Astronomy

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Small 239

Office hours:

MTWR 10-11am

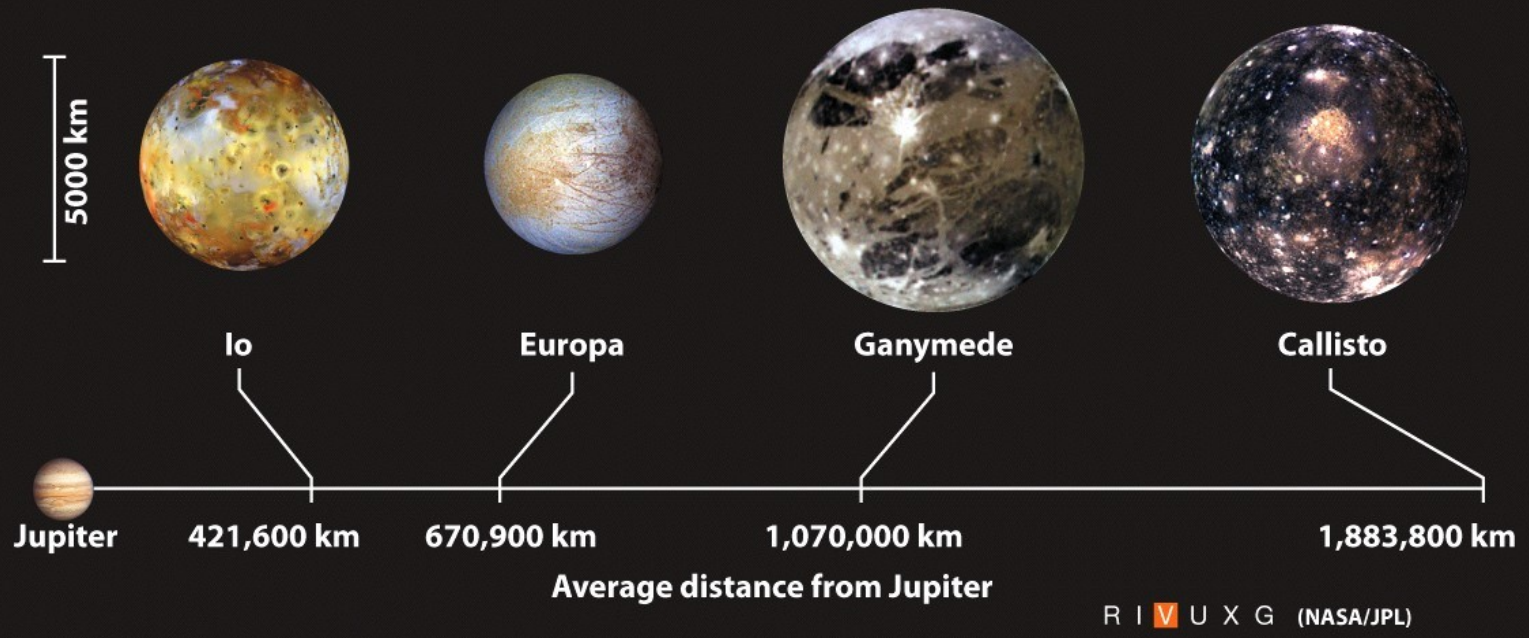
Satellites of Jupiter & Saturn

- Galilean satellites
- Similarities and differences among the Galilean satellites
- How the Galilean moons formed
- Io and volcanoes
- Io and Jupiter's magnetic field
- Oceans beneath Europa
- Geologic activity on Ganymede & Callisto
- Titan's thick atmosphere
- Jupiter's moons orbit the wrong way
- Volcanoes on Enceladus

Galilean Moons of Jupiter

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

Galilean Moons of Jupiter

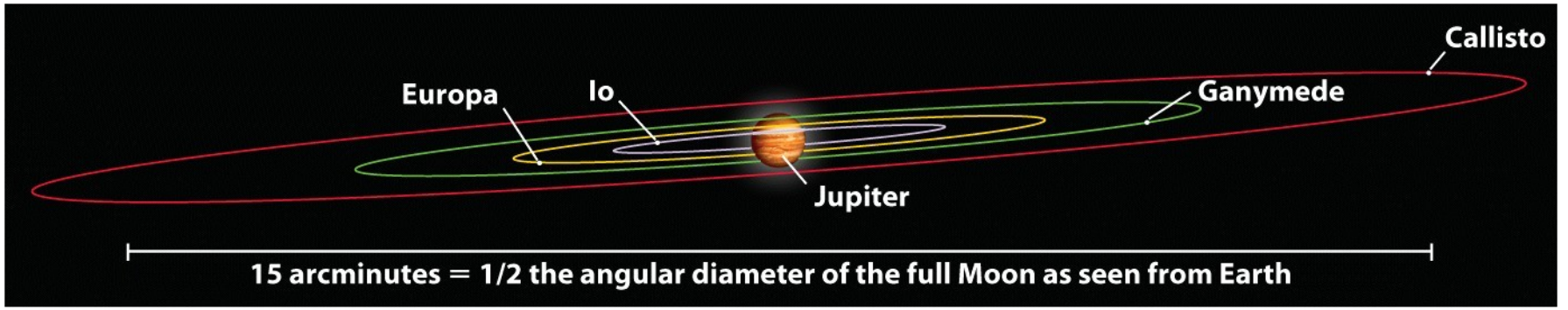


Figure 13-1
Universe, Tenth Edition

Galileo observed the inner large moons of Saturn in 1610. Galileo called them 'Medicean stars' ! All four orbit in the same plane around Jupiter's equator. Their orbital periods range from 1.8 days for Io to 16.7 days for Callisto.

The three inner Galilean moons are in synchronous rotation as they orbit Jupiter. Each rotates once as it orbits. The three inner moon's periods are in the ratio 1:2:4 because of gravitational force they exert on one another.

Transits, Eclipses and Occultations

Information about the Galilean moons was determined before spacecraft by observing transits, eclipses and occultations:

- A transit is when the moon passes between us and Jupiter.
- An eclipse is when the moon passes through Jupiter's shadow.
- An occultation is when the moon passes behind Jupiter.

An eclipse can be used to determine the diameter of the moon. When the moon starts to appear from Jupiter's shadow, timing interval for it to completely re-appear and knowing the orbital velocity (Kepler's law) give the diameter of the moon.

Spacecraft Data on the Galilean Moons

The first spacecrafts to flyby Jupiter were Pioneer 10 and 11 in 1973 and 1975. Much more information was gathered by the flyby missions of Voyager 1 and 2 in 1979 In 1995, the Galileo probe entered orbit around Jupiter. The Galileo mission also dropped a probe into the atmosphere. Cassini and New Horizons also did flybys on there way to out regions of the solar system.

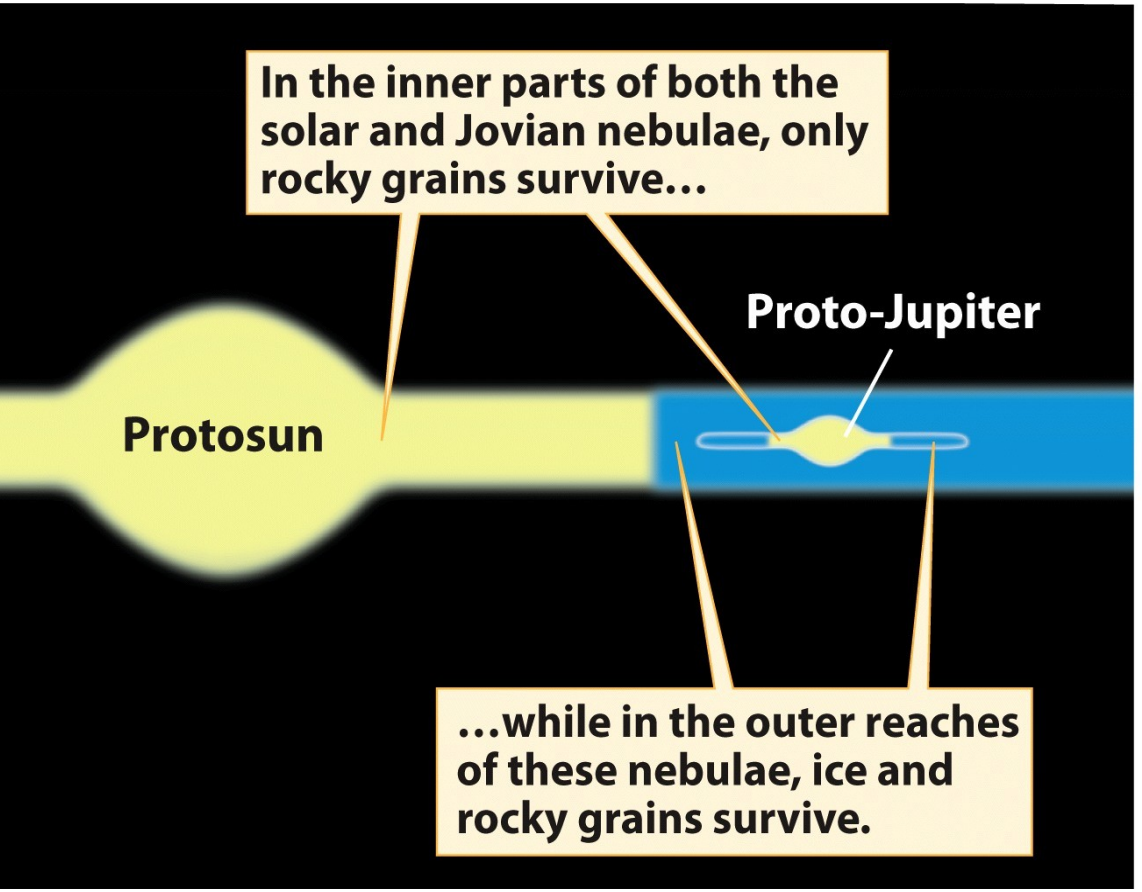
By careful measuring the gravitational deflection of the space probes as they approached the Galilean moons. the mass of the Galilean moons could be determined. This allowed the density of the moons to be determined (ρ = mass/volume). Ganymede and Callisto have densities of < 2000 kg/m^3. Io has a density of 3529 kg/m^3 while Europa has a density of 3018 kg/m^3

Spacecraft Data on the Galilean Moons

Because the density of Ganymede and Callisto are so small, they can not be primarily rock ($\rho_{moon} = 3344\ kg/m^3$)
Both are roughly equal parts of rock and ice.

With their higher density the inner moons (Io and Europa) are mostly rocky like the crust of the Earth. Spectroscopic data shows water ice on Ganymede, Callisto and Europa.
Io shows not evidence of water-ice.
Europa is primarily rocky with a water ice in the outer regions.

A Miniature Solar System



gure 13-3
niverse, Tenth Edition
2014 W. H. Freeman and Company

The Galilean moons formed like the planets formed around the Sun. Jupiter formed in a 'Jovian nebula'. Because Jupiter is so large the conversion of gravitational energy (Kelvin Helmholtz contraction) the region around Jupiter was warm. The higher temperatures near Jupiter allowed only rocky material to condense to form Io and Europa. Further out, ice could be retained and incorporated into Ganymede and Callisto. Jupiter can be considered a 'failed star'. It would have to be 80 times larger to have started the fusion process.

Io

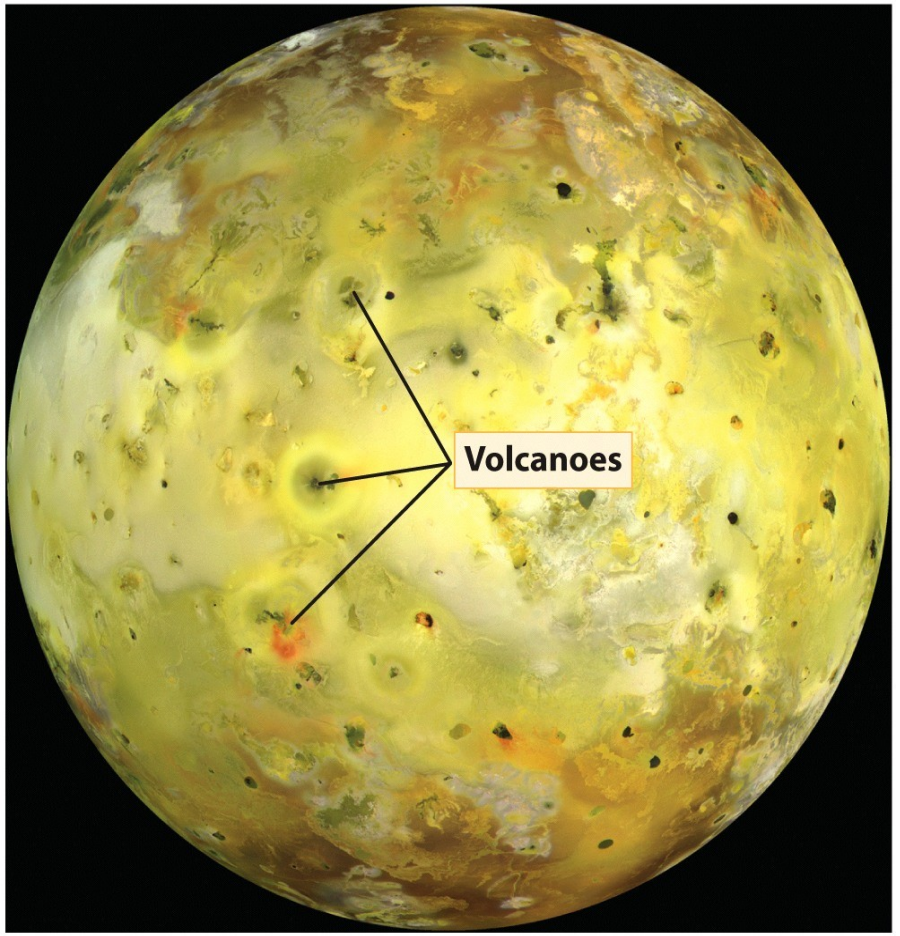
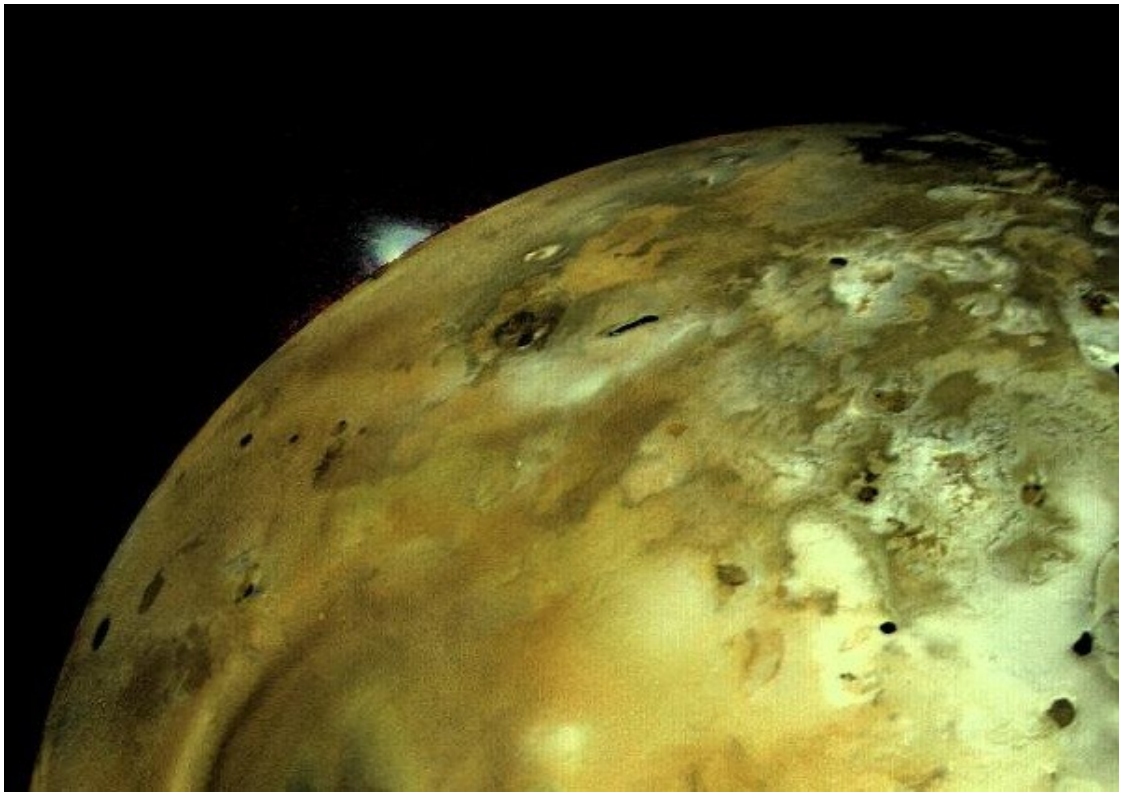


Figure 13-4a
Universe, Tenth Edition
JPL/NASA

Io is one of the most interesting objects in the solar system. The moon nearest to Jupiter is covered with sulfur and has very active volcanoes. We would expect it to be like the Earth's moon but it is geologically active. The tidal forces from Jupiter and the outer Galilean moons (1:2:4 resonance orbits) causes large tidal heating of Io. The tidal heating is about 2.5 W/m^2 (10^{14} watts total).

Io



When Voyager I flew by Jupiter in 1979, Volcanoes were almost completely unexpected. The images from Voyager showed 8 active volcanoes. If fact three scientist (Peale, Cassen and Reynolds) had publish a paper shortly before the flyby predicting the large tidal heating on Io and the possibility of volcanoes on Io.

Io

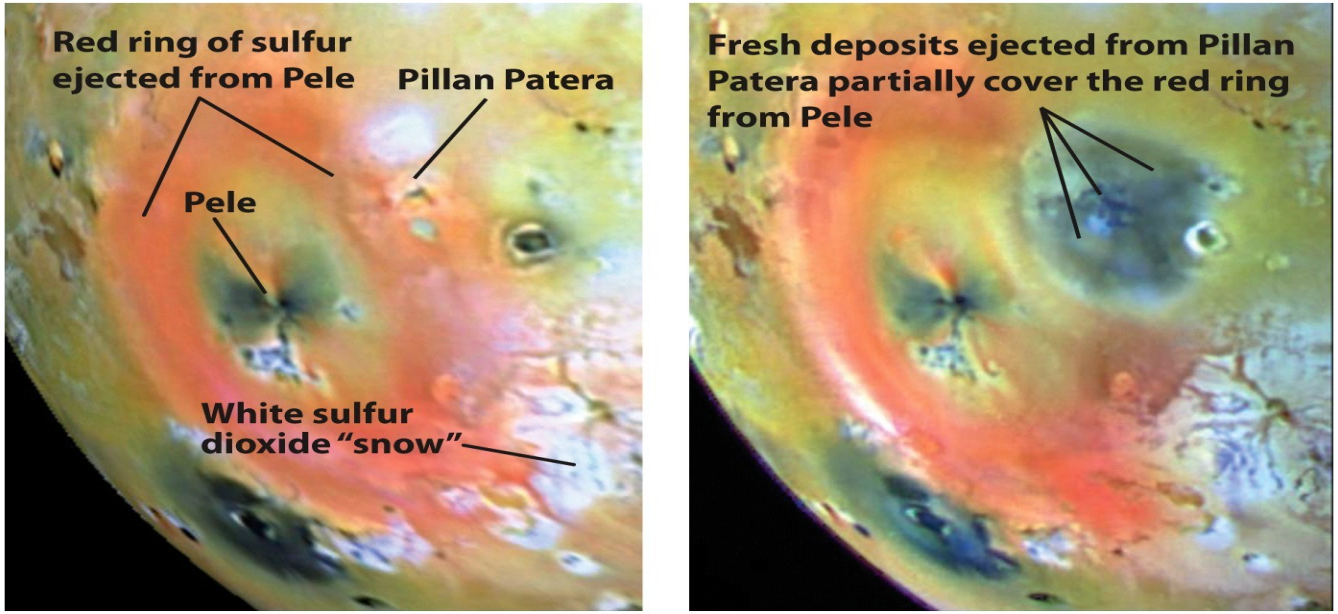


Figure 13-6
Universe, Tenth Edition
NASA/JPL

Voyager's spectrometers showed the plumes were mainly sulfur and SO_2. SO_2 is normally solid at the cold temperatures on Io. But under the surface where is is hot, the SO_2 turns to gas and explosively erupts at up to 1000 m/s. Io's volcanoes are more like geysers than volcanoes. The changing colors are due to the sulfur. When heated and then cooled yellow sulfur can range in color from red to orange and black. The white areas are solid SO_2 ('snow').

Io

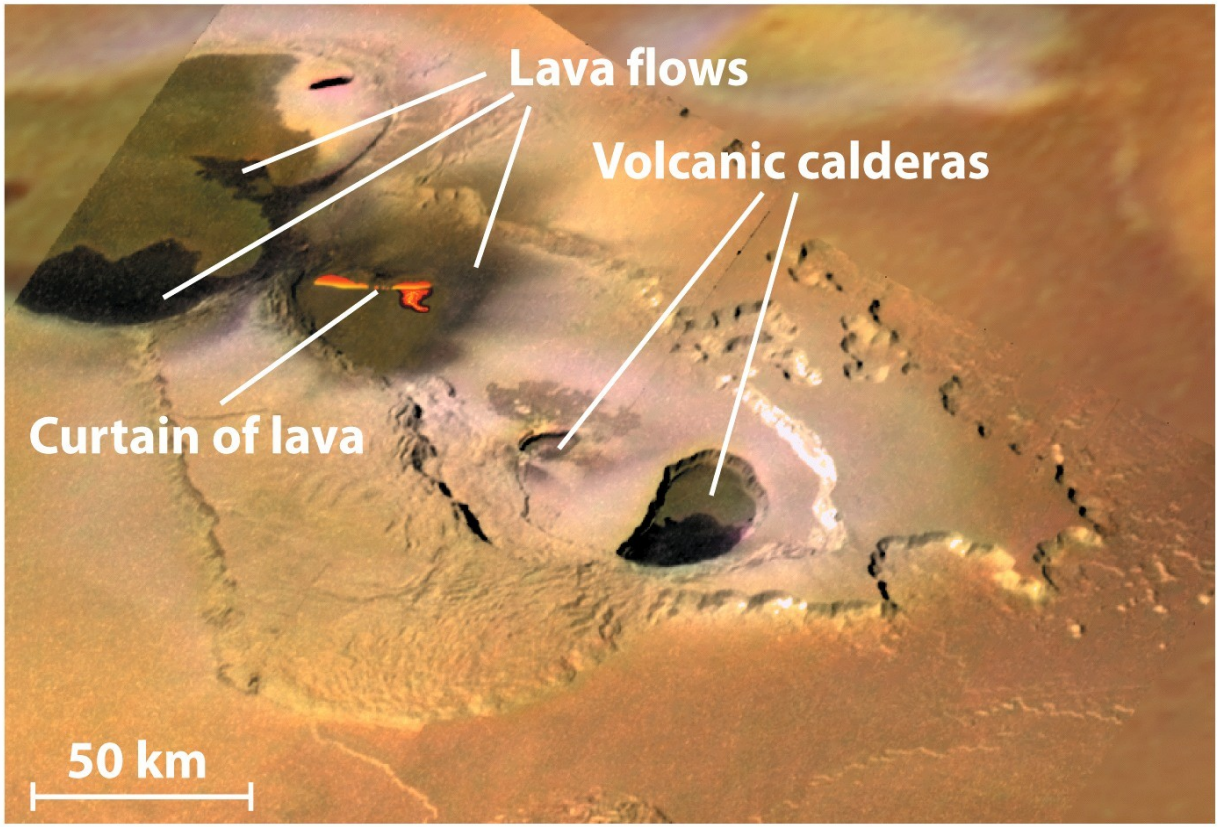


Figure 13-7
Universe, Tenth Edition
University of Arizona/JPL/NASA

Io's volcanic vents cover 5% of the moon. The temperature of the vents indicate there is also lava of molten iron and magnesium since the temperature is very high (1700-1200^{o} C). This is too high for sulfur or even silicates like lava on Earth. This image show a curtain of extremely hot lava. The crust of Io may only be 100 km thick floating on an 'ocean' of liquid magma. This may explain the volcanic activity observed over the entire moon. The volcanoes observed by Voyager are still active today.

Jupiter's Magnetosphere and Current on Io

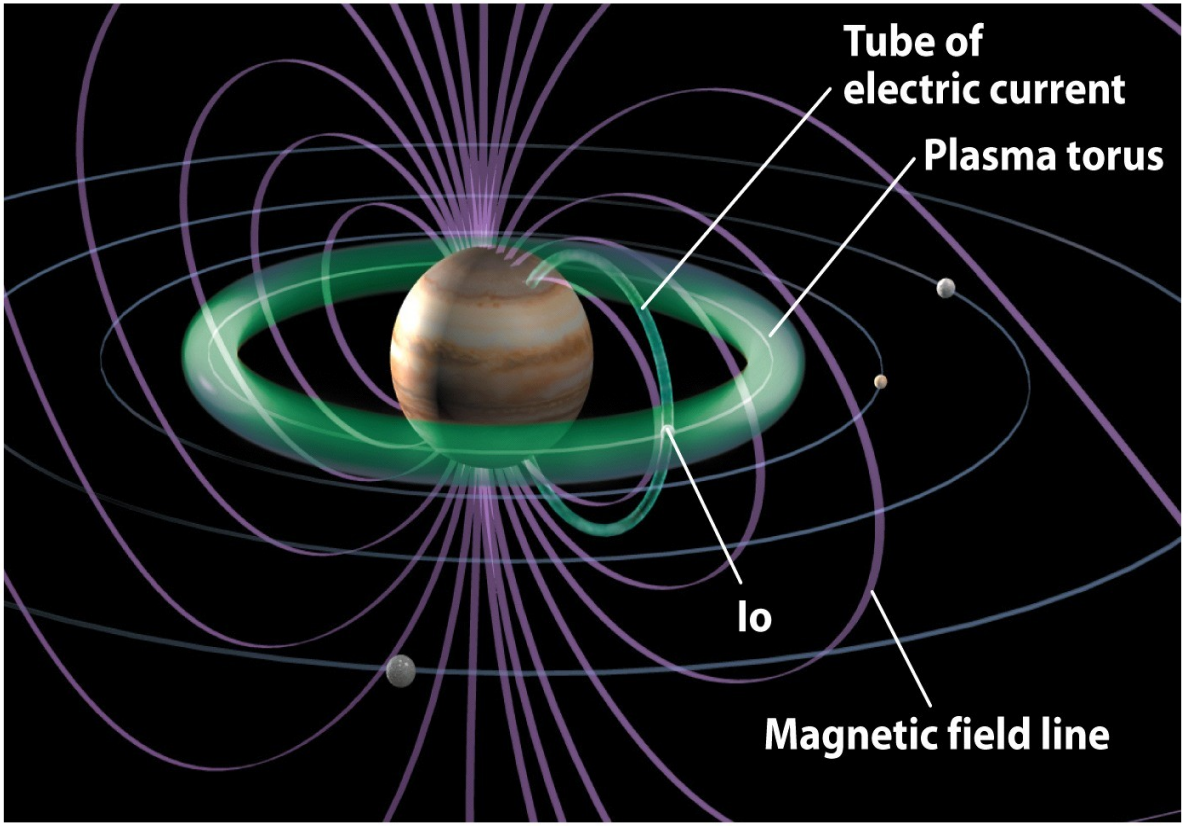


Figure 13-9b
Universe, Tenth Edition
Alfred T. Kamajian and Torrence V. Johnson, "The Galileo Mission to Jupiter and Its Moons," *Scientific American*, February 2000, p. 44

The main source of ions in the inner 'Van Allen' type belt around Jupiter is material from Io. This torus (donut) ring around Jupiter is a plasm ring (ionized material) at the radius of Io's orbit. As Jupiter's magnetic field rotates

It produces (induces) a voltage of 400,000 volts across Io causing a current of 5×10^6 amperes to flow through Io.

Europa

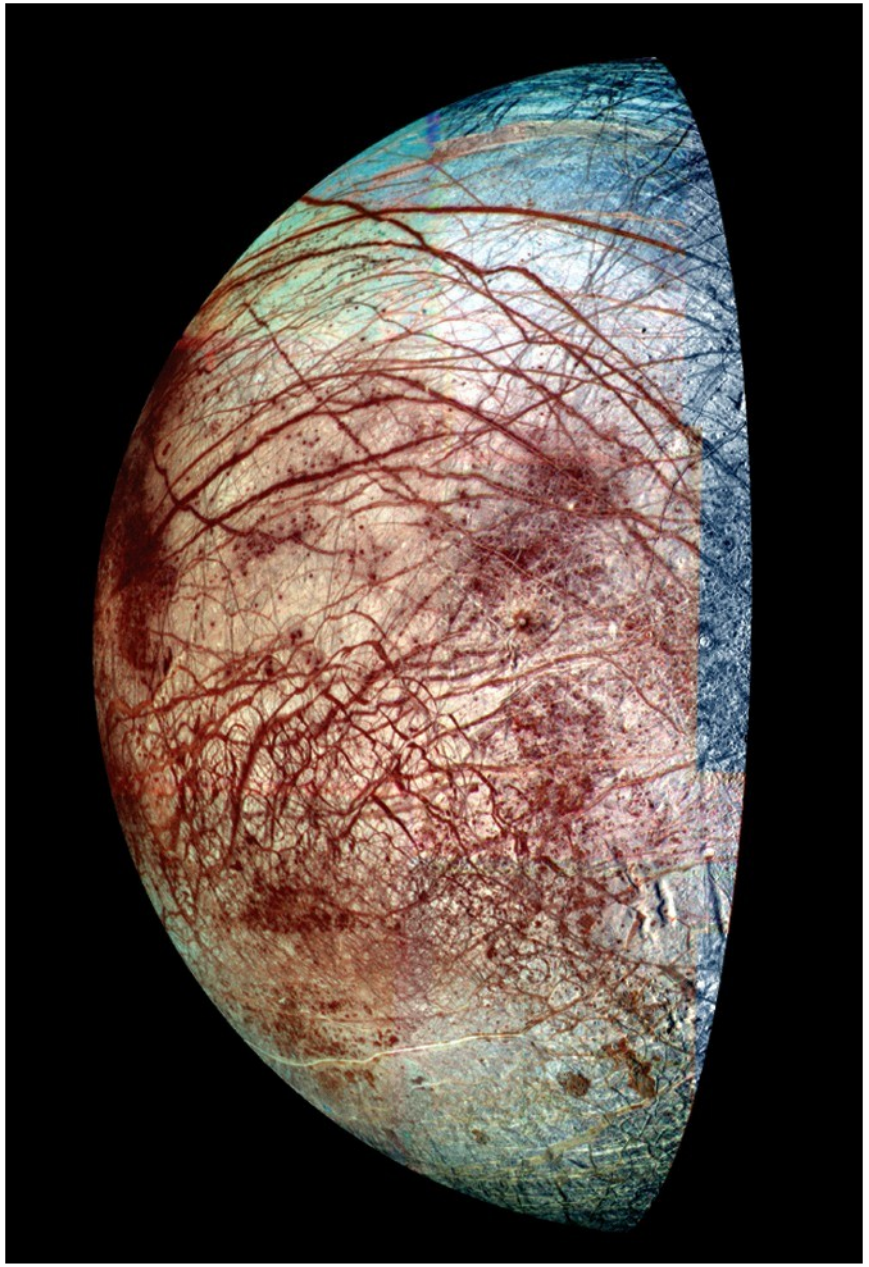


Figure 13-10
Universe, Tenth Edition
NASA/JPL/University of Arizona

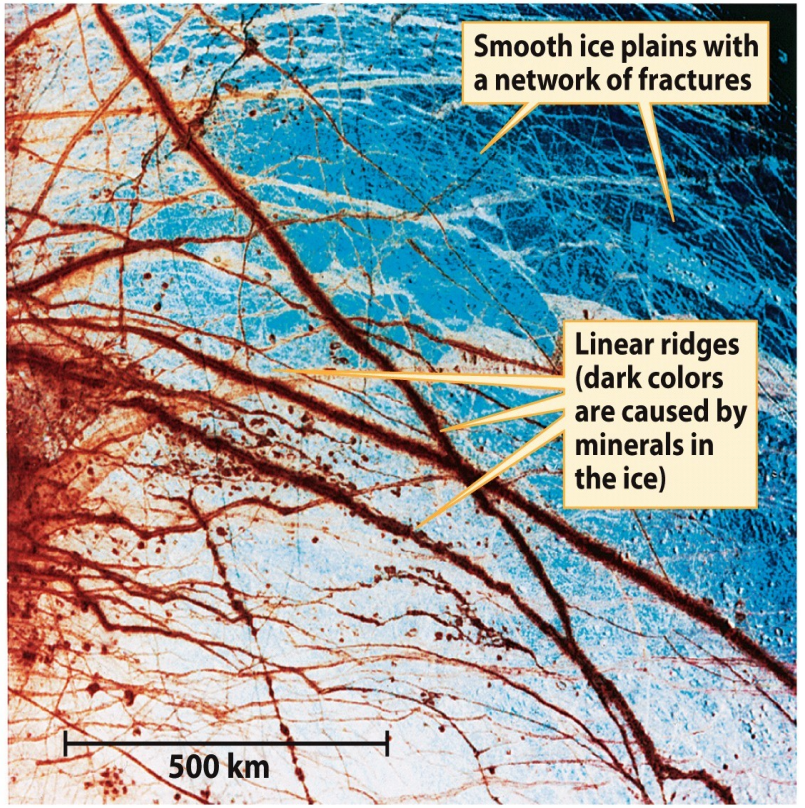
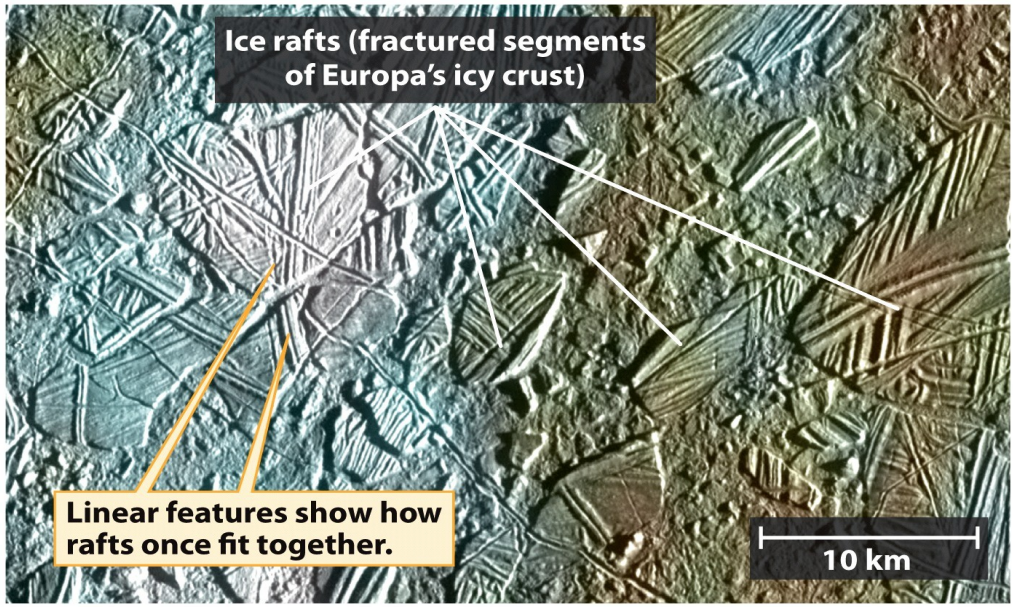


Figure 13-11
Universe, Tenth Edition
NASA/JPL

Europa is the second Galilean Moon of Jupiter and the smoothest object in the solar system (no mountains). Europa has a global network of strips and cracks.

Europa



Ice rafts on Europa

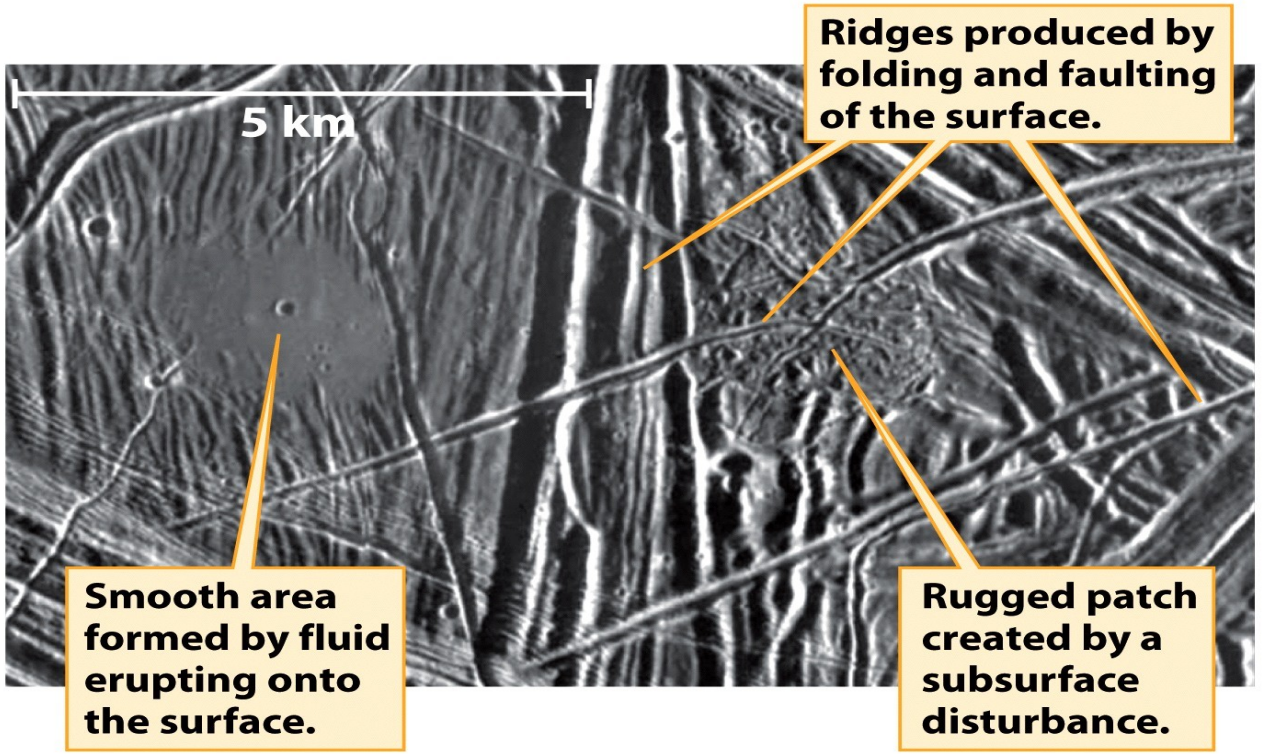
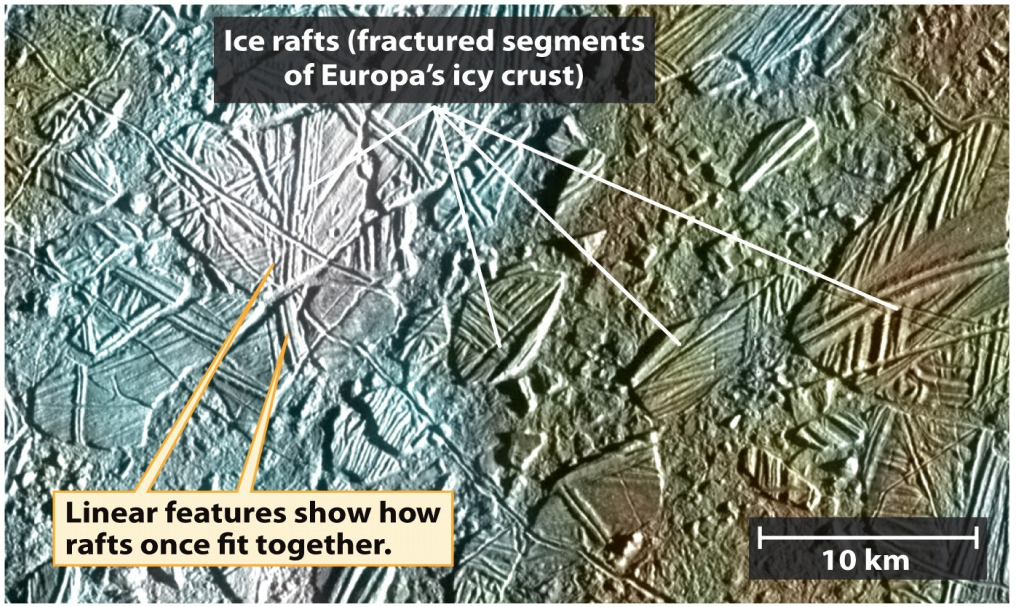


Figure 13-12
Universe, Tenth Edition

Europa is the smallest of the Galilean moons and did not retain as much heat. Spectroscopic data shows the surface of Europa is almost pure ice. The density of Europa (3018 kg/m^3) implies Europa is not a ball of ice but must have a rocky core that accounts for 85-90% of its mass. Tidal heat has forced the water to the surface where it froze into ice.

Europa



Ice rafts on Europa

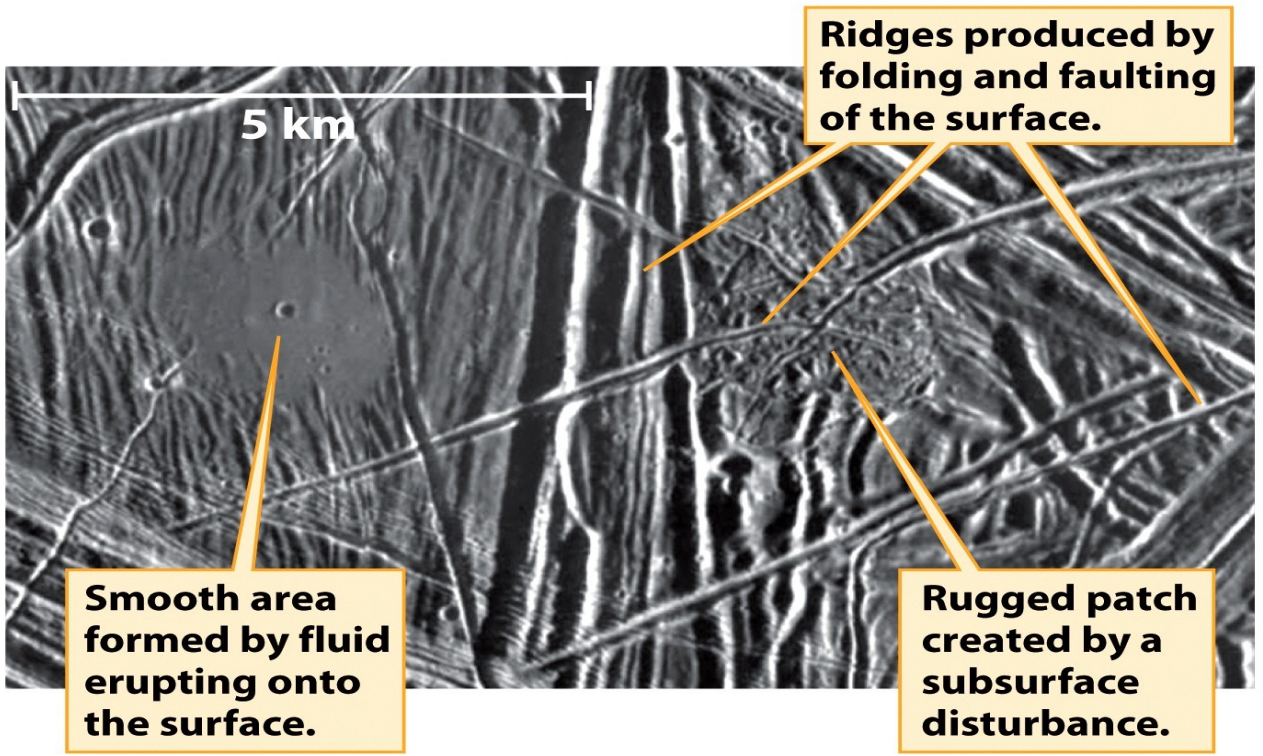


Figure 13-12
Universe, Tenth Edition

The structure of the surface of Europa is similar to ice floes and 'ice rafts' that are seen on earth. The ridges and cracks are caused by tidal stresses on the moon.

Europa's 'Underground' Ocean

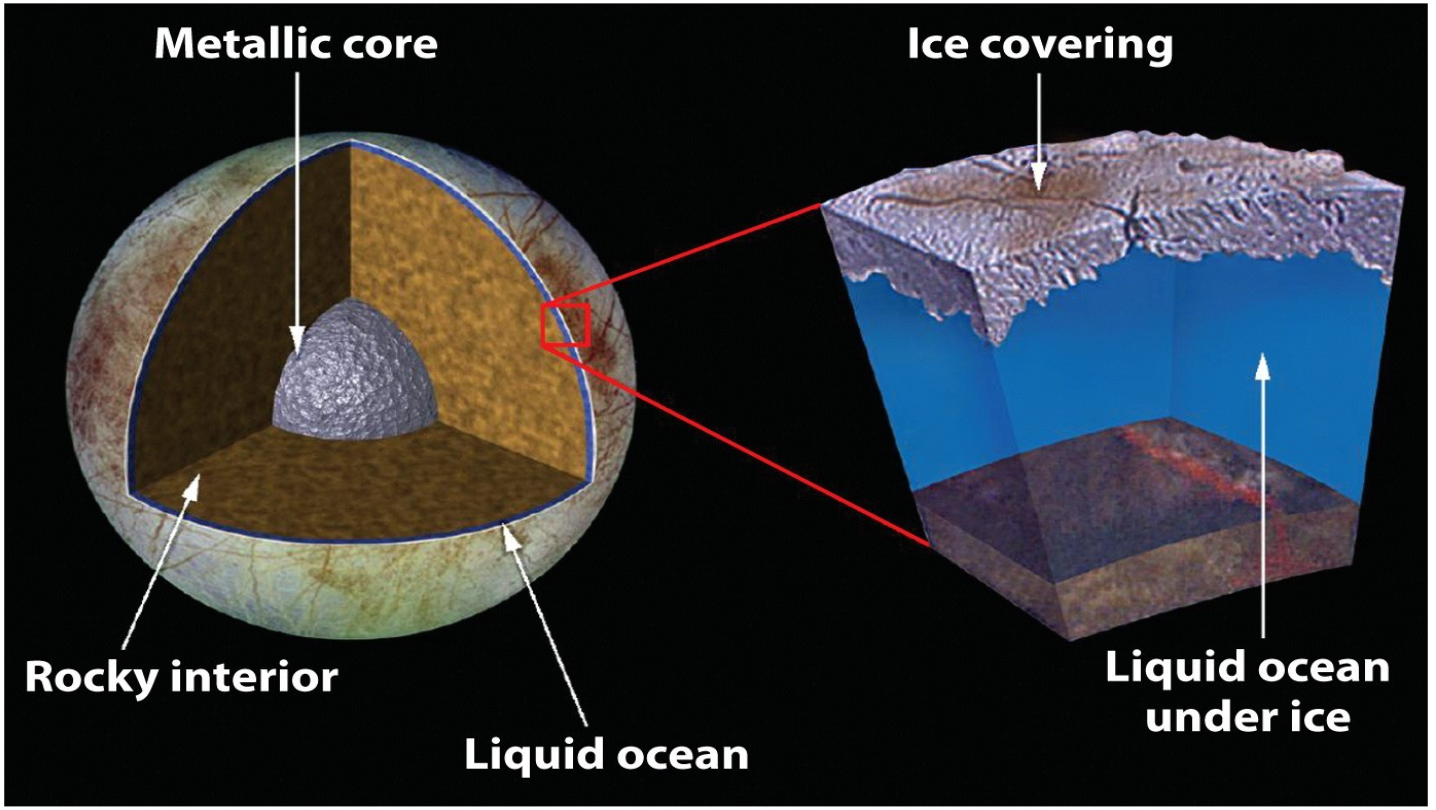


Figure 13-14
Universe, Tenth Edition
NASA/JPL

The Galileo orbiter magnetic field data show Europa does not have a steady magnetic field. Instead, inducted currents from Europa's motion through Jupiter's magnetic field produce currents in a subsurface 'ocean' of liquid salt water. This current produce a changing magnetic field around Europa.

Europa's 'Underground' Ocean

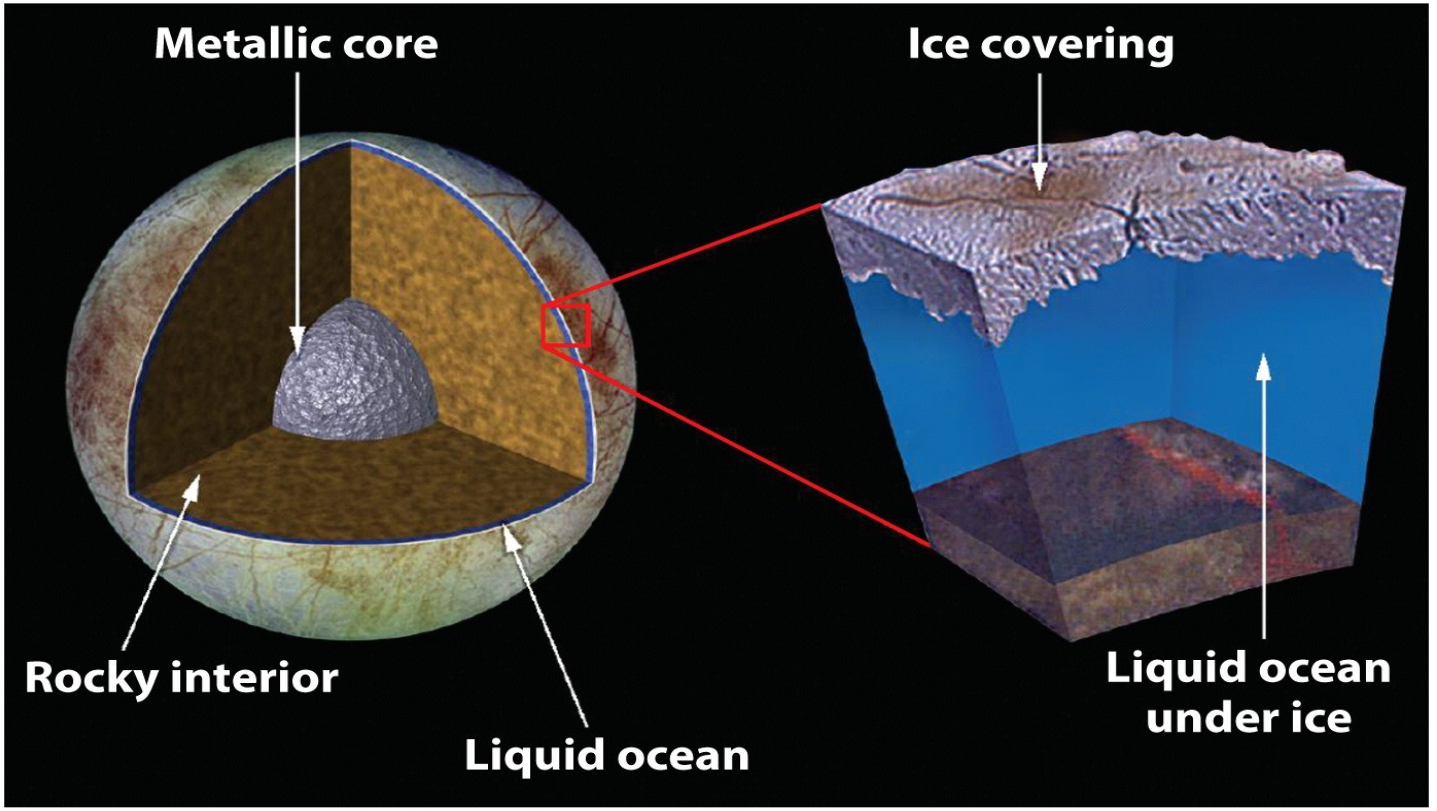


Figure 13-14
Universe, Tenth Edition
NASA/JPL

Europa's ocean of liquid water could be a place that supports life. The relatively warm liquid water with minerals and organic material is a place where microbial could evolve. When the Galileo mission ended in 2003, the orbiter was sent into Jupiter's atmosphere to avoid any possible contamination of Europa.

Ganymede

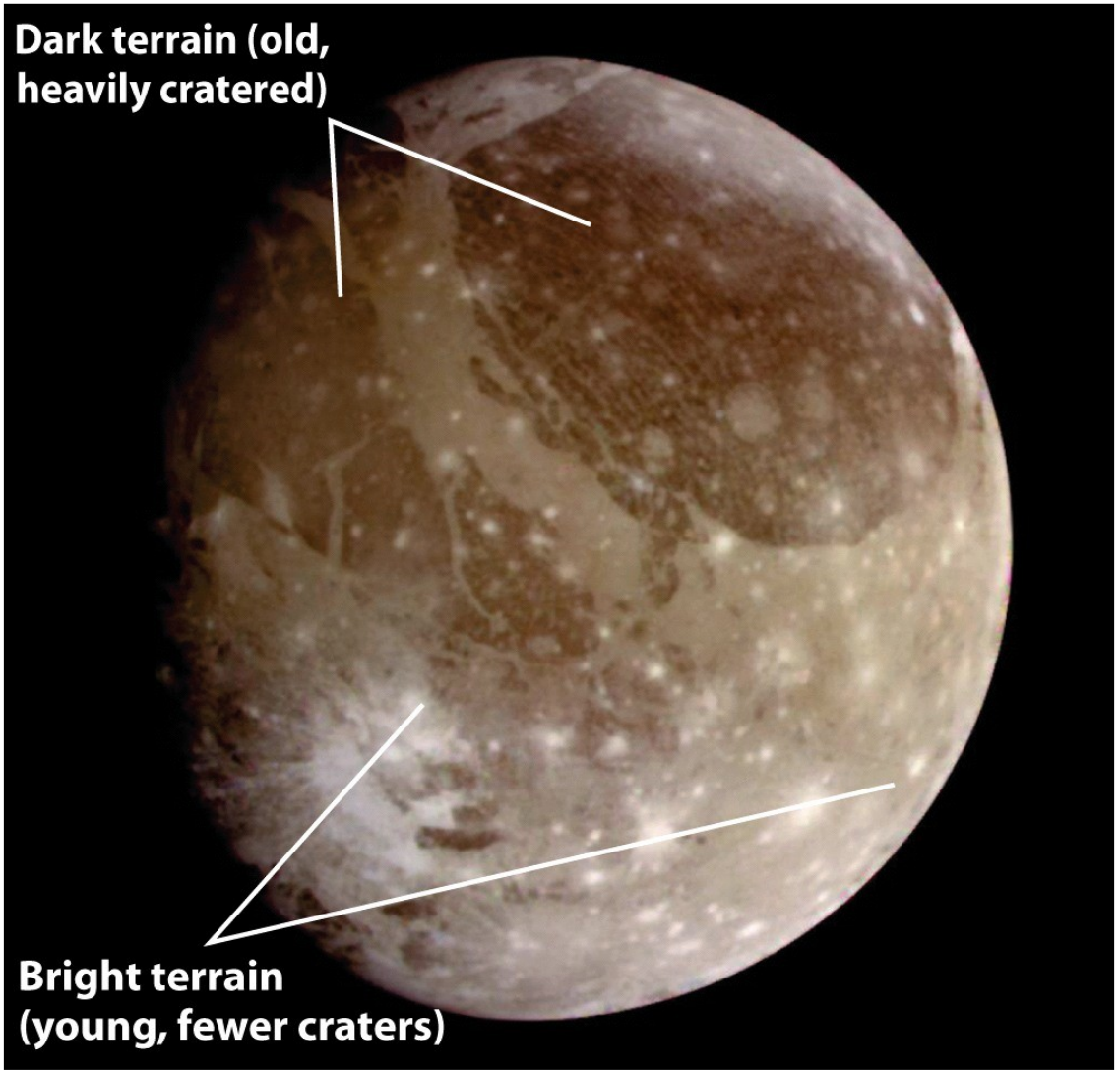


Figure 13-15
Universe, Tenth Edition
NASA/JPL

Ganymede is the largest moon in the solar system and even larger than Mercury. It is cratered like our Moon but the craters are ice and not rock. Like our moon it has two distinct terrains. The darker areas are heavily cratered and older. The light areas are younger with fewer craters. The light area crates have rays surrounding the impact site that are exposed ice

Ganymede

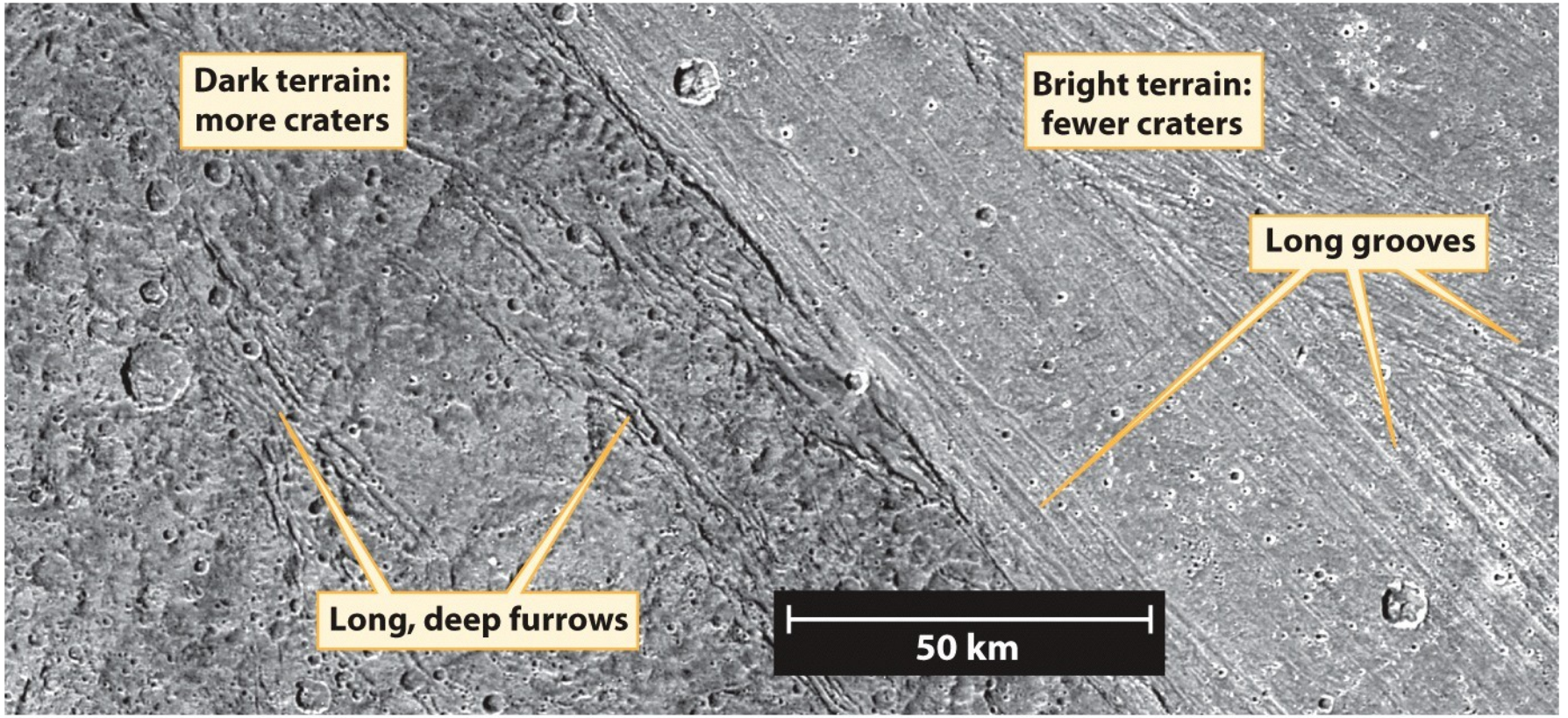


Figure 13-16
Universe, Tenth Edition
NASA

This Galileo image shows the difference between the darker areas (left) and the light areas (right). The dark area is heavily cratered. Note the linear features (furrows) in both the dark and light areas. The furrows are due to ancient geological activity. The craters on the right indicate the light area is probably a billion years old.

Ganymede's Magnetic Field and Interior

Ganymede has a magnetic field that is twice as strong as Mercury. Ganymede even has a small magnetosphere. A dynamo effect must be causing the field which would indicate a differentiated electrically conducting liquid core. This would imply a a warm interior but the moon is too small to have retained much of the heat from it's formation. Tidal force heating would not be significant in Ganymede's current orbit. Has it been deflected to its current orbit from a more elliptical orbit?

Even more surprising is the fact that Ganymede's field varies as it moves through the magnetic field of Jupiter (induction like on Europa?) This would indicate a possible ocean beneath the surface.

Callisto

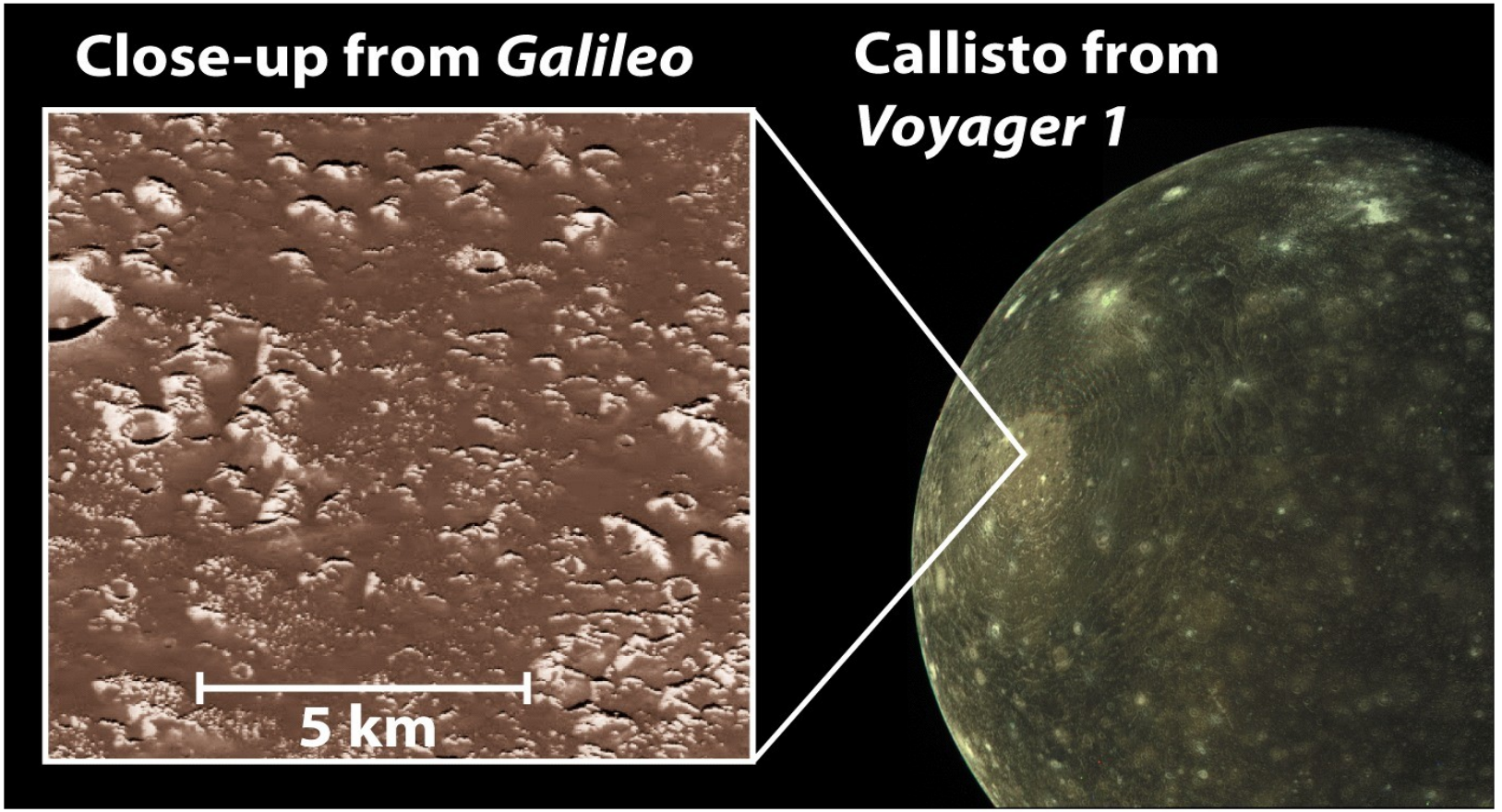


Figure 13-17
Universe, Tenth Edition
Arizona State University/JPL/NASA; right: JPL/NASA

Callisto's surface is heavily cratered but the surface is not as reflective as the other Galilean moons. The surface appears to be covered by a dark mineral deposit. There are few craters <1 km in diameter which may mean they have been eroded or covered by the dark mineral deposits.

Callisto's Interior

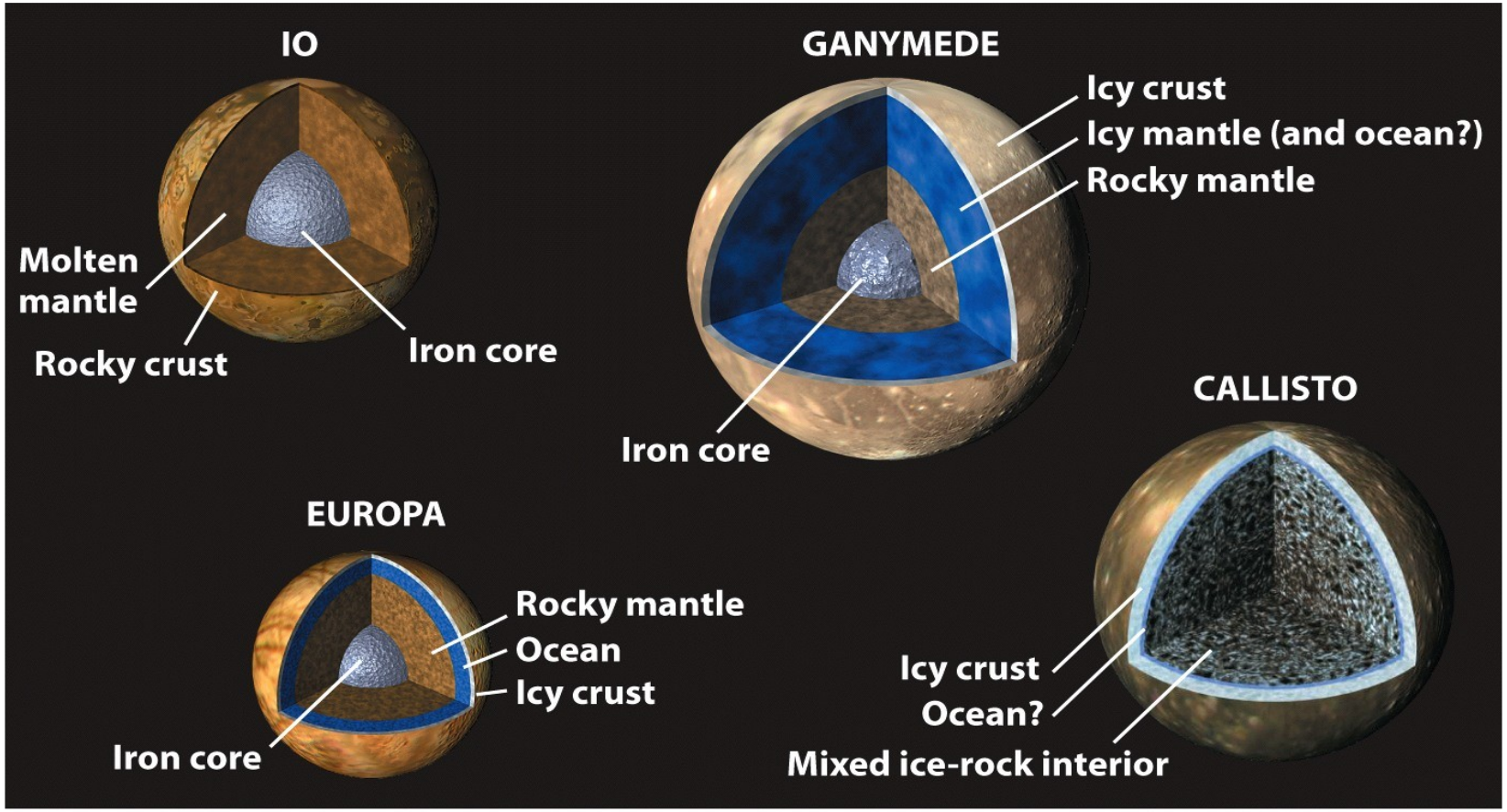


Figure 13-18
Universe, Tenth Edition
NASA/JPL

Callisto's interior is a bit of a mystery. It has a magnetic field that varies. Its interior is too cold for a liquid water ocean unless it has 'antifreeze' probably from NH_3.

Callisto is too small to have differentiated.

Saturn's Titan

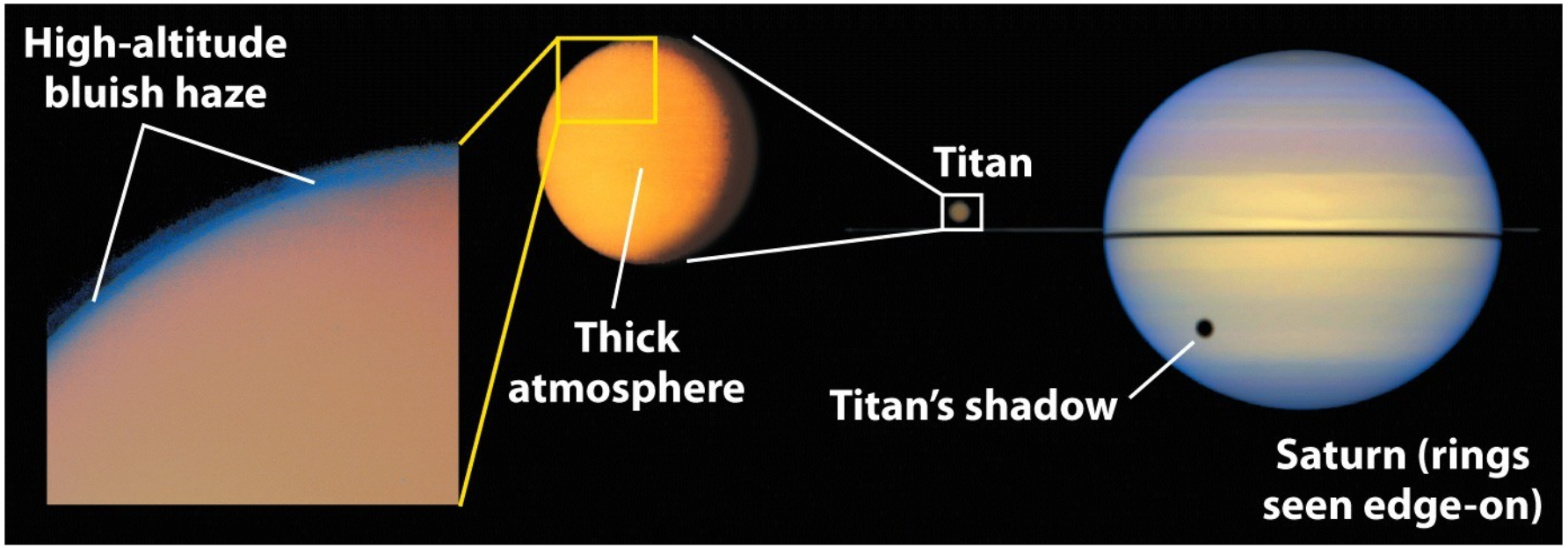


Figure 13-19
Universe, Tenth Edition
Left: JPL/NASA; center: NASA; right: Erich Karkoschka, LPL/STScI/NASA

Titan is the largest moon of Saturn. Titan is the only moon in the solar system with a substantial atmosphere. From Voyager spacecraft images, the moon appears featureless. The atmosphere is so thick the surface pressure is 1.5 times sea level pressure on Earth. It is 95% nitrogen possibly from comet impacts. 5% of the atmosphere is methane (CH_4).Its color is thought to be from hydrogen cyanide (HCN) chains.

Titan

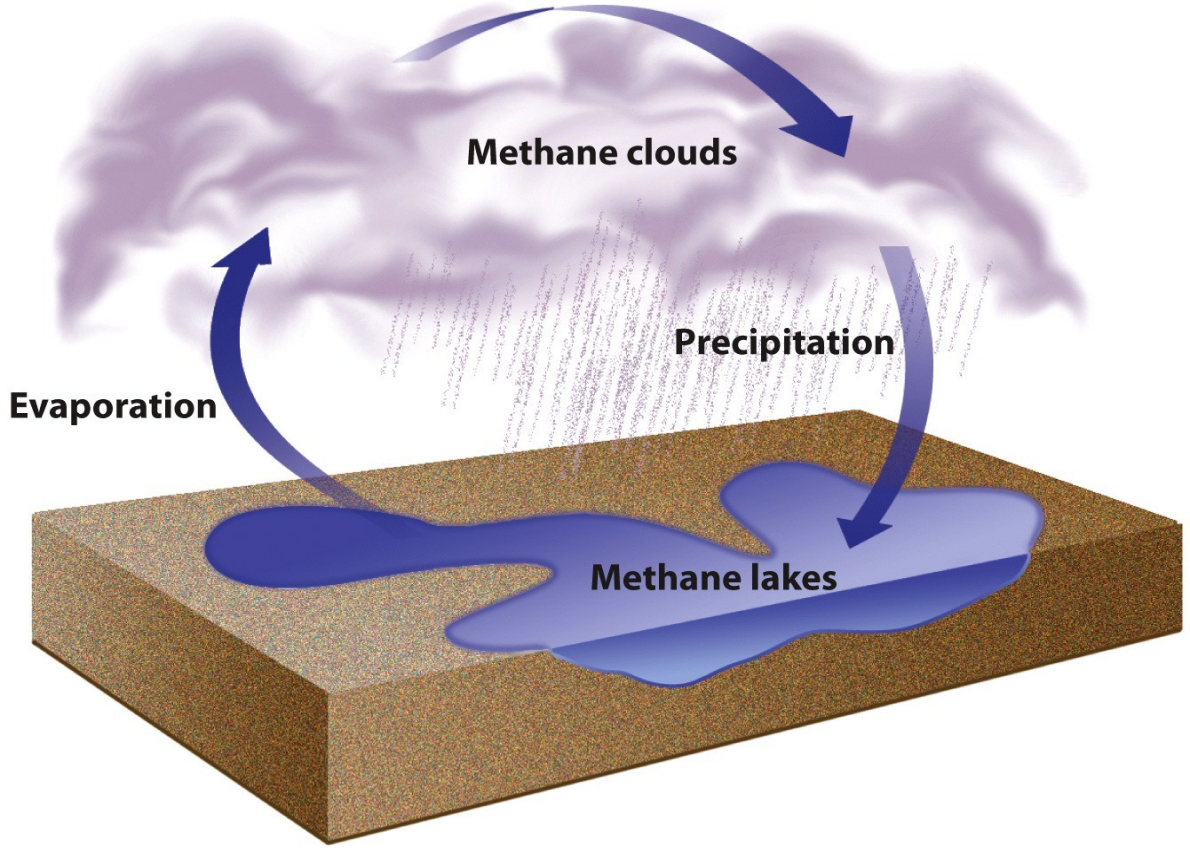


Figure 13-20
Universe, Tenth Edition

The atmosphere on Titan is very cold (95 K) but the pressure is high. Methane (CH_4) can exist as a gas, liquid or solid with these conditions of temperature and pressure. On Titan there are clouds of methane as well as methane rain and lakes and streams of liquid methane. The solid methane ice is only thought to exist at high altitudes which melts into rain. The surface of Titan is mainly water ice.

Titan

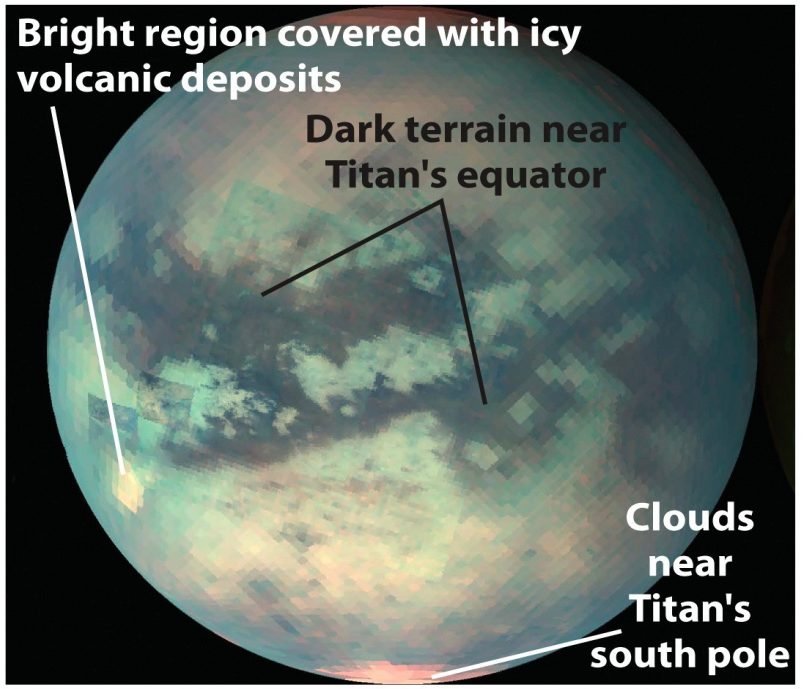


Figure 13-21a

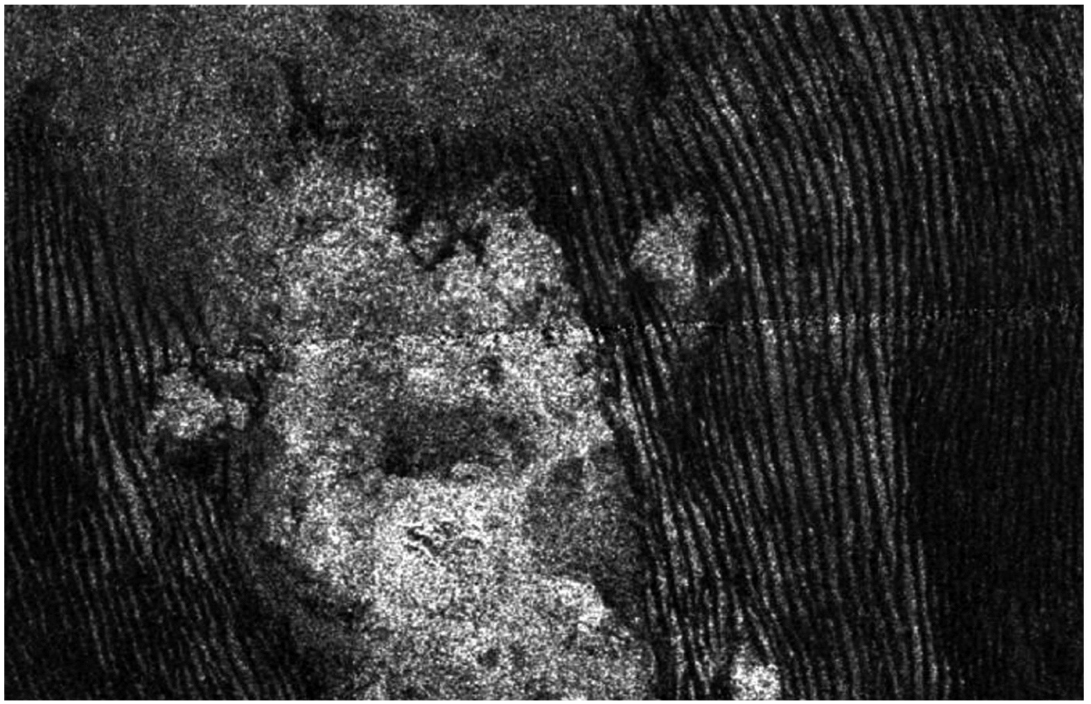


Figure 13-22
Universe, Tenth Edition
NASA/JPL/Caltech/ASI/ESA and USGS/ESA

The Cassini probe has 'mapped' the surface of Titan in the infrared. The atmosphere is more transparent to IR than visible light. The images show dark terrain near the equator.

The radar mapper on Cassini shows long 'sand dunes' like areas of water ice particles.

Saturn's Titan

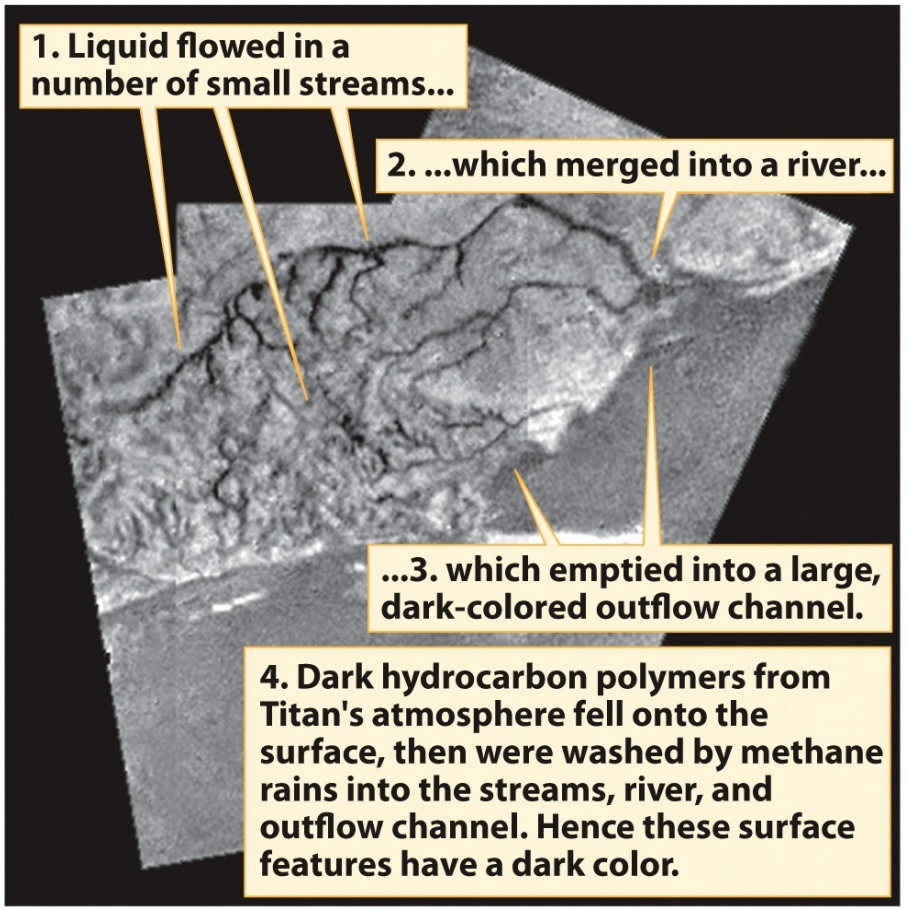


Figure 13-21b
Universe, Tenth Edition
NASA/JPL/ESA/University of Arizona

The Cassini mission included the Huygens lander which was dropped into the atmosphere of Titan. This image is from 6.5 km about the surface. There are clearly steams joining into a river of liquid that flows into a darker colored lake or ocean. Since it is too cold to be water, the flowing liquid is probably methane or possibly ethane.

Saturn's Titan

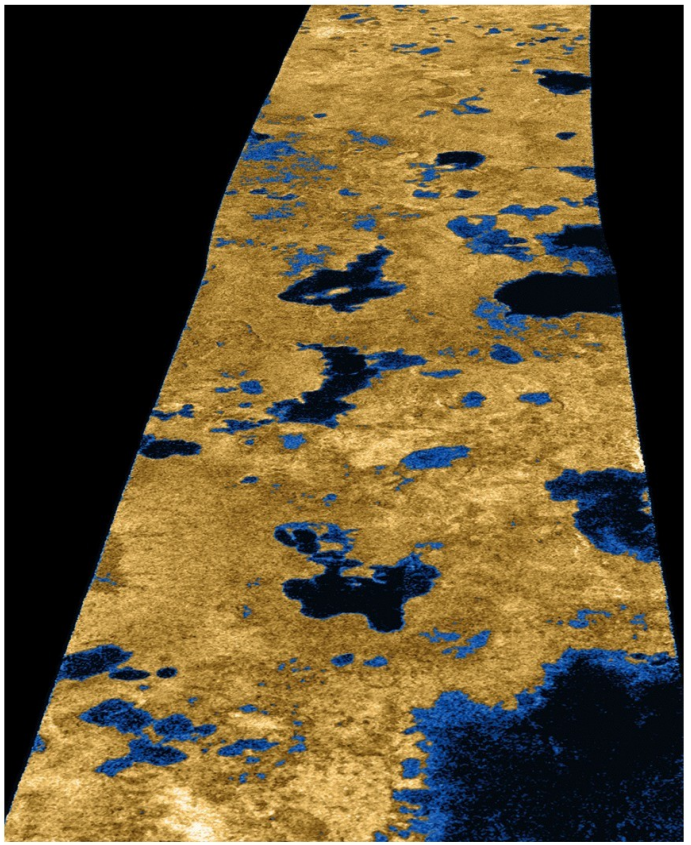


Figure 13-23a
Universe, Tenth Edition
NASA/JPL/USGS

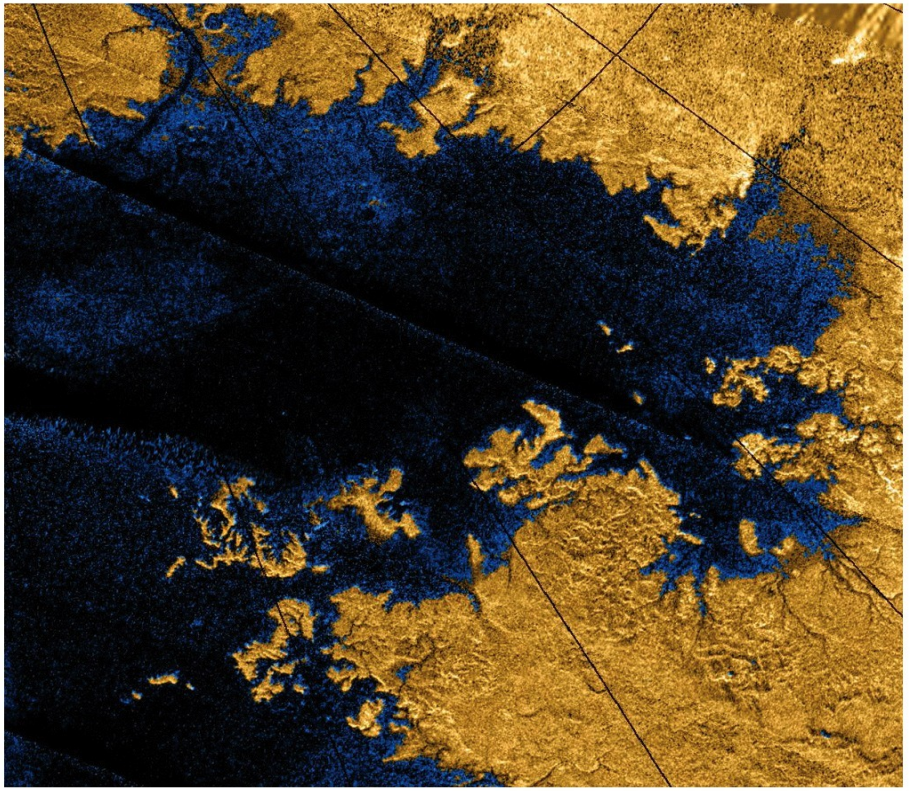


Figure 13-23b
Universe, Tenth Edition
NASA/JPL/USGS

These radar maps made during Huygens' decent show lakes of liquid methane or ethane. The right image is of Lake Ligeia Mare which is about the size of lake Superior (~350 miles wide)

Saturn's Titan

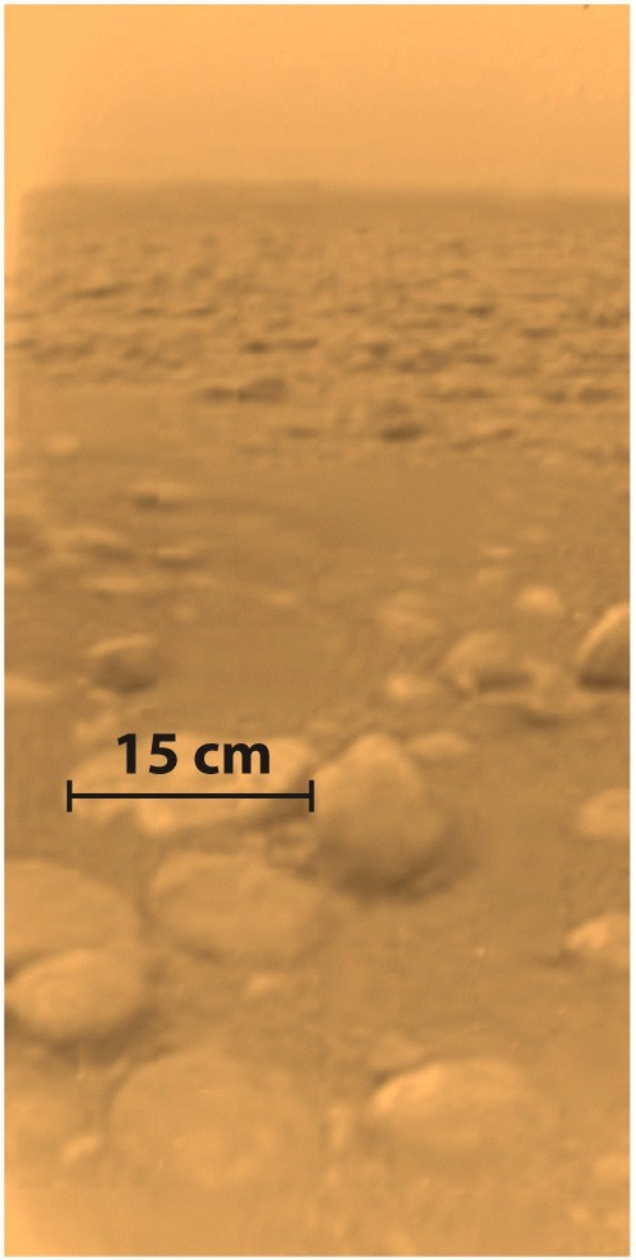


Figure 13-21c
Universe, Tenth Edition
NASA/JPL/ESA/University of Arizona

The is a true color image of the surface where the Huygens landed. The 'rocks' are made of water ice. The 15 cm 'rock' is about 85 cm from the lander.

Cryovolcanoes on Titan

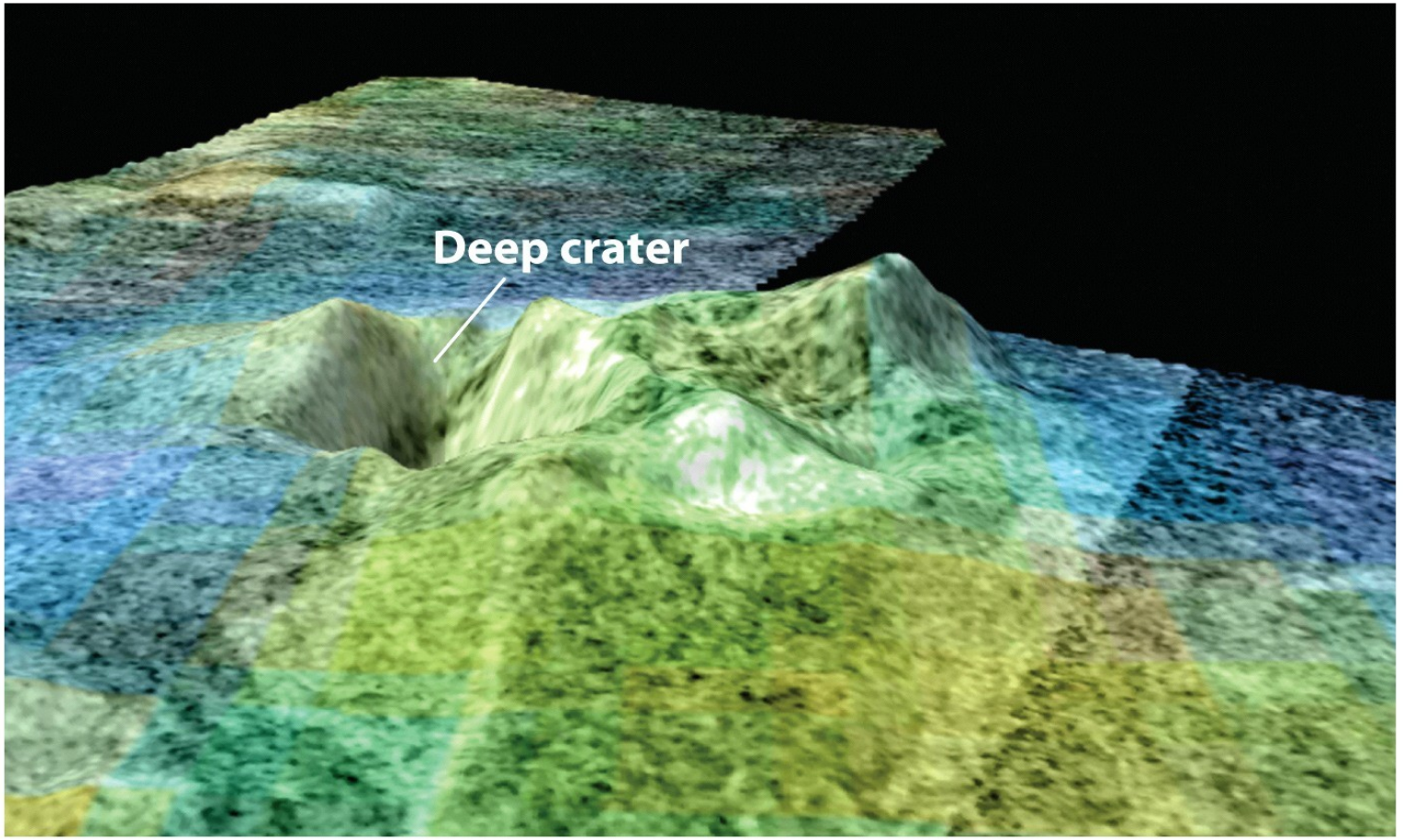


Figure 13-24
Universe, Tenth Edition
NASA/JPL-Caltech/USGS/University of Arizona

This false color image show 1000 m high mountains surrounding a 1500 m deep crater. This is a cryovolcanoe erupting a mixture of ice, ammonia and methane. The ammonia acts as 'antifreeze'. The blue is ice while the surrounding areas are ice covered with hydrocarbons.

Saturn's Titan

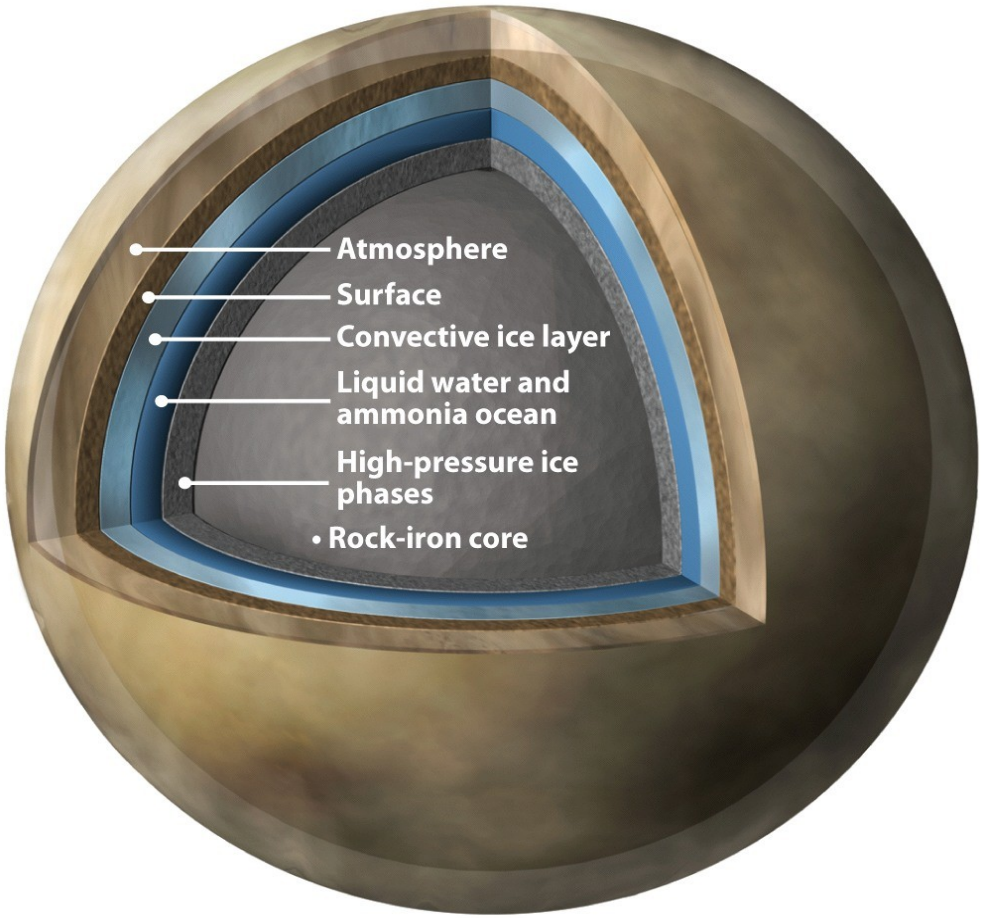


Figure 13-25
Universe, Tenth Edition
Illustration by Kevin Hand for *Scientific American*

Some measurements from Huygens suggest that may be an ocean of liquid H_2O underneath Titan's surface. Could they support life?

Titan is not large enough to have residual heat from its formation. What heat source powers the cryovolcanoes? This model of Titan's interior suggest radioactive material 500 million years ago but the real story remains a mystery.

Jupiter's Other Moons

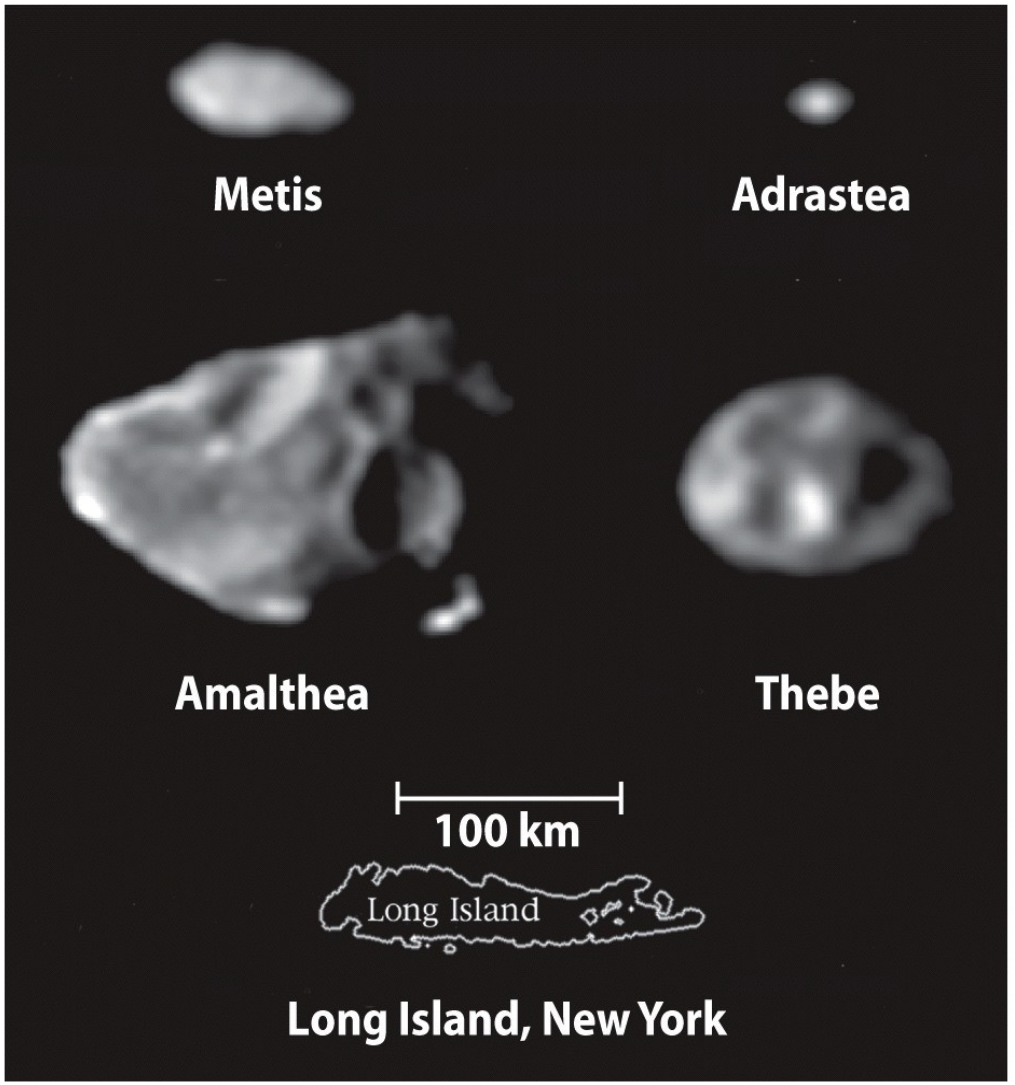


Figure 13-26
Universe, Tenth Edition
NASA/JPL; Cornell University

Besides the Galilean Moon's Jupiter has at least 63 smaller moons. Four inner moons orbit with semimajor axis of 1.8 to 3.1 times the radius of Jupiter. Amalthea is the largest at 270 x 150 km. The inner moons do not have enough gravity to pull themselves in a spherical shape. The inner moons orbit around Jupiter's equator. Their orbits are prograde.

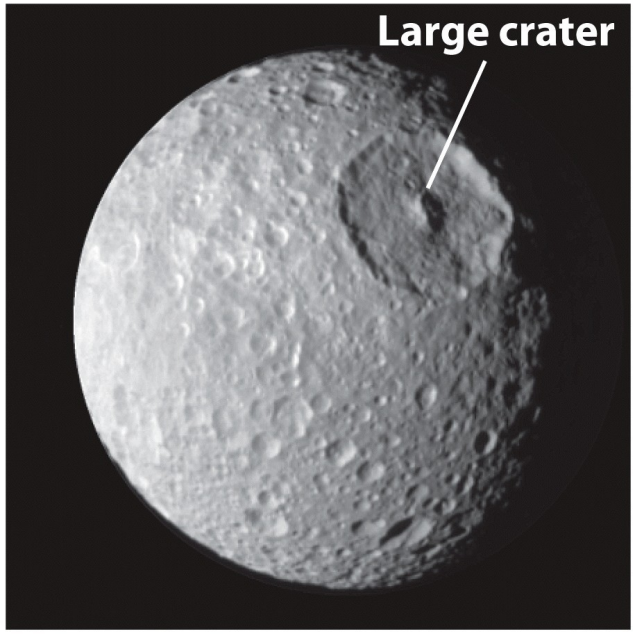
Jupiter's Other Moons

Jupiter has 59 outer moons. The range in size from 184 km to 1 km. They orbit far outside of Callisto and have highly inclined orbits. Most have orbits that are retrograde. The outer moons of Jupiter are thought to mainly be asteroids that have been captured by Jupiter's large gravity.

Saturn's Moderate Sized Moons

Saturn like Jupiter has many moons (62 as of 2012). Besides Titan, there are six moderate sized moons (400 – 1500 km diameter). All of the moderate sized moons were discovered in the 1800s. The moderate sized moon have low density (< 1400 kg/m^3) which means they are mostly ice (H_20 and NH_3). They orbit in a plane around Saturn's equator. There orbits are in the same direction as Saturn's rotation (prograde). Their orbits have semimajor axis of from 3 to 59 times the radius of Saturn.

Saturn's 6 Moderate Sized Moons



Mimas (diameter 392 km)

Figure 13-28a
Universe, Tenth Edition
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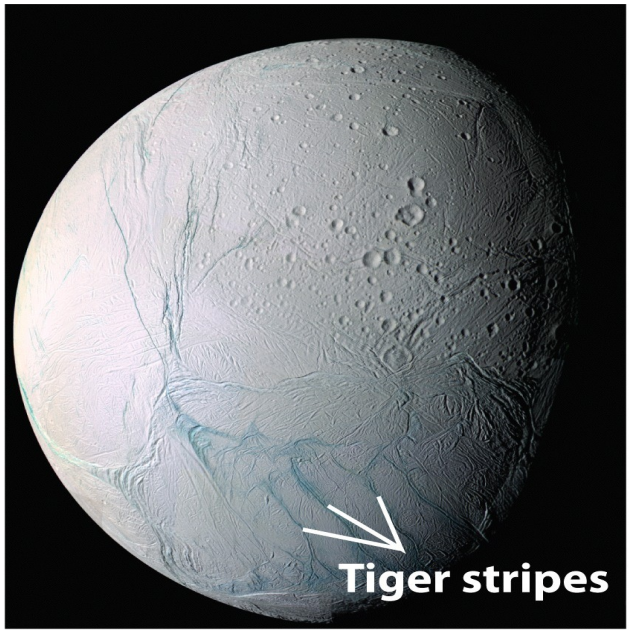

Figure 13-29a
Universe, Tenth Edition
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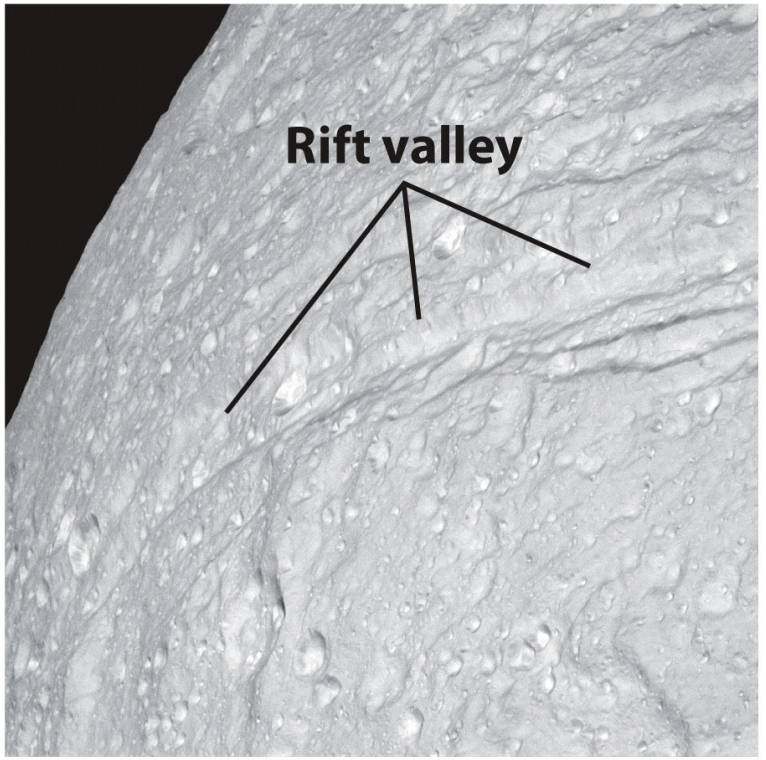
Mimas (left) and Enceladus (left) are the smallest (400-400 km) of the moderate sized moons. Mimas has a huge impact crater that came close ot shattering the smal moon. Enceladus has cryovolcanoes and regions of smooth surface. The cryovolcanoes eject ice crystals which form Saturn's E ring. The tiger stripes are areas where water is dissolving minerals. There may be a large subsurface ocean on Enceladus .

Saturn's 6 Moderate Sized Moons



Tethys (diameter 1060 km)

Figure 13-28b
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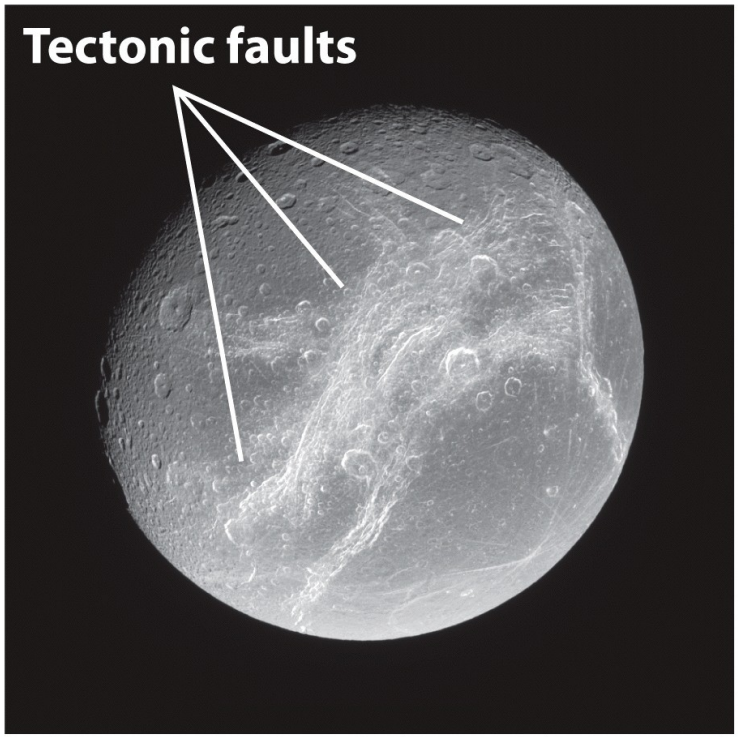

Dione (diameter 1120 km)

Figure 13-28c
Universe, Tenth Edition
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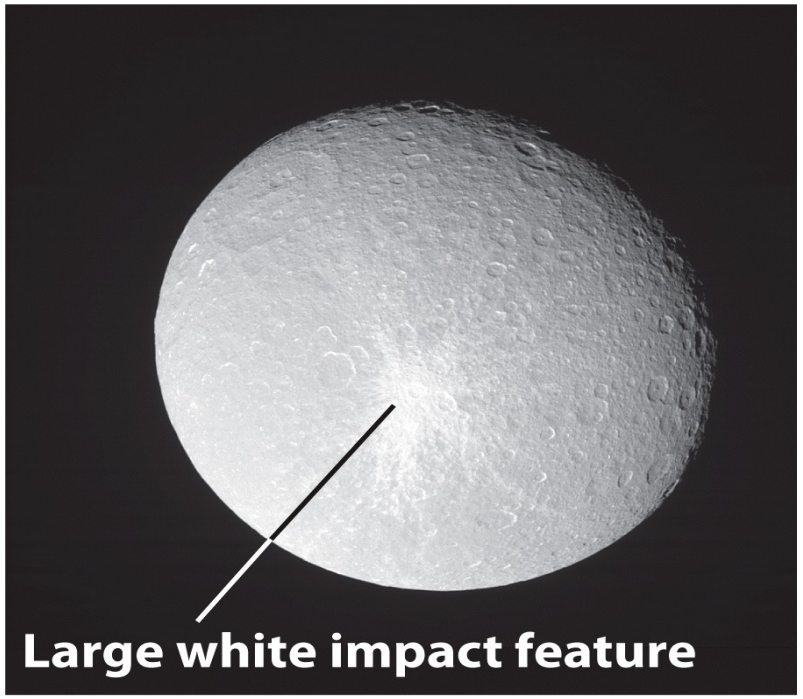
Tethys and Dione are the next largest of the moderate sized moons. Tethys is heavily cratered and has a large rift valley which could be from ice freezing or from a large impact. Dione's leading hemisphere is heavily cratered while the trailing hemisphere is not. There are what appear to be tectonic faults.

Saturn's 6 Moderate Sized Moons



Rhea (diameter 1530 km)

Figure 13-28d
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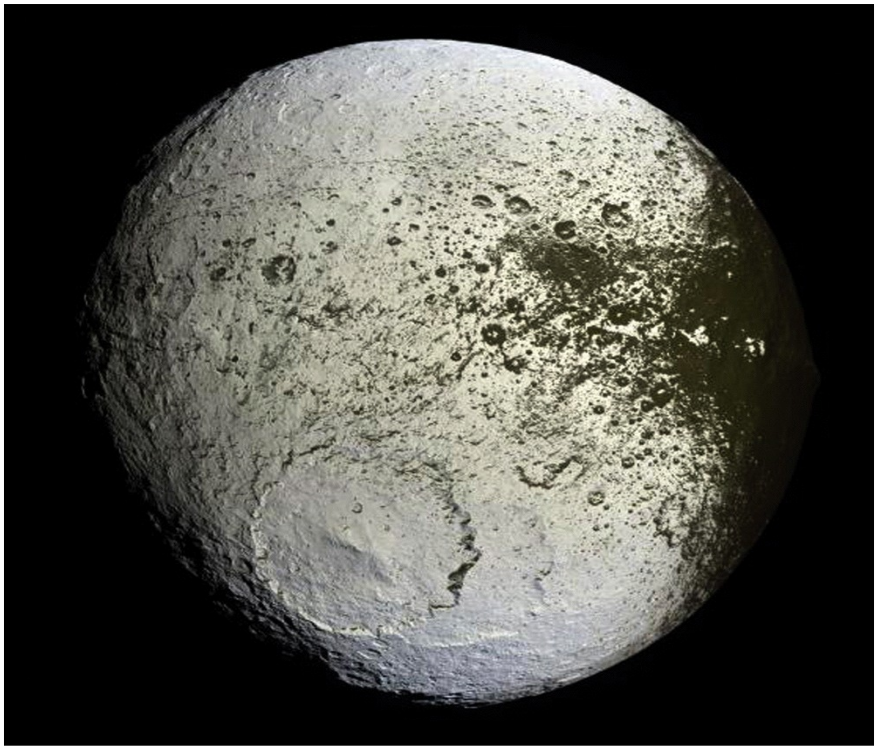

Figure 13-30a
Universe, Tenth Edition
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Rhea (left) and Lapetus are the largest of the moderate sized moons. Rhea has a large impact feature. Iapetus also has a large impact feature. The leading side of Iapetus is bright like the other moderate sized moons but the trailing hemisphere is very dark. The dark side is probably covered with debris from a recently discovered ring which warmed that area and melted away ices to expose the darker region.

Saturn's Many Small Moons

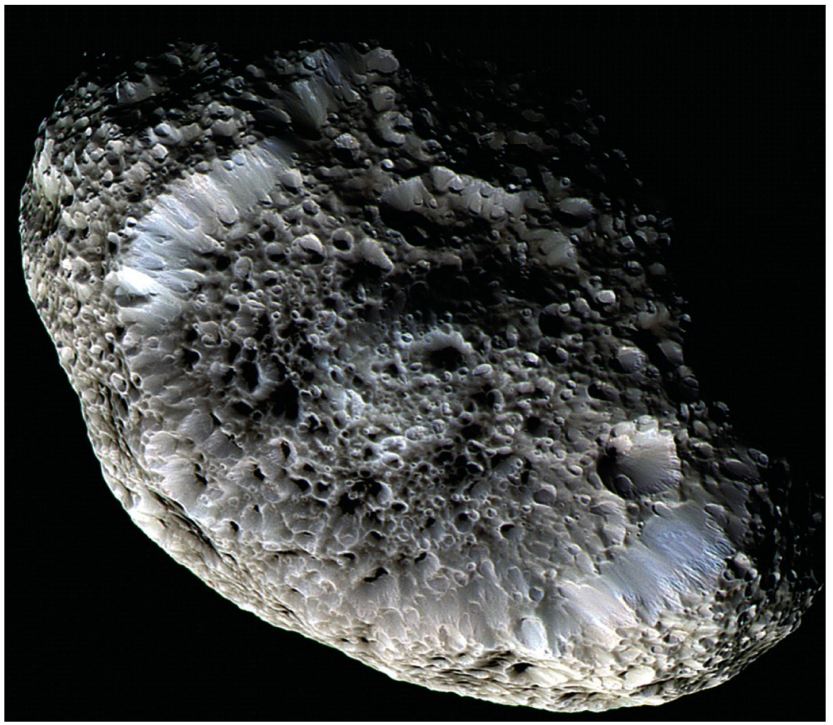

Figure 13-27
Universe, Tenth Edition
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There are 55 known smaller moons of Saturn. They range in size from 3 to 266 km in diameter. Their semi-major axis range out to 380 times the radius of Saturn. Some are in retrograde orbits which may be captured asteroids. Many have inclined orbits to Saturn's equator. Hyperion (left) has a density of ½ of water! It is probably very porous. It does no rotate but tumbles chaotically.