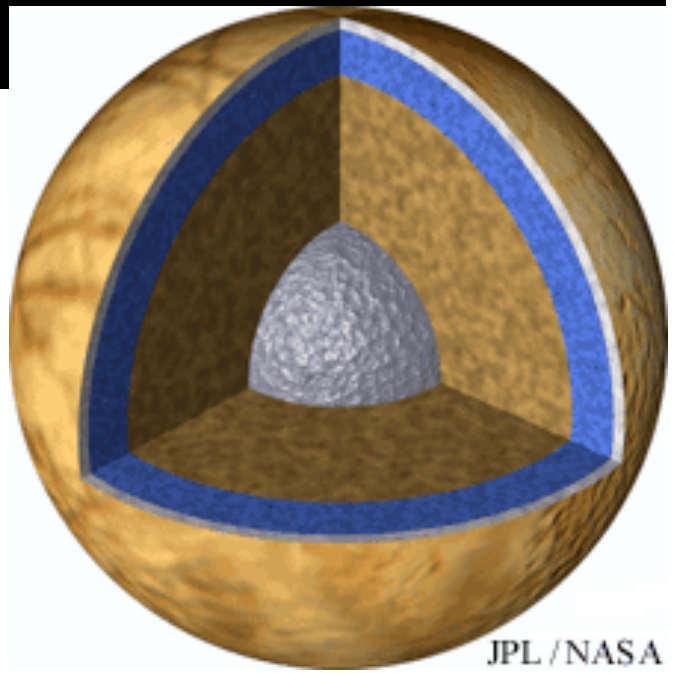
Figure 13-9a
Universe, Eighth Edition

Europa

- Couldn't be more different than Io



Europa
Water/ice layer



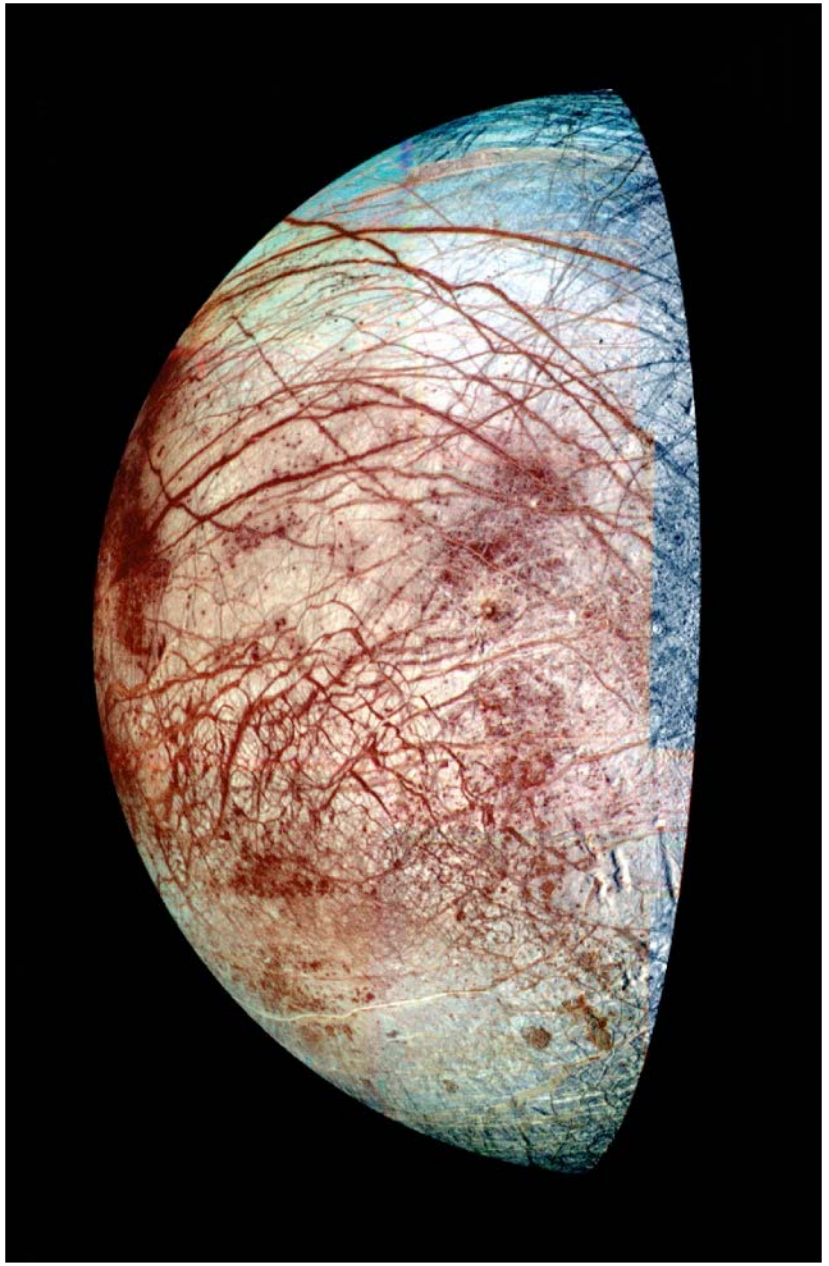
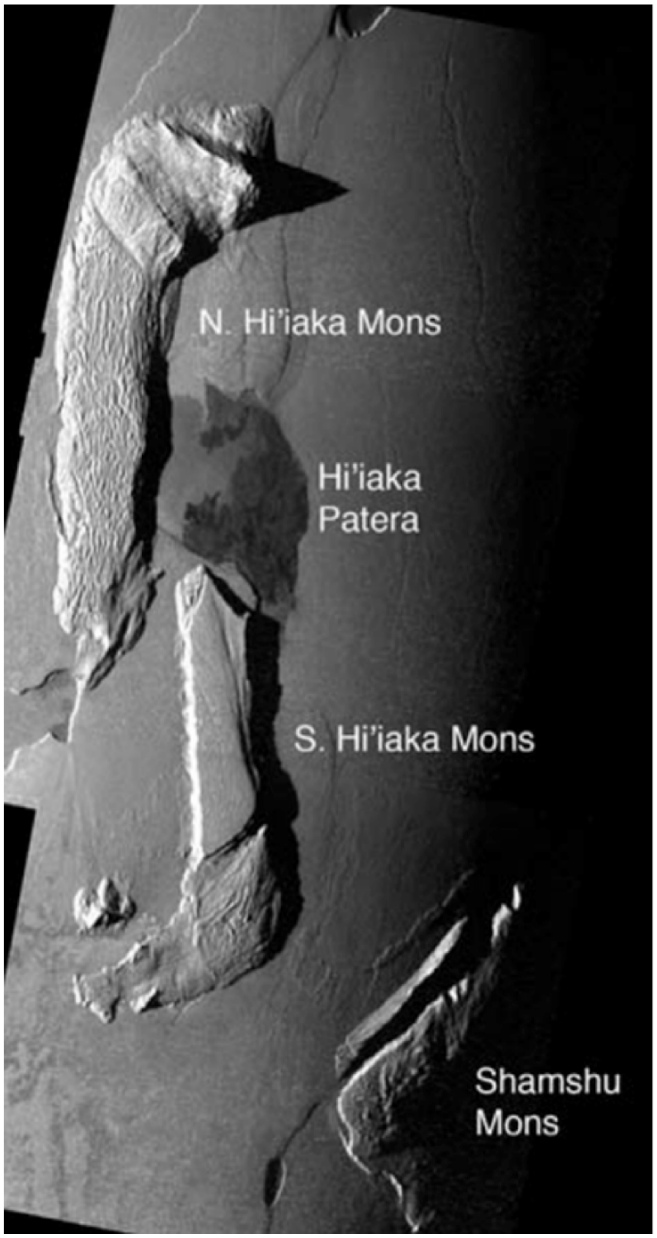


Figure 13-10
Universe, Eighth Edition

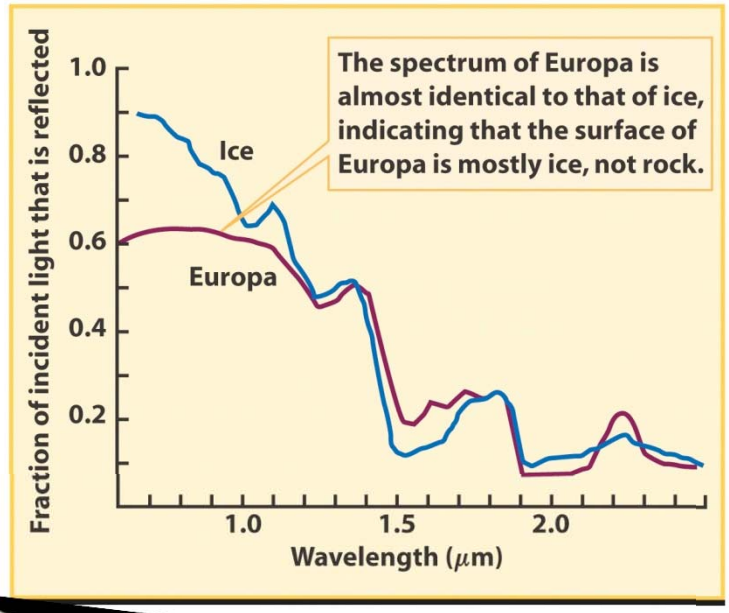
- **Europa is very smooth – almost no topography**
  - **Whereas Io has large mountains**

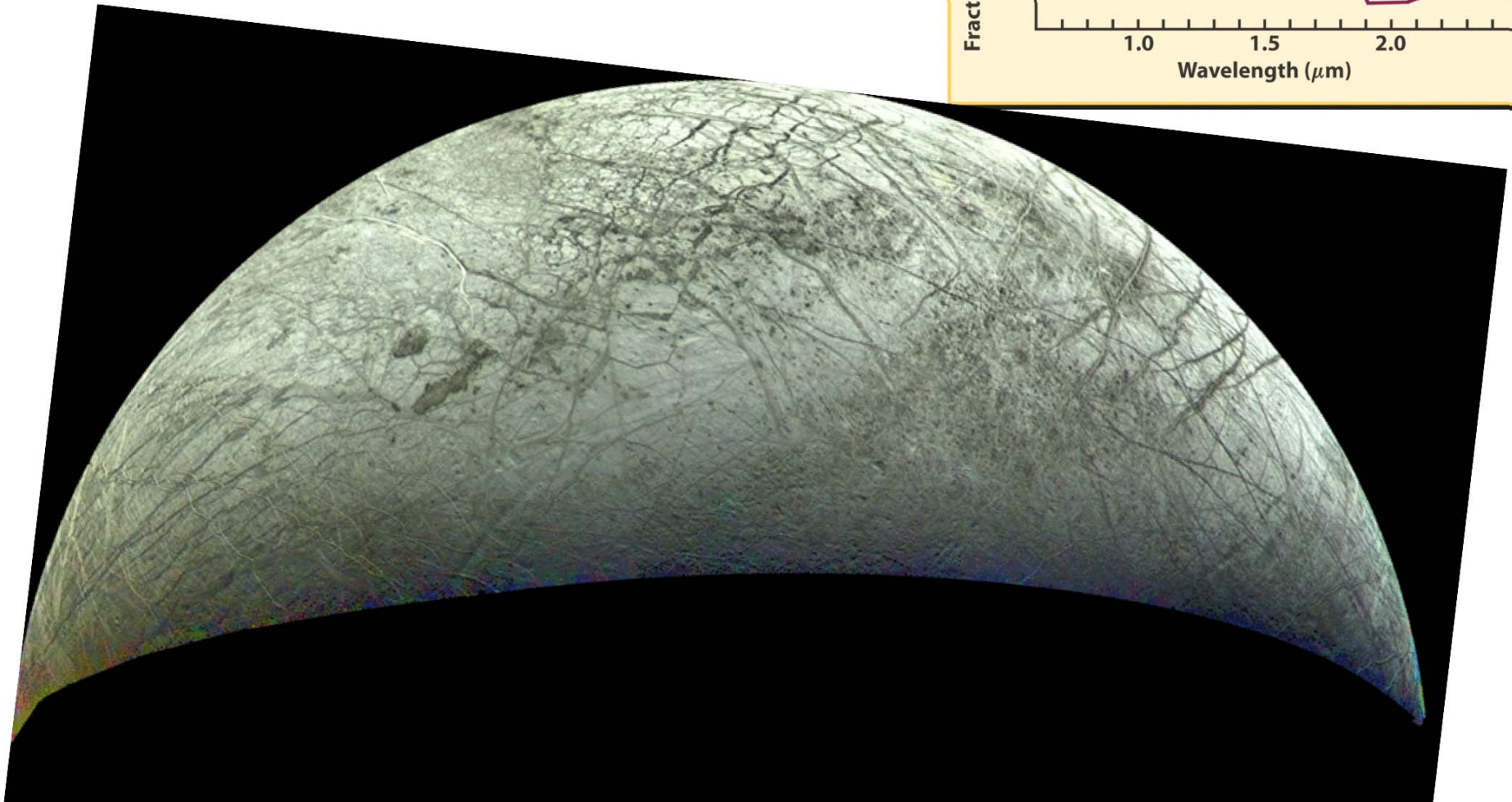
Europa



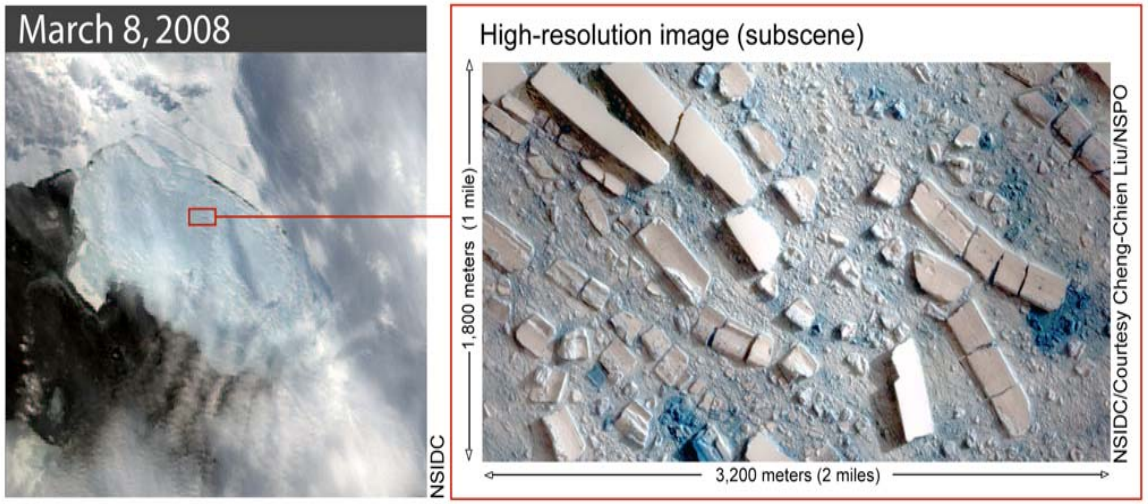
Io

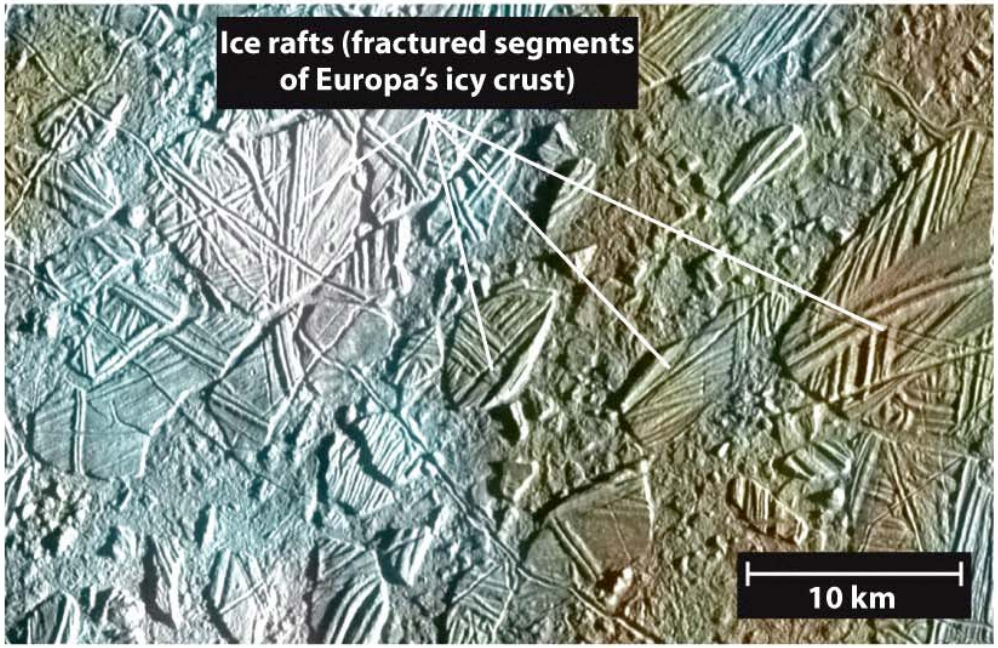
- **Different surface compositions**
  - **Io dominated from sulfur from volcanoes**
  - **Europa dominated by water ice**
  - **Europa is one of the brightest solar system objects**
    - **Albedo > 0.6**



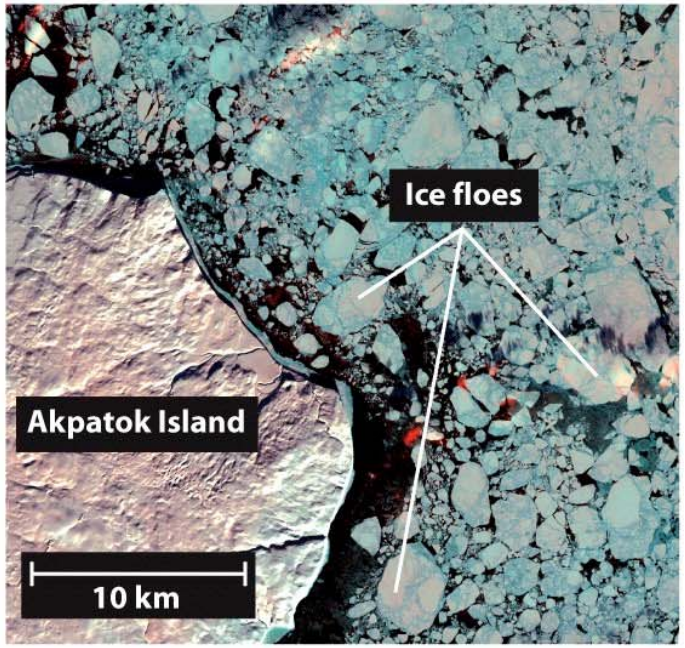


- **How do we know Europa has a liquid ocean?**
- **Surface features**
  - **Didn't convince everybody**





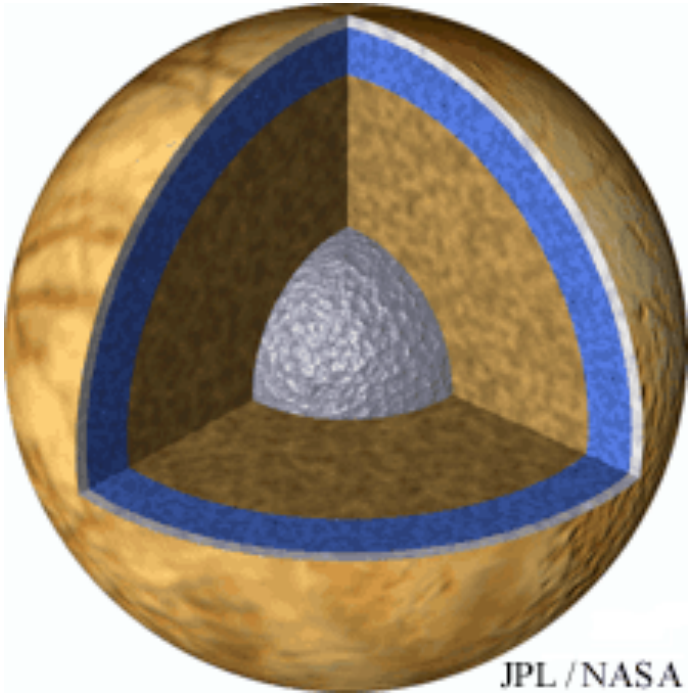
(a) Ice rafts on Europa



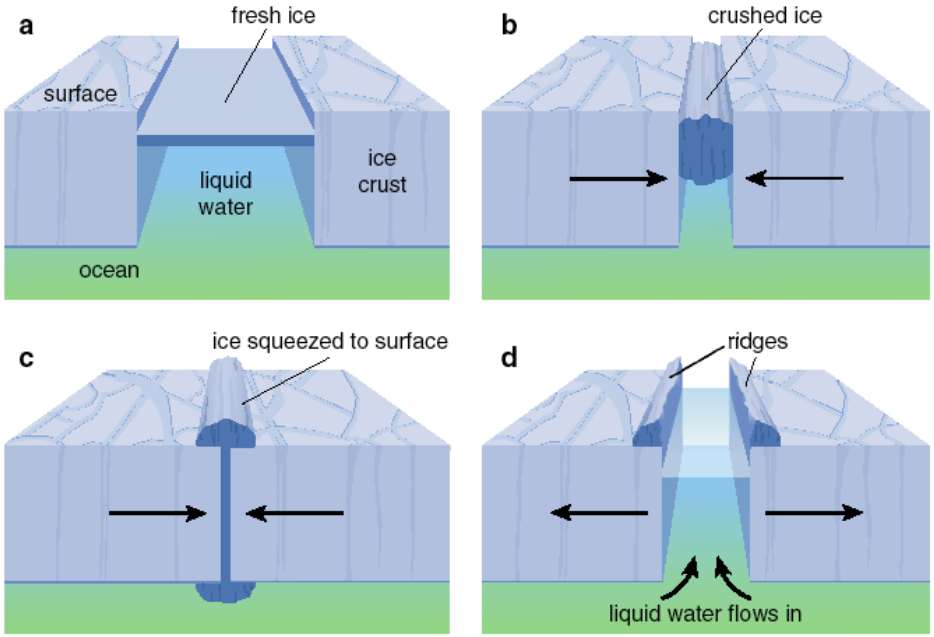
(b) Ice floes on Earth

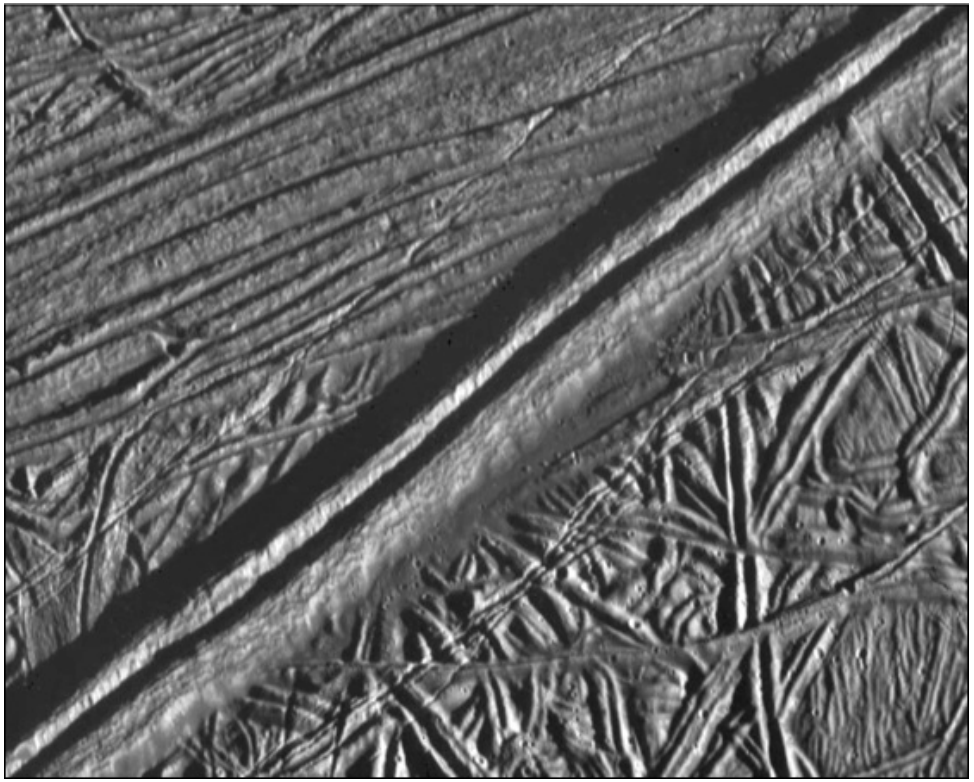
Figure 13-13
Universe, Eighth Edition

- **How do we know Europa has a liquid ocean?**
- **Induced magnetic field**
  - **Convinced everybody**
  - **Jupiter has a strong magnetic field**
  - **This 'magnetizes' a conducting fluid**
  - **The fluid for Europa is salty water**
  - **Galileo spacecraft detected the magnetic field of this fluid**
- **Why hasn't Europa frozen through?**
  - **Tidal pumping from Jupiter… again**



- **The surface of Europa is dominated by tectonics**
  - **All of Europa's geology is governed by the composition**
    - **Surface layer is brittle ice (cold)**
    - **Underneath that is ductile ice (warm)**
    - **Underneath that is a liquid ocean (100s of km deep!)**
  - **E.g. double ridges are common and form by repeated extension and compression**
    - **From tides**





- Liquid underneath has many things dissolved in it
- Ridges coated with this material
  - Produces color variations

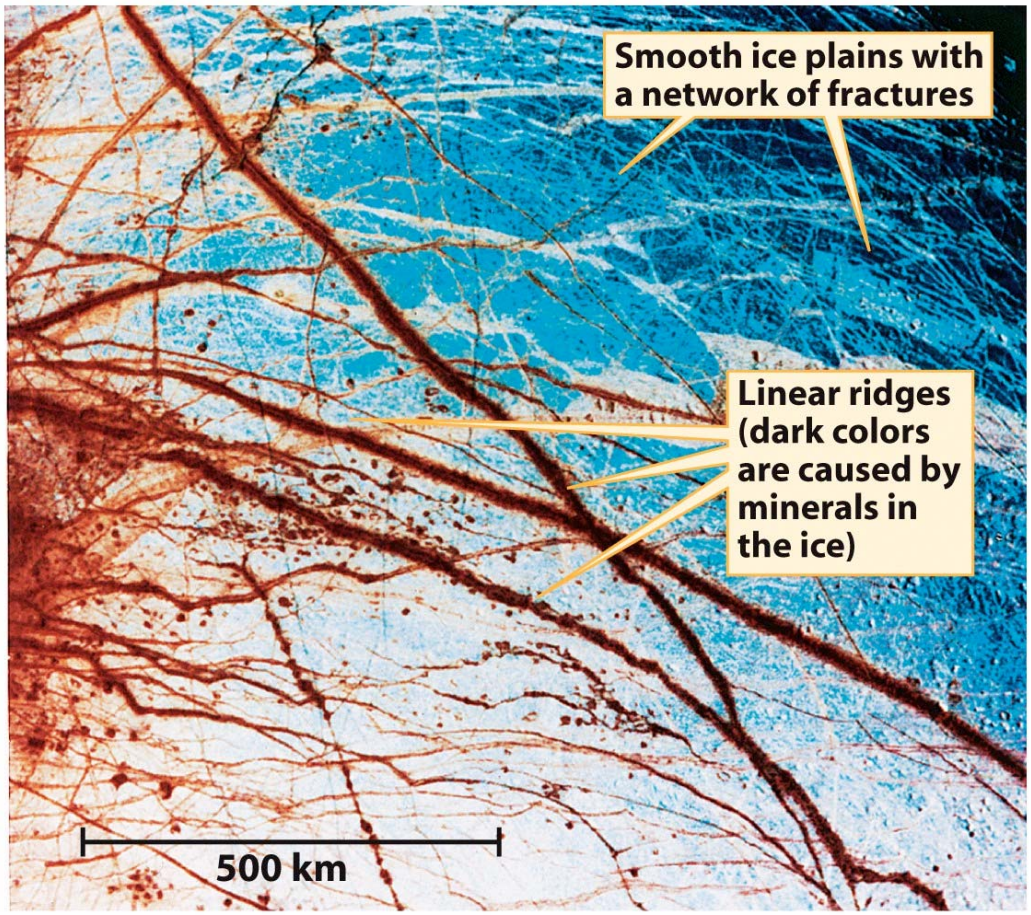
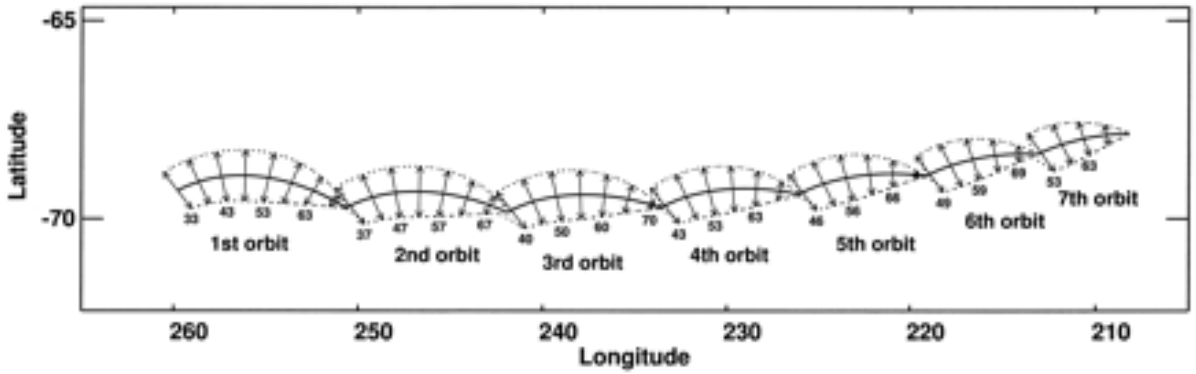


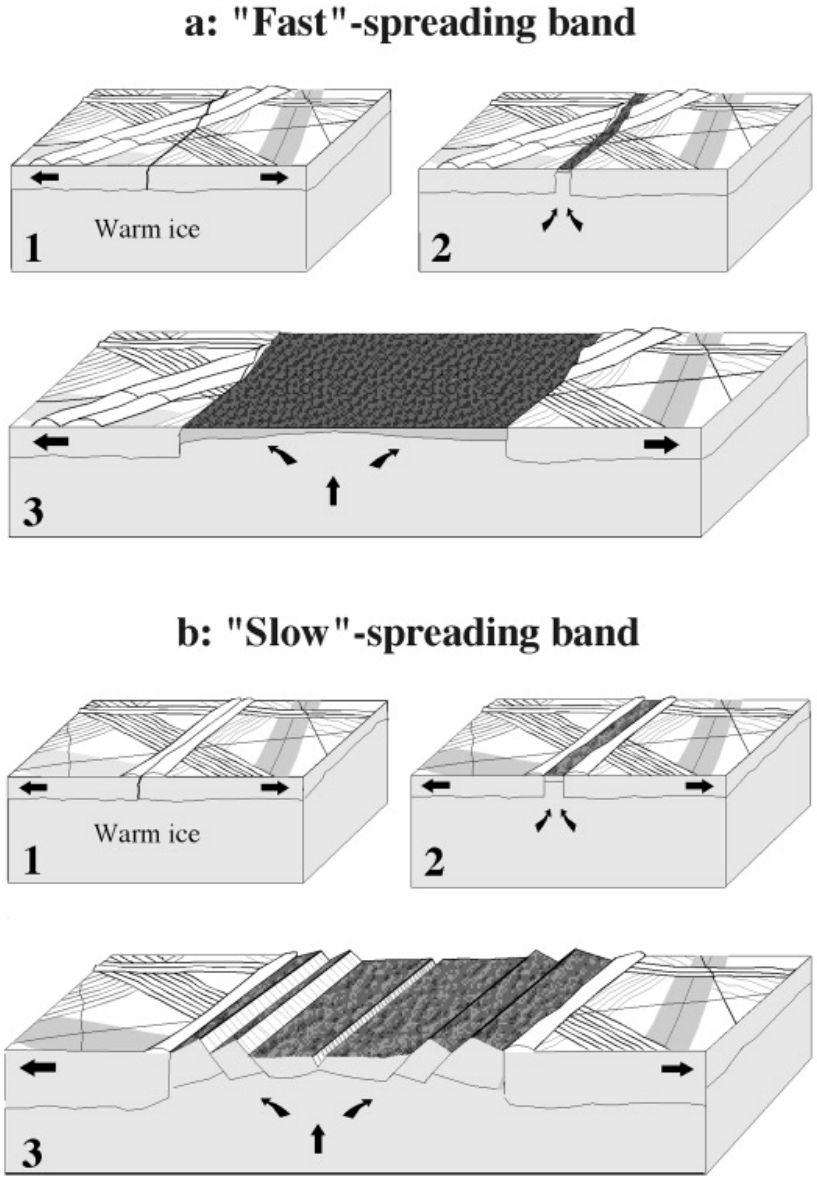
Figure 13-11
Universe, Eighth Edition

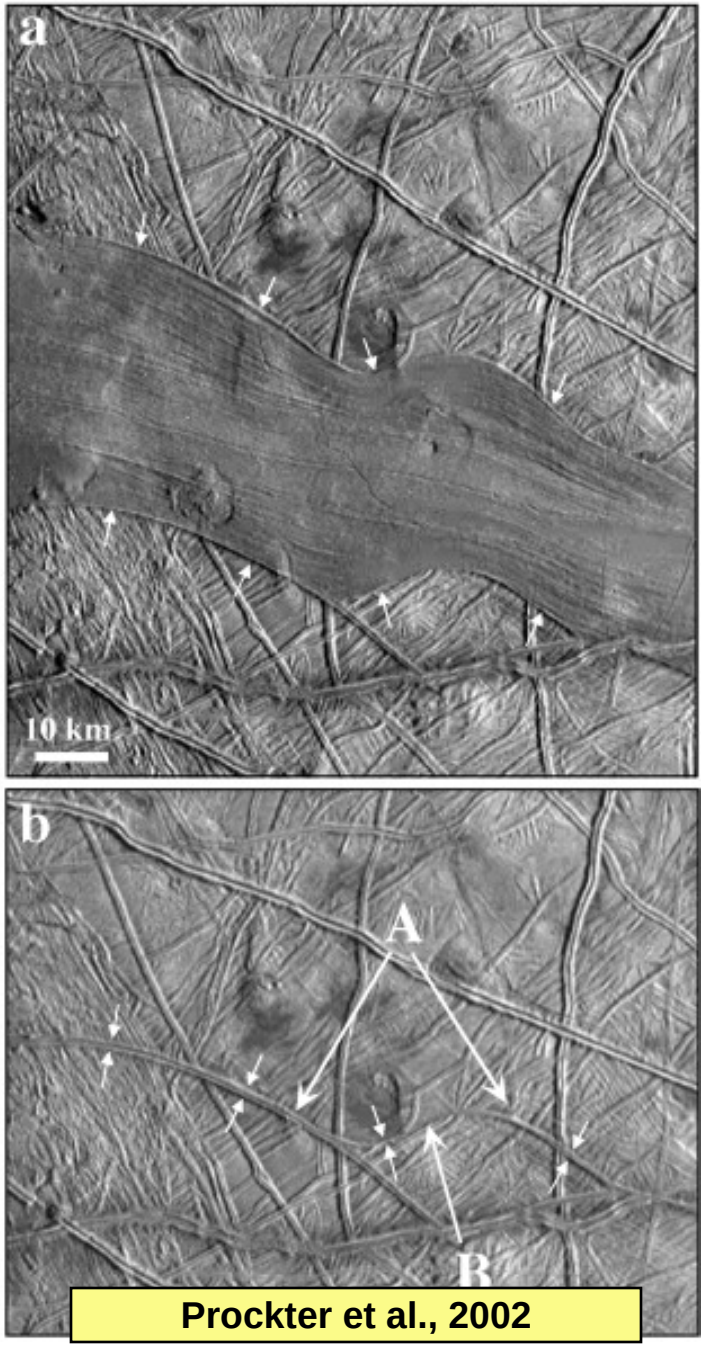
- **Some cracks are cycloids**
  - **Can be explained by cracking in response to tidal stresses**
  - **One cycloid per orbit**
  - **Cracks propagate at walking speed ~3 km hr^{-1}**
  - **You need a big tidal bulge to do this (100m)**
    - **Only possible with a subsurface ocean**



Hoppa et al., 1999

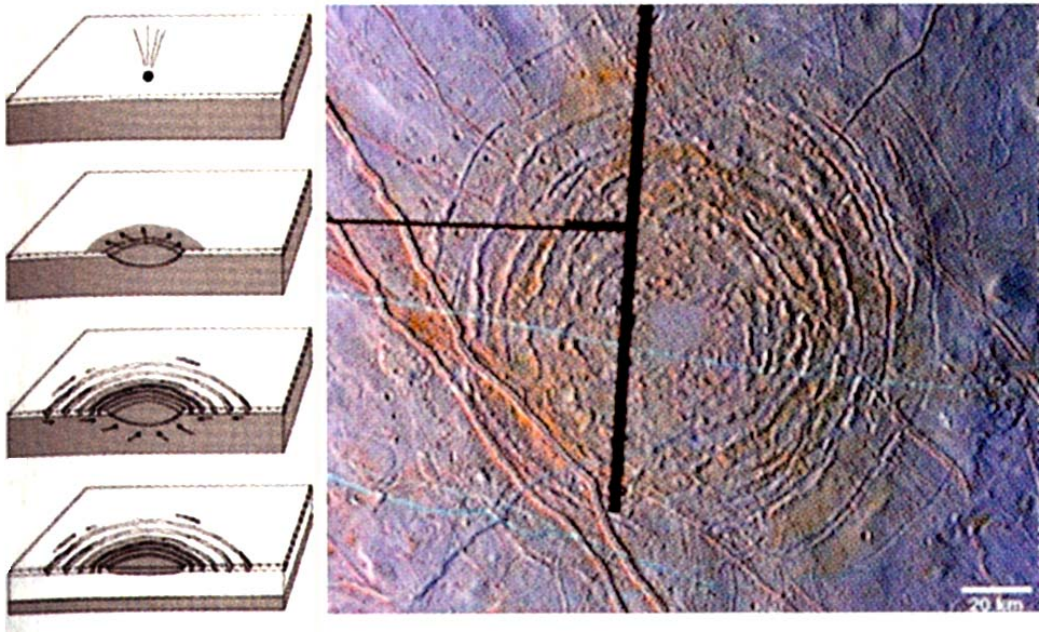
- **Pull apart bands are analogous to sea-floor spreading on the Earth**

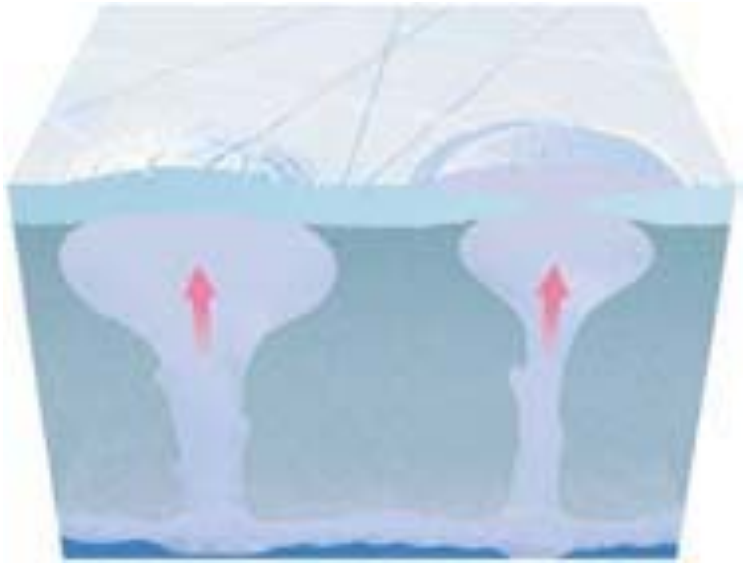




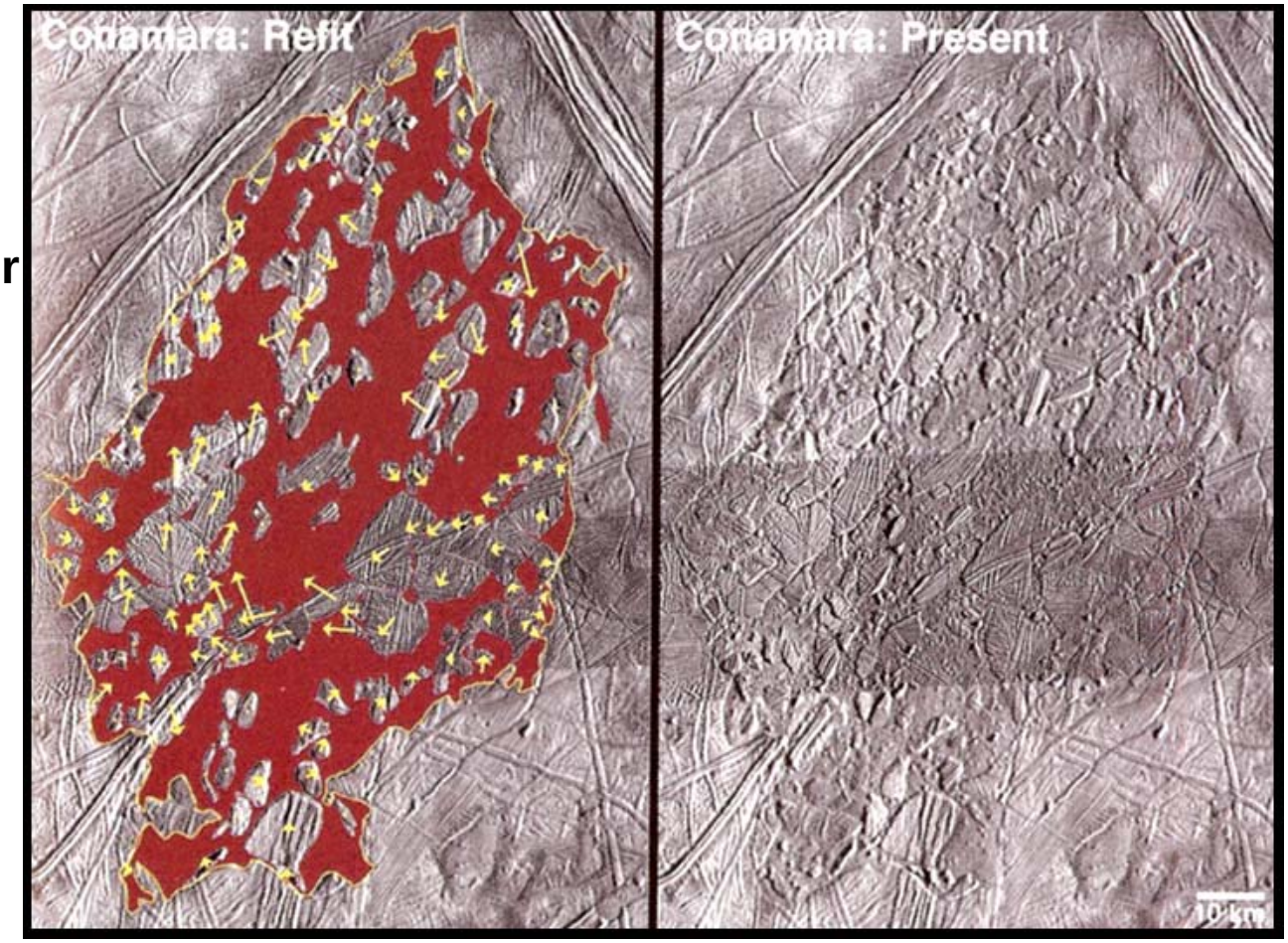
Prockter et al., 2002

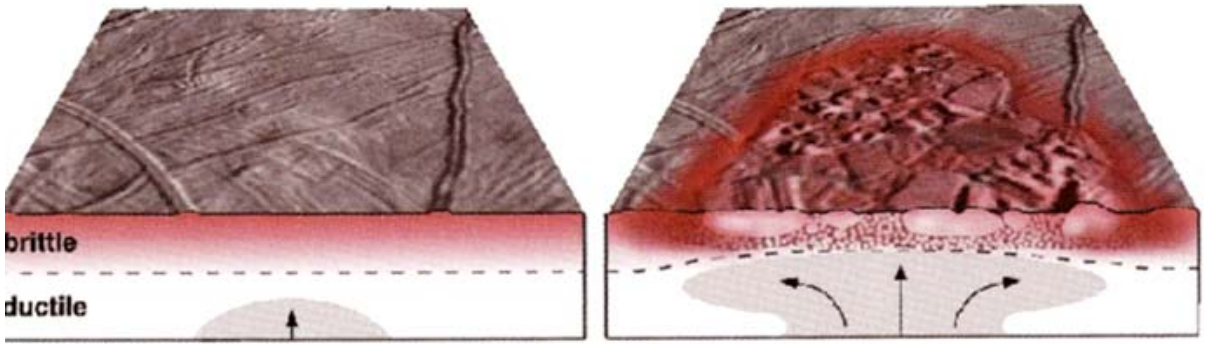
- **Impact craters and lenticulae**
  - **Affected by flow of warmer deeper ice**





- Chaos
  - Regions of mottled terrain
  - Still contain islands or previous crust
  - A big lenticula
- Material has disappeared
  - No net extension or contraction





- **Europa can get complicated with all these processes overlapping**

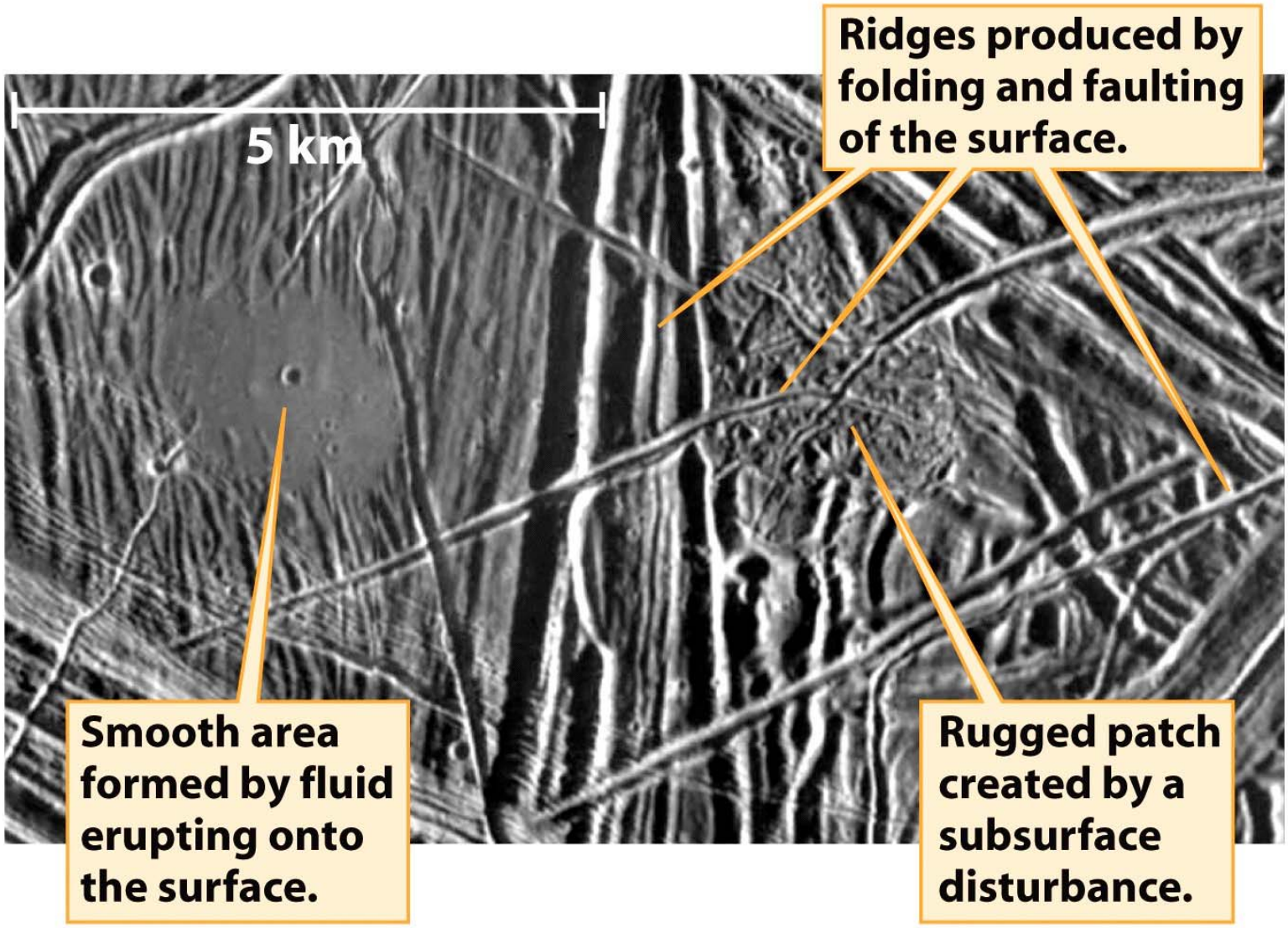
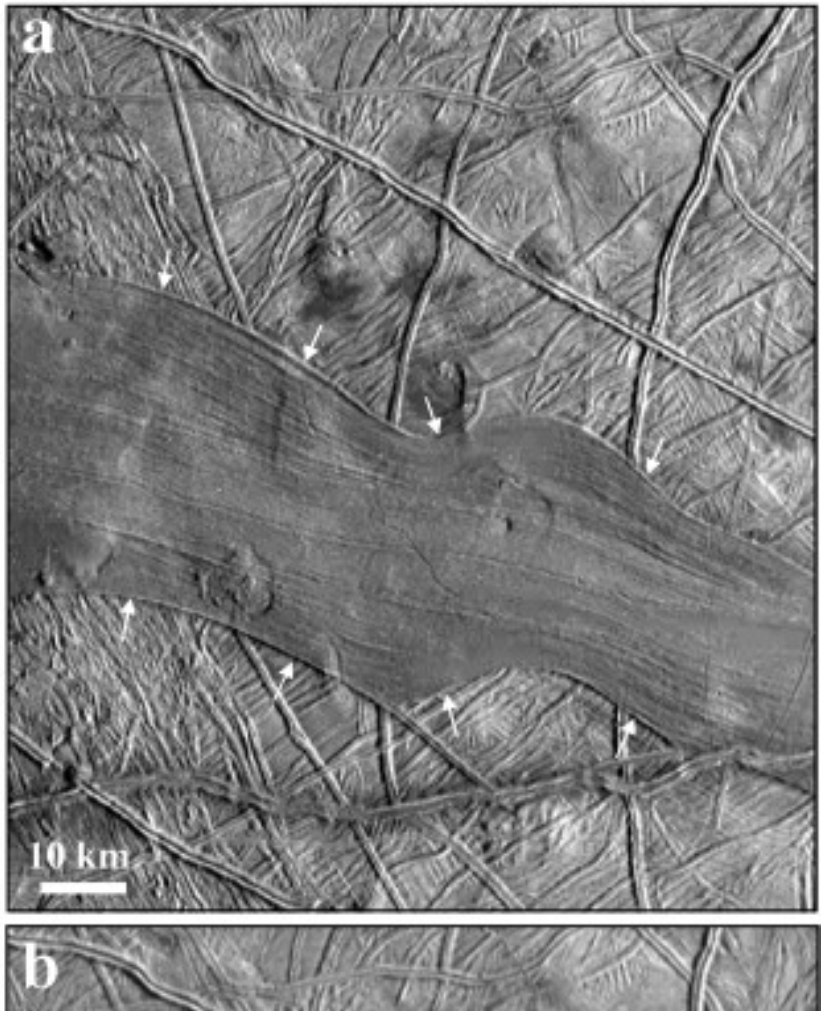


Figure 13-12
Universe, Eighth Edition

- **Anybody spot the problem with this?**
  - **Extensional features are everywhere…**



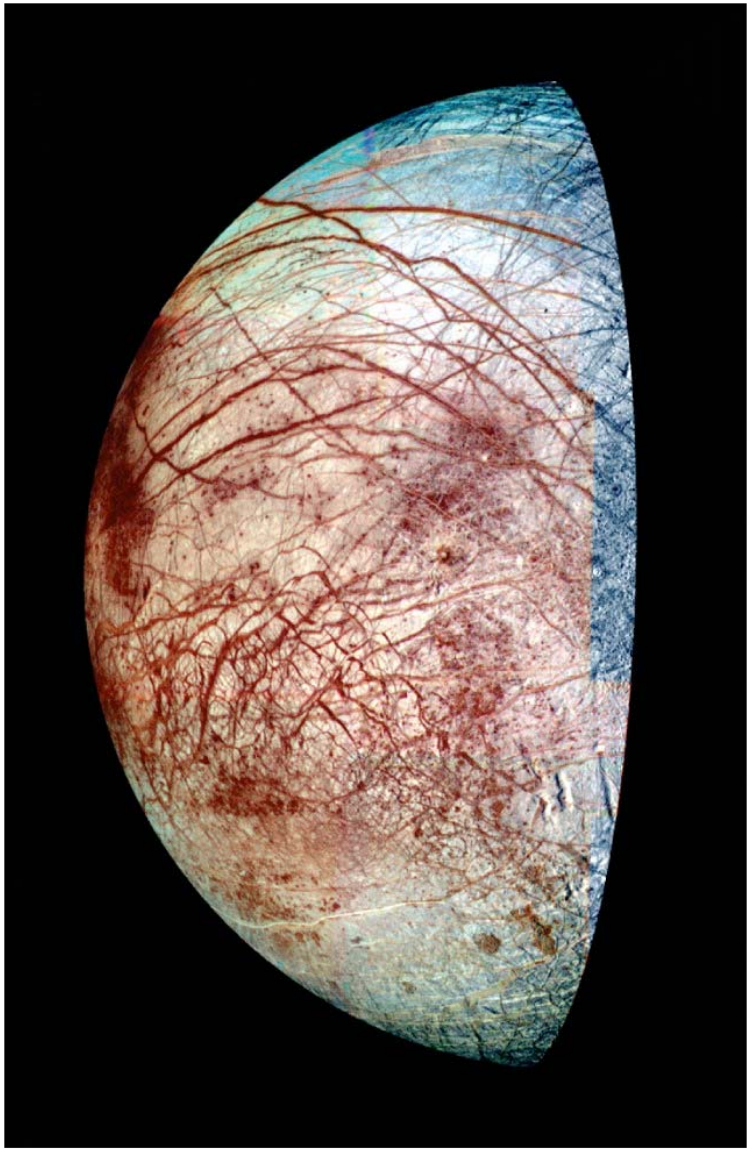


Figure 13-10
Universe, Eighth Edition

- **Anybody spot the problem with this?**
  - **Extensional features are everywhere**
  - **Surface area of Europa is increasing**
  - **Is Europa expanding?**

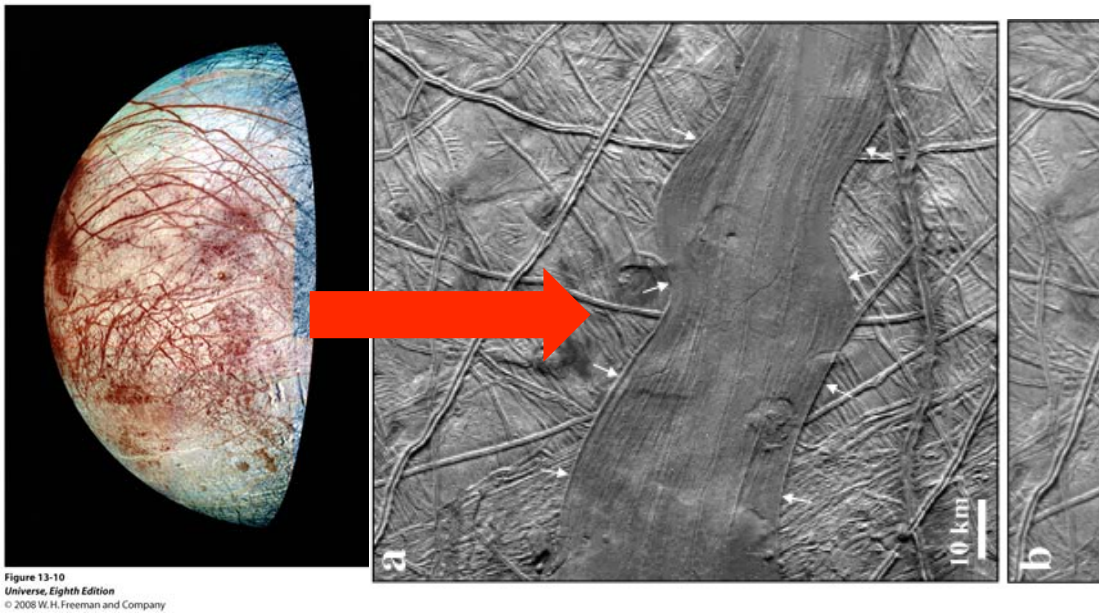
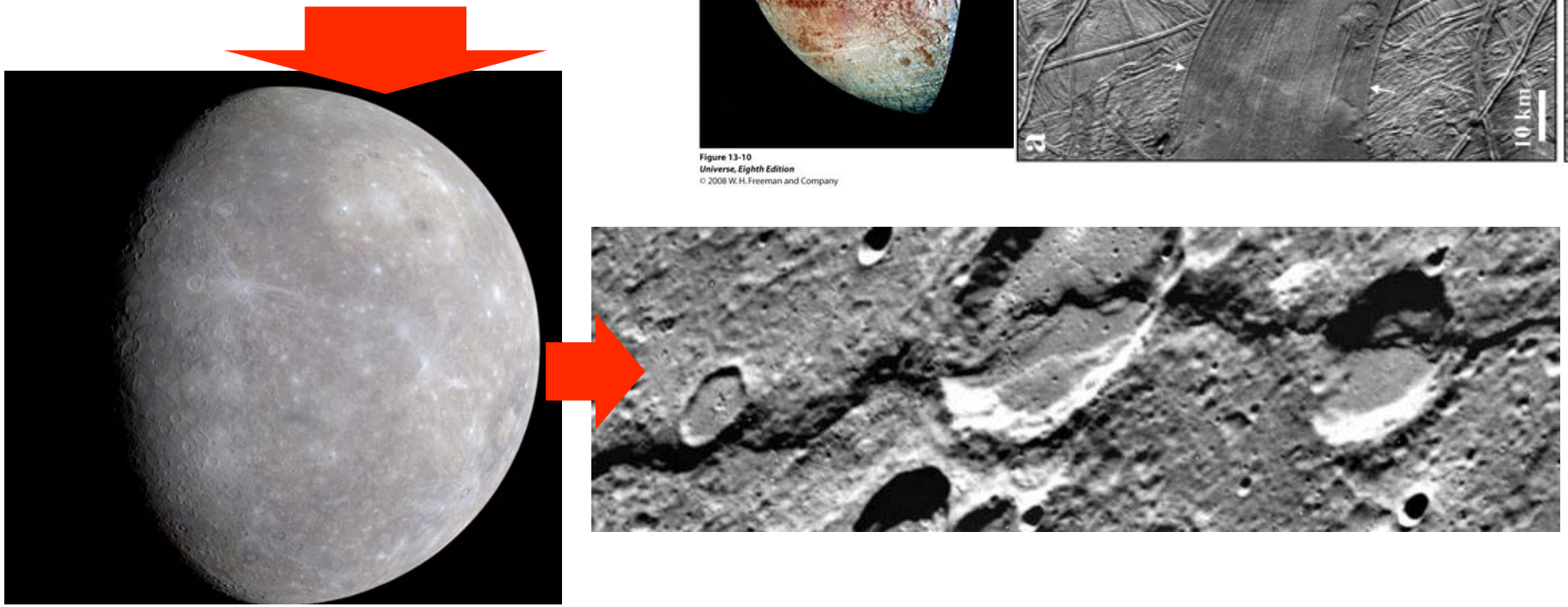
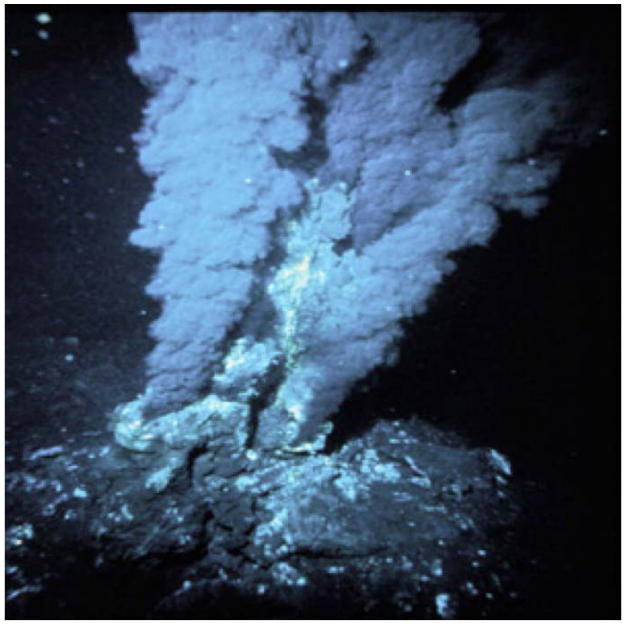


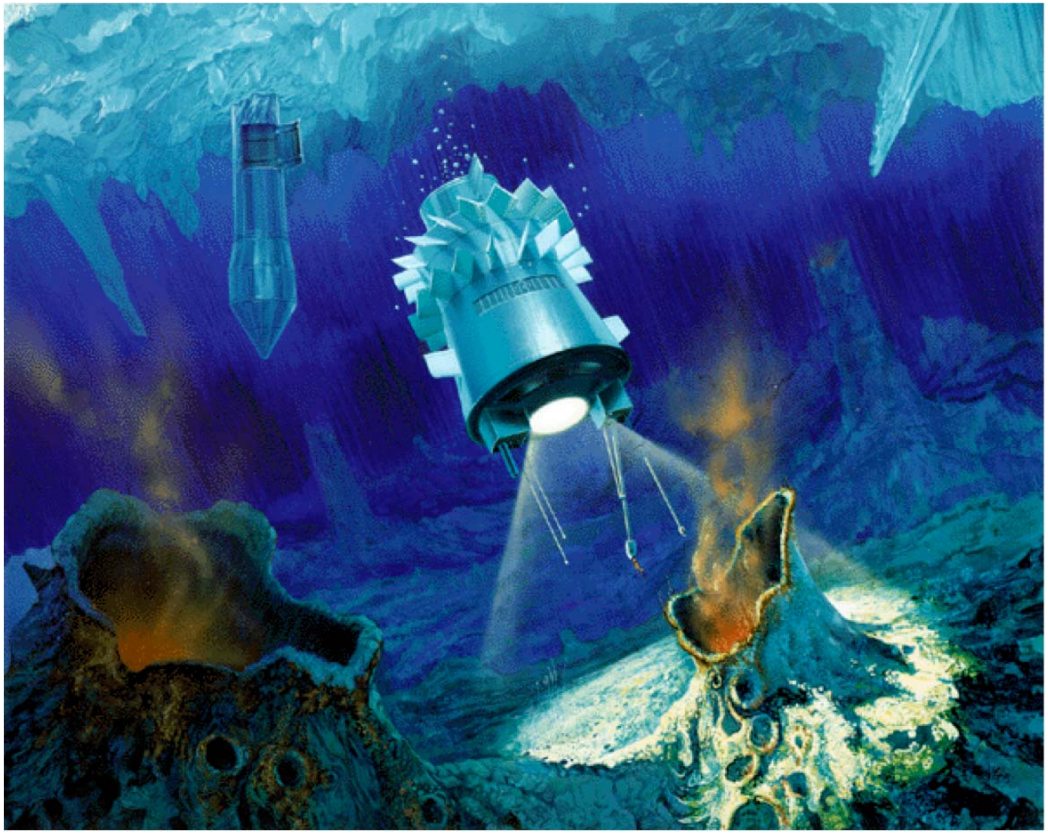
Figure 13-10
Universe, Eighth Edition

  - **Opposite problem from Mercury**
  - **Mercury shrank**
  - **Generates compressive features**



- **Astrobiology on Europa?**
  - **Heat energy & Liquid water**
  - **Enough for life? No problem!**





Future exploration?

Callisto

- The dullest possible object – average in every way
  - The most homogenous interior possible – no differentiation
  - No magnetic field
  - No surface geology except impact craters
  - Might have a thin ocean

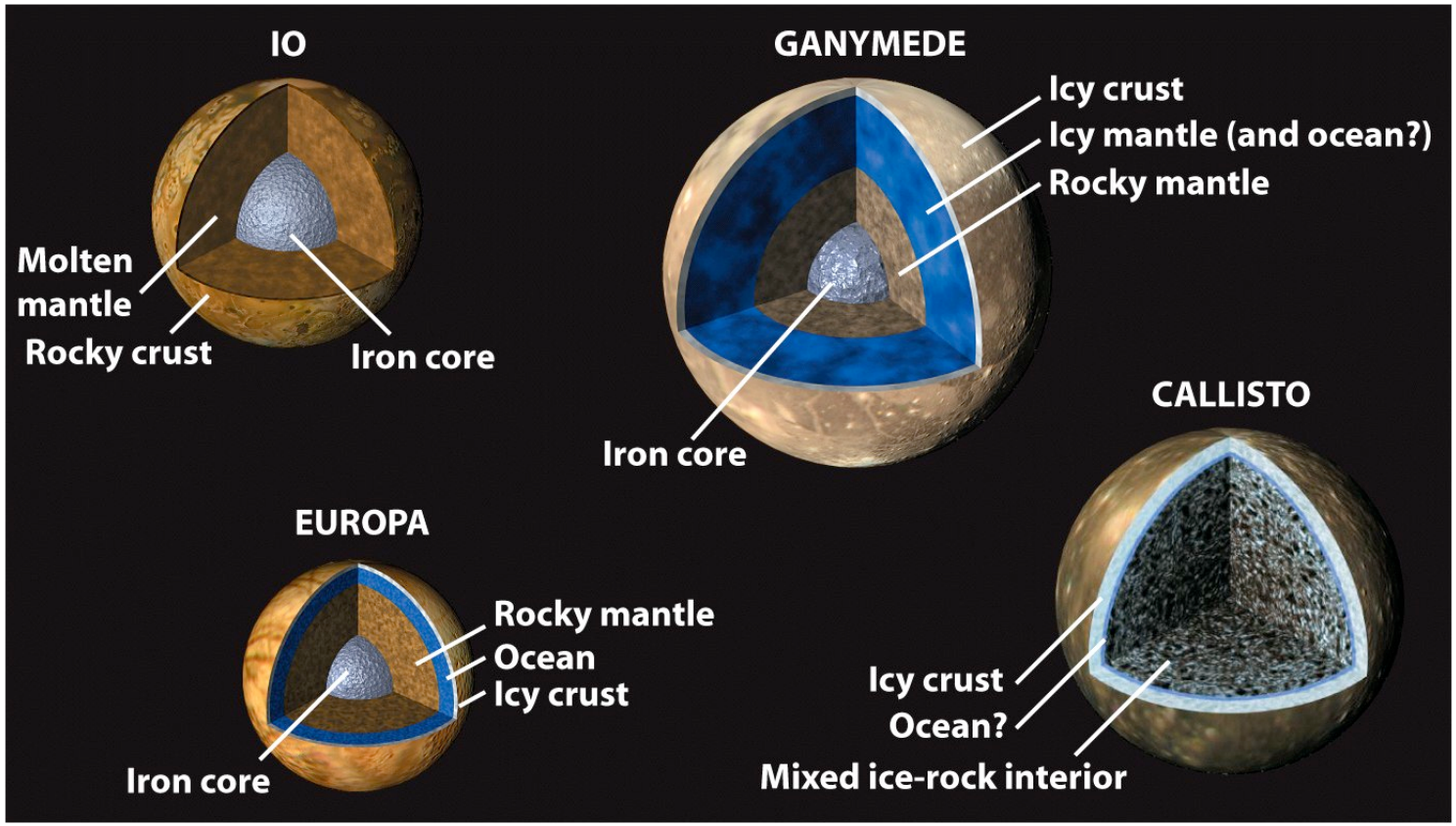


Figure 13-17
Universe, Eighth Edition

- Surface material is icy
- Covered in brownish material
  - Possibly a sublimation lag
    - Ice ablates away concentrating dirt is used to suspend at the surface
- Peaks and crater rims poke through the brown material

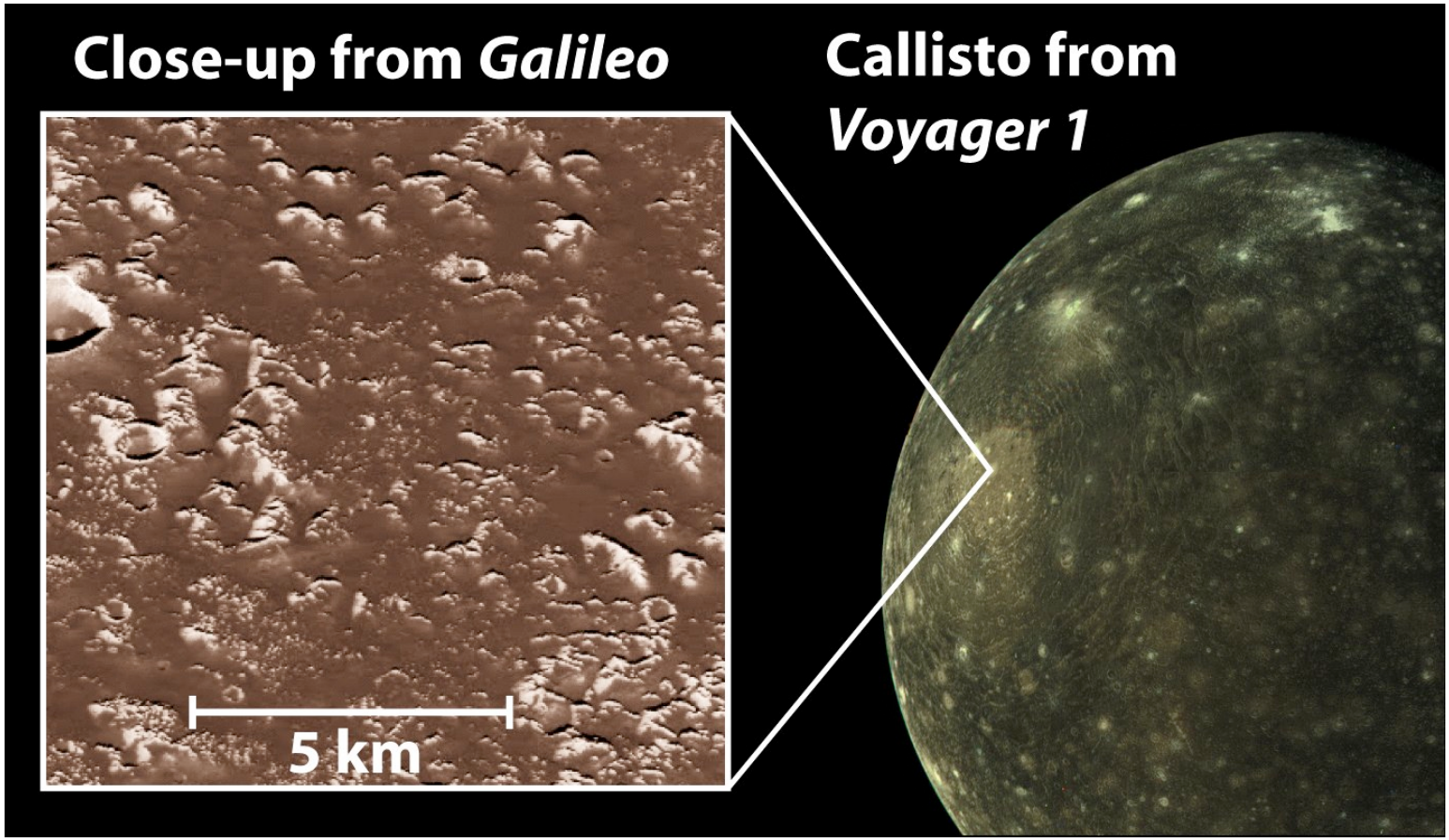
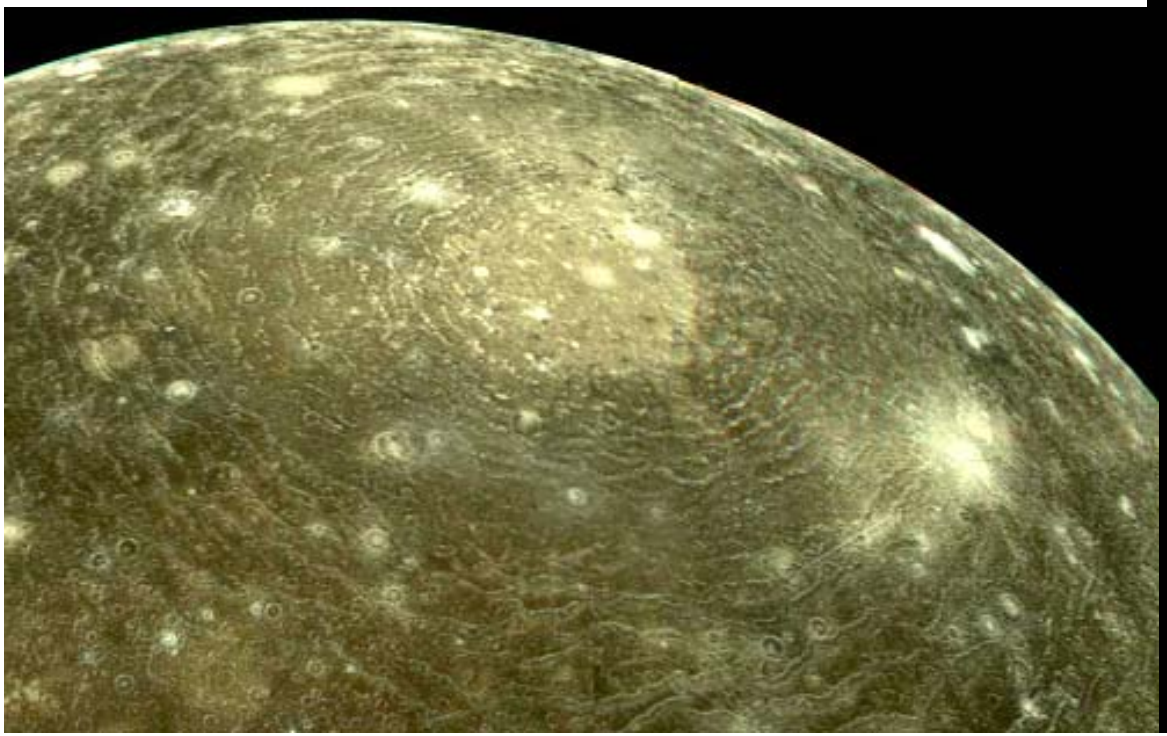
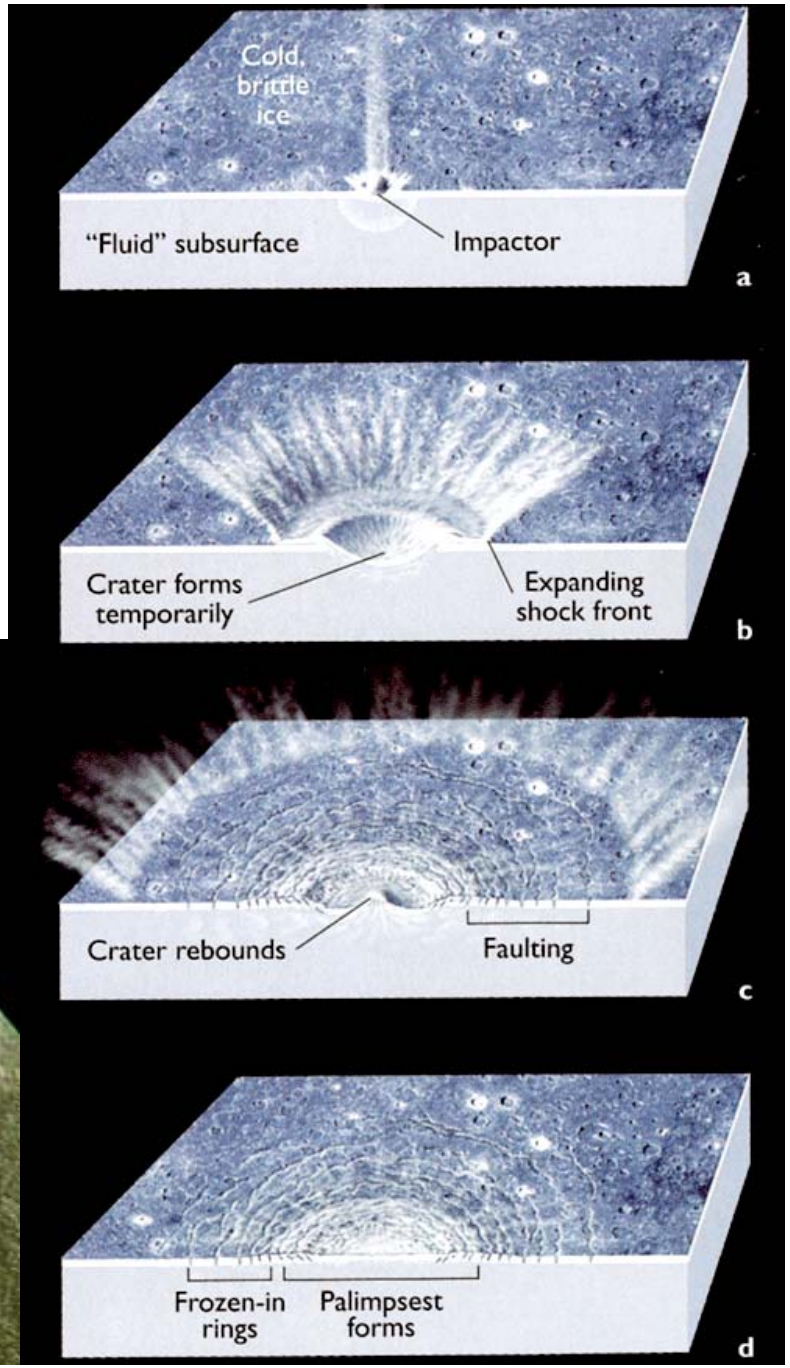


Figure 13-16
Universe, Eighth Edition

- Callisto is an icy version of the lunar highlands
- Large impact basins differ from Lunar examples
  - Evenly spaced concentric fractures
  - Extension of upper brittle layer
  - Flow of lower ductile layers towards crater
  - E.g. Valhalla 1000km across, 20 rings

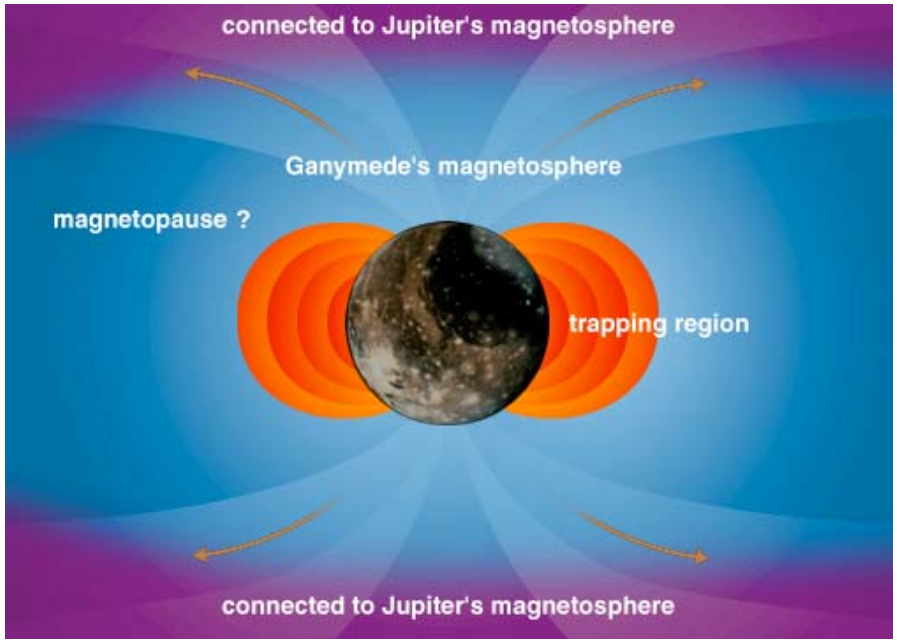


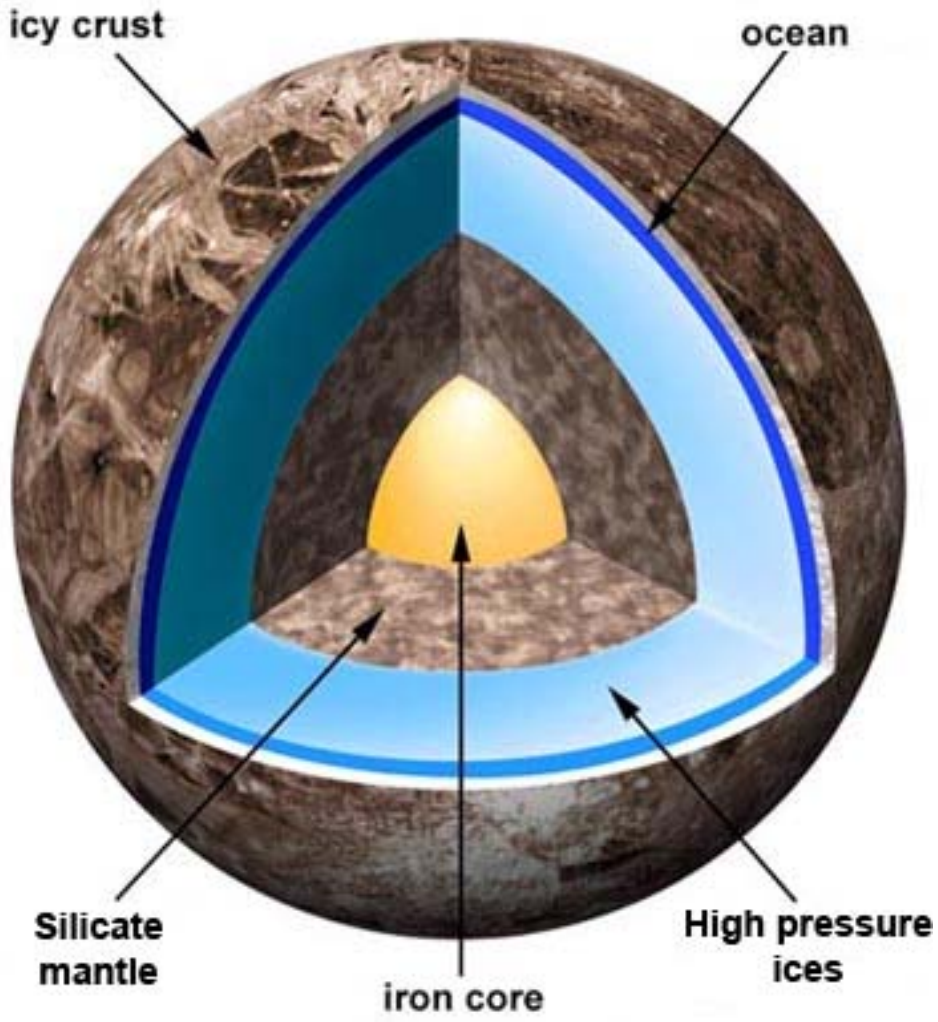


Ganymede

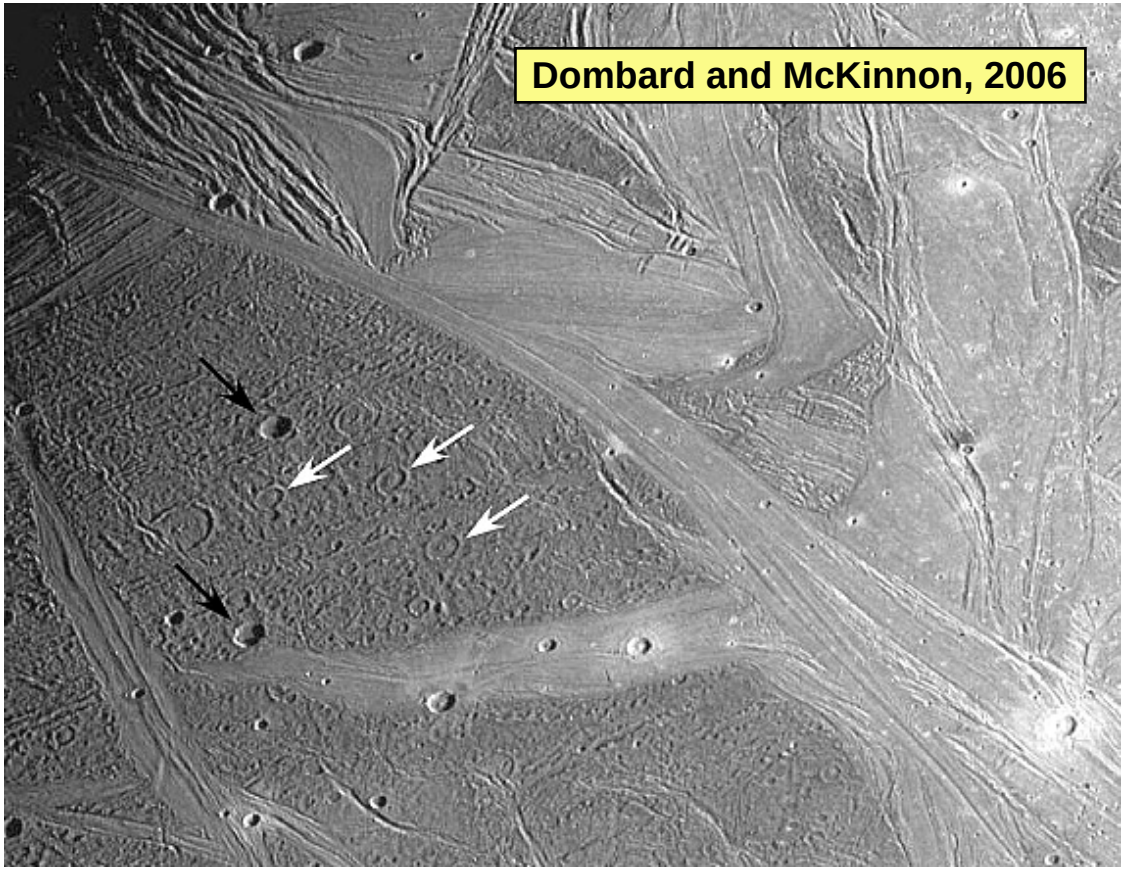
- In contrast to Callisto, Ganymede has **everything**
- Largest moon in the solar system
- Tectonic activity like Europa
- Subsurface ocean like Europa
- Exotic high-pressure ice
  - Under the ocean
- Internal convection
- A magnetic field
- Impact basins like Callisto

- **Liquid ocean sandwiched…**
  - Ice I above
  - Probably ice III below
- **Magnetic field**
  - Only moon with its own field
  - Implies convection of conductive material
  - In iron-core or salty-ocean?

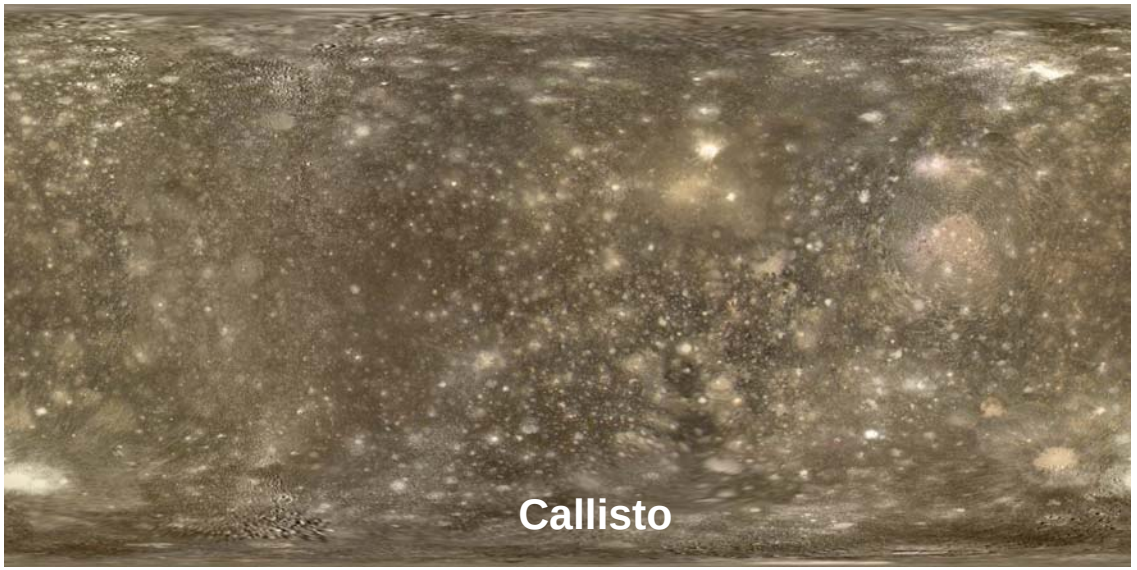


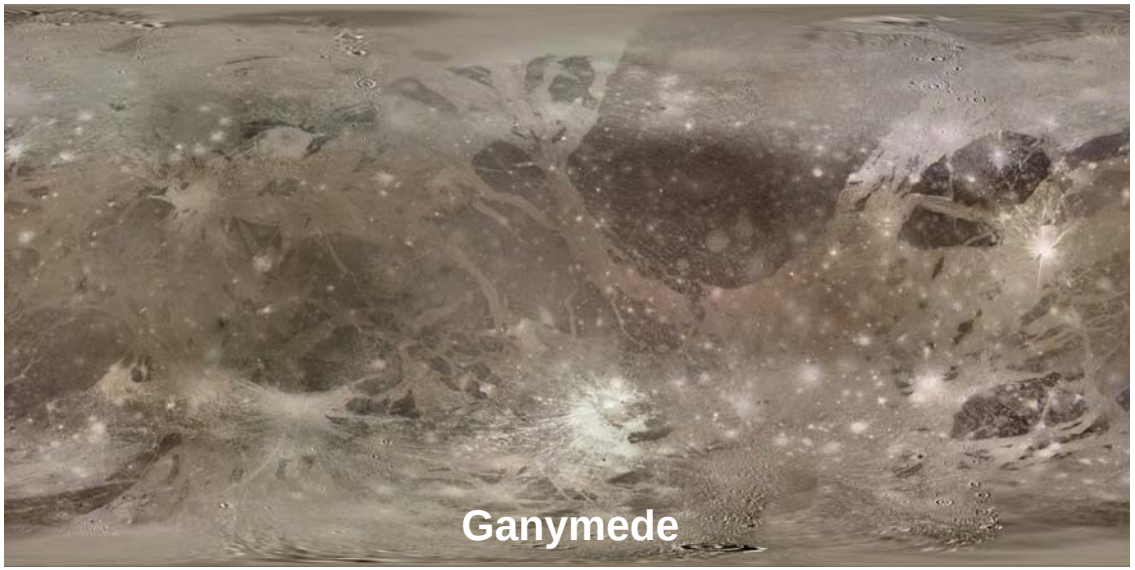


- **Near-surface ocean causes spreading bands like on Europa**
  - **About 2/3 of the surface**
  - **Except bright bands are still ~2 billion years old**
  - **Europa's surface is less than 0.05 billion years old**
- **Dark material (between bands) looks much like Callisto**
  - **About 1/3 of the surface**
  - **Concentric furrows in places**
    - **Remains of Valhalla-type basins?**



- **Why are Ganymede and Callisto so different?**
  - **They're about the same size and density**
- **Distance from Jupiter is a possibility**
  - **Callisto never heated up and didn't differentiate**
  - **Ganymede was close enough for tidal heating to cause differentiation**
  - **Differentiation caused a change in the volume of the planet**





In this lecture…

- The frost line
  - Applies to Jupiter's mini-system as well as the solar system at large
- Jupiter has faint rings and many small captured satellites as moons
- Galilean satellites are large enough to be considered small planets
- Io
  - The most volcanically active world – several eruptions in progress today
- Europa
  - Has an ocean 100s of km deep and the most active tectonics of any planet
- Callisto – a lump of inactive ice and dirt
- Ganymede – has everything
  - Ocean, magnetic field, Europa-like tectonics, impact craters etc…

Next: Saturn's Rings and Moons (in 1 week, excludes Titan)

- Reading
  - Chapter 13 to revise this lecture
  - Chapter 12-13 remaining sections for next lecture