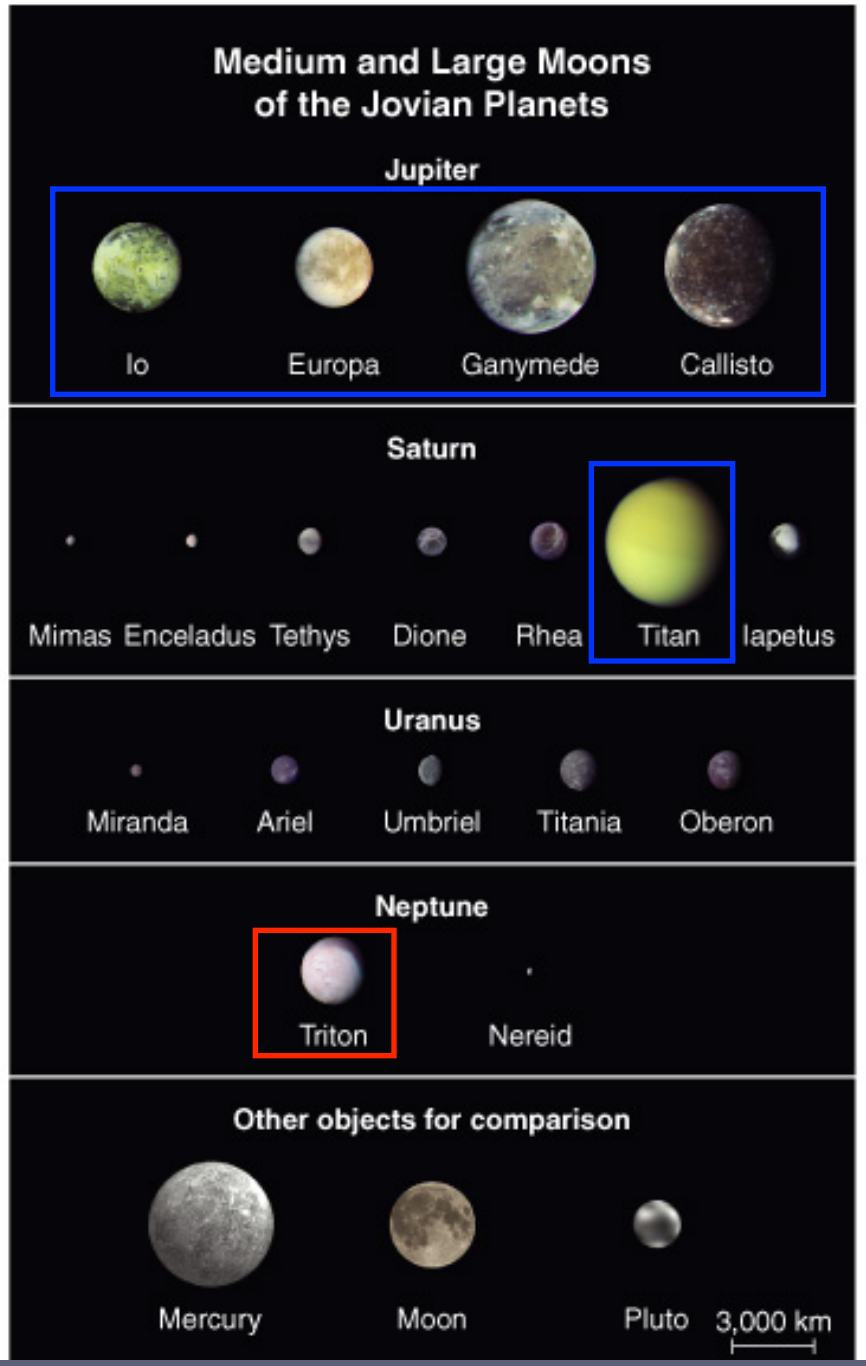
Roger Freedman • Robert Geller • William Kaufmann III

Universe

Tenth Edition

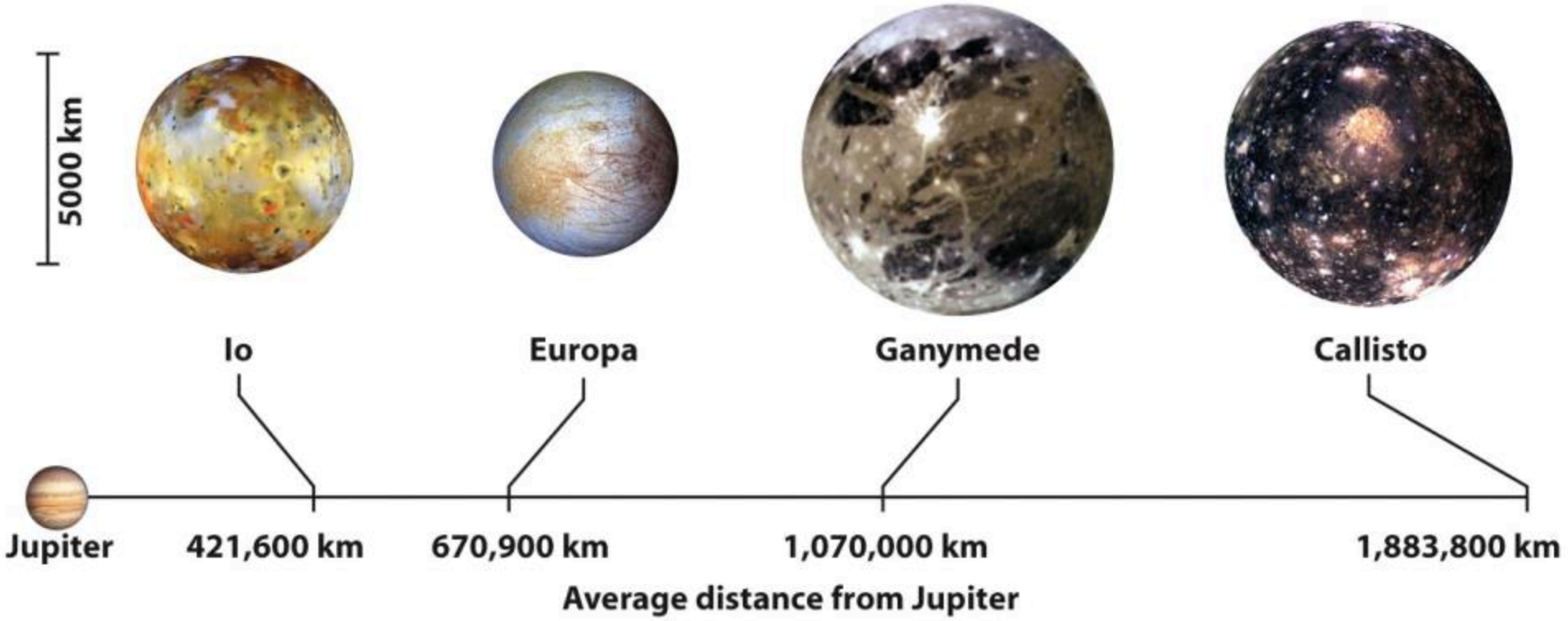
Chapter 13: Jupiter and Saturn's Satellites of Fire and Ice



Medium & Large Jovian Moons

- Enough self-gravity to be spherical
- Have substantial amounts of ice.
- Formed in orbit around jovian planets. (except Triton)
- Circular orbits in same direction as planet rotation. (except Triton)

All 4 Galilean moons orbit prograde, in Jupiter's equatorial plane, and are in synchronous ("same face") rotation around Jupiter

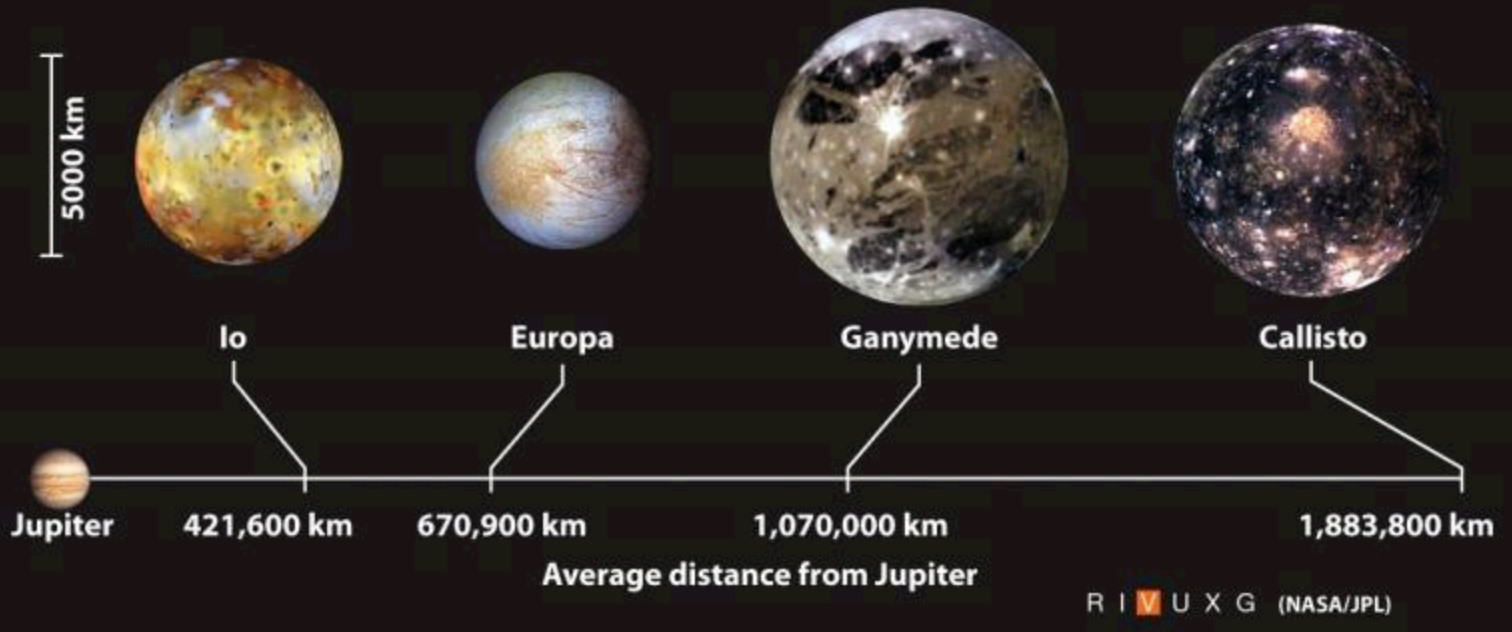


Note: Jupiter is shown to the same scale as the distances of the satellites from Jupiter. Compared to this scale, the images of the satellites themselves have been enlarged 74 ×

Table 13-1 photos
Universe, Tenth Edition
NASA/JPL

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 (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



Note: Jupiter is shown to the same scale as the distances of the satellites from Jupiter. Compared to this scale, the images of the satellites themselves have been enlarged 74 ×

Table 13-1
Universe, Tenth Edition

13-2: Data from spacecraft reveal the unique properties of the Galilean satellites

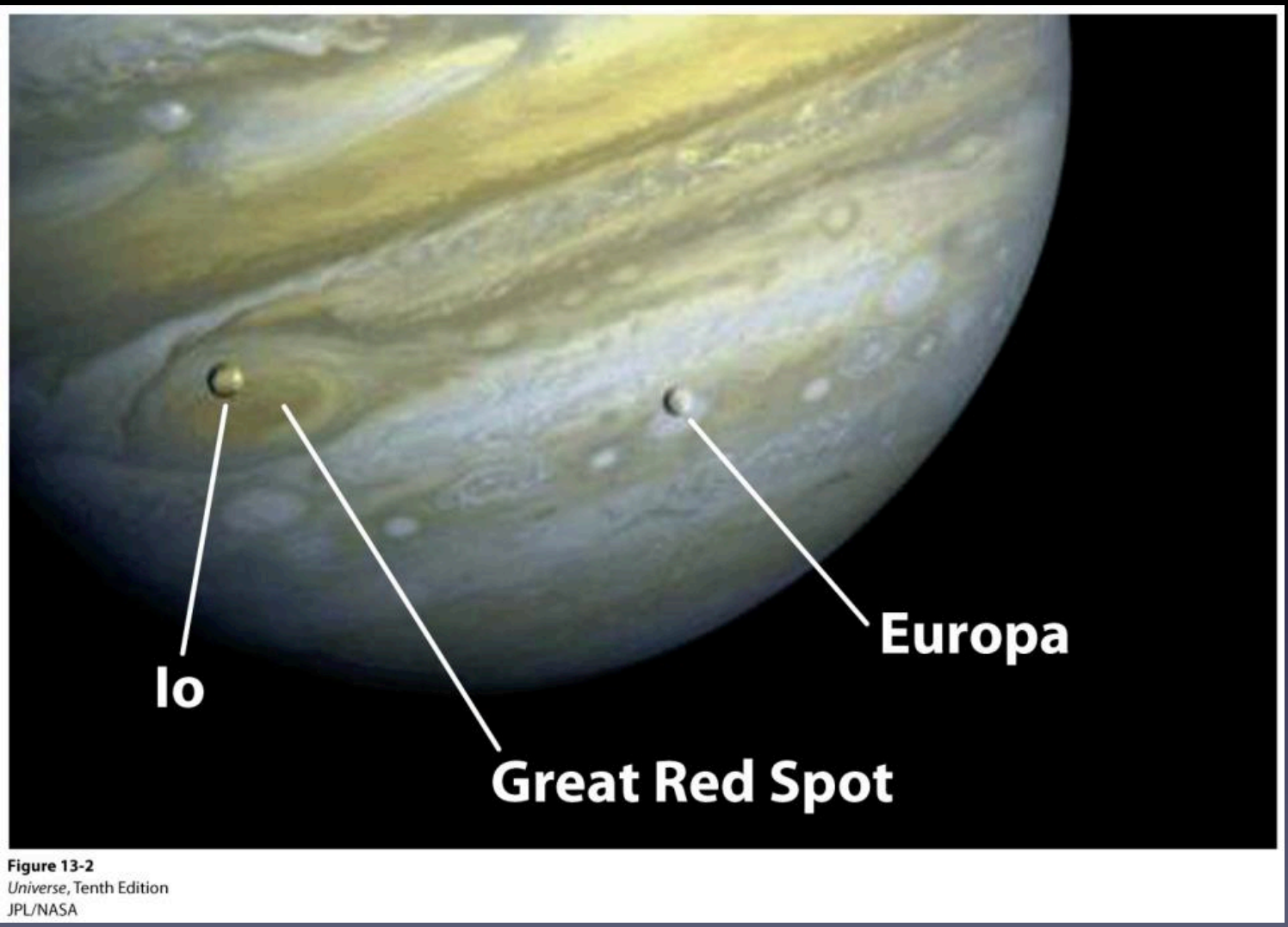
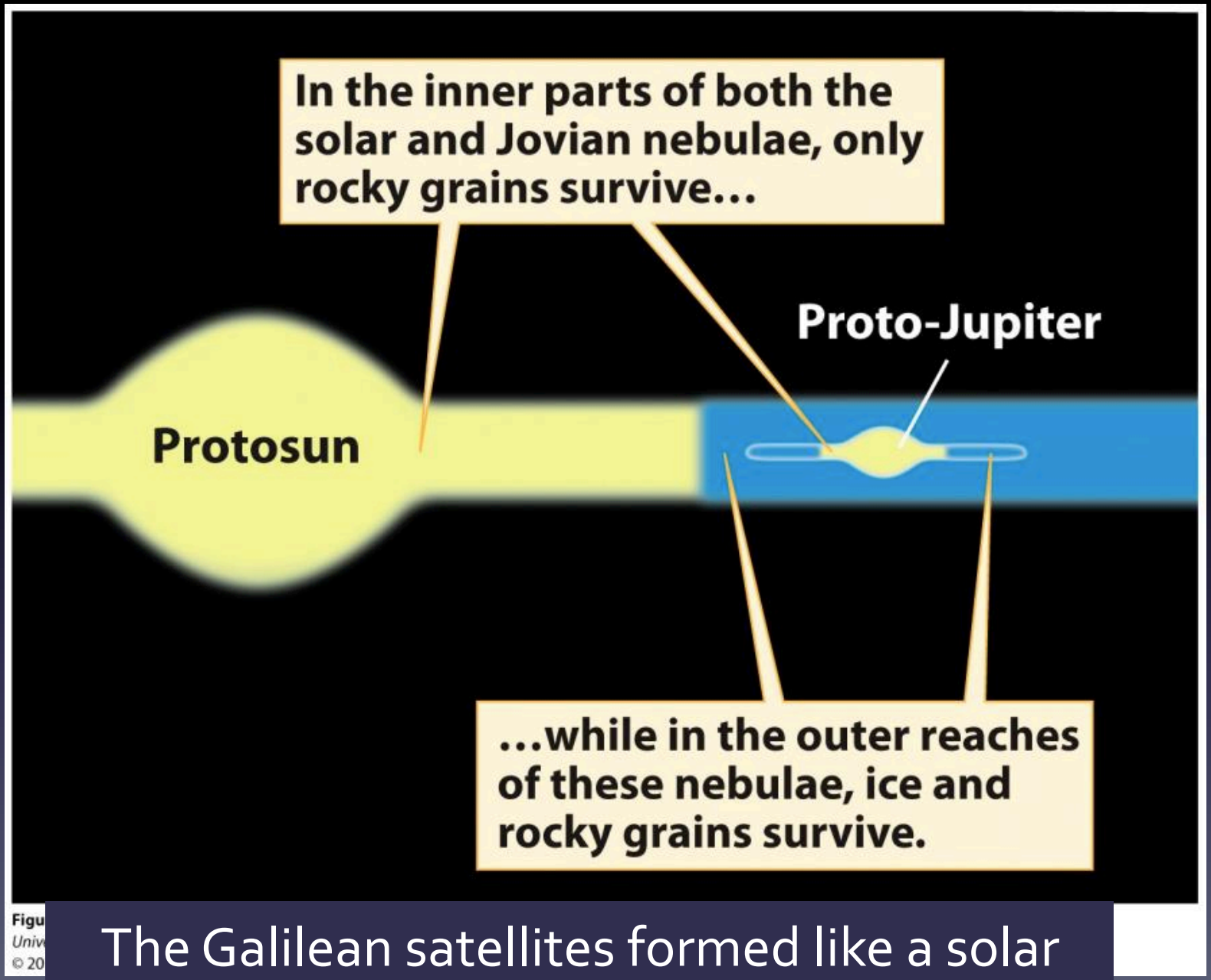


Figure 13-2
Universe, Tenth Edition
JPL/NASA

Io and Europa from Voyager 1



The Galilean satellites formed like a solar system in miniature

13-4: Io is covered with colorful sulfur compounds ejected from active volcanoes

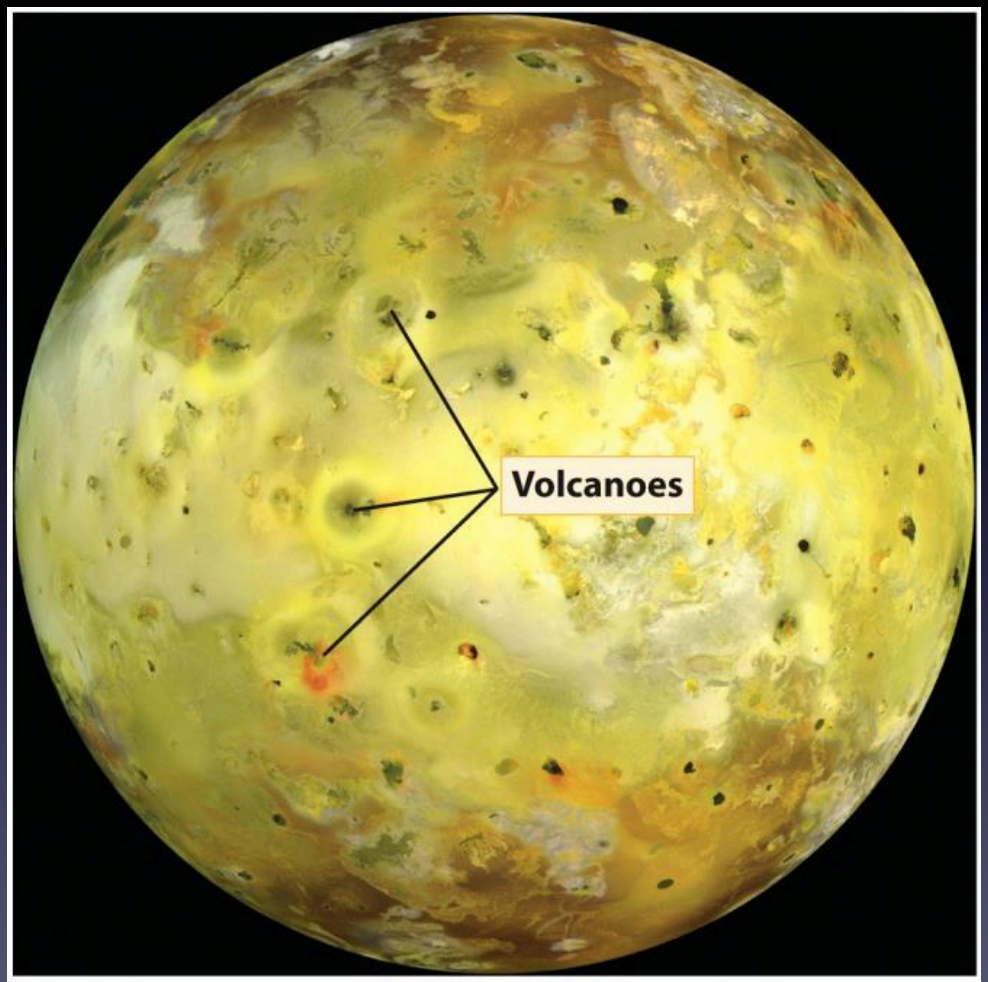
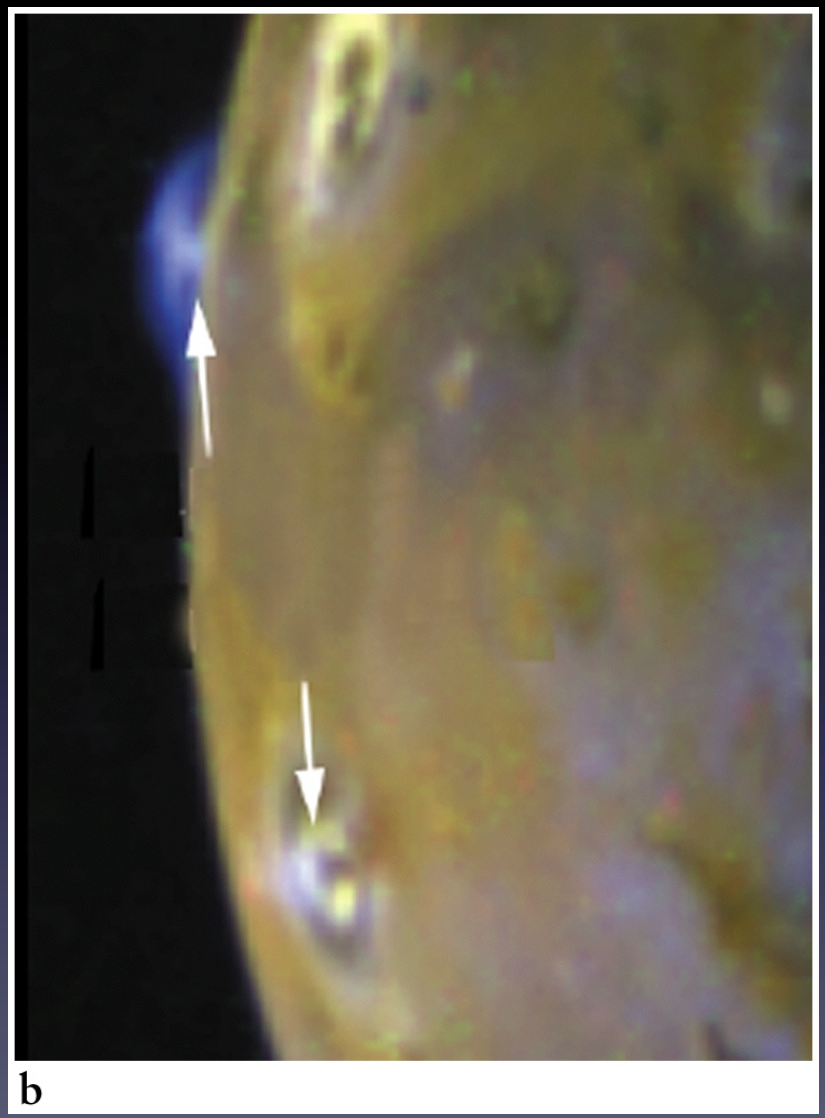


Figure 13-4a
Universe, Tenth Edition
JPL/NASA

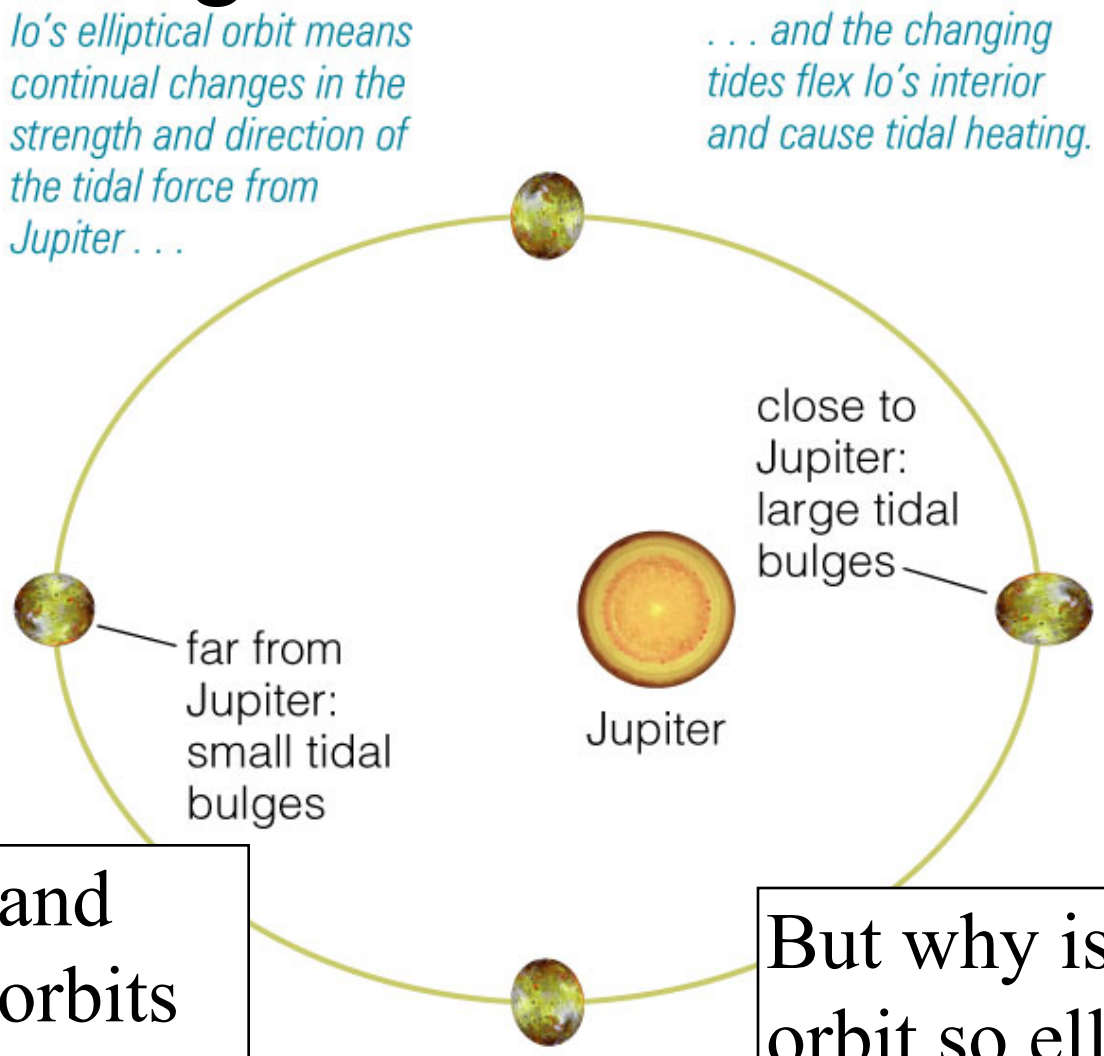
The Colors of Io



b

- Volcanic plumes on Io. Photographed by Voyager in 1970s
- Io is the most volcanically active body in the solar system, but why?

Tidal Heating

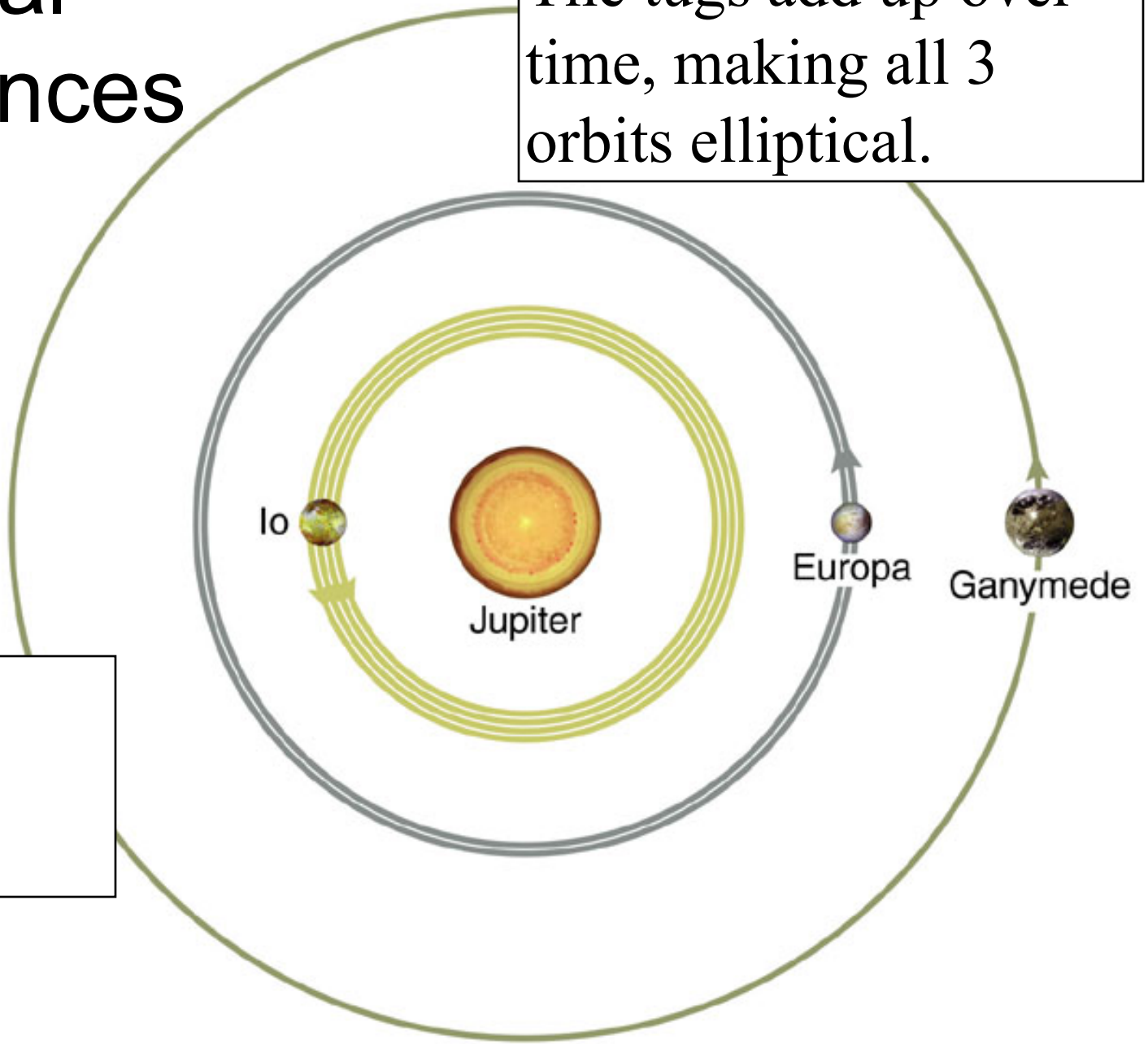


Io is squished and stretched as it orbits Jupiter

But why is its orbit so elliptical?

Orbital Resonances

The tugs add up over time, making all 3 orbits elliptical.



Every 7 days, these 3 moons line up.

4:2:1 Orbital Resonance

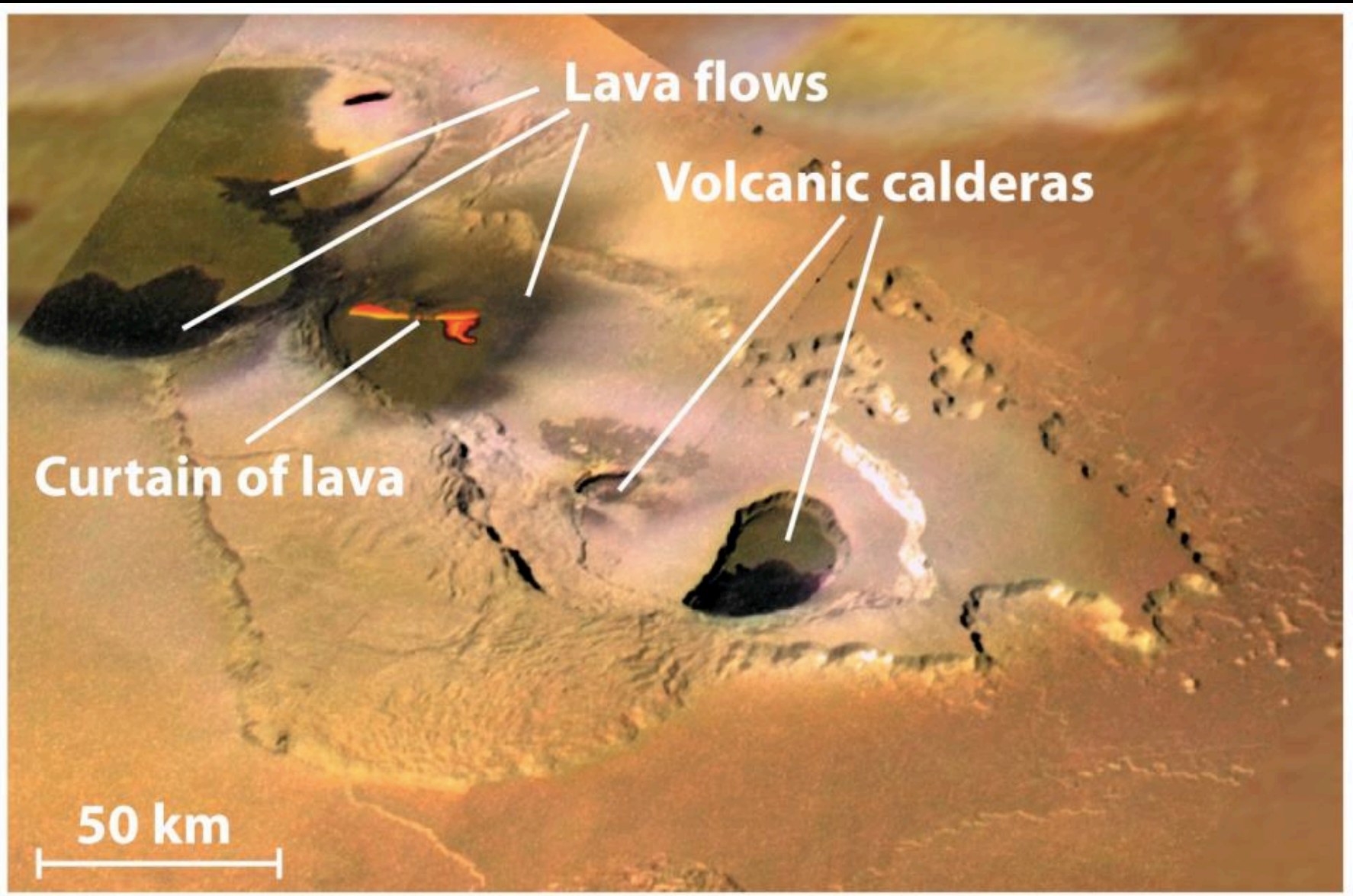
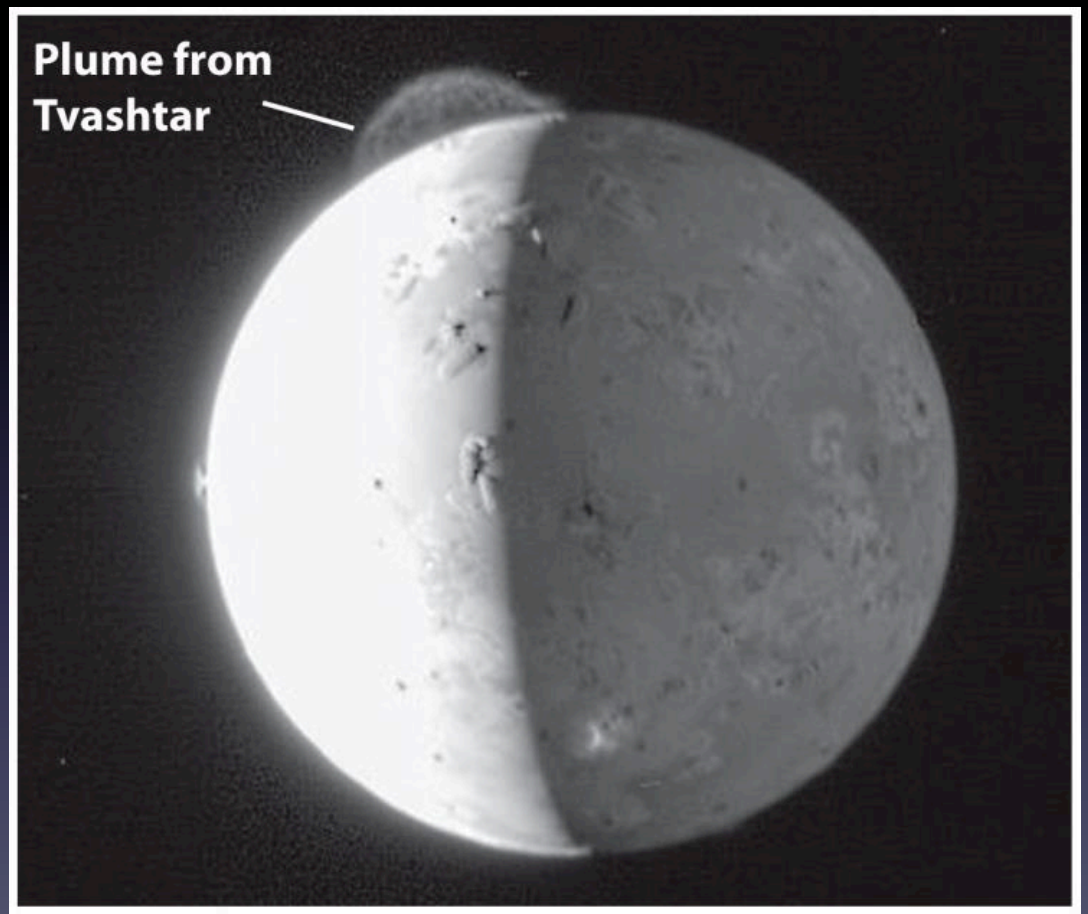


Figure 13-7
Universe, Tenth Edition
University of Arizona/JPL/NASA

Io's Lava Flows and a Curtain of Fire

Volcanoes are really sulfur-driven geysers

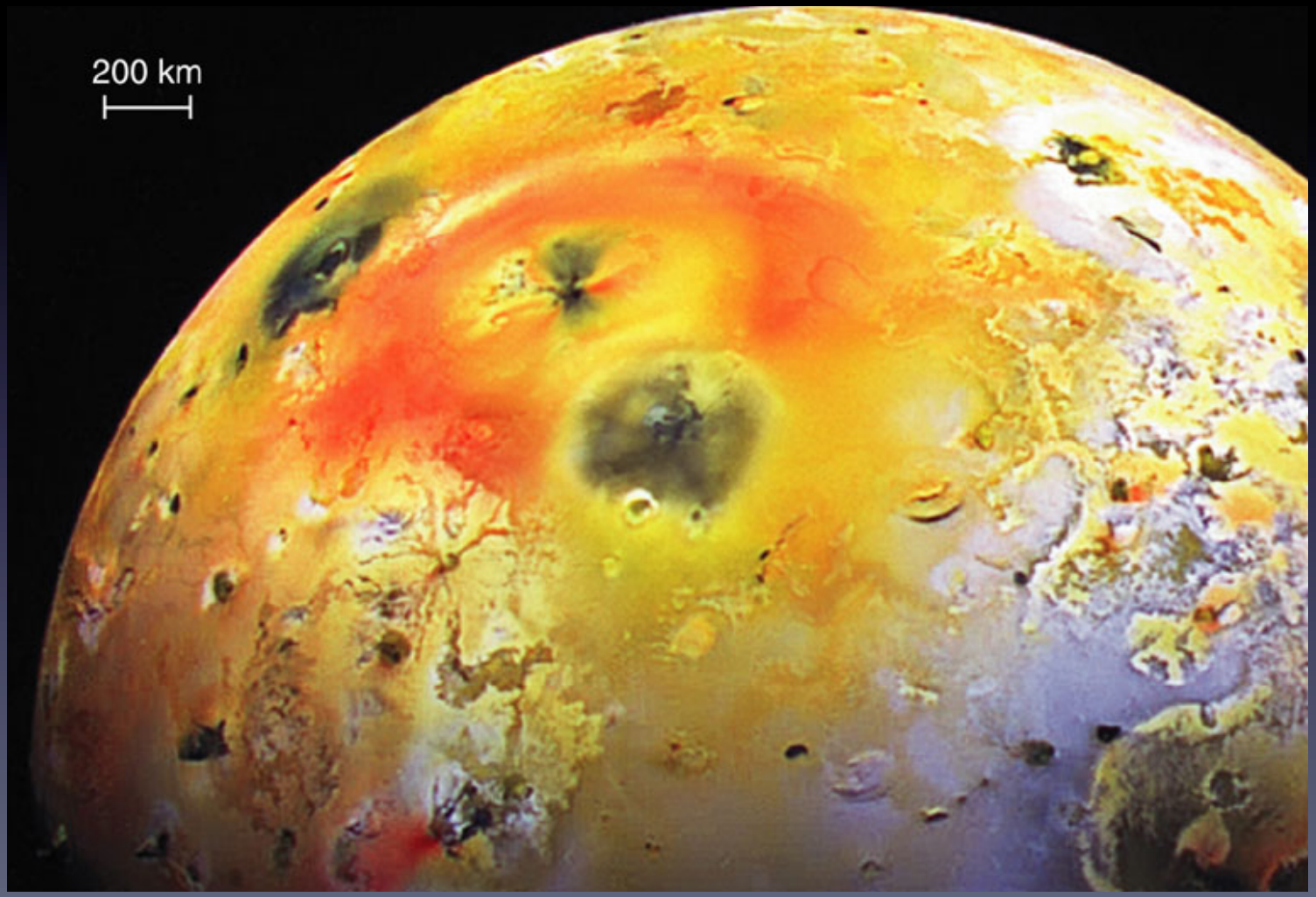


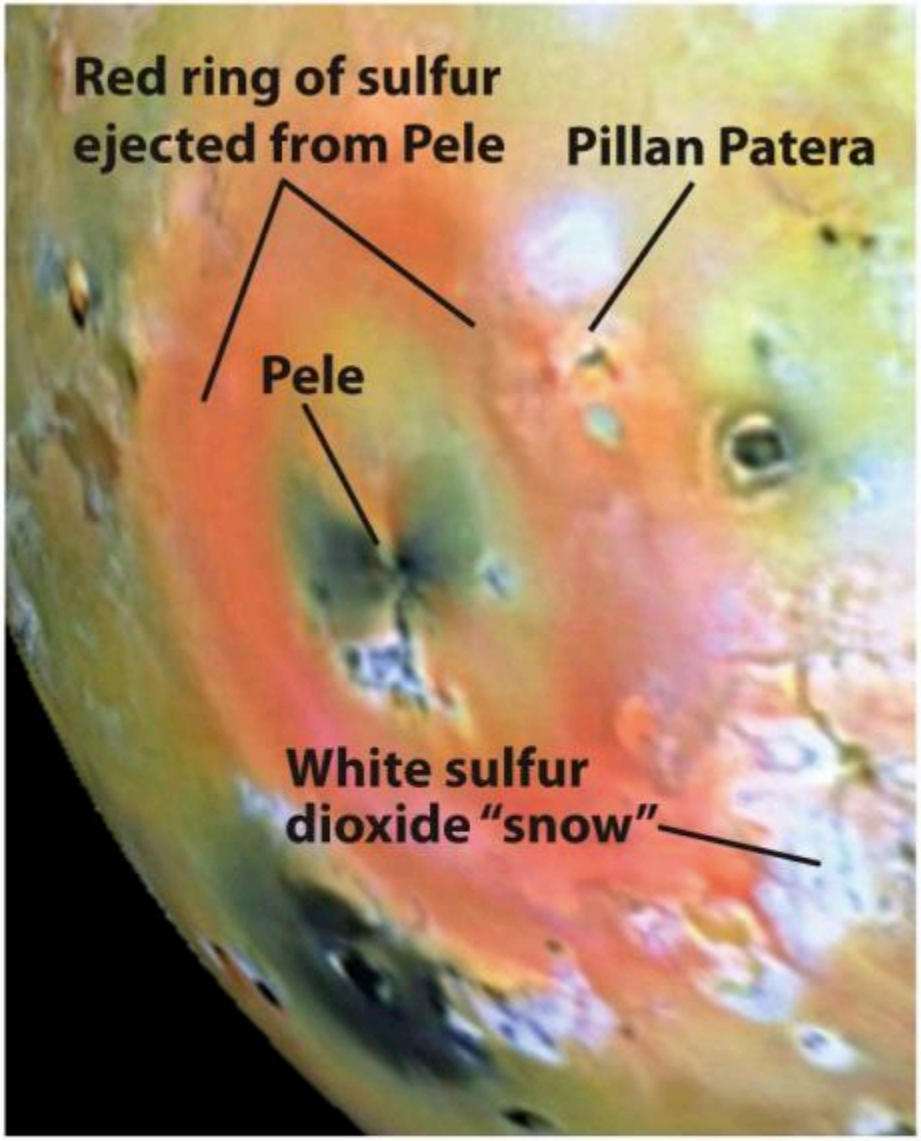
New Horizons, 2007

Figure 13-5c
Universe, Tenth Edition
NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

- Rapid ejecta: high plumes
- From liquid sulfur being explosively heated

Color of sulfur compounds depend on rate of heating and cooling





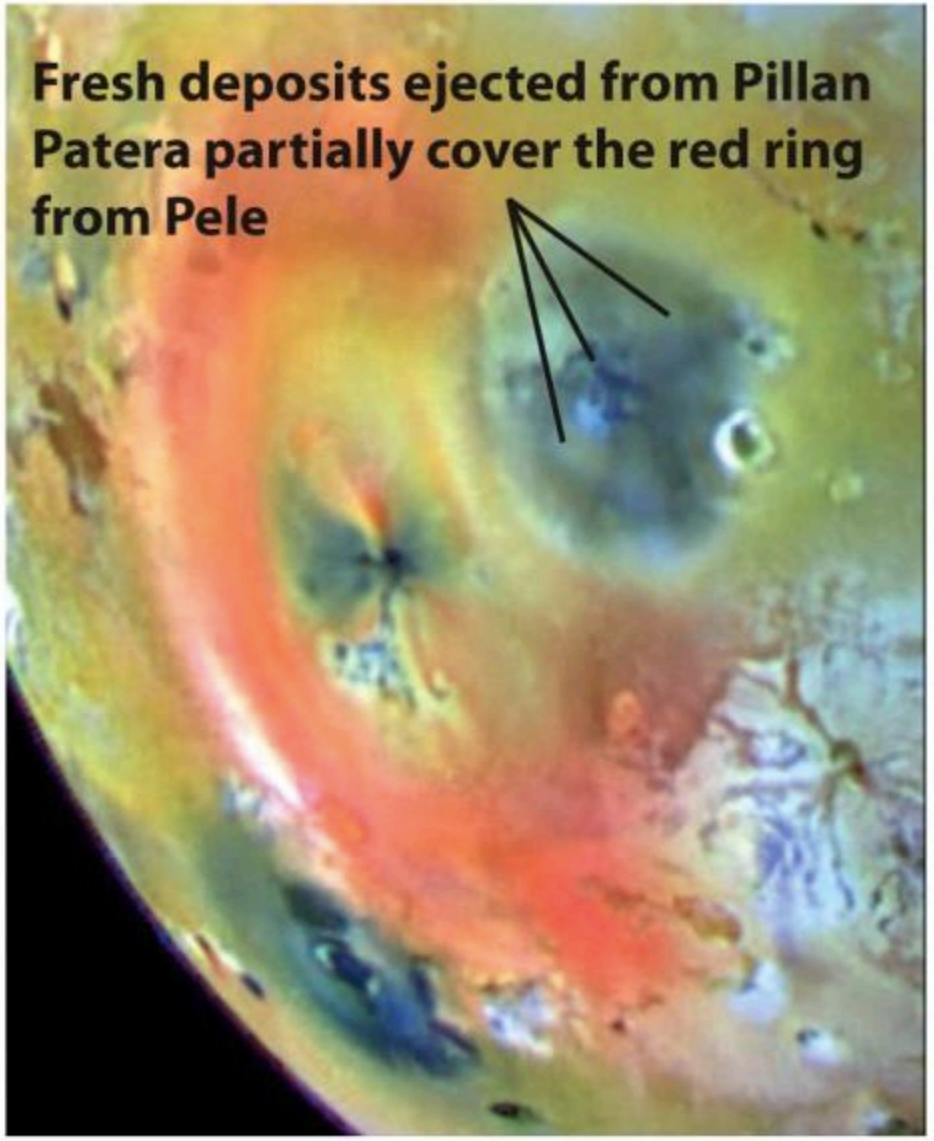


Figure 13-6
Universe, Tenth Edition
NASA/JPL

Rapid Changes on Io

13-5: Jupiter's magnetic field makes electric currents flow through Io

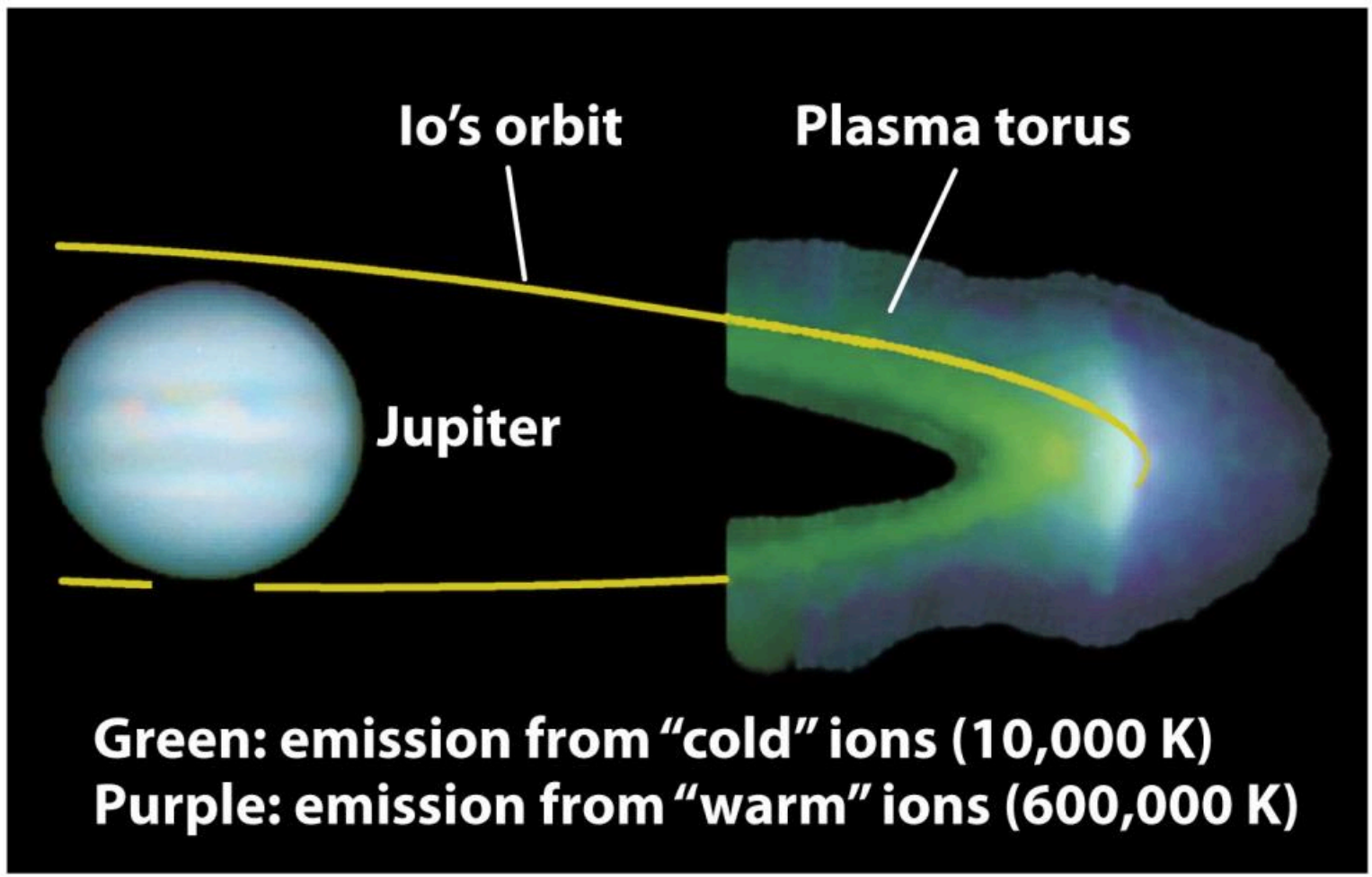


Figure 13-9a
Universe, Tenth Edition
Courtesy of J. Trauger

The Io Torus

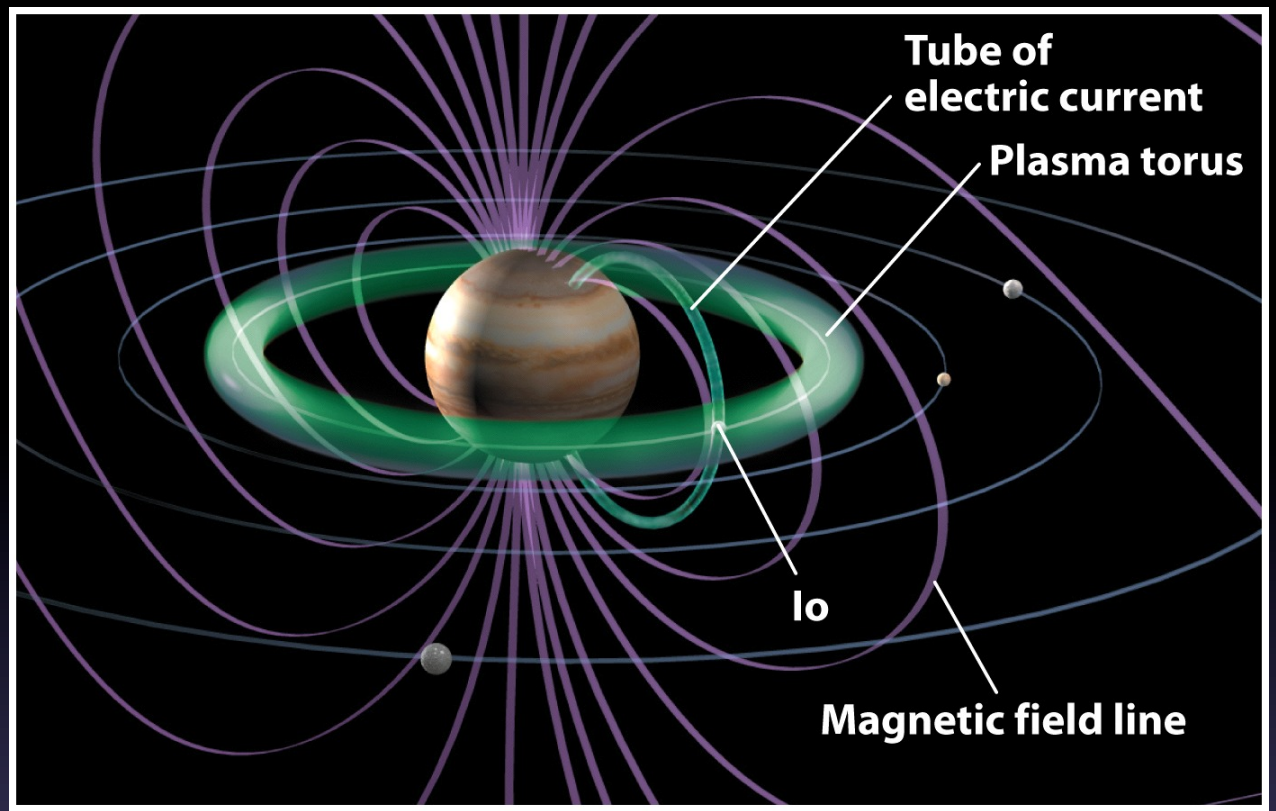
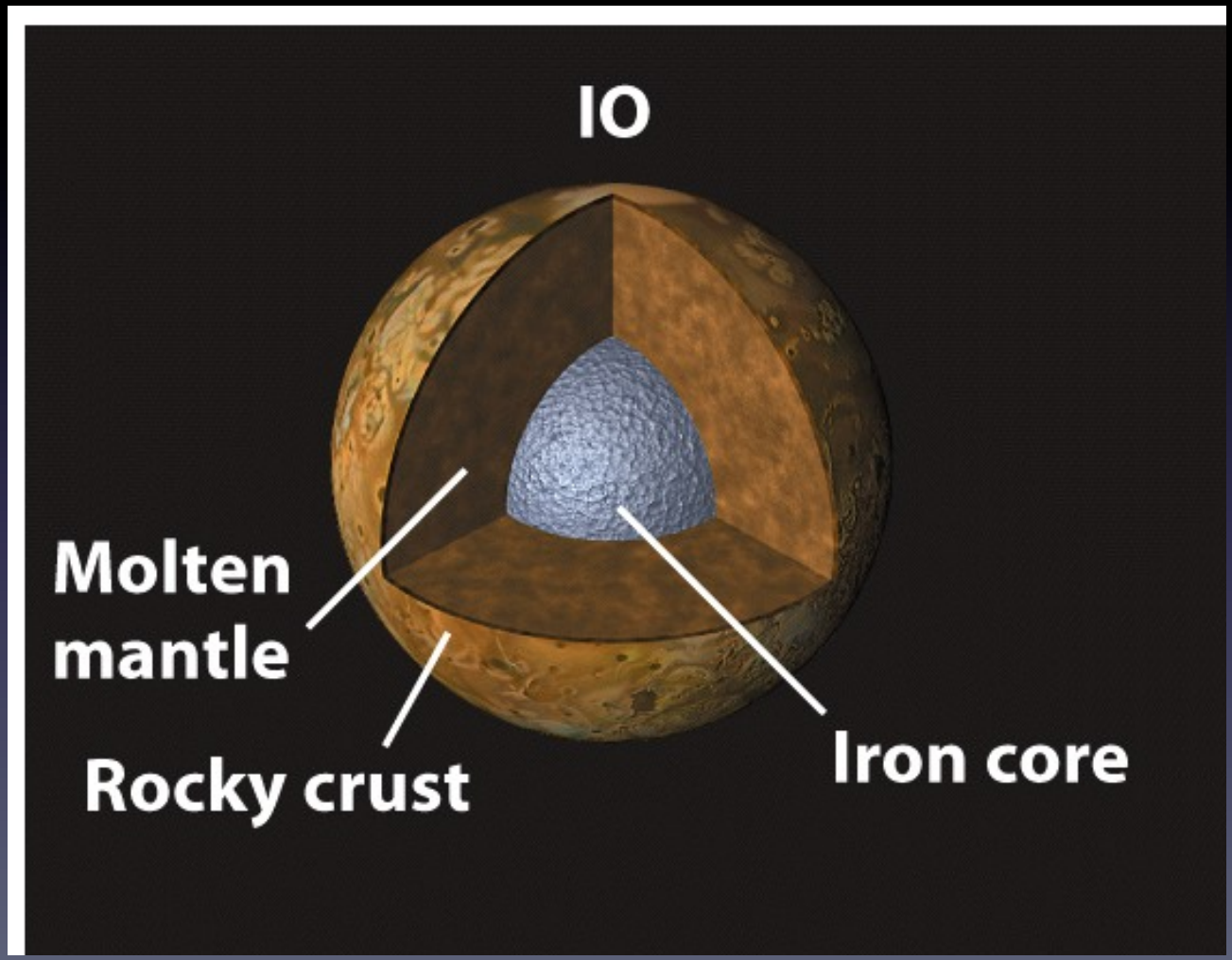


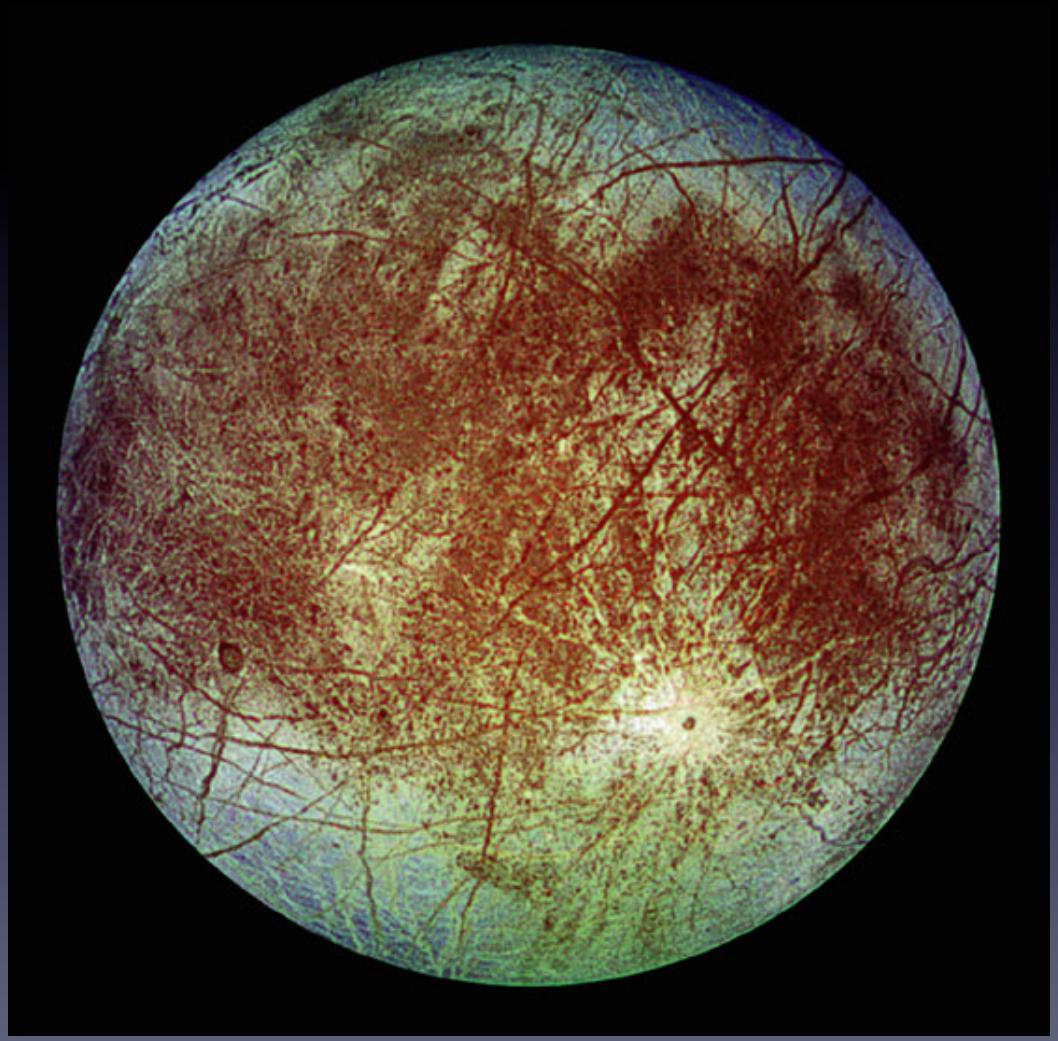
Figure 13-9b
Universe, Tenth Edition
Alfred T. Kamajian and Torrence V. Johnson, "The Galileo Mission to Jupiter and Its Moons," *Scientific American*, February 2000, p. 44

- Jupiter's magnetic field sweeps up ions from Io's volcanic outgassing into a ring called the Io torus
- This sets up a current loop between Io and Jupiter (flux tube)

Mass and oblateness measurements indicate Io is differentiated



13-6: Europa is covered with a smooth layer of ice that may cover a worldwide ocean



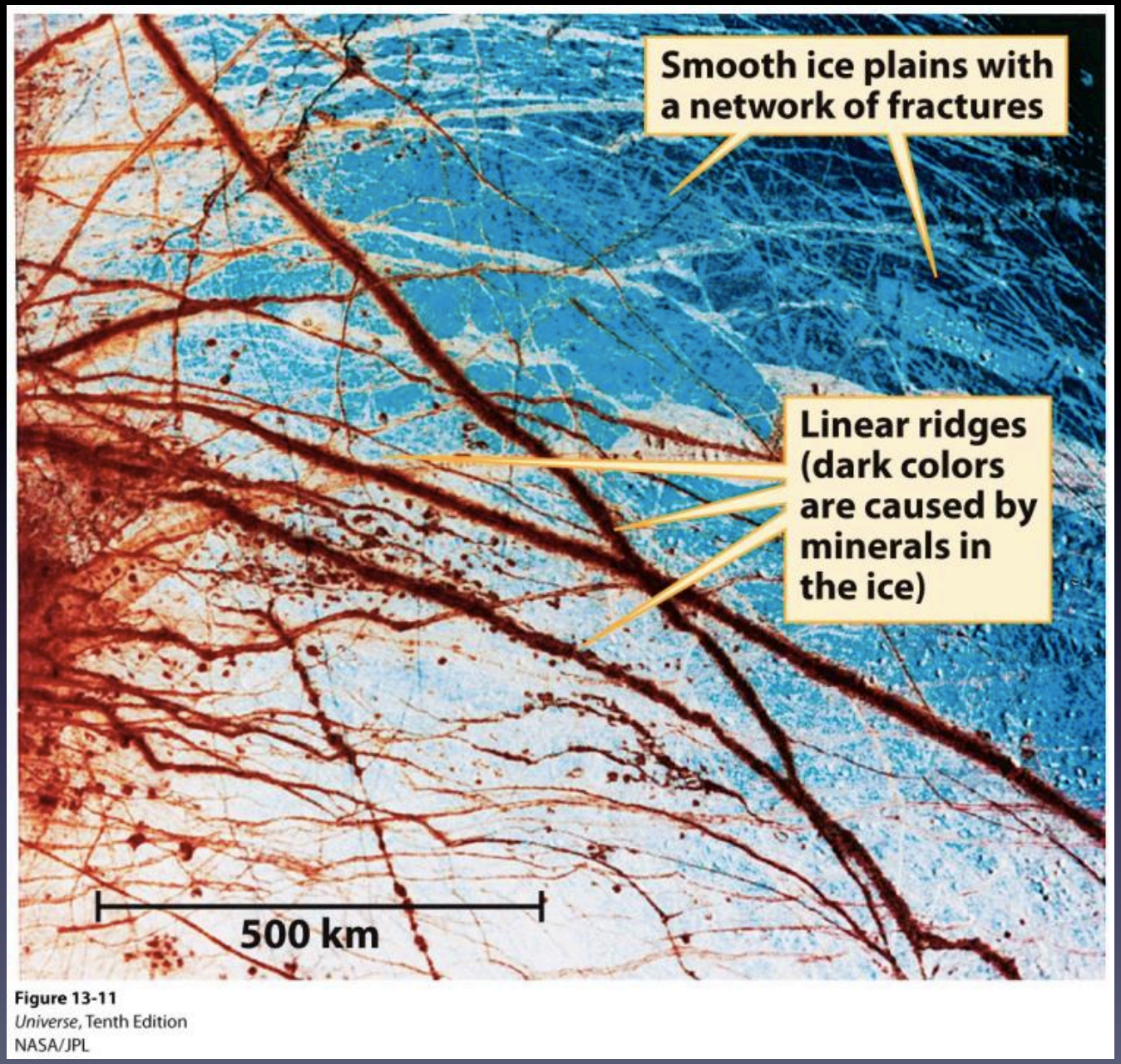


Figure 13-11
Universe, Tenth Edition
NASA/JPL

Europa's Fractured Crust

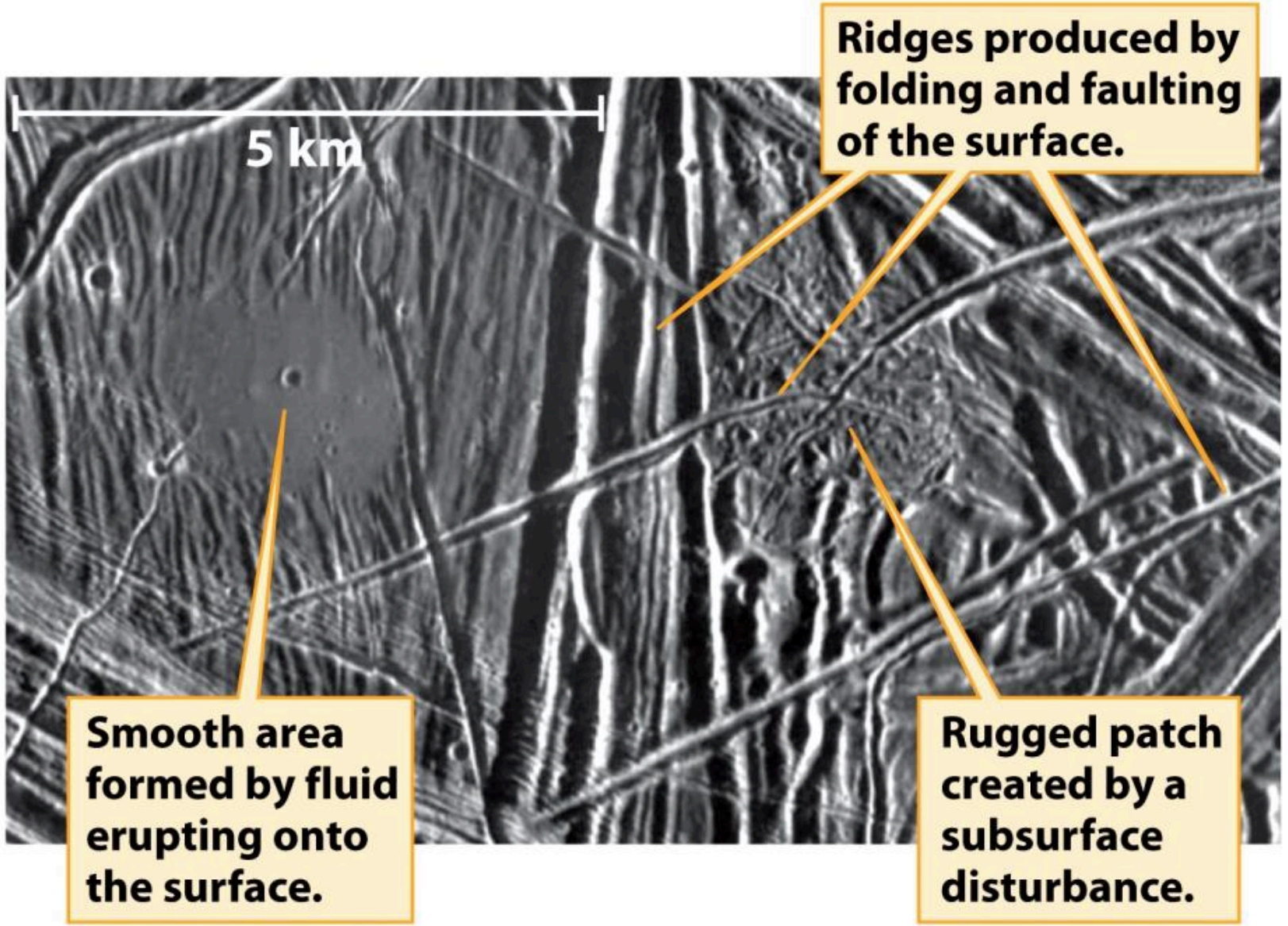
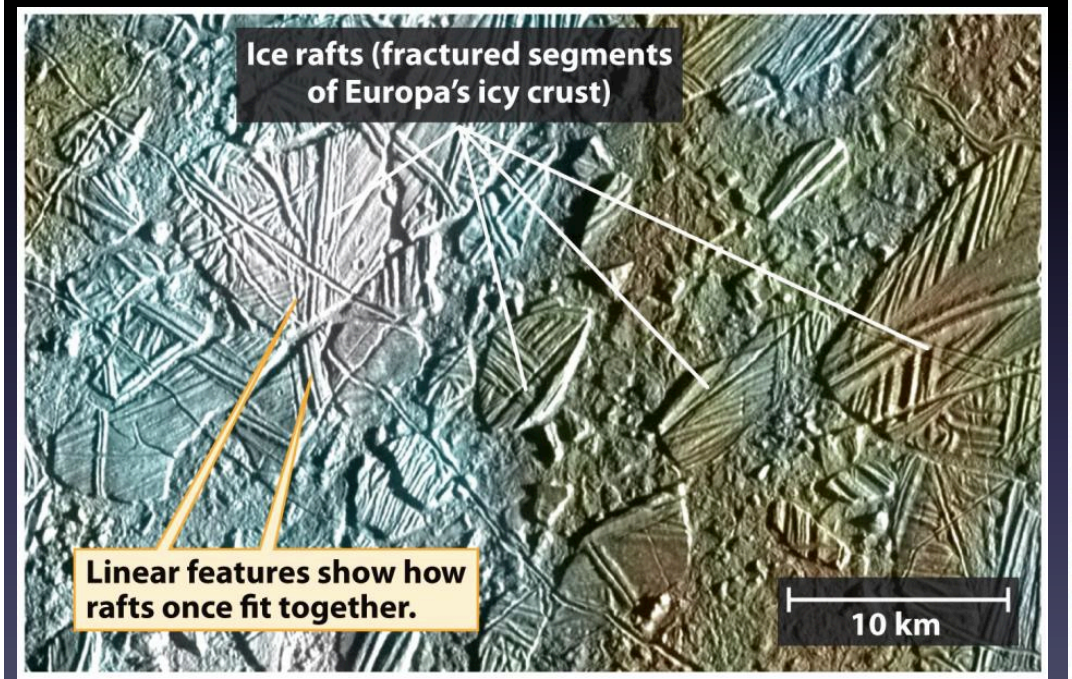


Figure 13-12
Universe, Tenth Edition
NASA/JPL

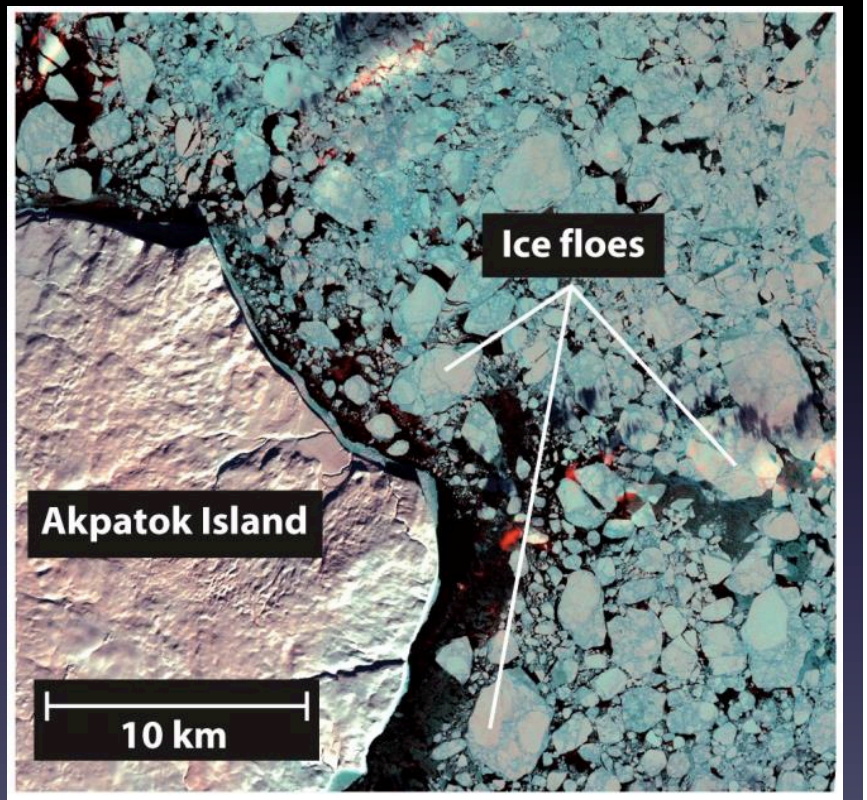
Ice "tectonics": There is interior heat from tidal stresses

Ice rafts



Ice rafts on Europa

Figure 13-13a
Universe, Tenth Edition
NASA/JPL



Ice floes on Earth

Figure 13-13b
Universe, Tenth Edition
USGS and NASA

Moving Ice on Europa and Earth

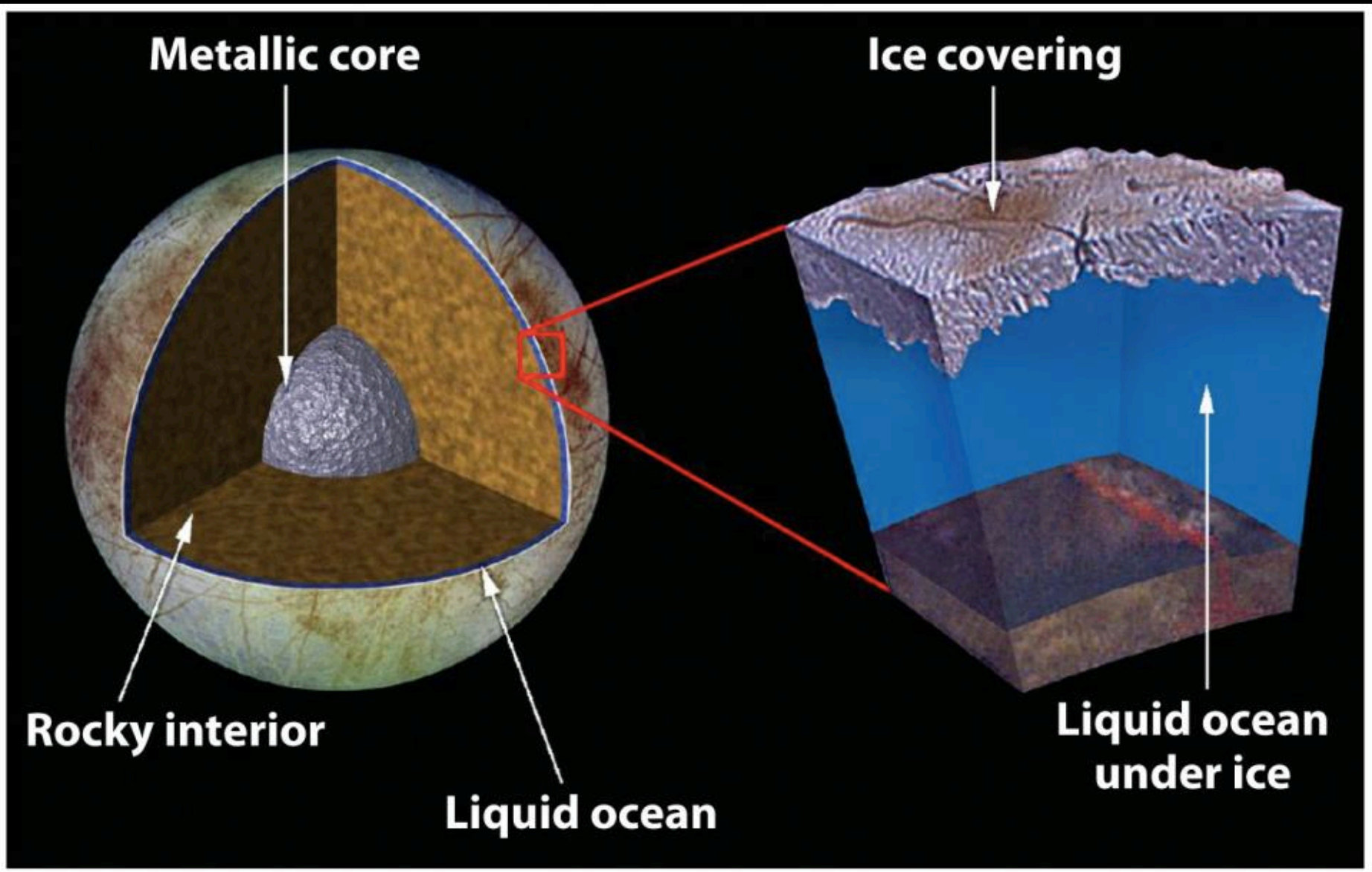


Figure 13-14
Universe, Tenth Edition
NASA/JPL

Europa's Ocean: Best bet for life in Solar System

Ganymede

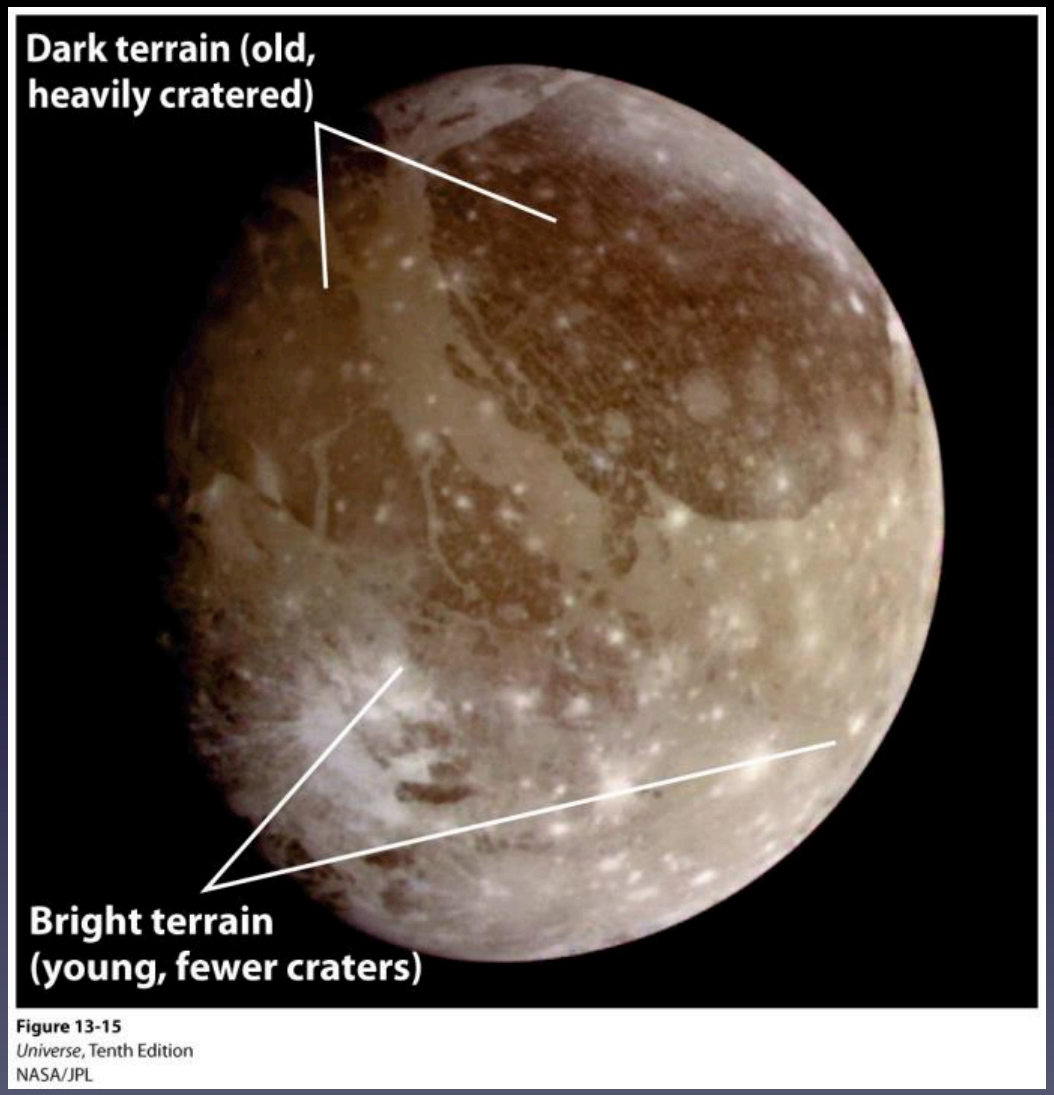
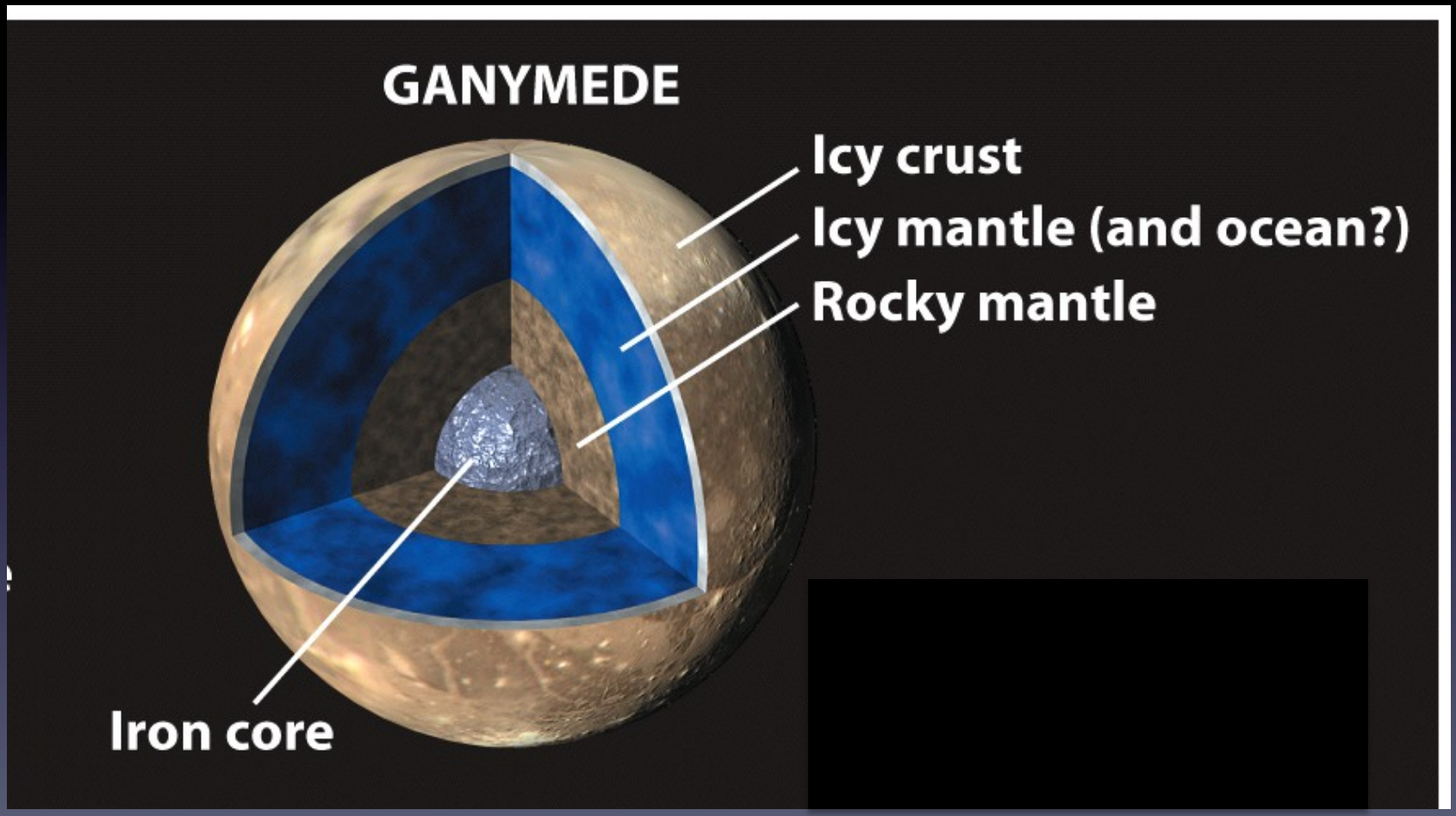


Figure 13-15
Universe, Tenth Edition
NASA/JPL

- Largest moon in the solar system
- Clear evidence of geological activity in the past
- Tidal heating plus heat from radioactive decay?

Ganymede is differentiated



Europa and Ganymede's Magnetic Fields

Both:

- Weak variable magnetic field
- From moving through Jupiter's magnetic field
  - Induces electric currents in subsurface (salty) ocean, which produce a magnetic field
- Ganymede:
  - Also has its own internally generated magnetic field – requires partly molten core: still has some internal heat

Europa and Ganymede's atmospheres

- Solar wind ions hit surface; knock water molecules loose
- Solar UV photons break apart water molecules: H_2O -> H, H, O
- H escapes; O atoms combine into O_2 (which eventually escape)

Callisto

Callisto

- Heavily cratered iceball , but no small craters
- Covered with dark, dusty material

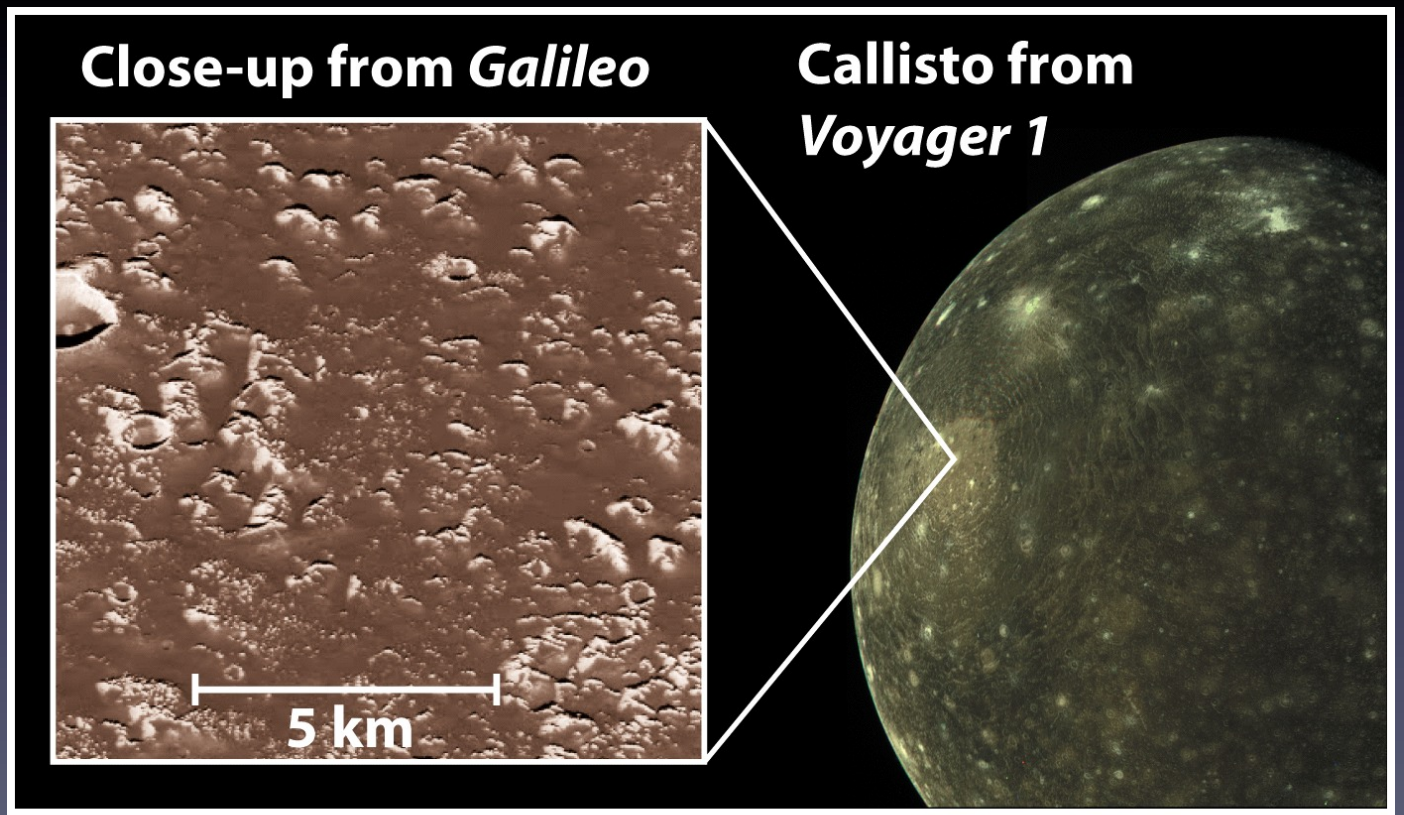


Figure 13-17
Universe, Tenth Edition
Arizona State University/JPL/NASA; right: JPL/NASA

Callisto's Magnetic Field

- Weak variable magnetic field induced by Jupiter (like Europa) – must have electrically conducting material: salty ocean?
- But no internal heating source! Not differentiated: cold inside. How is there a subsurface ocean? Ammonia in water??

Interiors of the Galilean Satellites

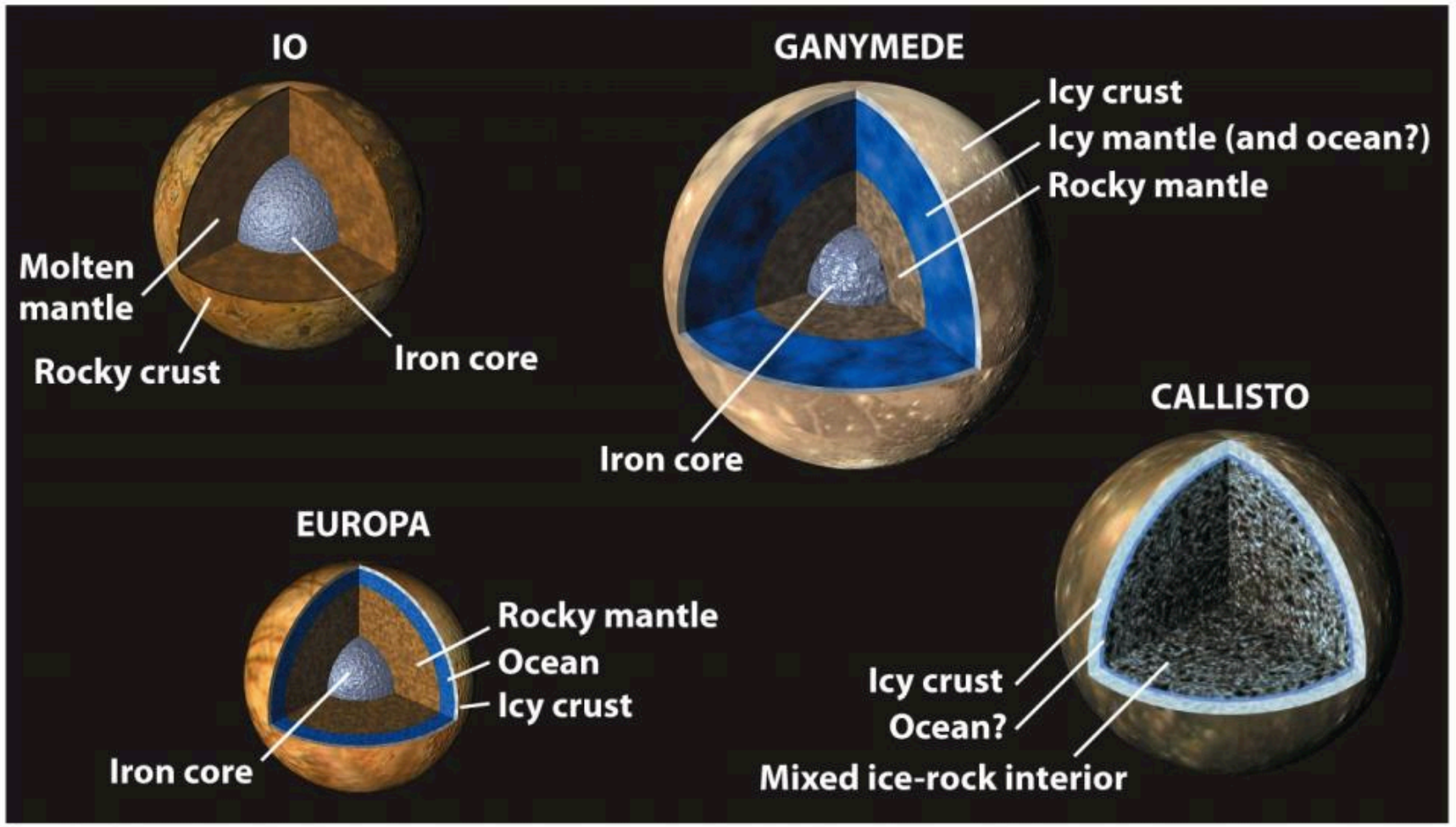


Figure 13-18
Universe, Tenth Edition
NASA/JPL

13-8: Saturn's moon Titan has a thick atmosphere and hydrocarbon lakes

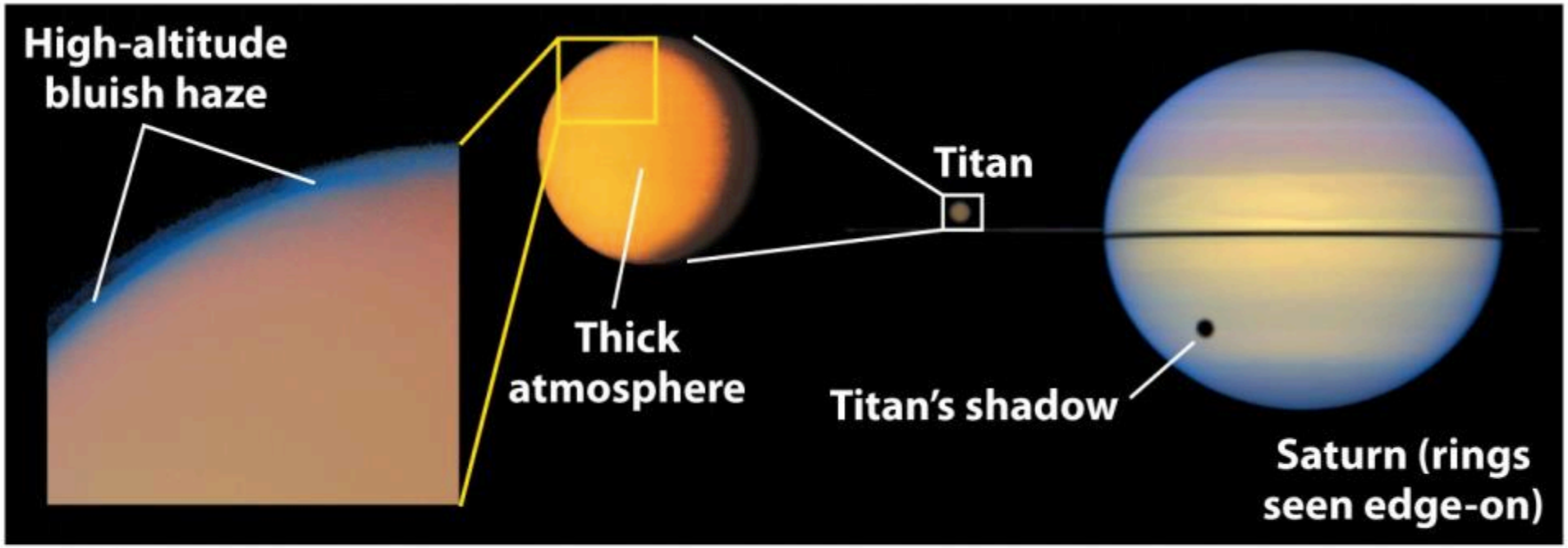


Figure 13-19
Universe, Tenth Edition
Left: JPL/NASA; center: NASA; right: Erich Karkoschka, LPL/STScI/NASA

Titan's atmosphere consists mostly of nitrogen (95%) with some methane, and ethane. Originated from comet impacts

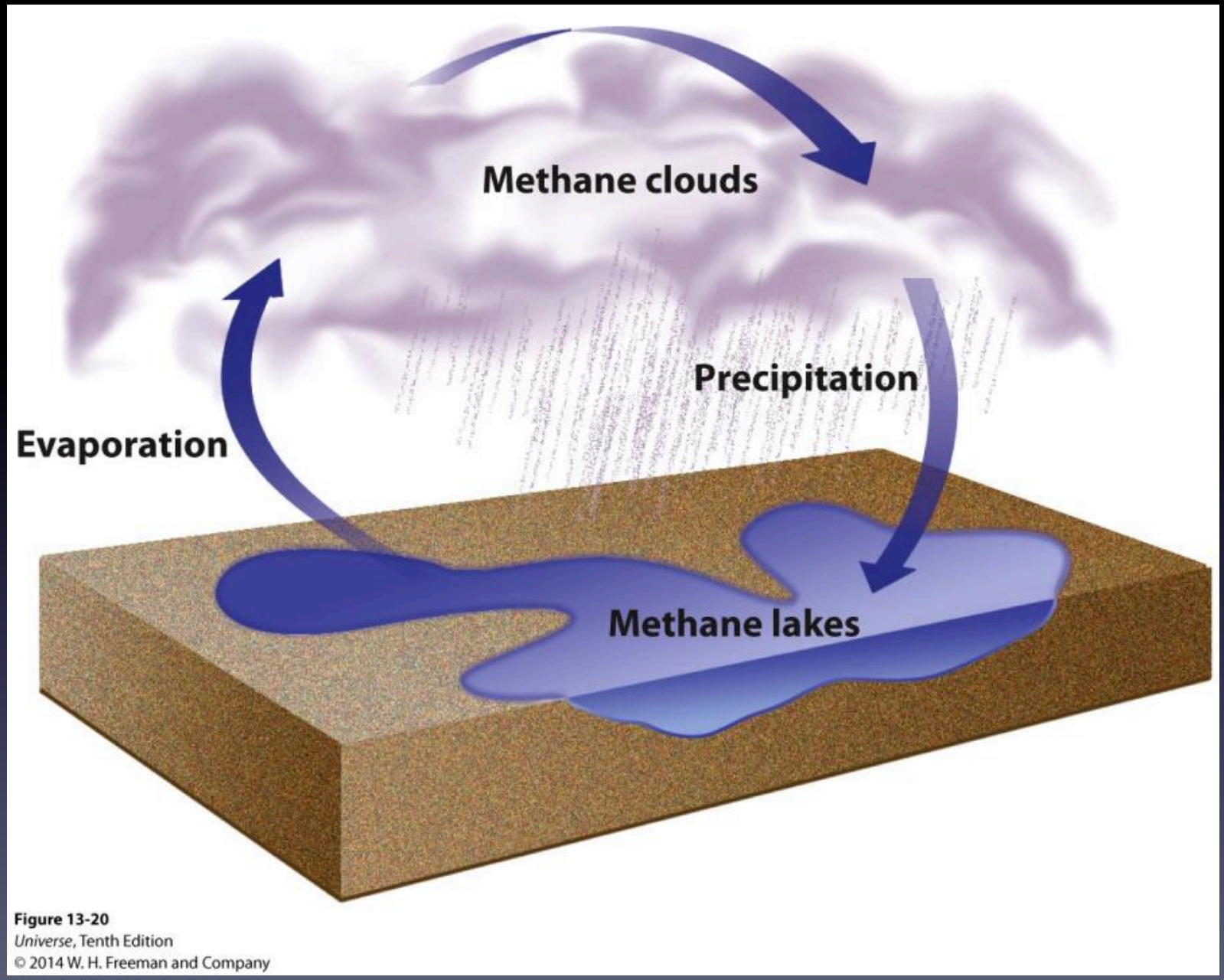


Figure 13-20
Universe, Tenth Edition

Methane Cycle on Titan

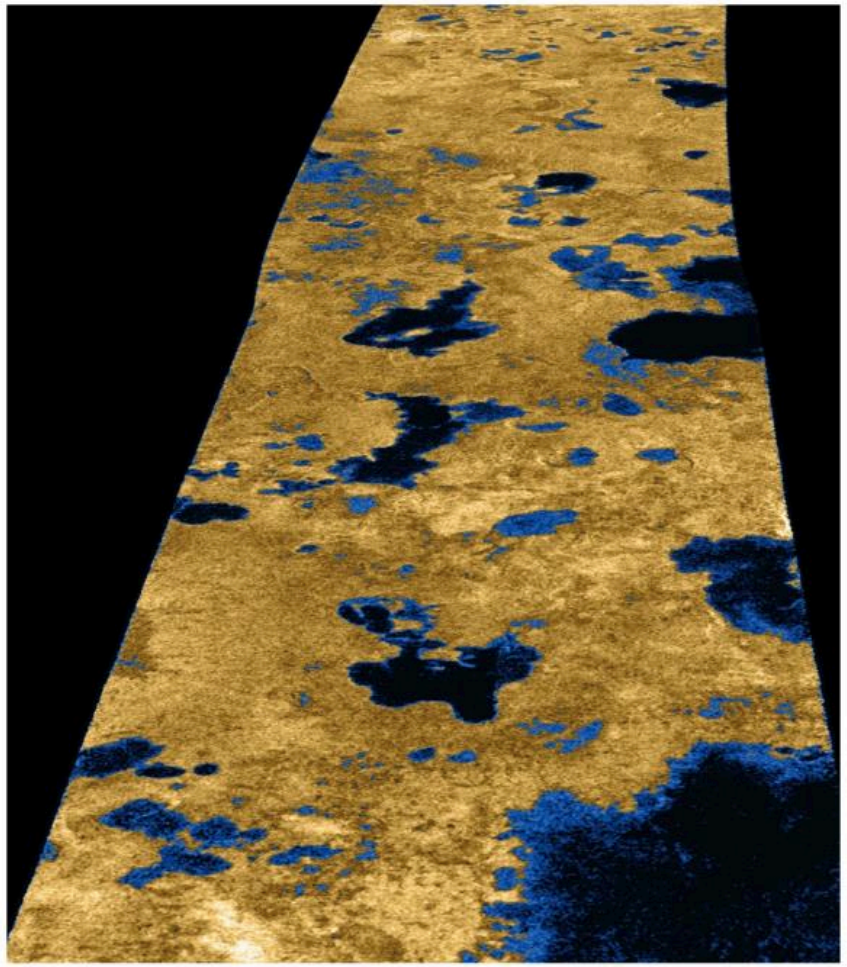


Figure 13-23a
Universe, Tenth Edition
NASA/JPL/USGS

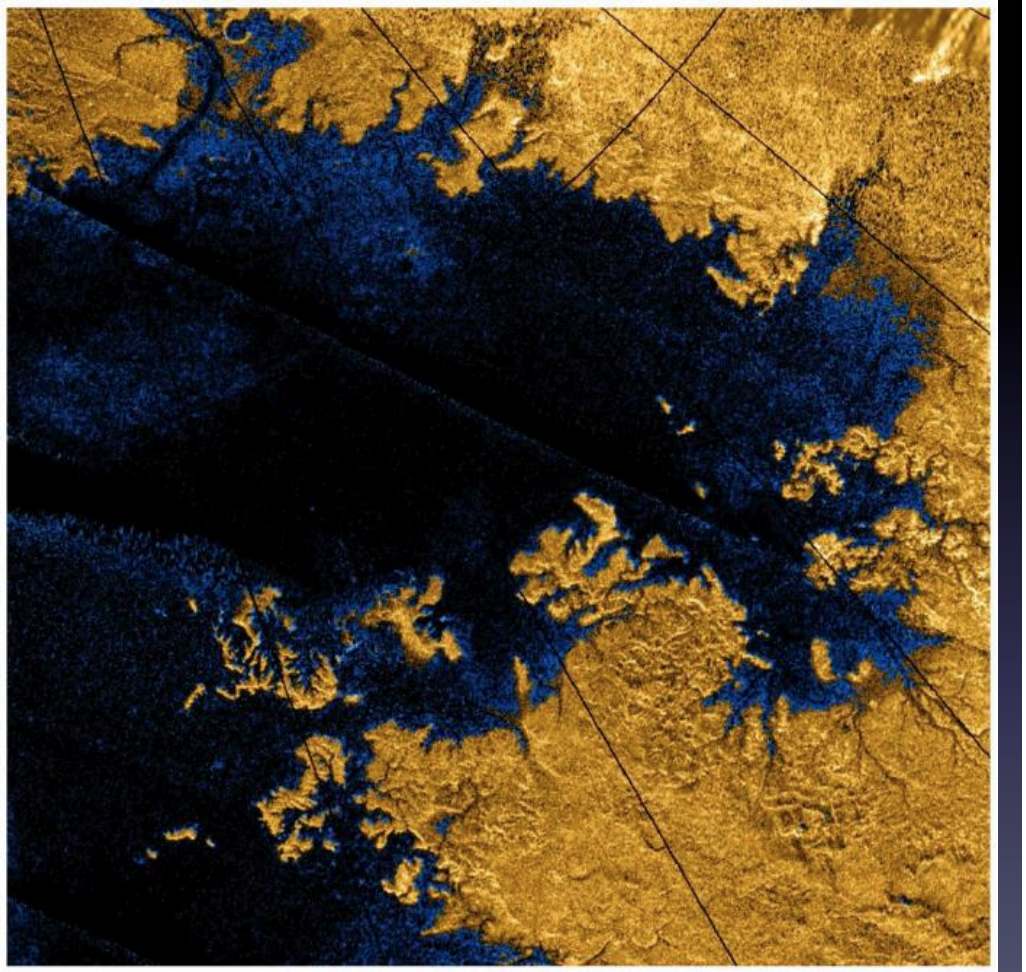
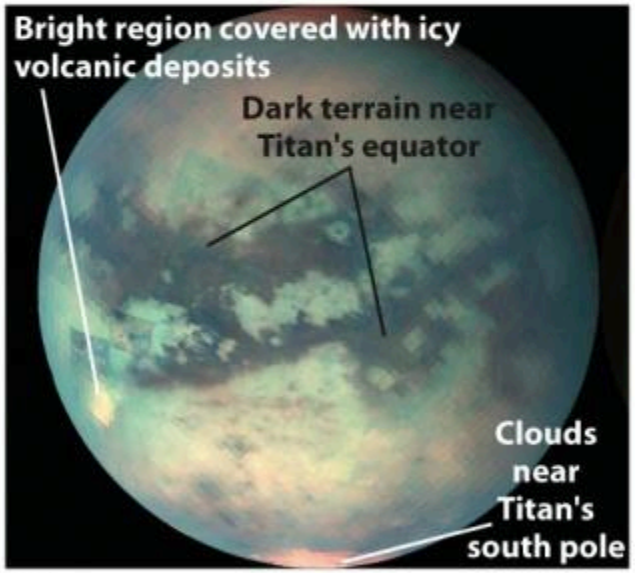
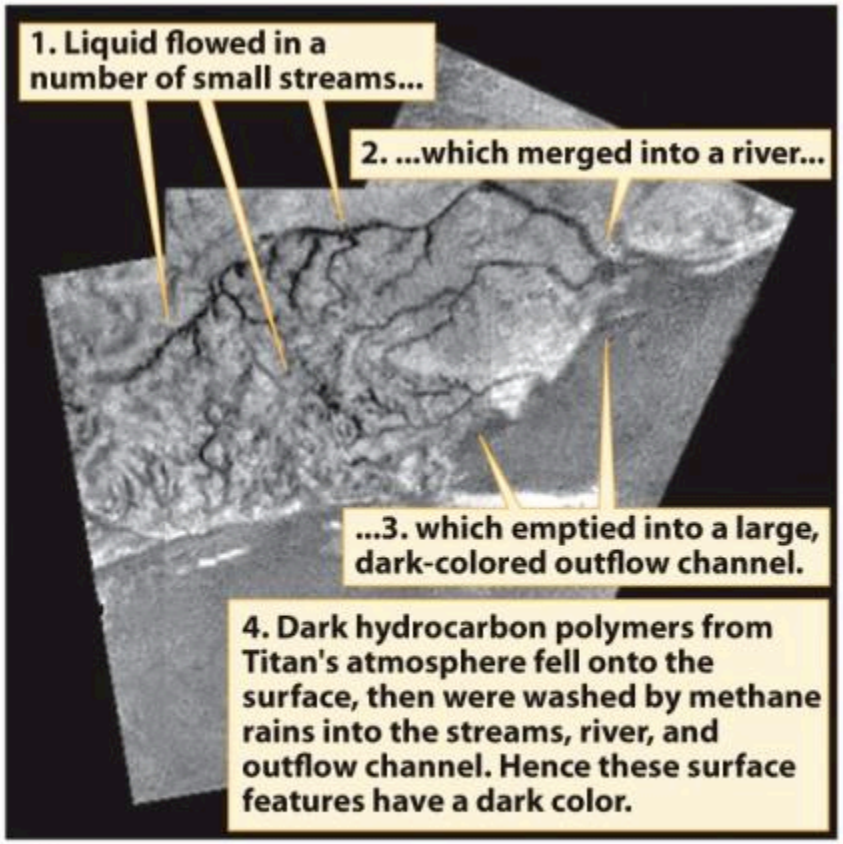


Figure 13-23b
Universe, Tenth Edition
NASA/JPL/USGS

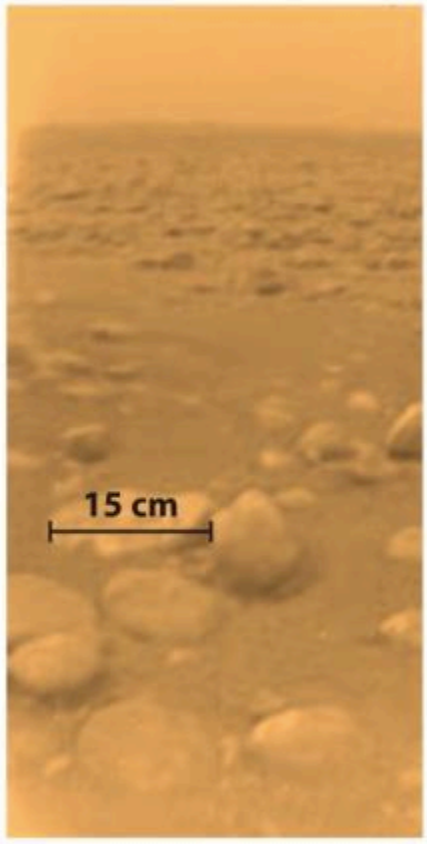
Hydrocarbon (methane, ethane) Seas on Titan



(a)



(b)



(c)

Figure 13-21
Universe, Tenth Edition
NASA/JPL/ESA/University of Arizona

Beneath Titan's Clouds

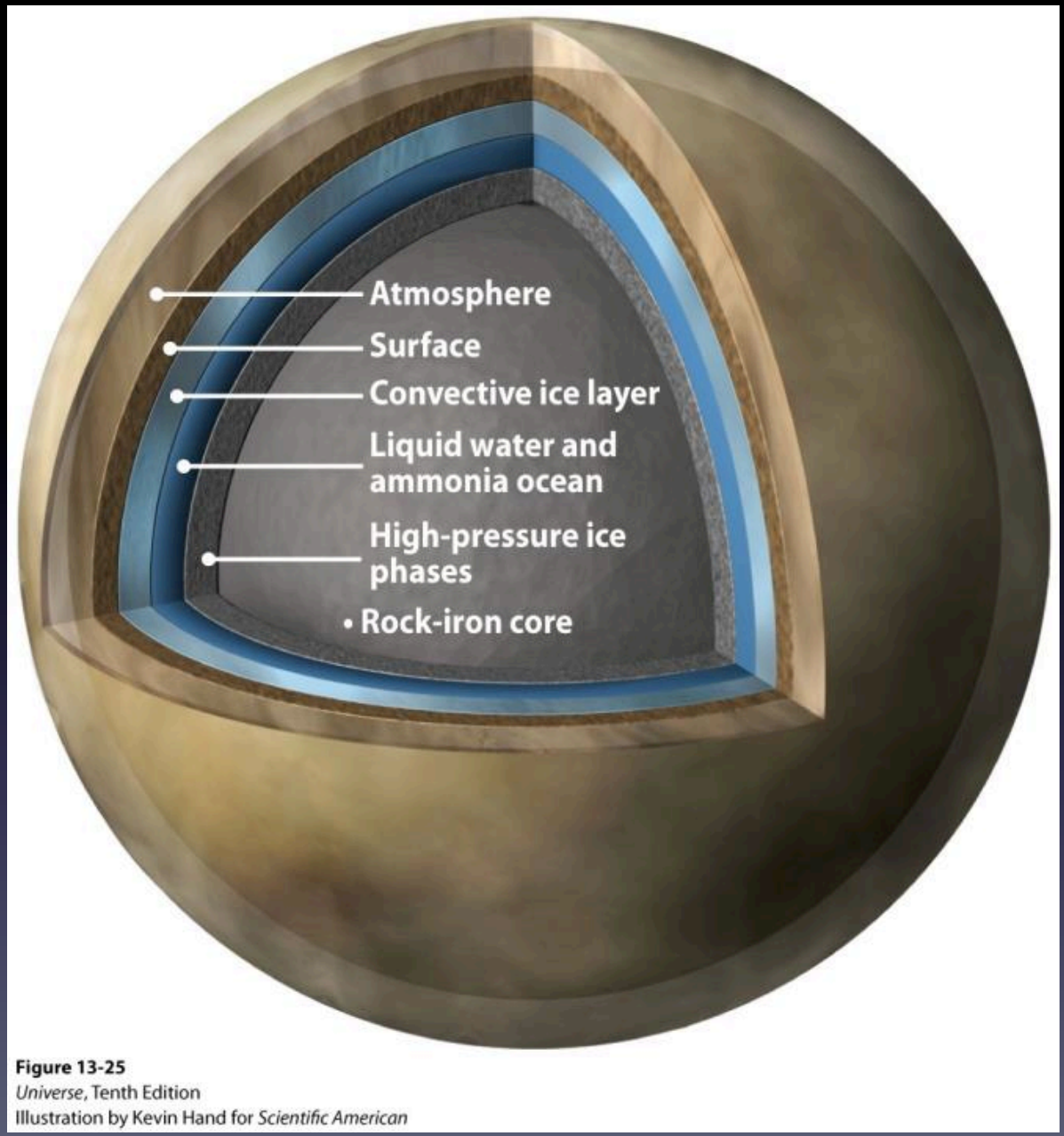


Figure 13-25
Universe, Tenth Edition
Illustration by Kevin Hand for *Scientific American*

Titan's Interior: differentiated, but cold today

13-9: Jupiter has dozens of small satellites that have different origins

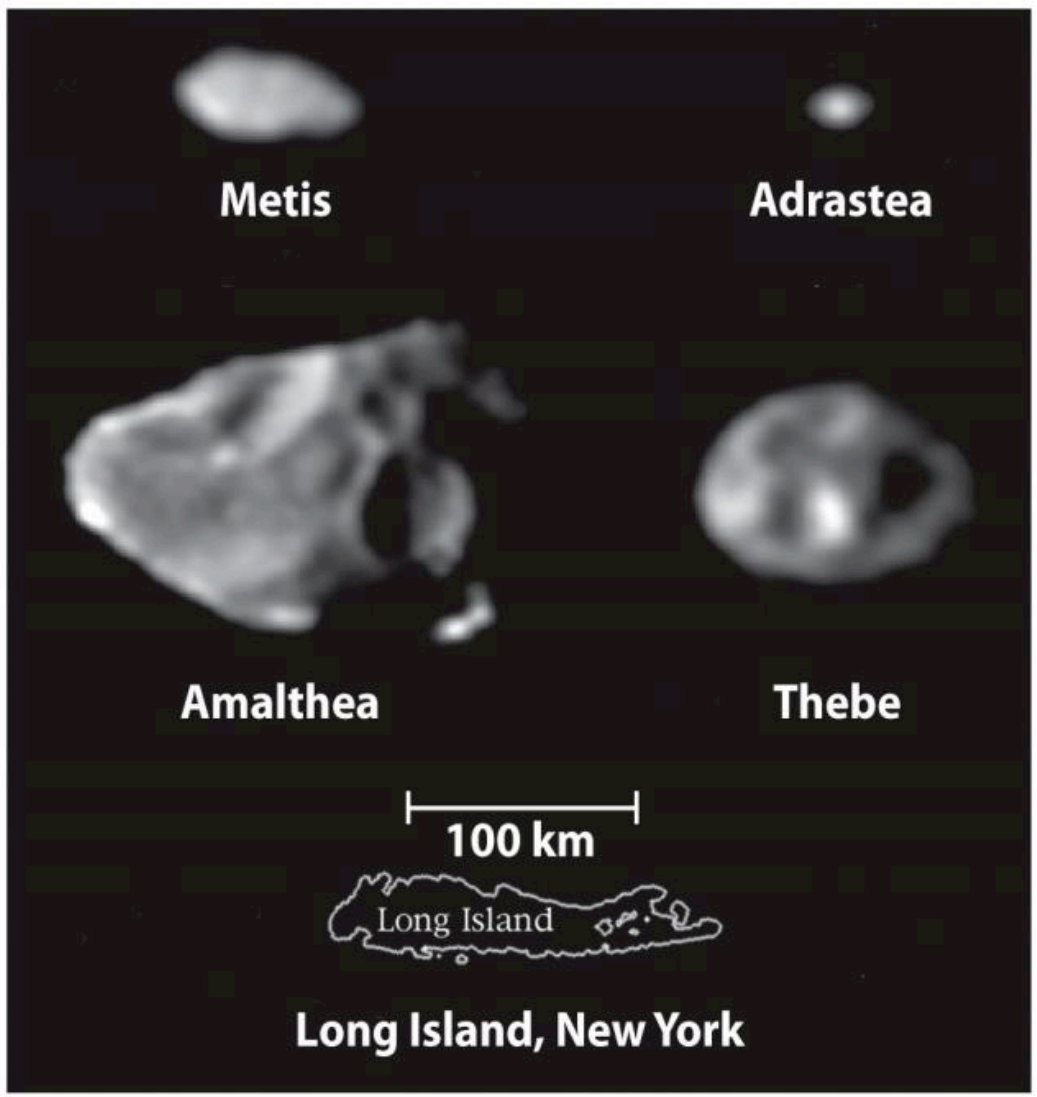


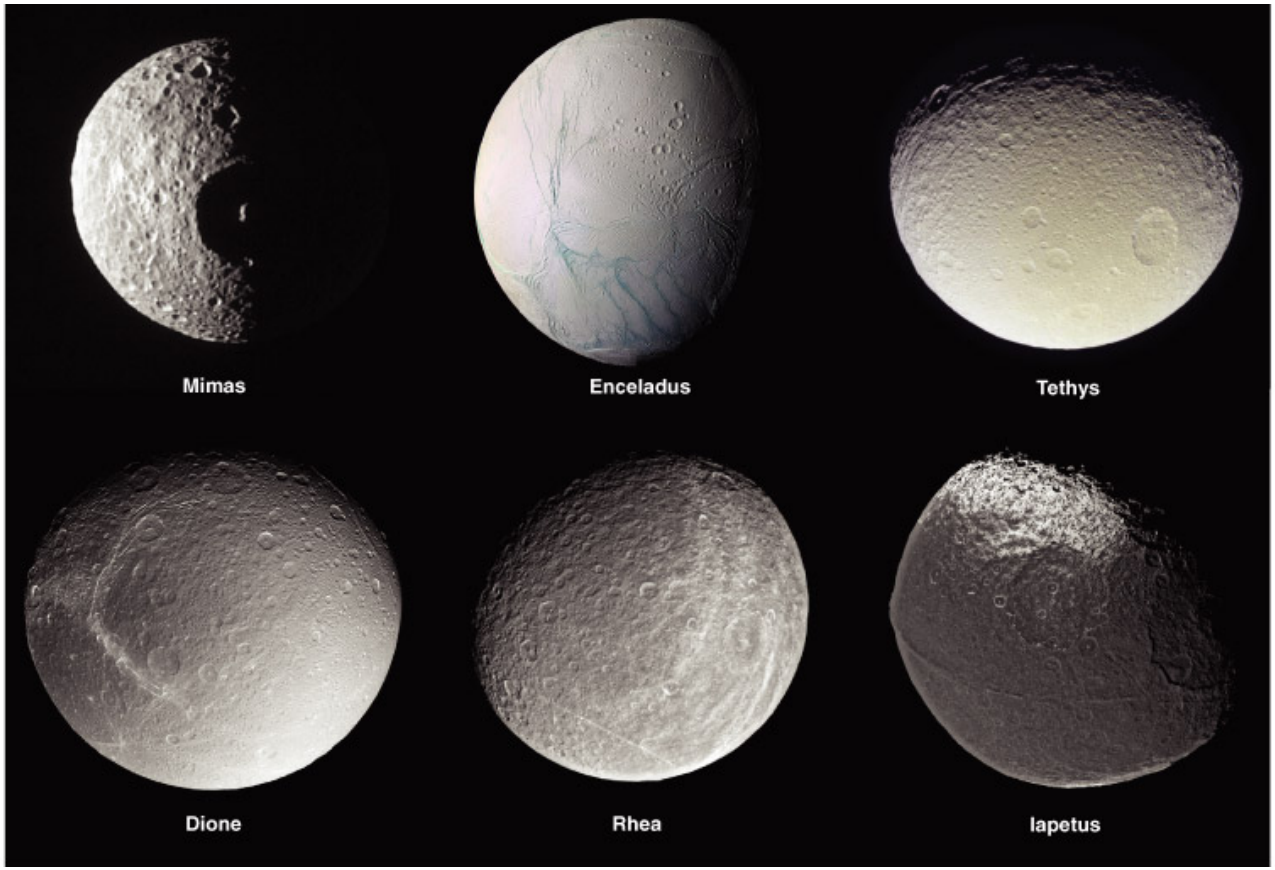
Figure 13-26
Universe, Tenth Edition
NASA/JPL; Cornell University

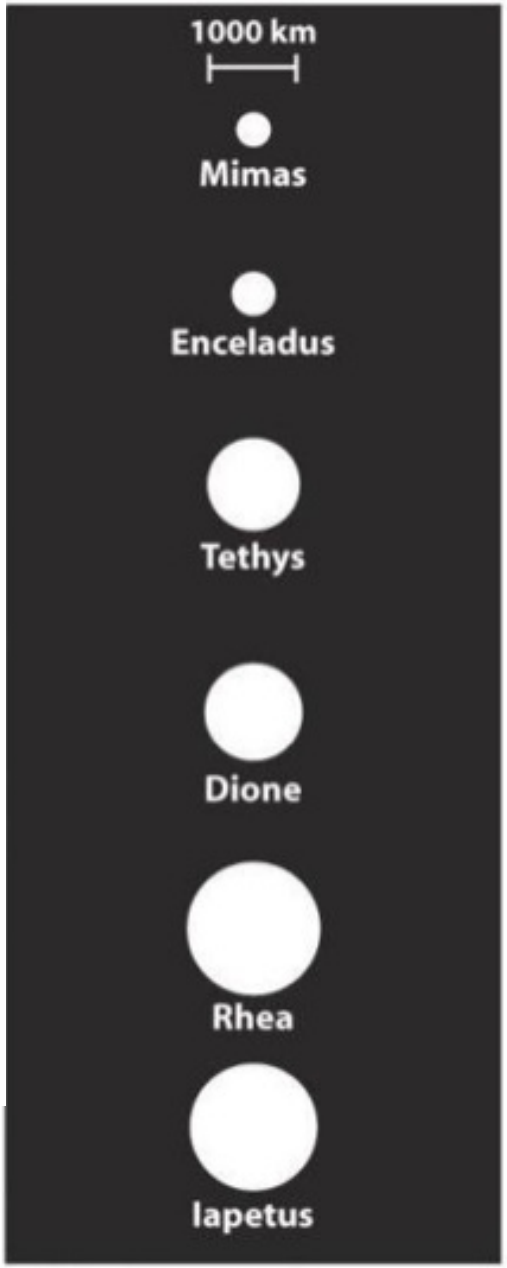
- 4 inner in regular orbits
- 59 outer in inclined retrograde orbits: captured asteroids

Saturn has many small satellites that have different origins

- 55 small
  - Some in close regular orbits: remnants of collisions?
  - Most in outer, inclined retrograde orbits: captured asteroids

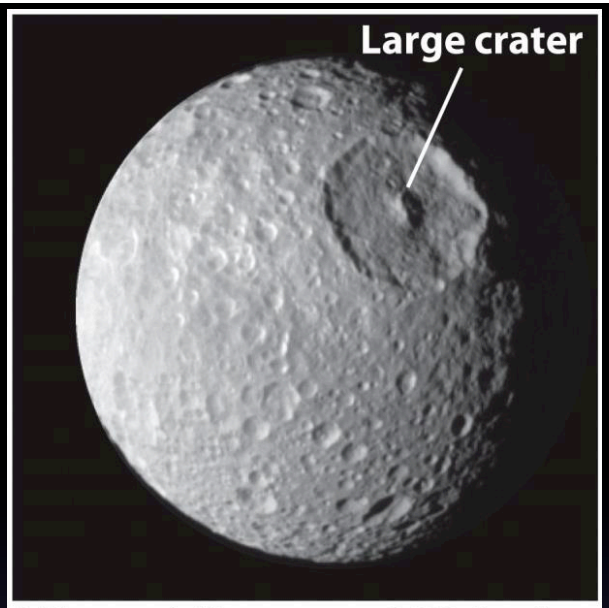
Medium Moons of Saturn





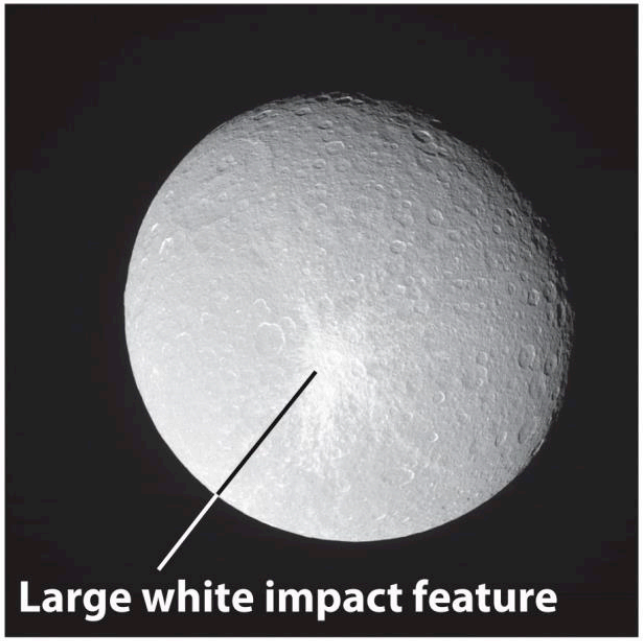
(g) Satellites to scale

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



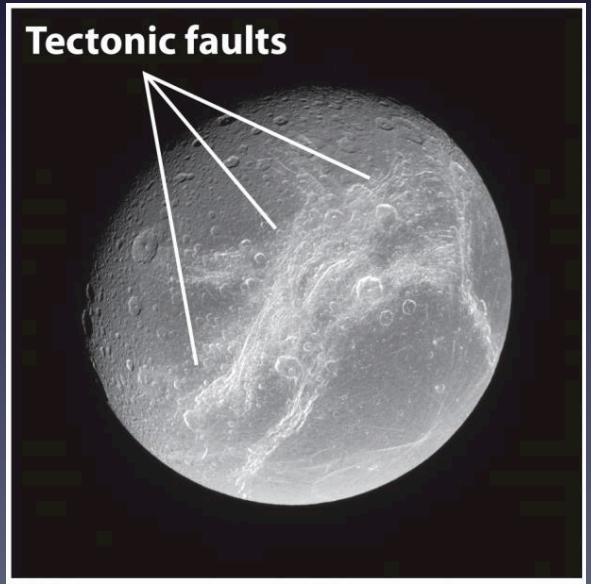
Mimas (diameter 392 km)

Figure 13-28a
Universe, Tenth Edition
NASA/JPL/Space Science Institute



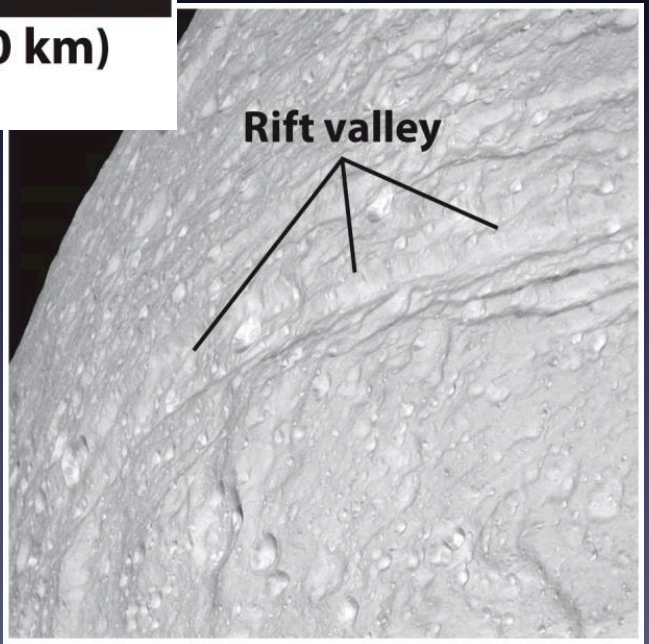
Rhea (diameter 1530 km)

Figure 13-28d
Universe, Tenth Edition
NASA/JPL/Space Science Institute



Dione (diameter 1120 km)

Figure 13-28c
Universe, Tenth Edition
NASA/JPL/Space Science Institute



Tethys (diameter 1060 km)

Figure 13-28b
Universe, Tenth Edition
NASA/JPL/Space Science Institute

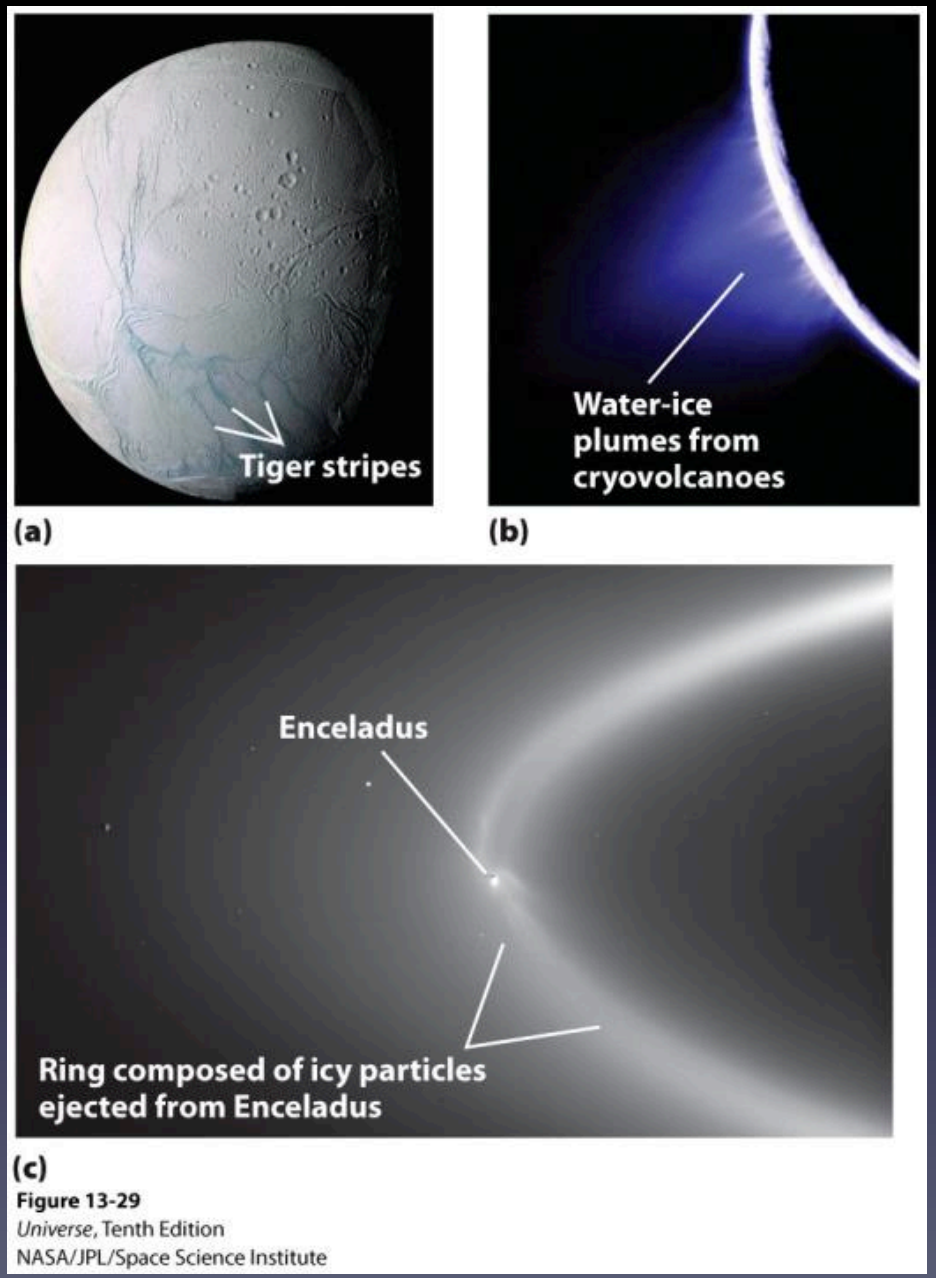
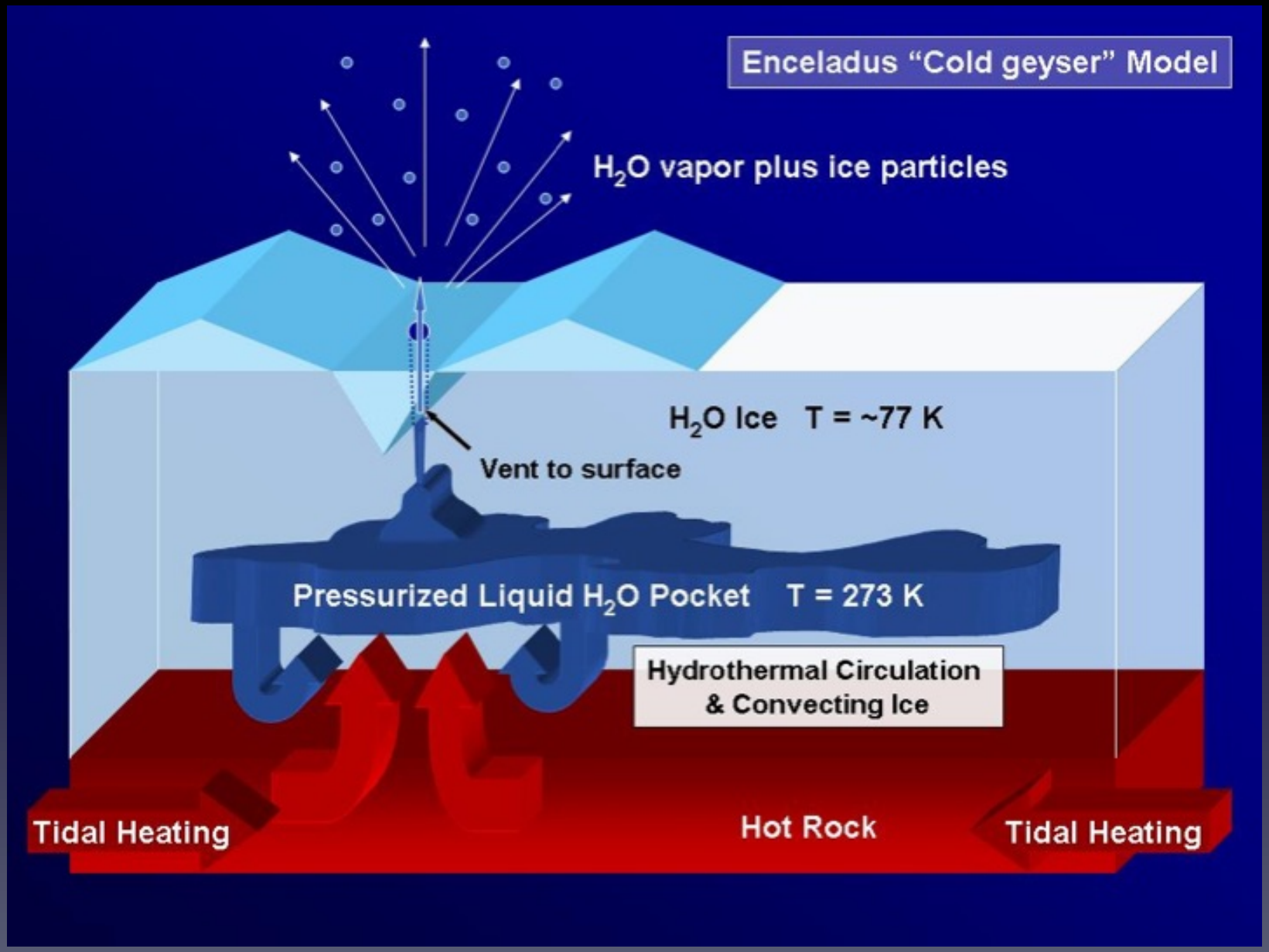


Figure 13-29
Universe, Tenth Edition
NASA/JPL/Space Science Institute

Cryovolcanoes on Enceladus


Enceladus "Cold geyser" Model
H_2O vapor plus ice particles
H_2O Ice T = ~77 K
Vent to surface
Pressurized Liquid H_2O Pocket T = 273 K
Hydrothermal Circulation & Convecting Ice
Tidal Heating
Hot Rock
Tidal Heating

Water plume from Enceladus

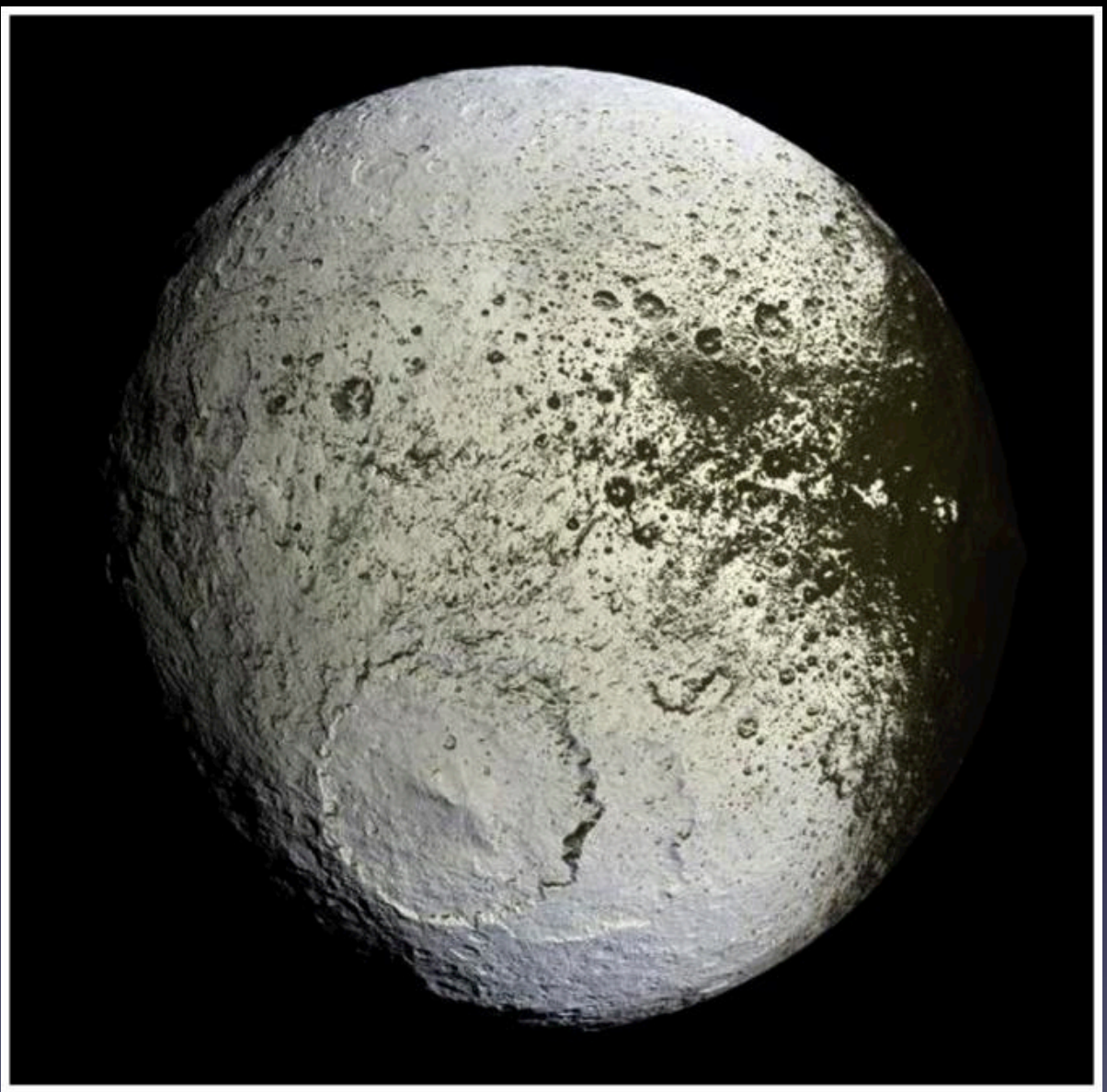


Figure 13-30a
Universe, Tenth Edition
NASA/JPL/Space Science Institute

The Two Faces of Iapetus

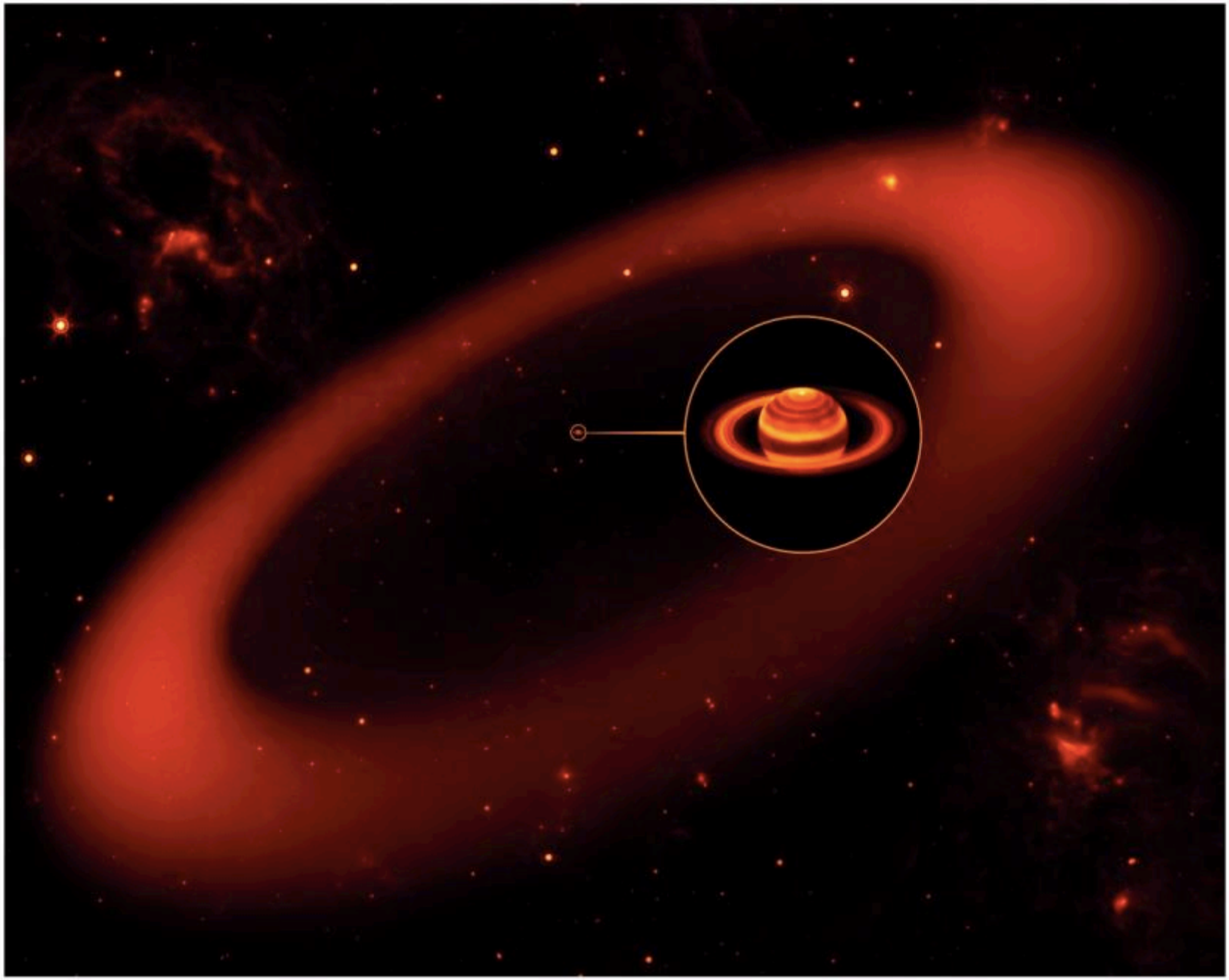


Figure 13-30b
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Key Ideas

- **Nature of the Galilean Satellites:** The four Galilean satellites orbit Jupiter in the plane of its equator. All are in synchronous rotation.
- The orbital periods of the three innermost Galilean satellites, Io, Europa, and Ganymede, are in the ration 1:2:4. This forms an orbital resonance.
- The two innermost Galilean satellites, Io and Europa, have roughly the same size and density as our Moon. They are composed principally of rocky material. The two outermost Galilean satellites, Ganymede and Callisto, are roughly the size of Mercury. Lower in density than either the Moon or Mercury, they are made of roughly equal parts ice and rock.
- The Galilean satellites probably formed in a similar fashion to our solar system but on a smaller scale.

Key Ideas

- **Io:** Io is covered with a colorful layer of sulfur compounds deposited by frequent explosive eruptions from volcanic vents. These eruptions resemble terrestrial geysers.
- The energy to heat Io's interior and produce the satellite's volcanic activity comes from tidal forces that flex the satellite. This tidal flexing is aided by an orbital resonance: the 1:2:4 ratio of orbital periods among the inner three Galilean satellites.
- The Io torus is a ring of electrically charged particles circling Jupiter at the distance of Io's orbit.
- When Jupiter's magnetic field sweeps over the Galilean satellites, it induces electric currents, which in turn, create and induced magnetic field.

Key Ideas

- **Europa:** While composed primarily of rock, Europa is covered with a smooth layer of water ice.
- The surface has hardly any craters, indicating a geologically active history. Other indications are a worldwide network of long cracks and ice rafts that indicate a subsurface layer of liquid water or soft ice. As for Io, tidal heating is responsible for Europa's internal heat.
- There is probably an ocean beneath Europa's frozen surface. Minerals dissolved in this ocean may explain Europa's induced magnetic field.

Key Ideas

- **Ganymede:** Two types of terrain are found on the icy surface of Ganymede: areas of dark, ancient, heavily cratered surface and regions of heavily grooved, lighter-colored, younger terrain.
- Ganymede is highly differentiated, and probably has a metallic core. It has a surprisingly strong magnetic field and a magnetosphere of its own.
- While there is at present little tidal heating of Ganymede, it may have been heated in this fashion in the past. An induced magnetic field suggests that it, too, has a layer of liquid water beneath the surface.

Key Ideas

- **Callisto:** Callisto has a heavily cratered crust of water ice. The surface shows little sign of geologic activity, because there was never any significant tidal heating of Callisto. However, some unknown processes have erased the smallest craters and blanketed the surface with a dark, dusty substance.
- Magnetic field data seem to suggest that Callisto has a shallow subsurface ocean.

Key Ideas

- **Titan:** The largest Saturnian satellite, Titan, is a terrestrial world with a dense nitrogen atmosphere and an important 5 percent methane. Temperatures and pressures on Titan are near the point where methane can be found in a solid, liquid, or gas phase.
- Titan shows evidence for flooding expected from methane rain, and many lakes near its north pole. Methane appears to work in a cycle similar to water in Earth's hydrological cycle

Key Ideas

- **Other Satellites:** As of 2012, Jupiter has a total of 67 confirmed satellites and Saturn has a total of 62.
- Beyond the Galilean satellites, Jupiter has many small satellites that move in much larger orbits that are noticeably inclined to the plane of Jupiter's equator. Many of these orbit in the direction opposite to Jupiter's rotation. These do not appear to have formed with Jupiter, and are thought to be captured asteroids.

Key Ideas

- In addition to Titan, six moderate-sized moons circle Saturn in regular orbits: Mimas, Enceladus, Tethys, Dione, Rhea, and Iapetus. They are probably composed largely of ice, but their surface features and histories vary significantly. The other, smaller moons include shepherd satellites that control the shapes of Saturn's rings and captured asteroids in large retrograde orbits.
- Enceladus ejects plumes of water from a region near its south pole. Minerals detected in these plumes indicate a subsurface ocean in contact with a rocky mantle.