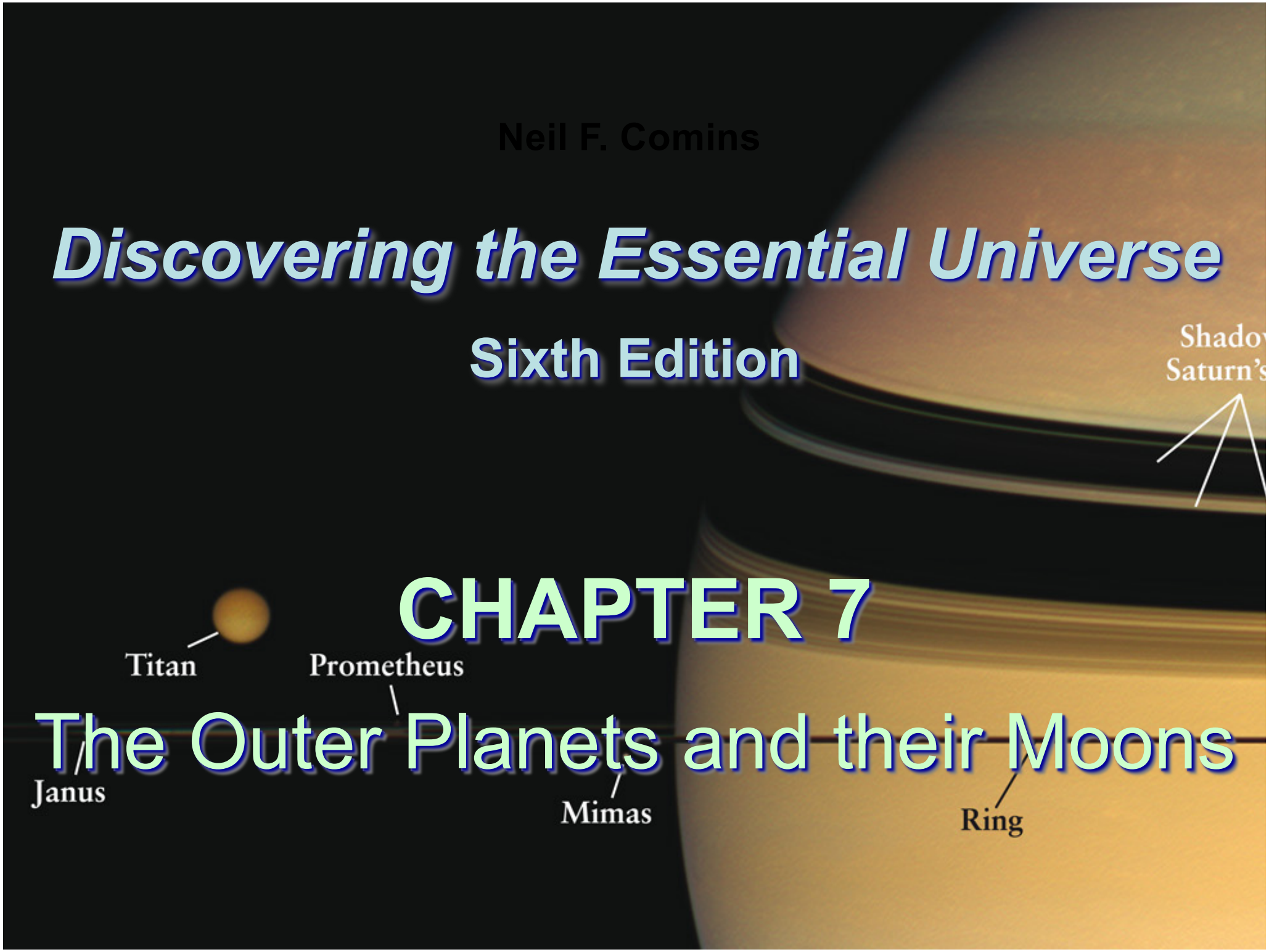
Neil F. Comins

Discovering the Essential Universe

Sixth Edition



CHAPTER 7

The Outer Planets and their Moons

In this chapter you will discover…

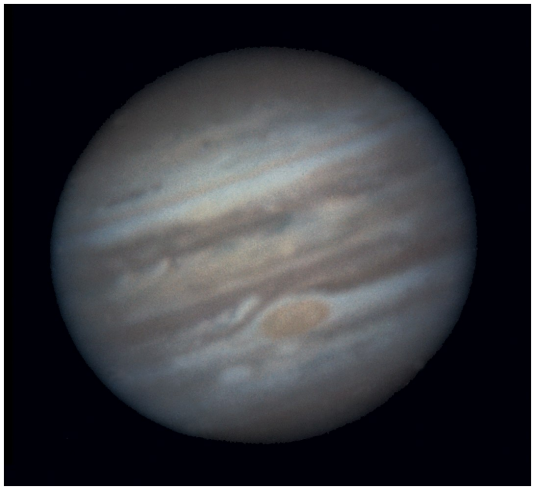
- Jupiter, an active, vibrant, multicolored world more massive than all of the other planets combined, with a diverse system of moons
- Saturn, with its spectacular system of thin, flat rings and numerous moons, including bizarre Enceladus and Titan
- Uranus and Neptune, ice giants similar to each other and different from Jupiter and Saturn

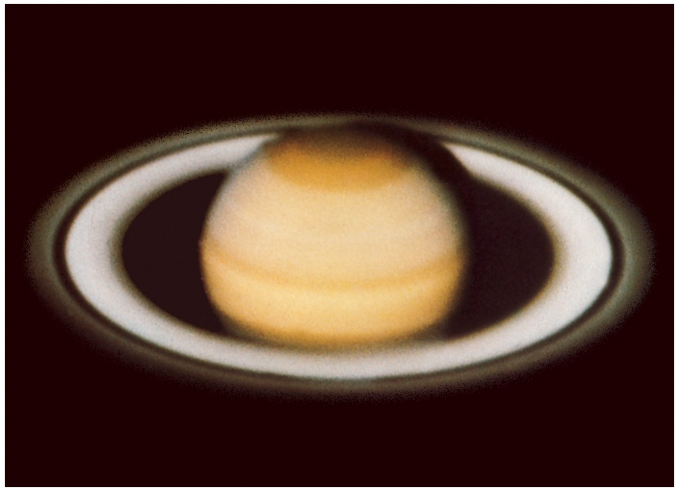
table 14-1 | Jupiter Data

Average distance from Sun:	5.203 AU = 7.783 × 10^8 km
Maximum distance from Sun:	5.455 AU = 8.160 × 10^8 km
Minimum distance from Sun:	4.950 AU = 7.406 × 10^8 km
Eccentricity of orbit:	0.048
Average orbital speed:	13.1 km/s
Orbital period:	11.86 years
Rotation period:	$9^h\ 50^m\ 28^s$ (equatorial) $9^h\ 55^m\ 29^s$ (internal)
Inclination of equator to orbit:	3.12°
Inclination of orbit to ecliptic:	1.30°
Diameter:	142,984 km = 11.209 Earth diameters (equatorial) 133,708 km = 10.482 Earth diameters (polar)
Mass:	1.899 × 10^{27} kg = 317.8 Earth masses
Average density:	1326 kg/m^3
Escape speed:	60.2 km/s
Surface gravity (Earth = 1):	2.36
Albedo:	0.44
Average temperature at cloudtops:	−108°C = −162°F = 165 K
Atmospheric composition (by number of molecules):	86.2% hydrogen (H_2), 13.6% helium (He), 0.2% methane (CH_4), ammonia (NH_3), water vapor (H_2O), and other gases

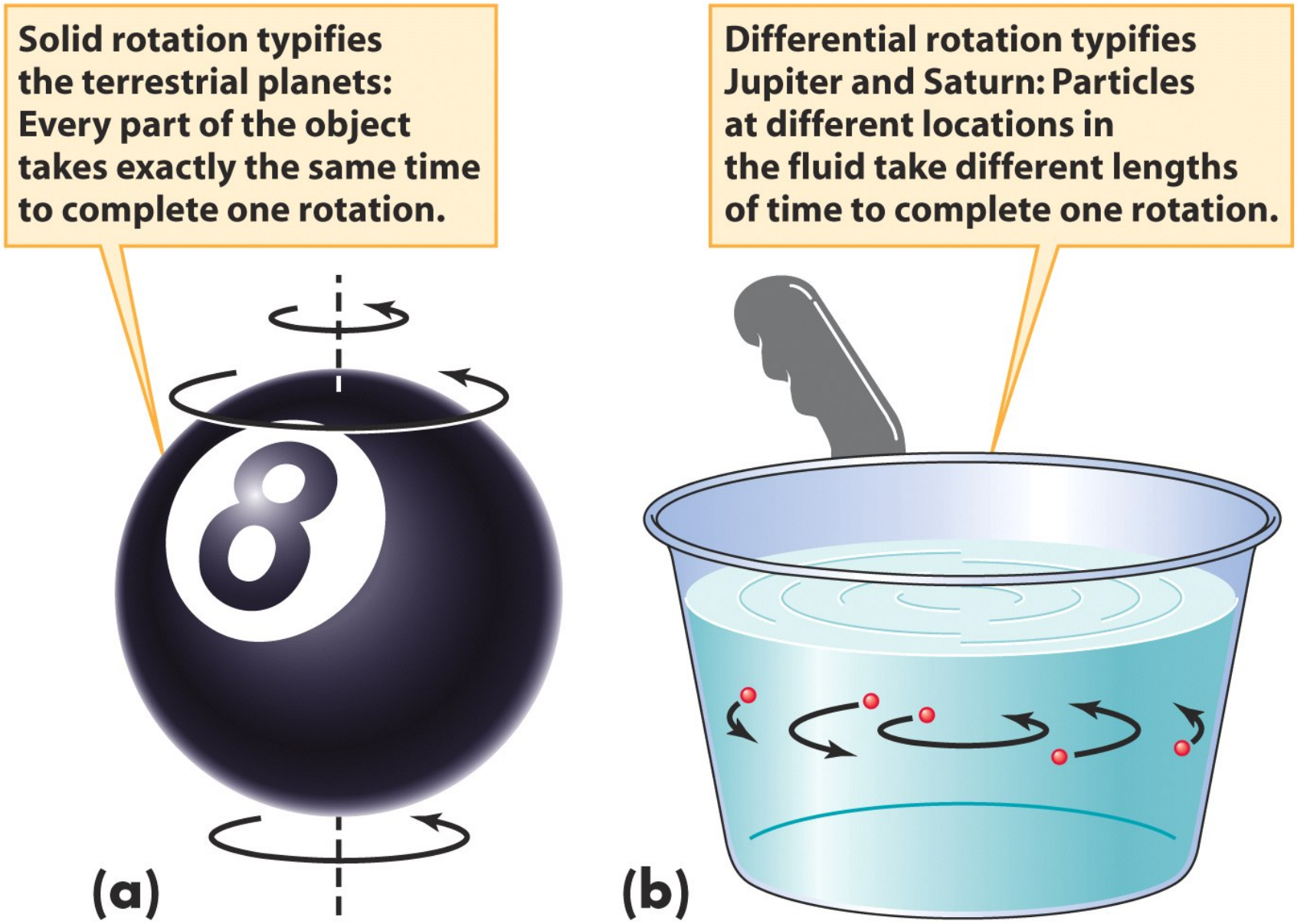
Jupiter and Saturn are the most massive planets in the solar system

- Jupiter and Saturn are both much larger than Earth
- Each is composed of 71% hydrogen, 24% helium, and 5% all other elements by mass
- Both planets have a higher percentage of heavy elements than does the Sun
- Jupiter and Saturn both rotate so rapidly that the planets are noticeably flattened





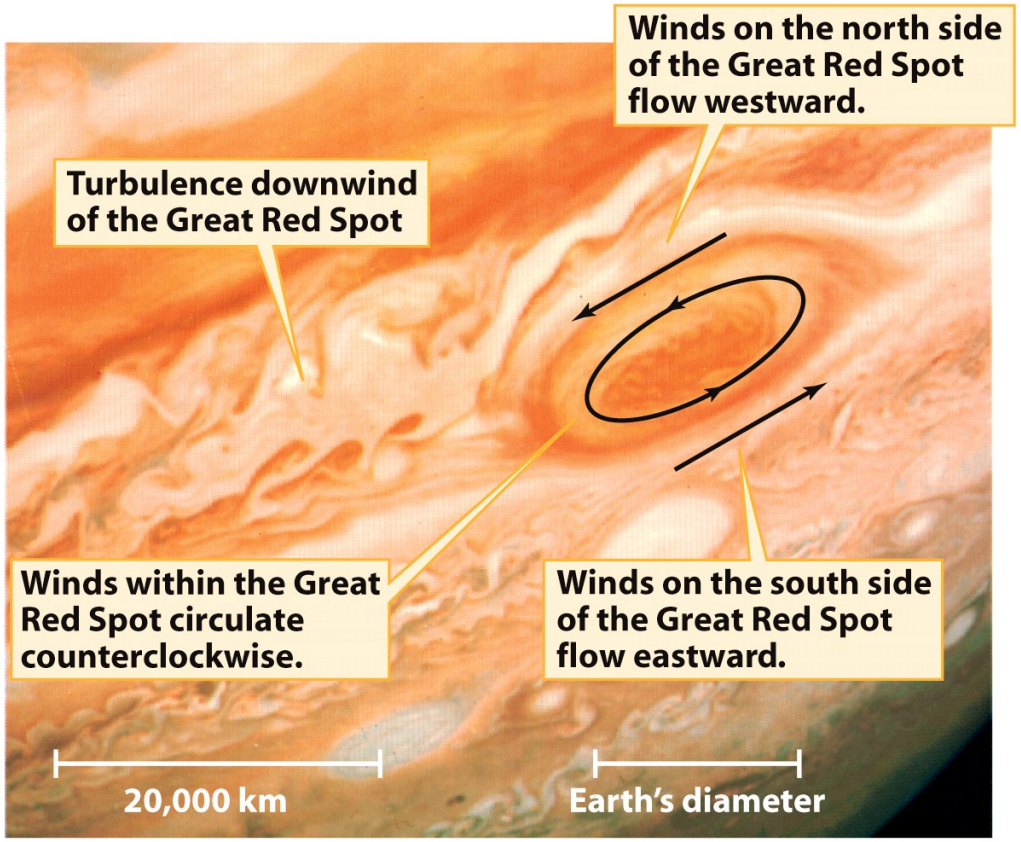
Unlike the terrestrial planets, Jupiter and Saturn exhibit differential rotation



Spacecraft images show remarkable activity in the clouds of Jupiter and Saturn

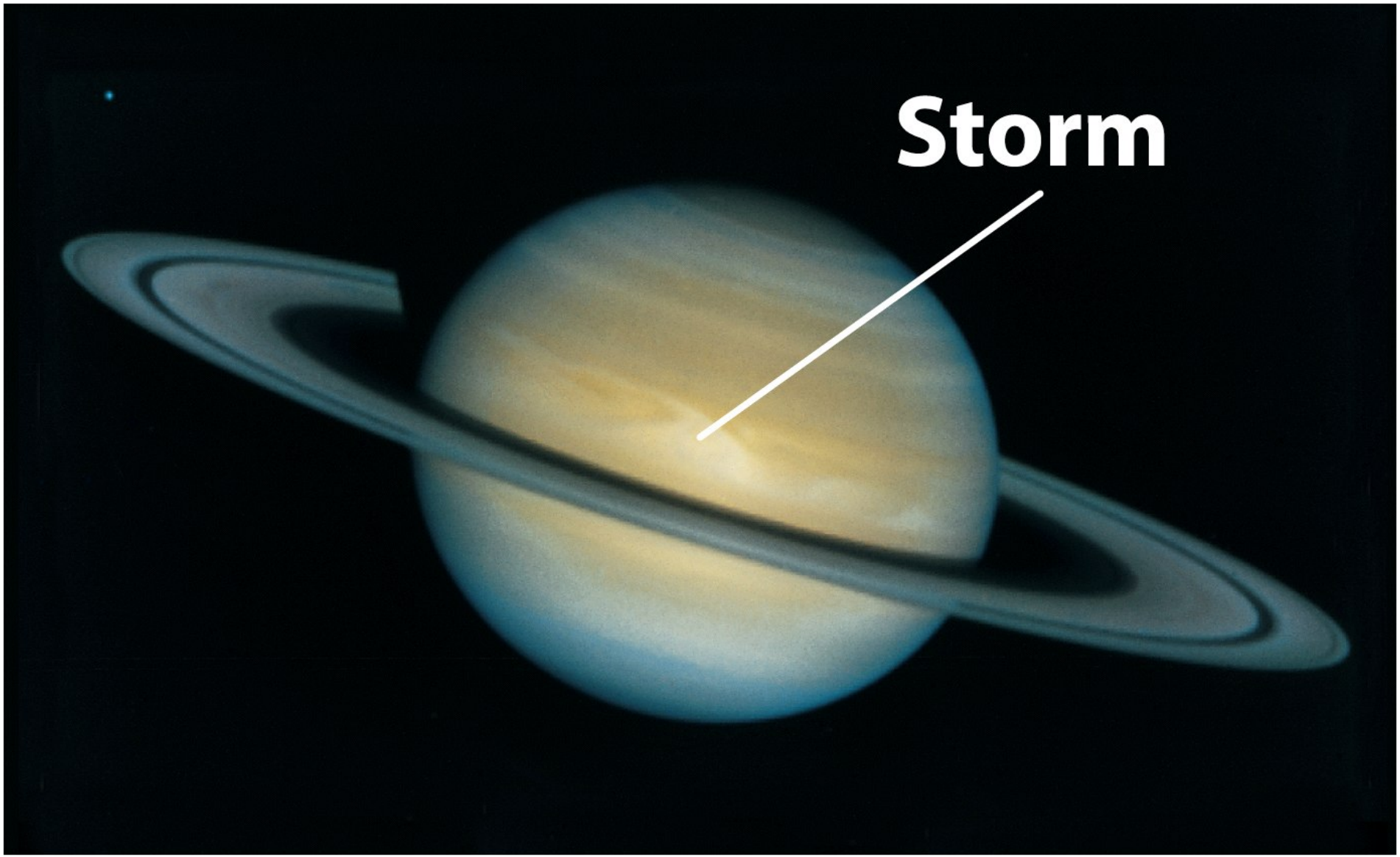
(a) *Pioneer 11*, December 1974 (b) *Voyager 2*, July 1979 (c) HST, February 1995

Storms

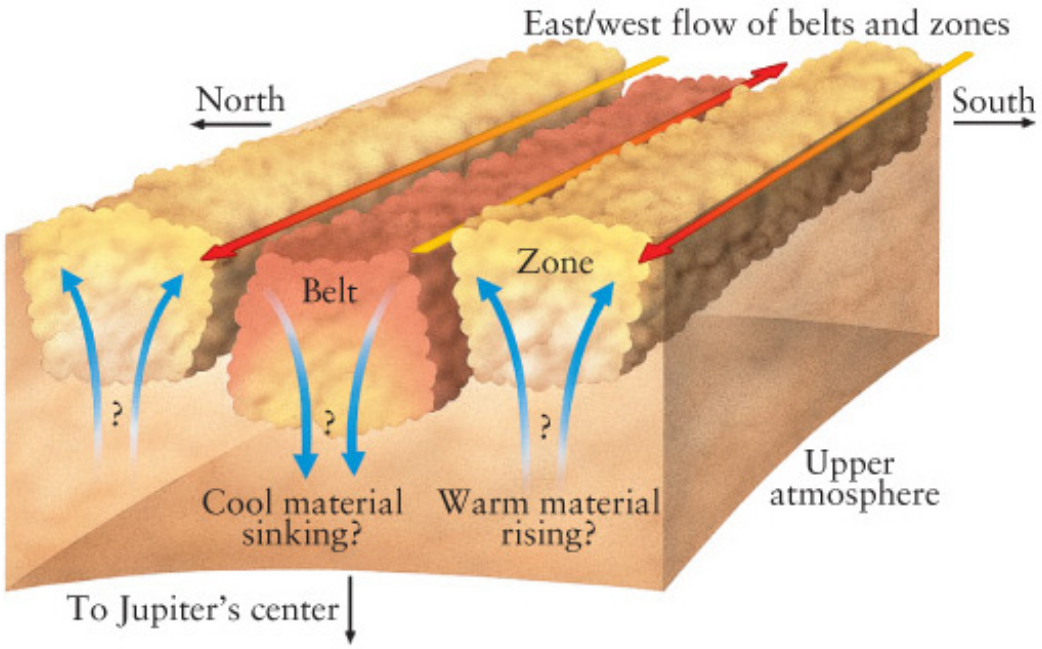


- Both Jupiter and Saturn emit more energy than they receive from the Sun
- Presumably both planets are still cooling
- The colored ovals visible in the Jovian atmosphere represent gigantic storms
- Some, such as the Great Red Spot, are quite stable and persist for many years

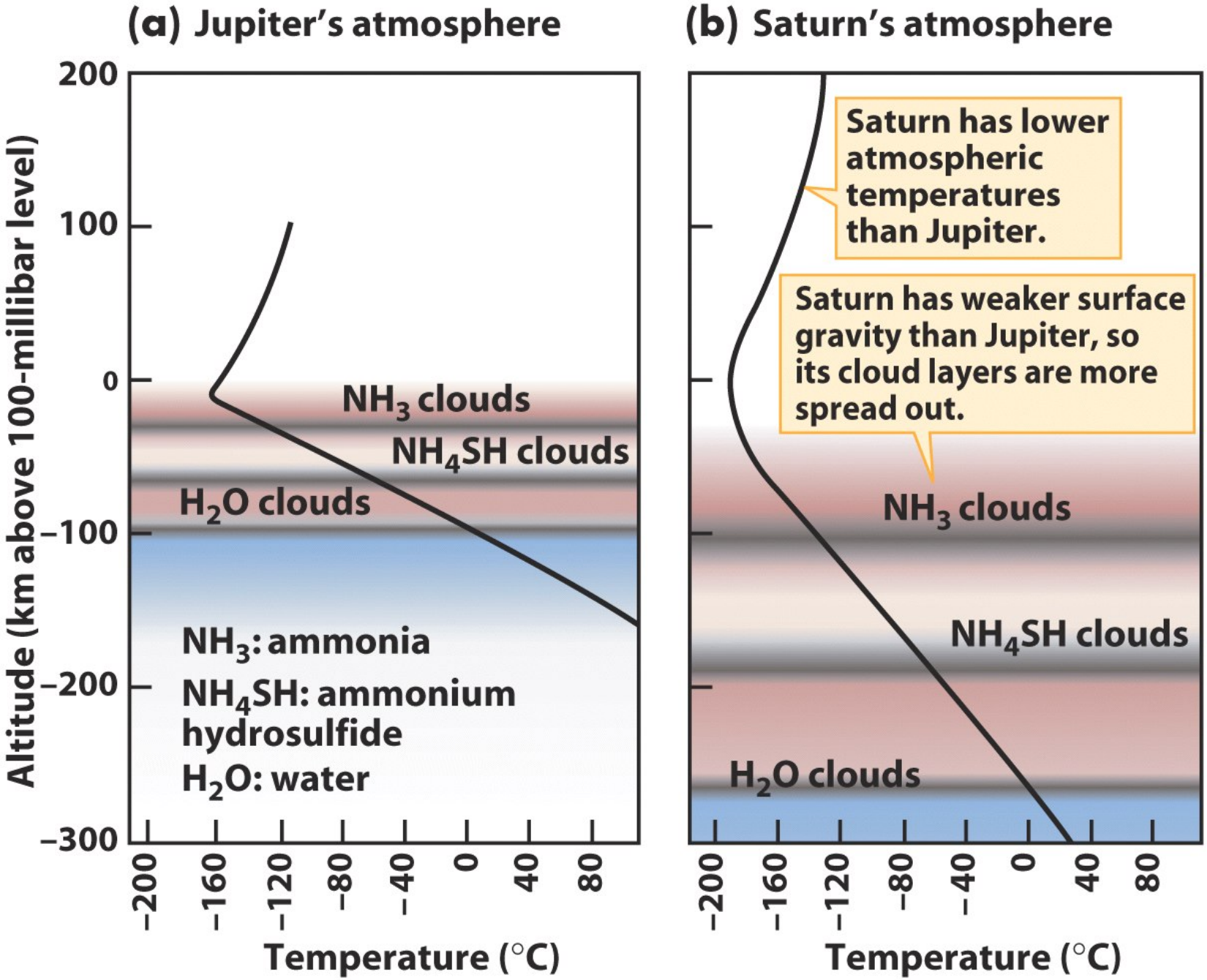
Storms in Saturn's atmosphere seem to be shorter-lived



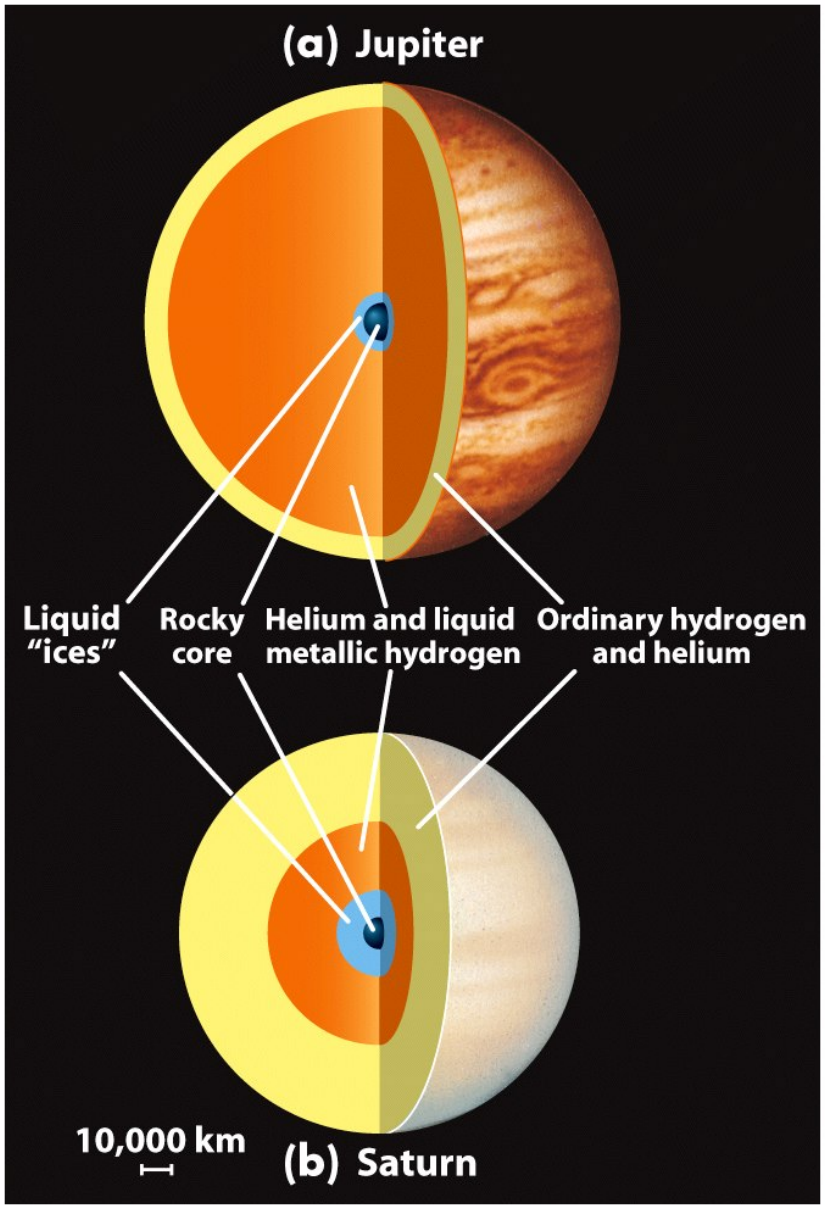
Original Model of Jupiter's Belts and Zones



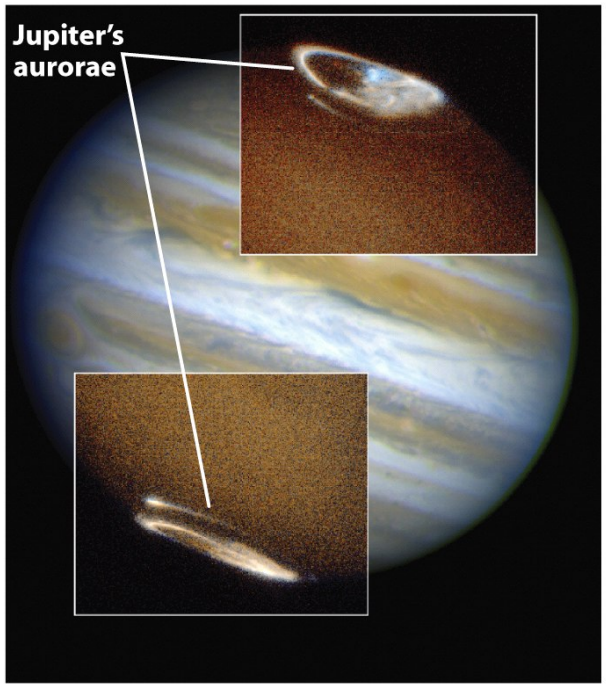
The light-colored zones and dark-colored belts in Jupiter's atmosphere were believed, until recently, to be regions of rising and descending gases, respectively. In the zones, gases warmed by heat from Jupiter's interior were thought to rise upward and cool, forming high-altitude clouds. In the belts, cooled gases were thought to descend and undergo an increase in temperature; the cloud layers seen there are at lower altitudes than in the zones. Observations by the *Cassini* spacecraft on its way to Saturn suggest that just the opposite may be correct! In either case, Jupiter's rapid differential rotation shapes the rising and descending gas into bands of winds parallel to the planet's equator


(a) Jupiter's atmosphere
(b) Saturn's atmosphere
Altitude (km above 100-millibar level)
200
100
0
−100
−200
−300
NH3 clouds
NH4SH clouds
H2O clouds
NH3: ammonia
NH4SH: ammonium hydrosulfide
H2O: water
−200
−160
−120
−80
−40
0
40
80
Temperature (°C)
Saturn has lower atmospheric temperatures than Jupiter.
Saturn has weaker surface gravity than Jupiter, so its cloud layers are more spread out.
NH3 clouds
NH4SH clouds
H2O clouds
−200
−160
−120
−80
−40
0
40
80
Temperature (°C)

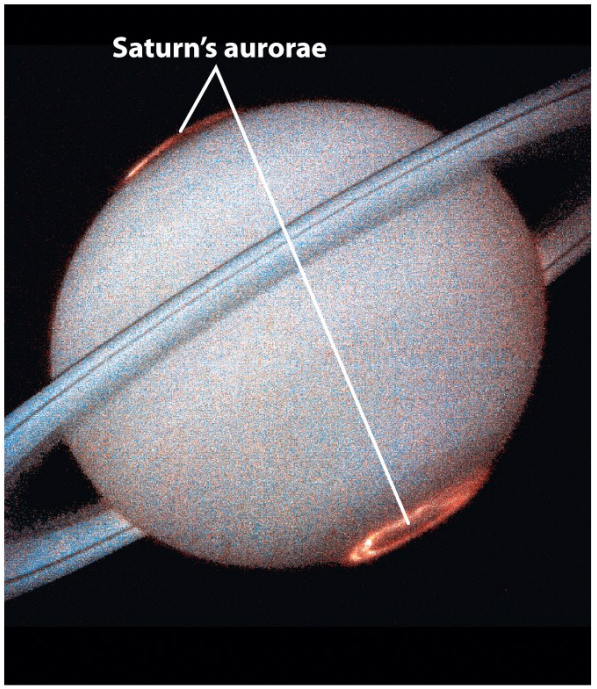
The oblateness of Jupiter and Saturn reveals their rocky cores



- Jupiter probably has a rocky core several times more massive than the Earth
- The core is surrounded by a layer of liquid “ices” (water, ammonia, methane, and associated compounds)
- On top of this is a layer of helium and liquid metallic hydrogen and an outermost layer composed primarily of ordinary hydrogen and helium
- Saturn’s internal structure is similar to that of Jupiter, but its core makes up a larger fraction of its volume and its liquid metallic hydrogen mantle is shallower than that of Jupiter



(a) Jupiter



(b) Saturn

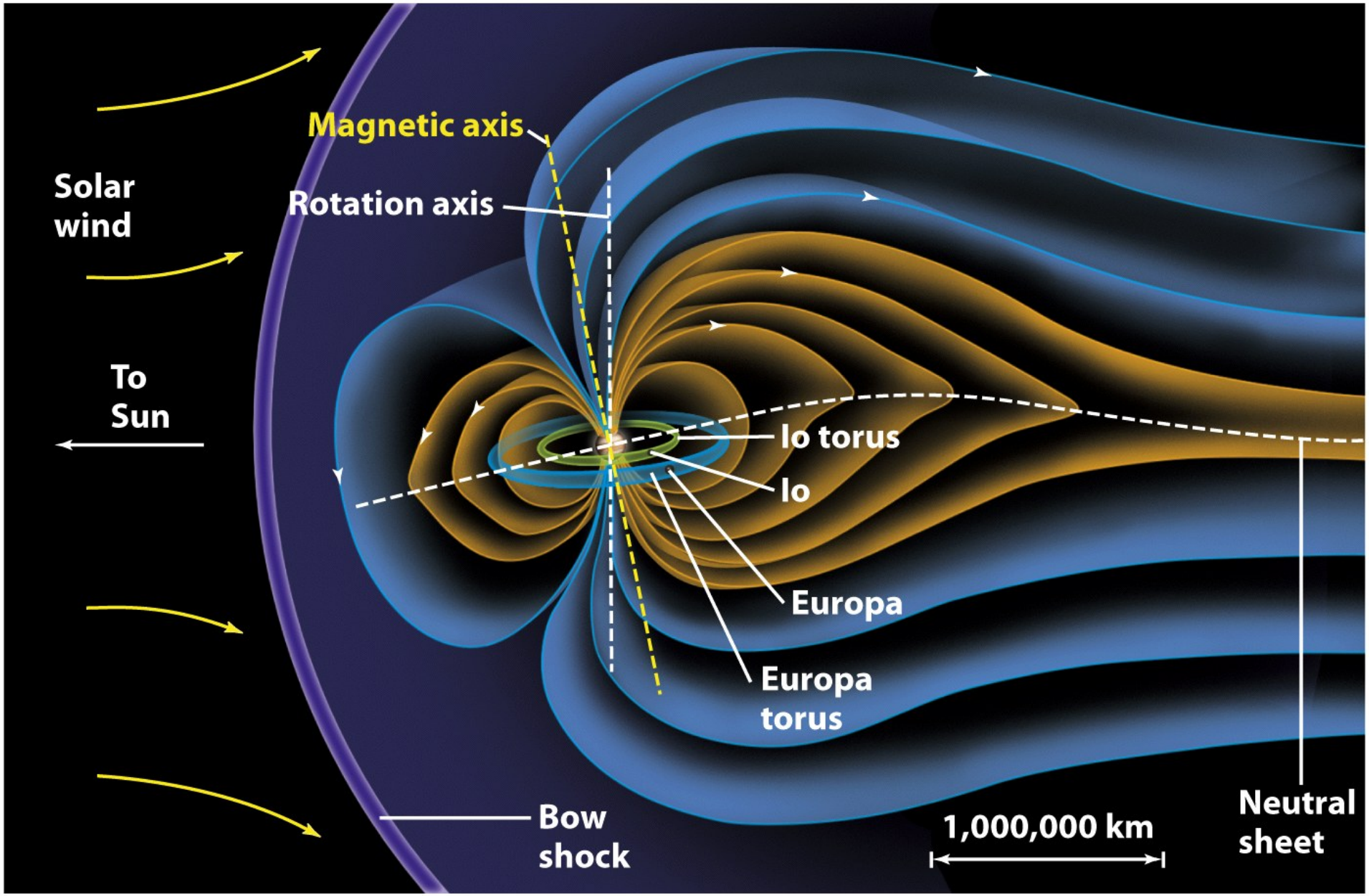


Figure 8-9
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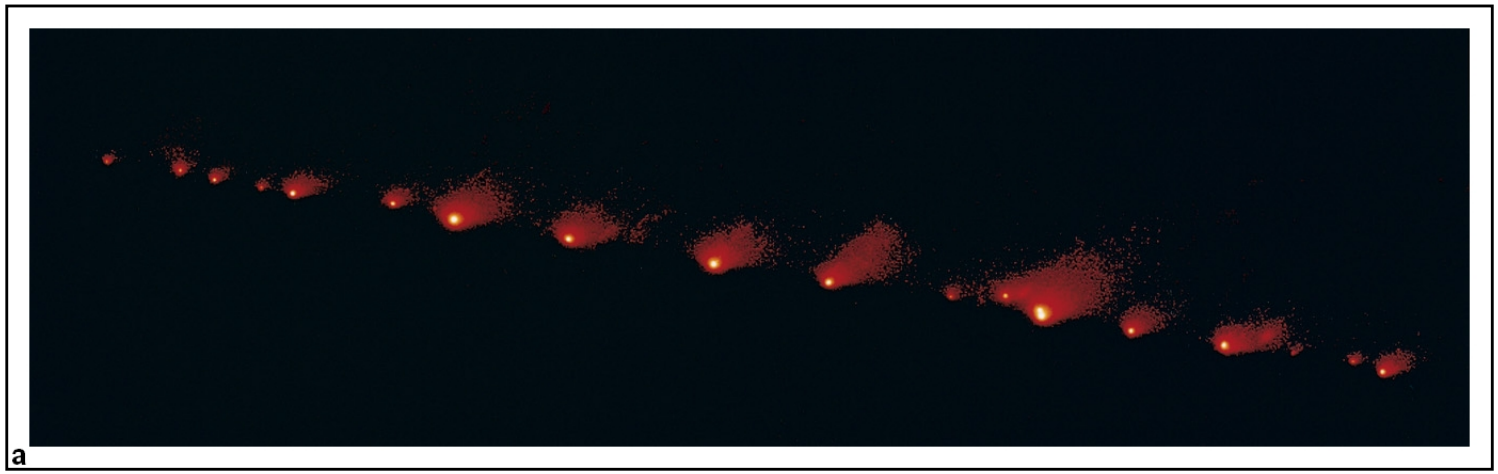
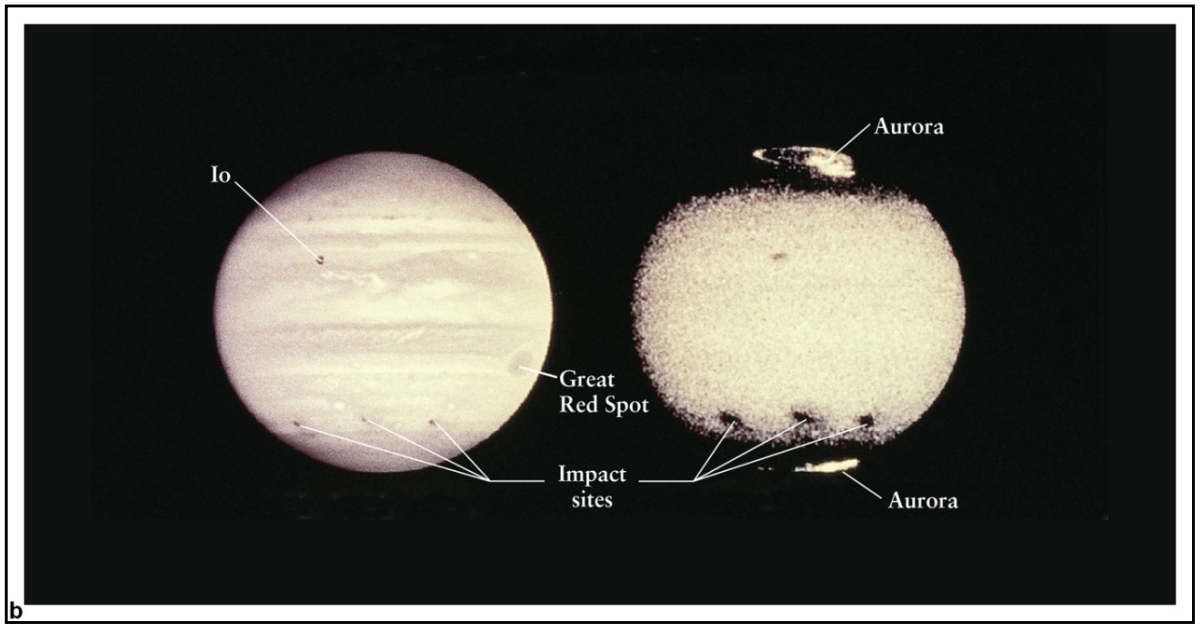
Comet Shoemaker-Levy 9 and Its Encounter with Jupiter



The comet, originally orbiting Jupiter, was torn apart by the planet's gravitational force on July 7, 1992, fracturing into at least 21 pieces. This comet originally orbited Jupiter, and its returning debris, shown here in May 1994, struck the planet between July 16 and July 22, 1994.

Comet Shoemaker-Levy 9 and Its Encounter with Jupiter



Shown here are visible (left) and ultraviolet (right) images of Jupiter taken by the Hubble Space Telescope after three pieces of Comet Shoemaker-Levy 9 struck the planet. Astronomers had expected white remnants (the color of condensing ammonia or water vapor); the darkness of the impact sites may have come from carbon compounds in the comet debris. Note the auroras in the ultraviolet image.

What is the energy released by the impact of the pieces of the comet Shoemaker-Levi 9 on Jupiter?

$E_{kin} = \frac{1}{2}mv^2$ Kinetic energy

$m = \varrho \cdot V$ $V = \frac{4}{3}\pi r^3$ Volume of a sphere with radius r

ϱ Mass density

Example:

v = v_{esc} for Jupiter

$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

$$v_{esc} = \sqrt{\frac{2 \cdot 6.673 \cdot 10^{-11} \cdot 1.90 \cdot 10^{27}}{7.149 \cdot 10^{7}}}$$

$= 59.6$ km s^{-1}

M = $1.90 \cdot 10^{27}$ kg. (Jupiter)

R= 71,490 km. (Jupiter)

G= $6.673 \cdot 10^{-11}$ N m^{2}kg^{-2}

Assume for comet piece: ϱ= 2,500 kg m^{-3}

r= 5 km

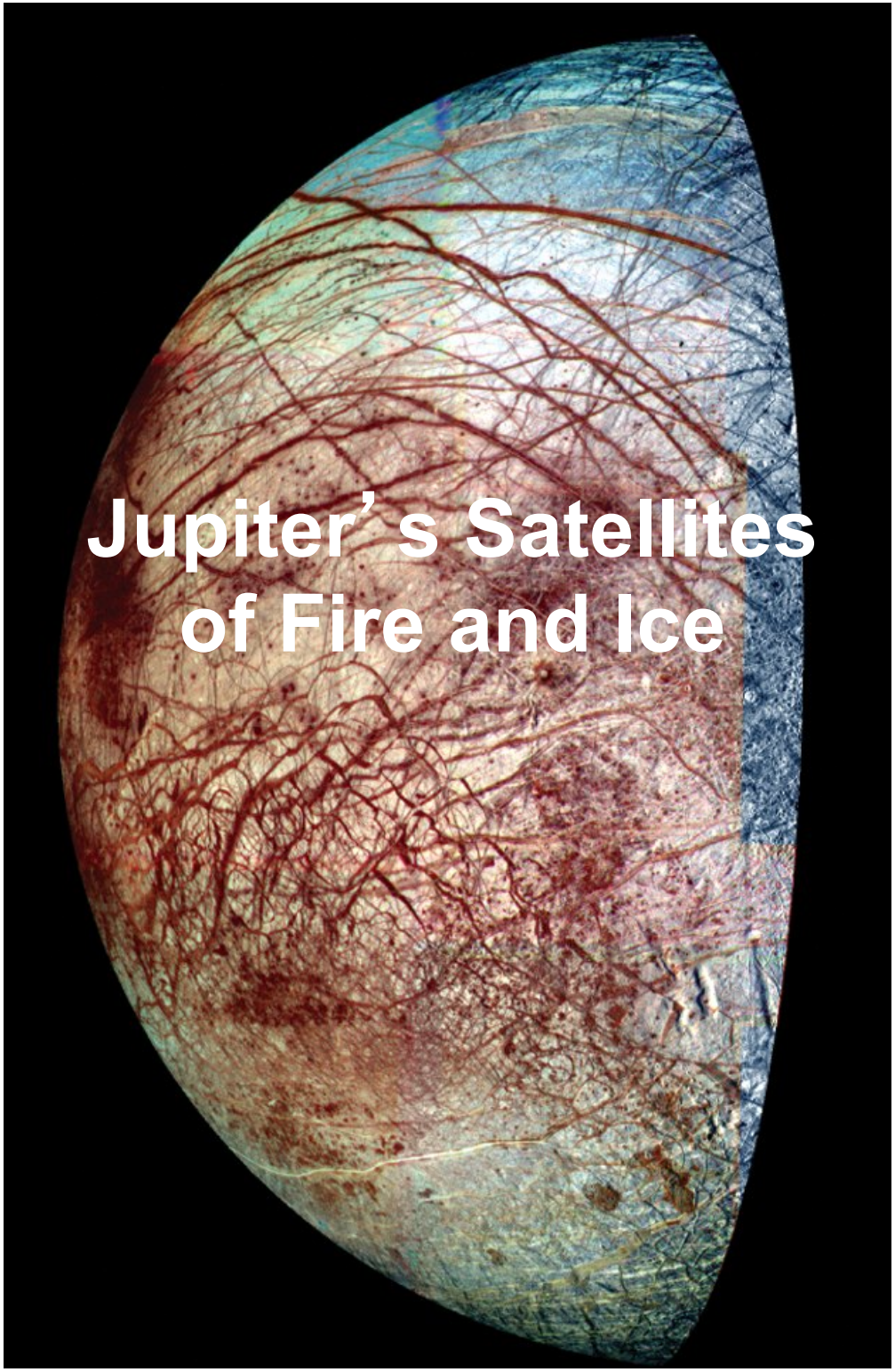
m= $2.5 \cdot 10^{3} \cdot \pi \cdot (5 \cdot 10^{3})^{3} = 1.3 \cdot 10^{15}$ kg

$E_{kin} = \frac{1}{2} \cdot 1.3 \cdot 10^{15} \cdot (5.96 \cdot 10^{4})^2$

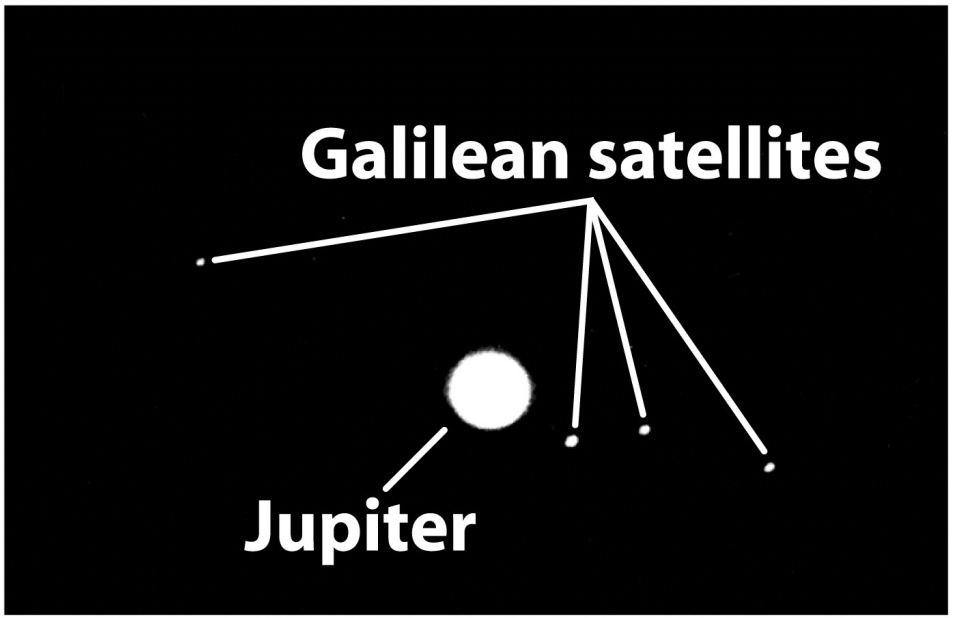
$= 2.31 \cdot 10^{24}$J

Hiroshima Atomic bomb: E=$8.4 \cdot 10^{13}$J

$2.8 \cdot 10^{10}$ = 28 Bill Hiroshima bombs

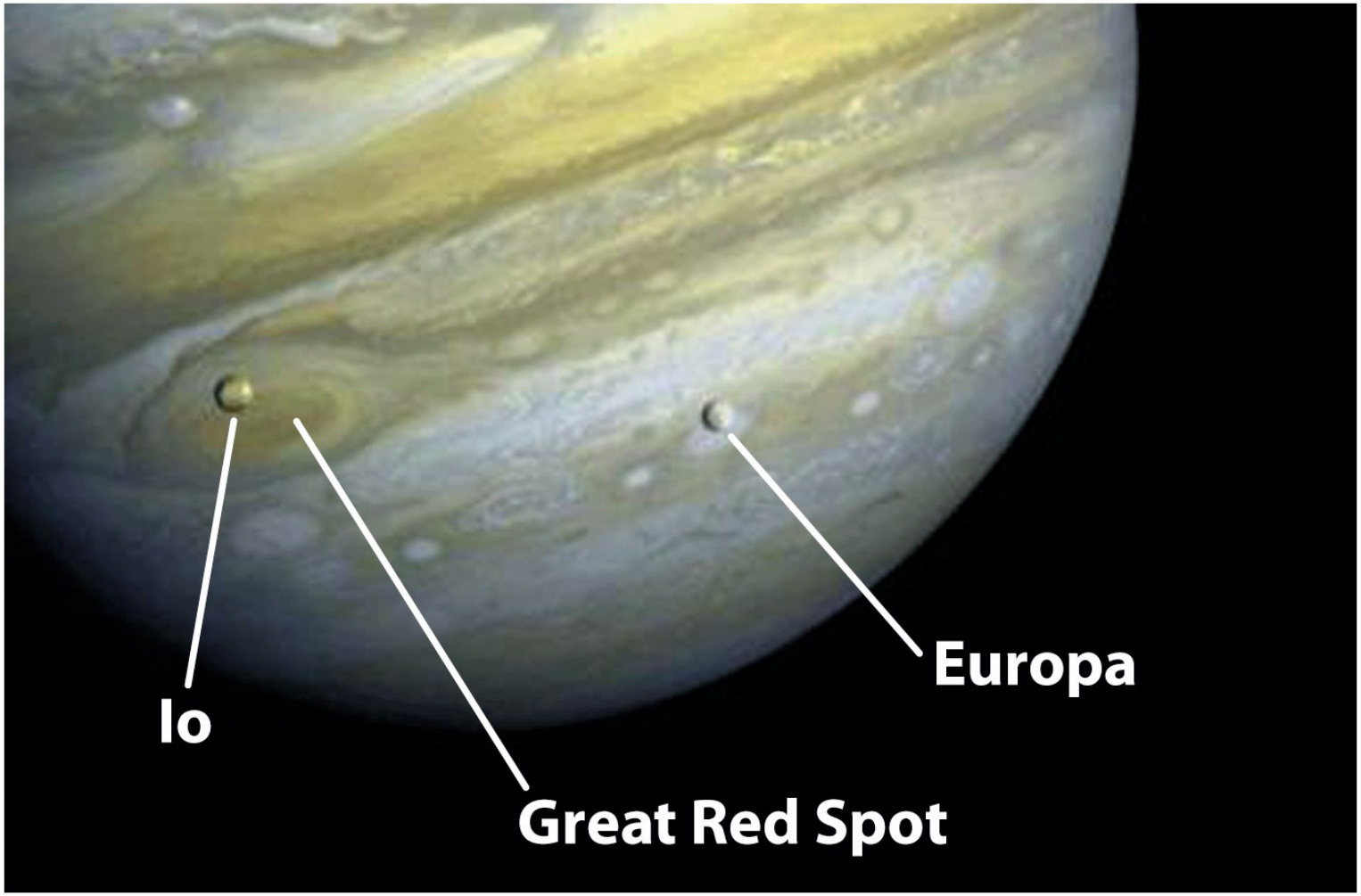

Jupiter’s Satellites
of Fire and Ice

Jupiter's Galilean satellites are easily seen with Earth-based telescopes

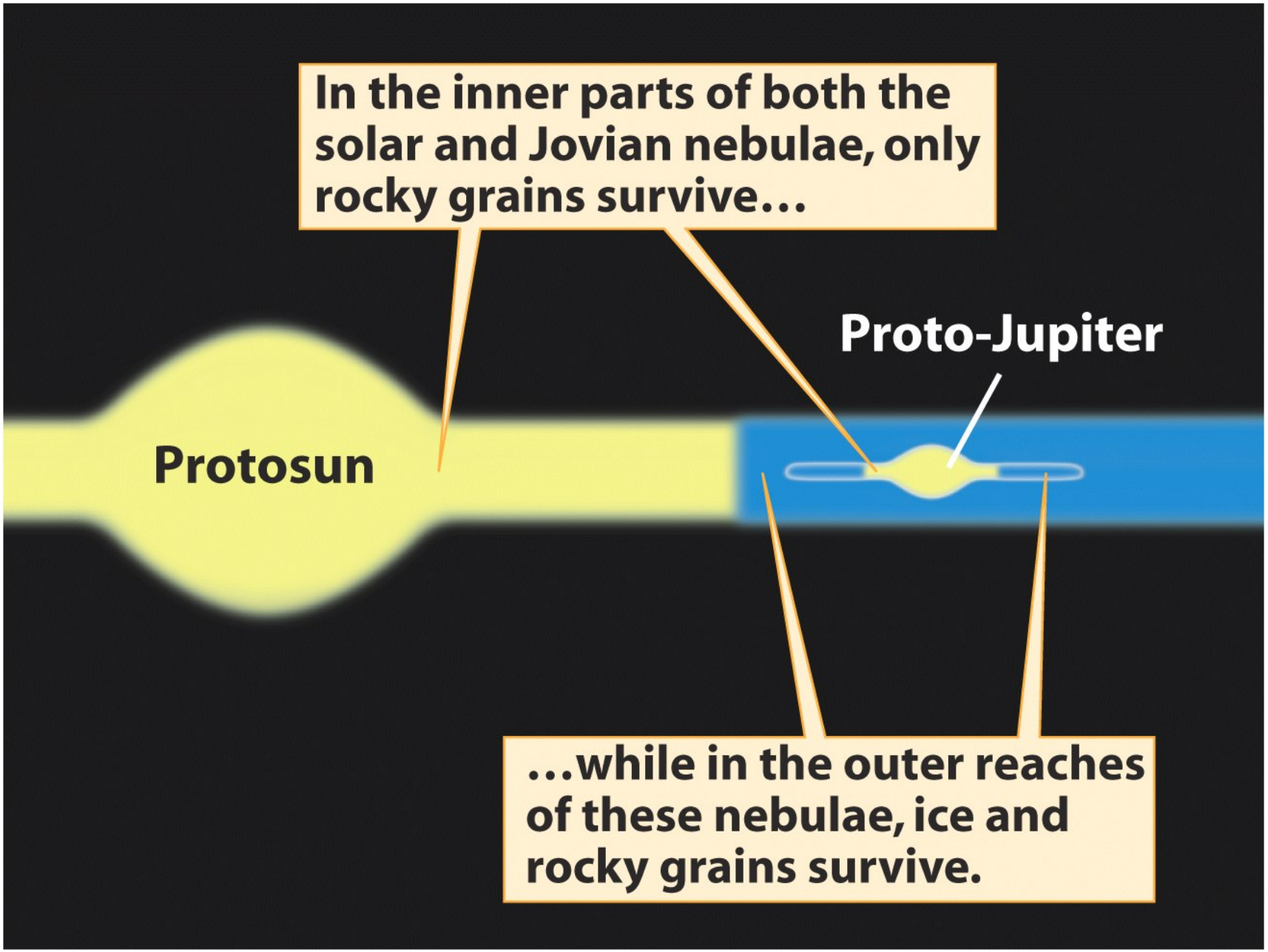


- The four Galilean satellites orbit Jupiter in the plane of its equator
- All are in synchronous rotation
- The orbital periods of the three innermost Galilean satellites, Io, Europa, and Ganymede, are in the ratio 1:2:4

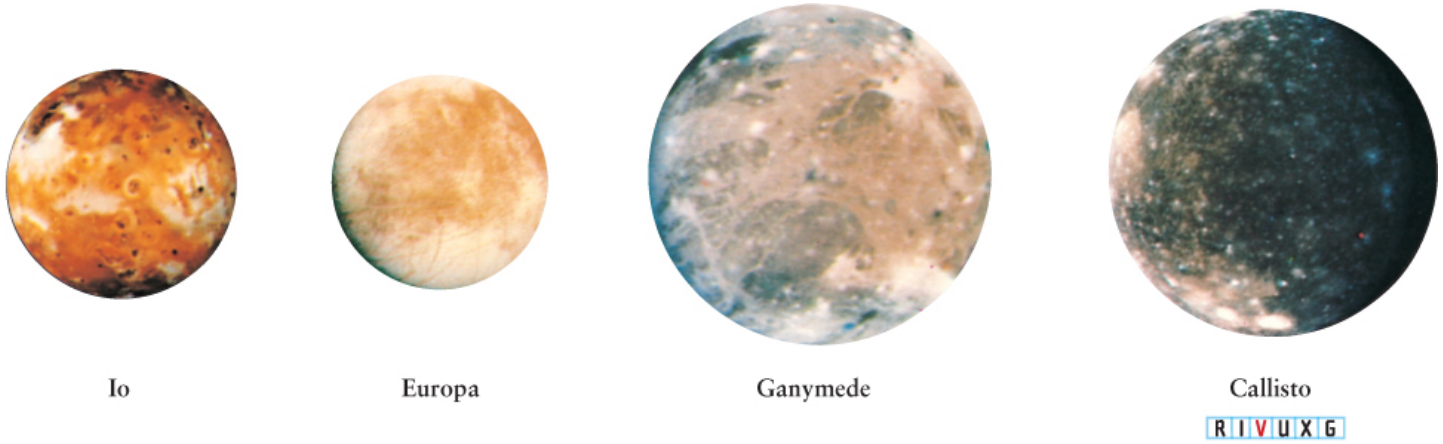
The Galilean satellites formed like a solar system in miniature



The Galilean satellites probably formed in a similar fashion to our solar system but on a smaller scale



The Galilean Satellites



- Io is covered with colorful sulfur compounds ejected from active volcanoes
- 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 the 1:2:4 ratio of orbital periods among the inner three Galilean satellites

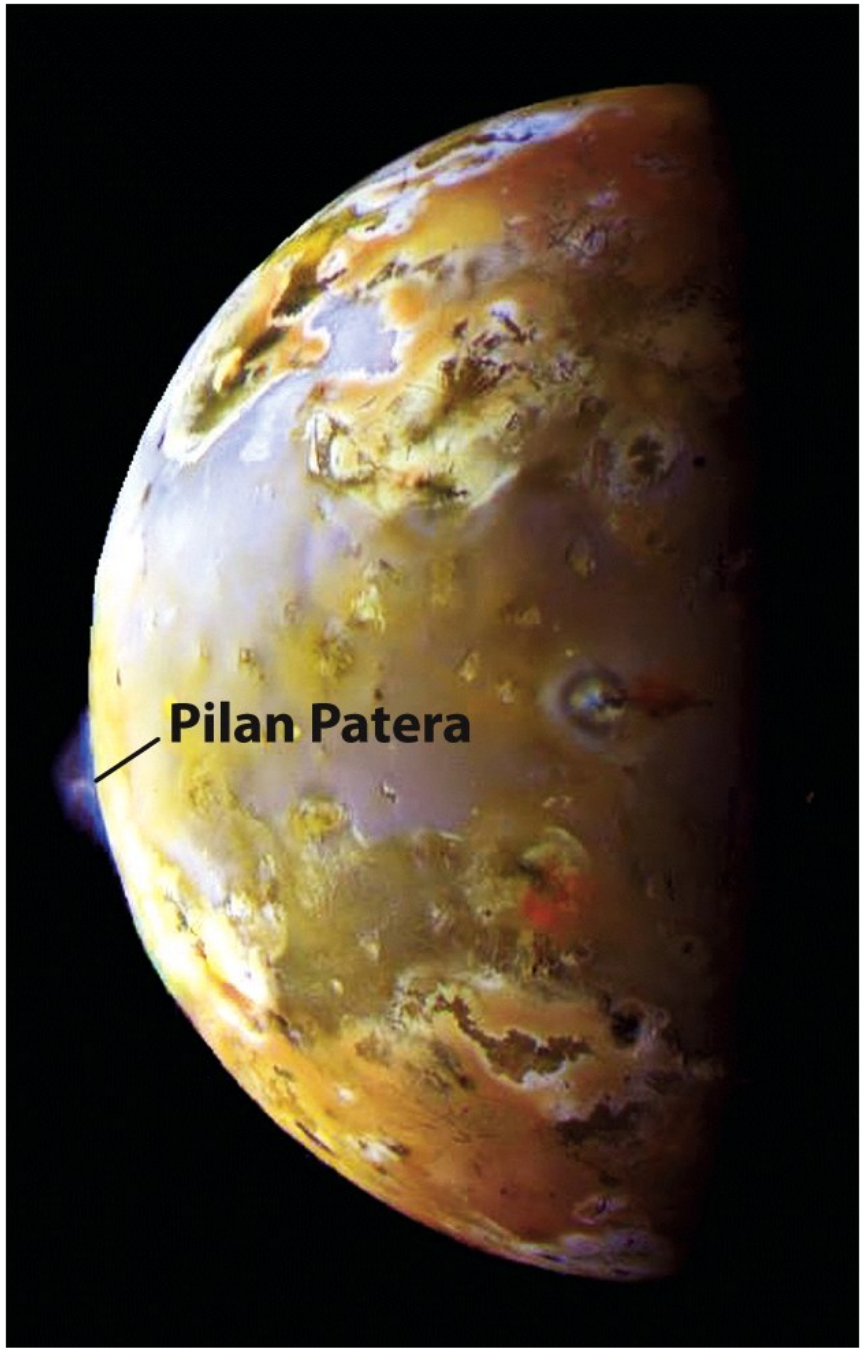


Figure 8-12b
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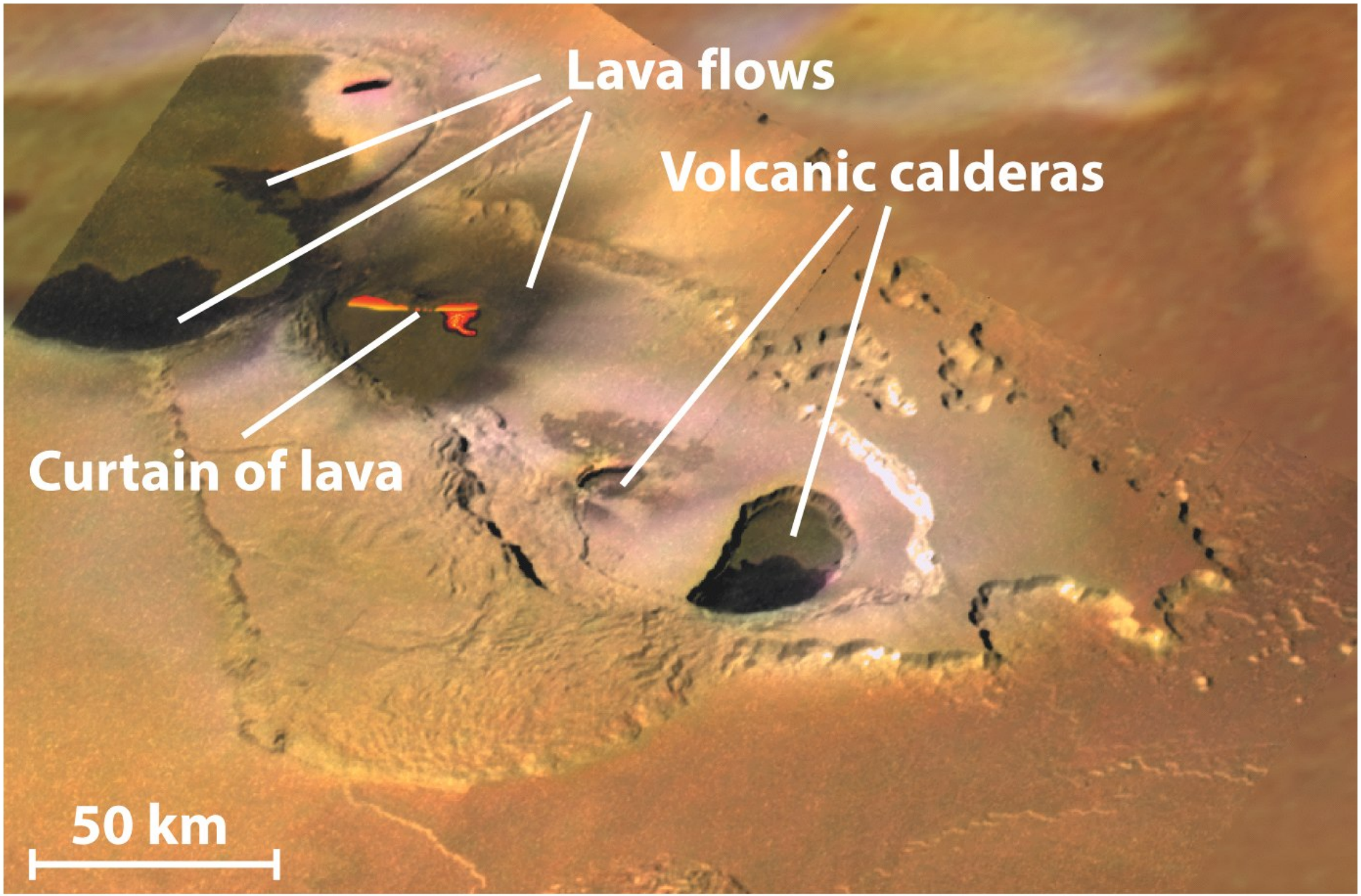
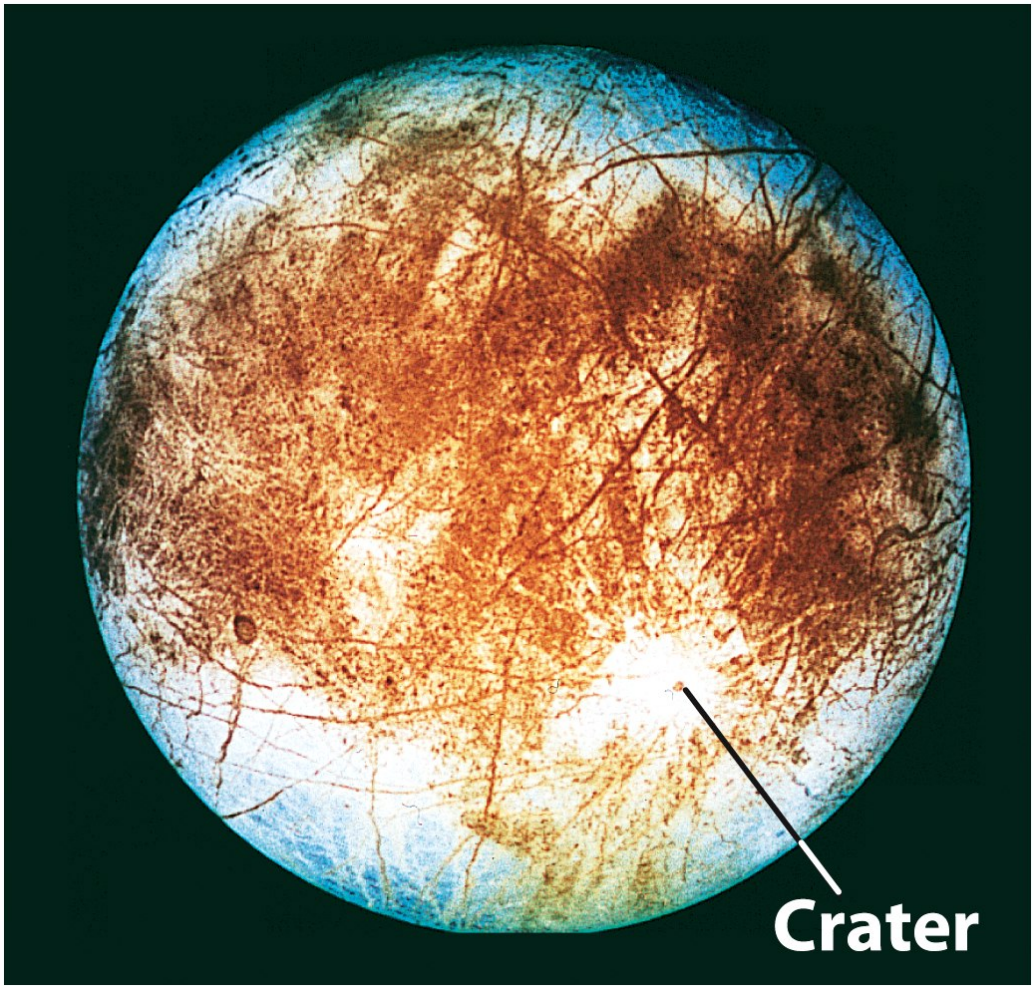

Lava flows
Volcanic calderas
Curtain of lava
50 km

Europa is covered with a smooth layer of ice that may cover a worldwide ocean



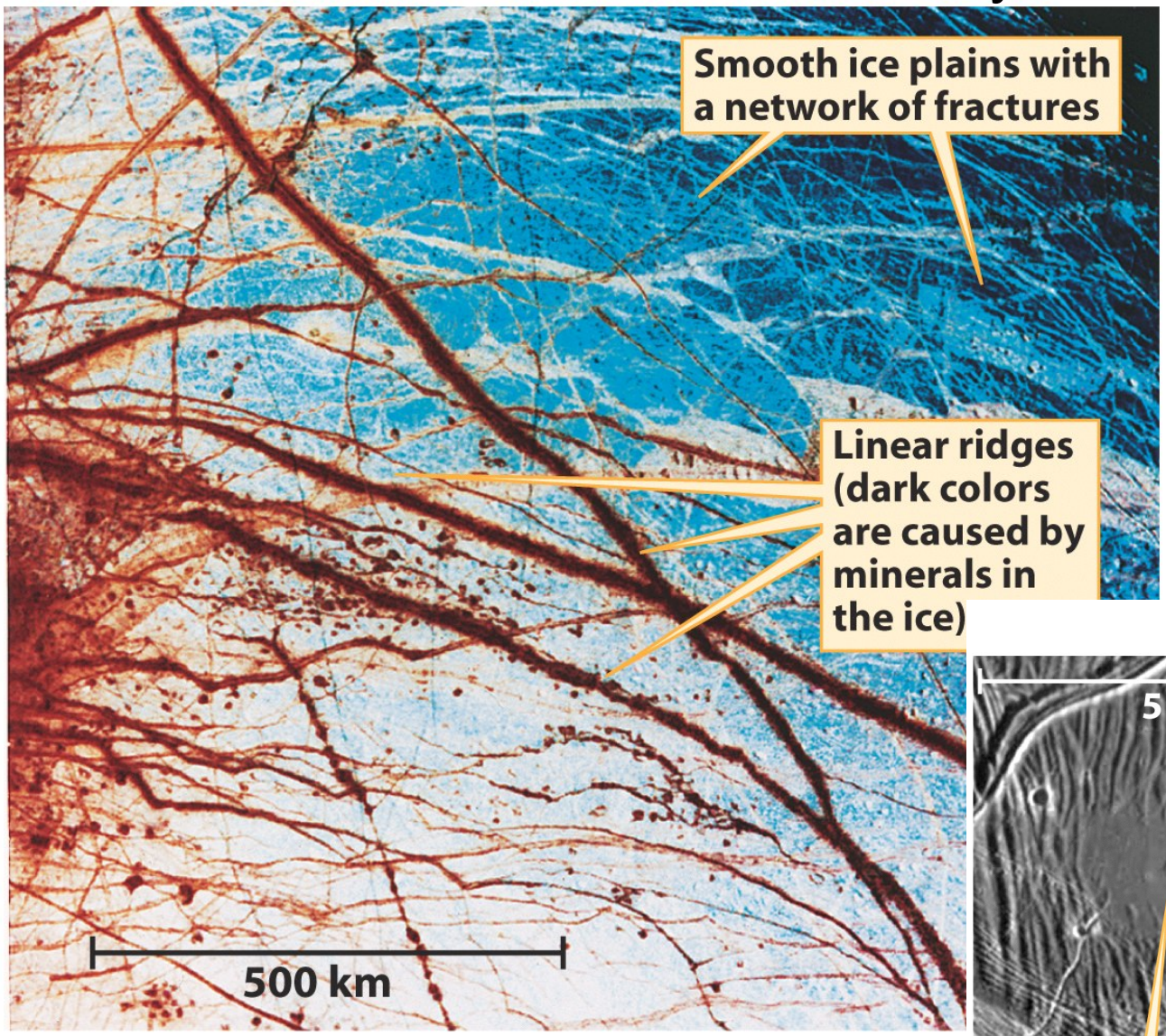
- While composed primarily of rock, Europa is covered with a smooth layer of water ice

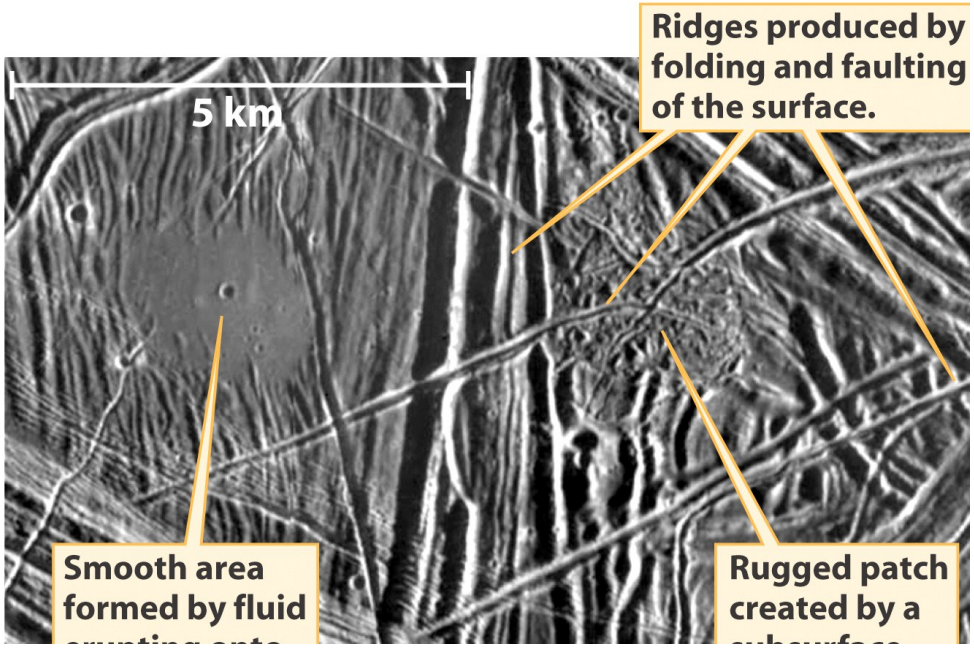
The surface has hardly any craters, indicating a geologically active history

As for Io, tidal heating is responsible for Europa's internal heat

Minerals dissolved in this ocean may explain Europa's induced magnetic field

Other indications are a worldwide network of long cracks and ice rafts that indicate a subsurface layer of liquid water or soft ice





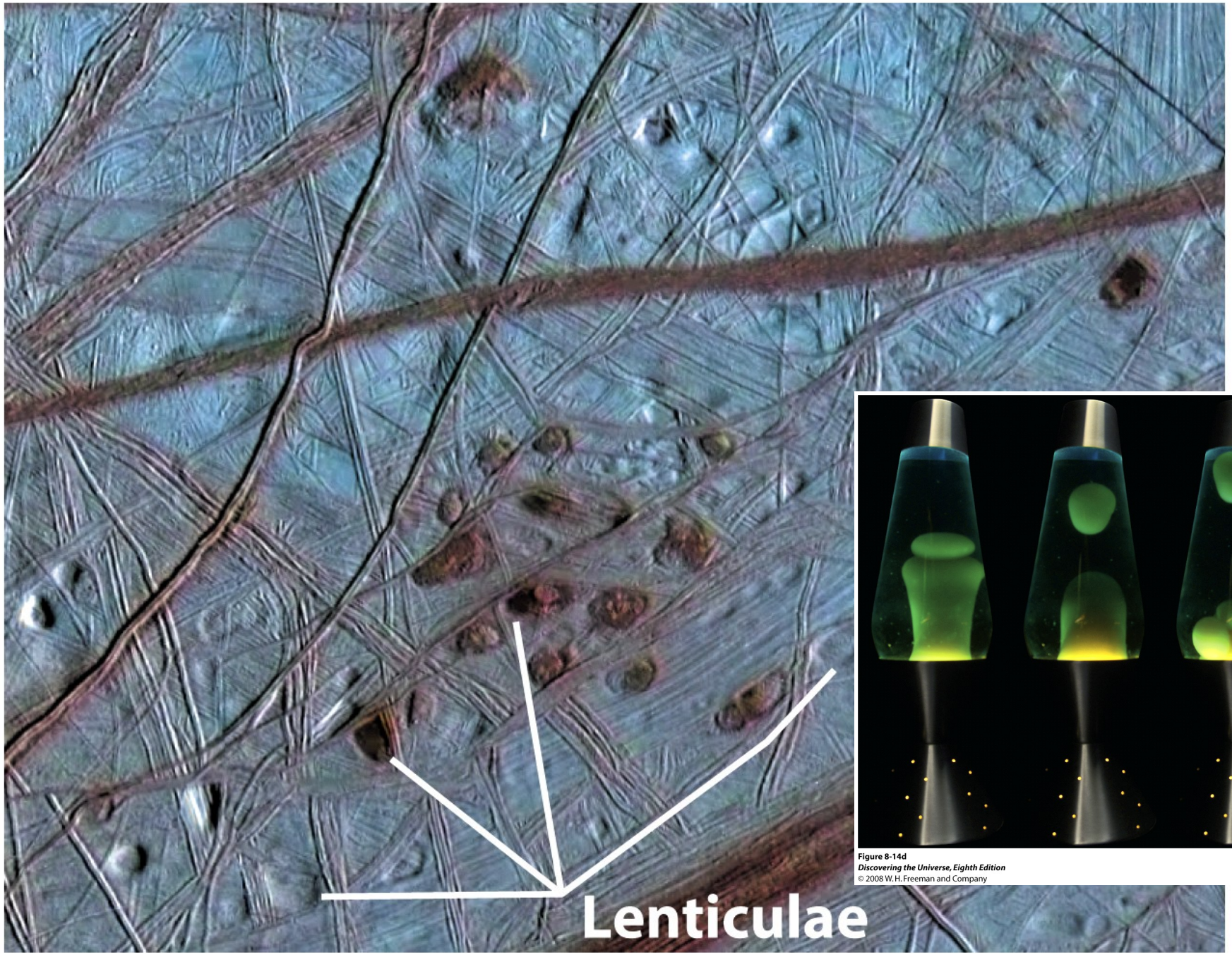


Figure 8-14c
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Figure 8-14d
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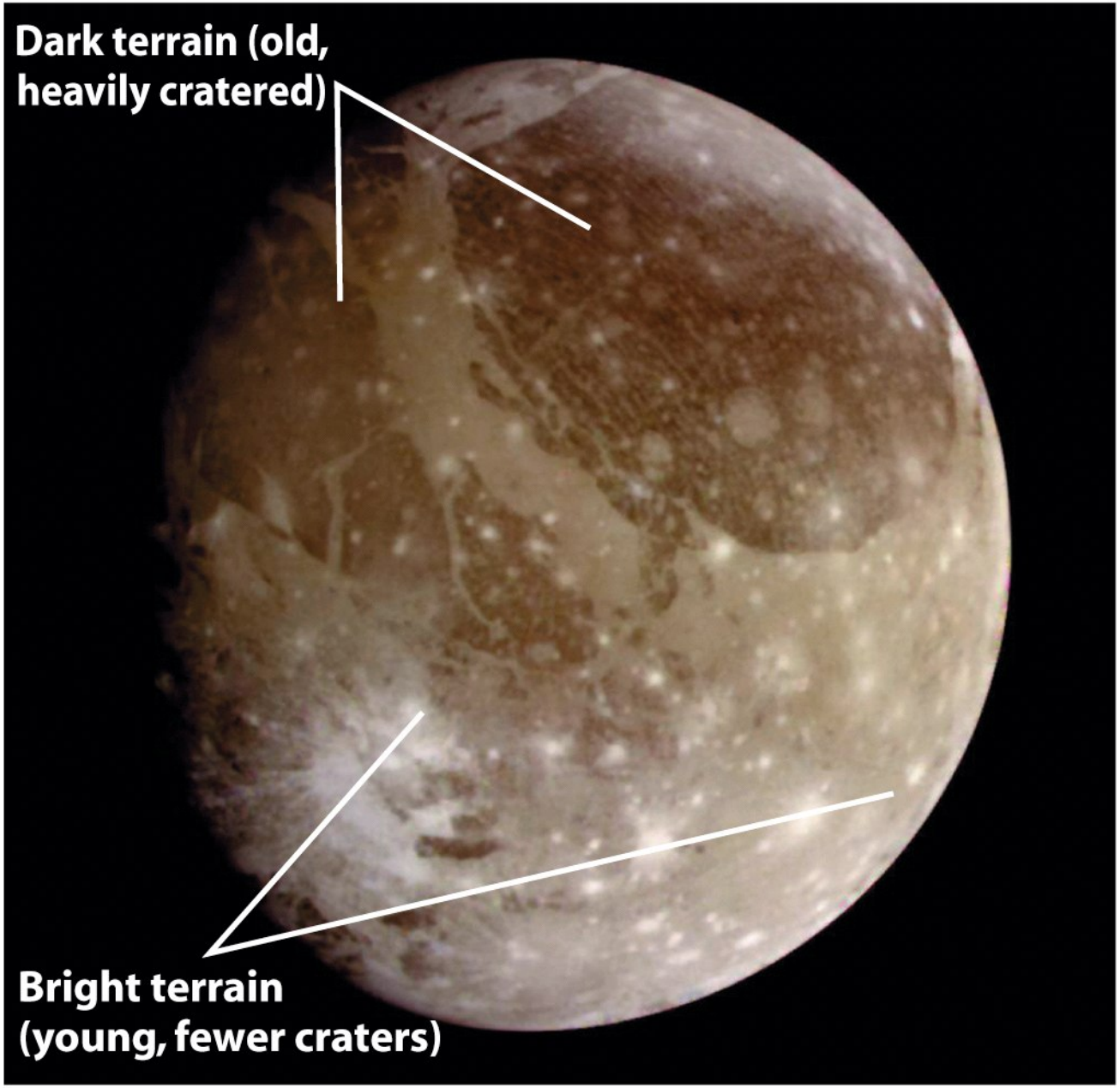
Ganymede



- 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

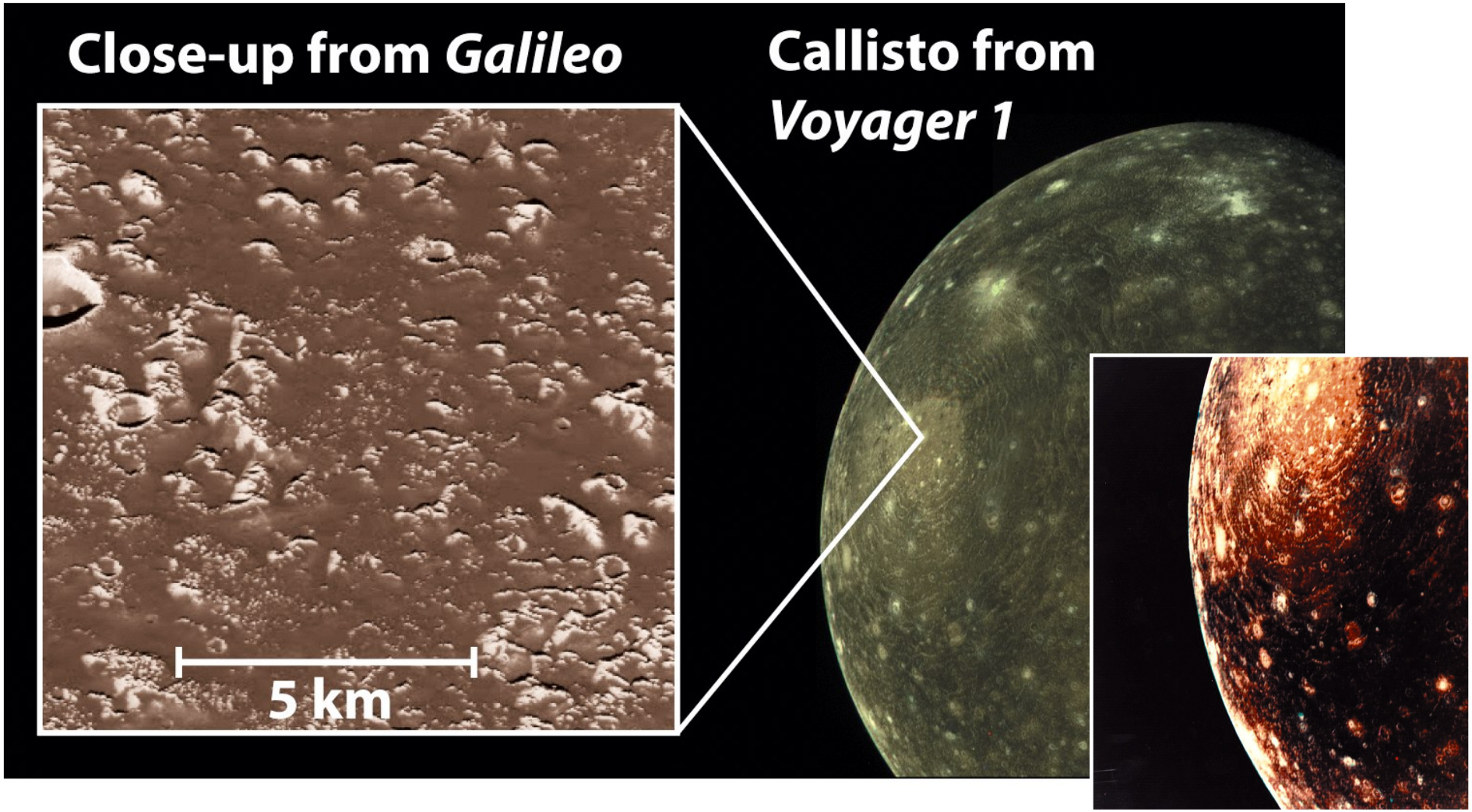


Figure 8-17a
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- Callisto has a heavily cratered crust of water ice
- The surface shows little sign of geologic activity, because there was never any significant tidal heating of Callisto
- However, some unknown processes have erased the smallest craters and blanketed the surface with a dark, dusty substance
- Magnetic field data seem to suggest that Callisto has a shallow subsurface ocean

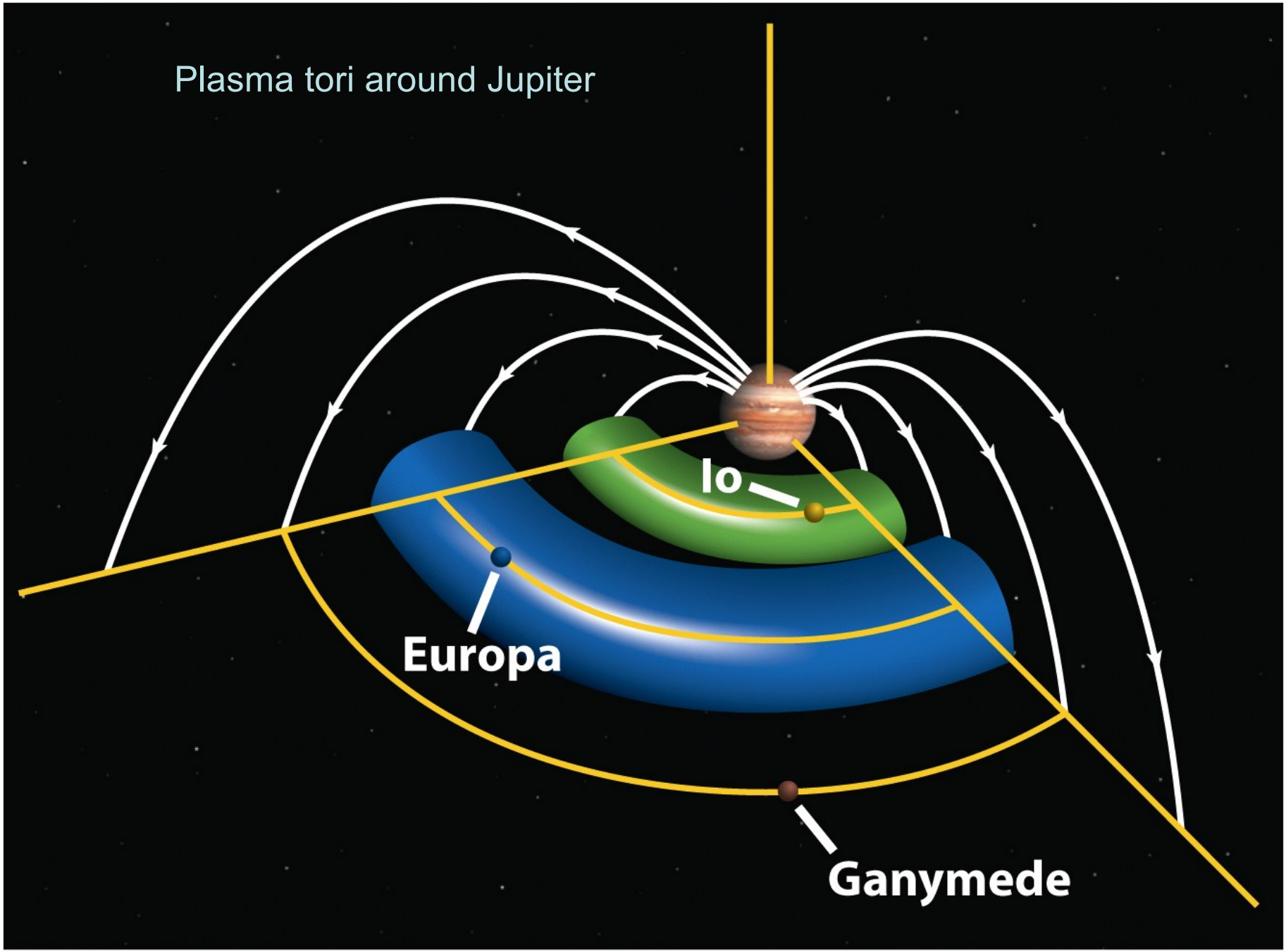

Figure 8-19b
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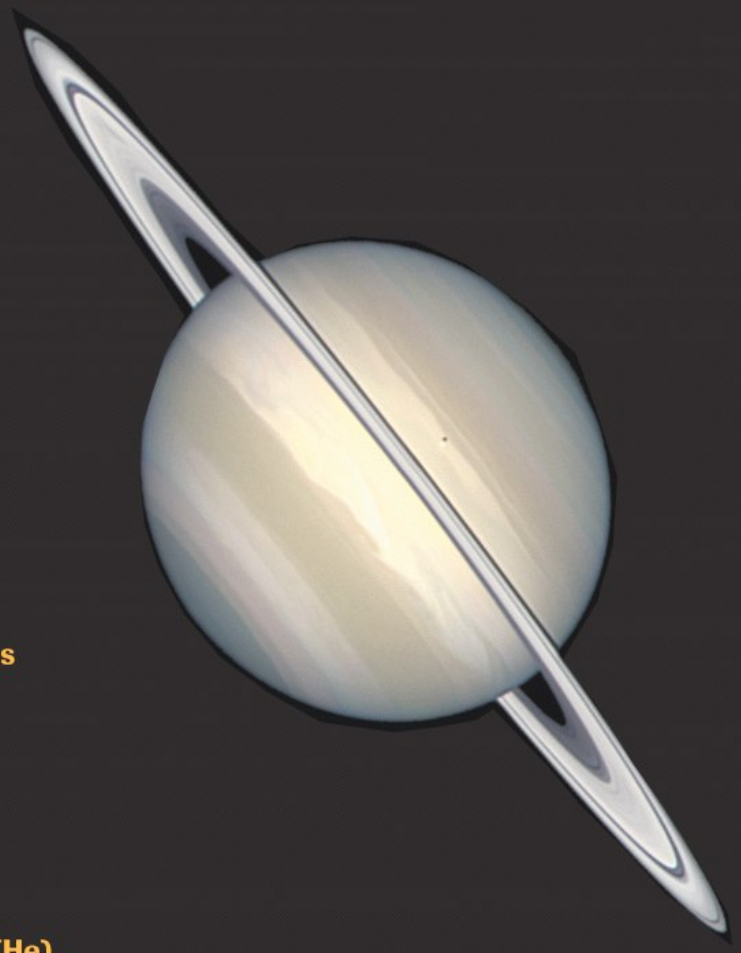
table 14-2 Saturn Data

Average distance from Sun:	9.572 AU = 1.432×10^9 km
Maximum distance from Sun:	10.081 AU = $1.508 \times 3\ 10^9$ km
Minimum distance from Sun:	9.063 AU = 1.356×10^9 km
Eccentricity of orbit:	0.053
Average orbital speed:	9.64 km/s
Orbital period:	29.37 years
Rotation period:	$10^h\ 13^m\ 59^s$ (equatorial) $10^h\ 39^m\ 25^s$ (internal)
Inclination of equator to orbit:	26.73°
Inclination of orbit to ecliptic:	2.48°
Diameter:	120,536 km = 9.449 Earth diameters (equatorial) 108,728 km = 8.523 Earth diameters (polar)
Mass:	5.685×10^{26} kg = 95.16 Earth masses
Average density:	687 kg/m^3
Escape speed:	35.5 km/s
Surface gravity (Earth = 1):	0.92
Albedo:	0.46
Average temperature at cloudtops:	−180°C = −292°F = 93 K
Atmospheric composition (by number of molecules):	96.3% hydrogen (H_2), 3.3% helium (He), 0.4% methane (CH_4), ammonia (NH_3), water vapor (H_2O), and other gases



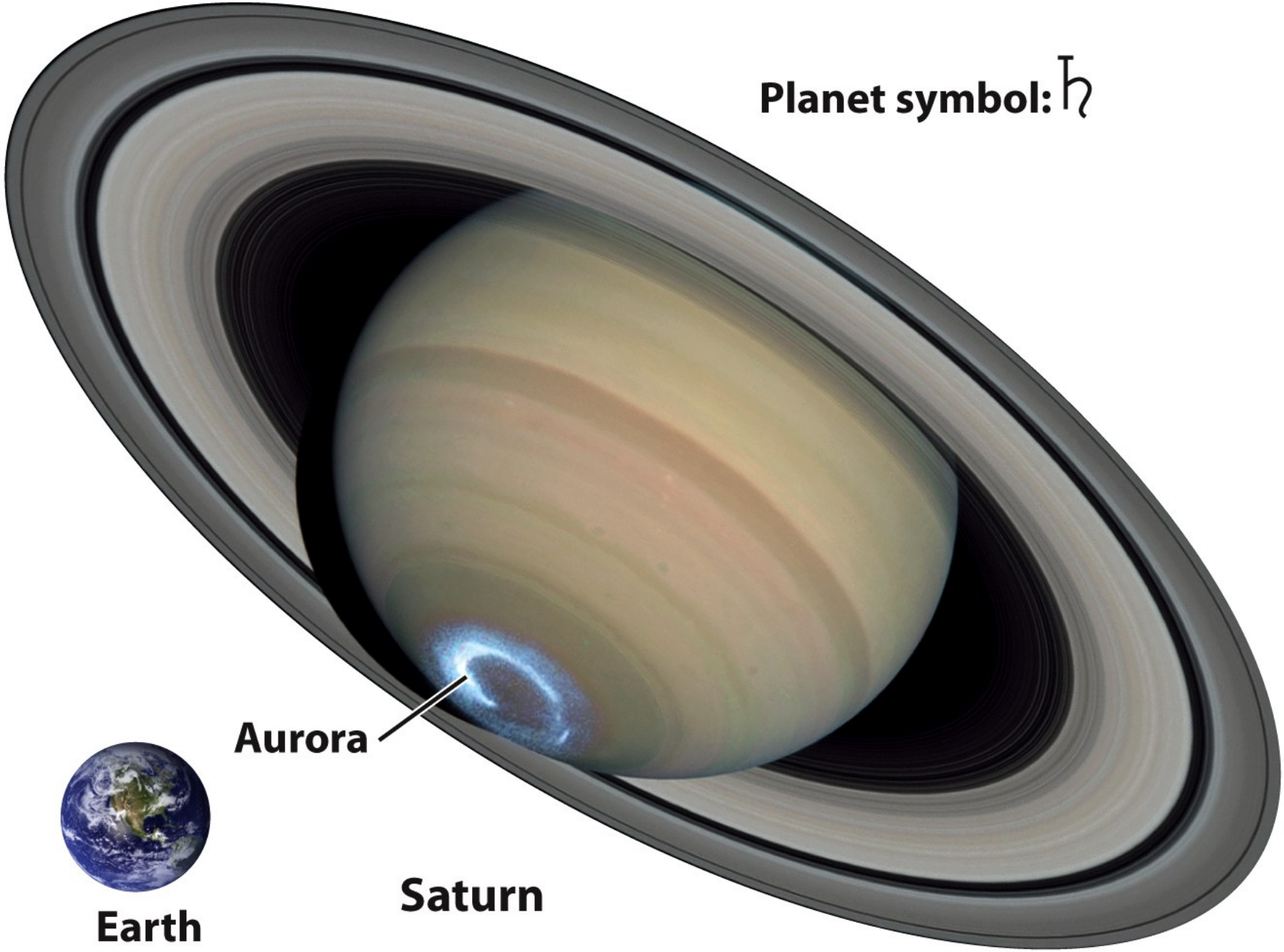


Figure 8-20
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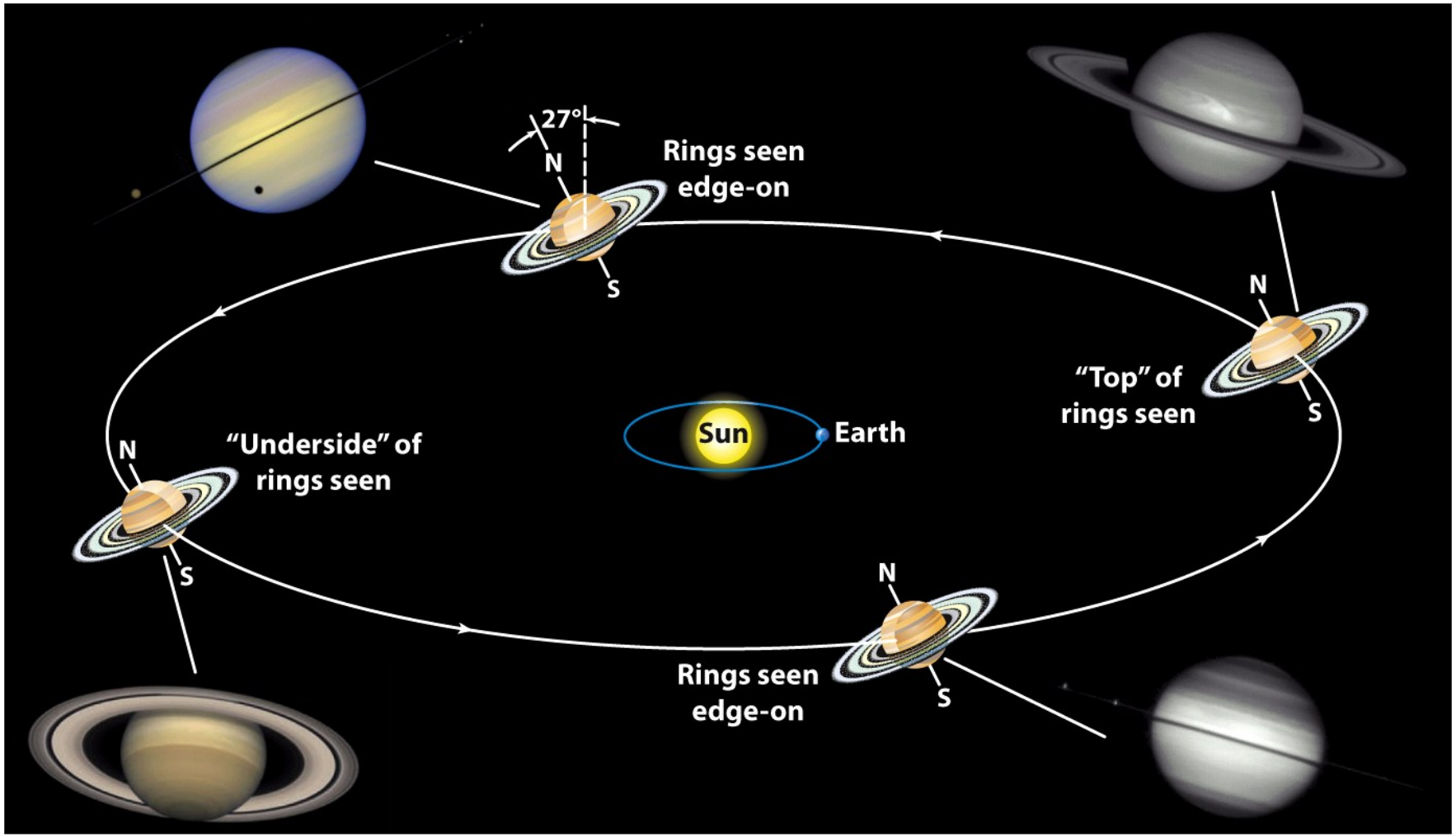

Figure 8-23
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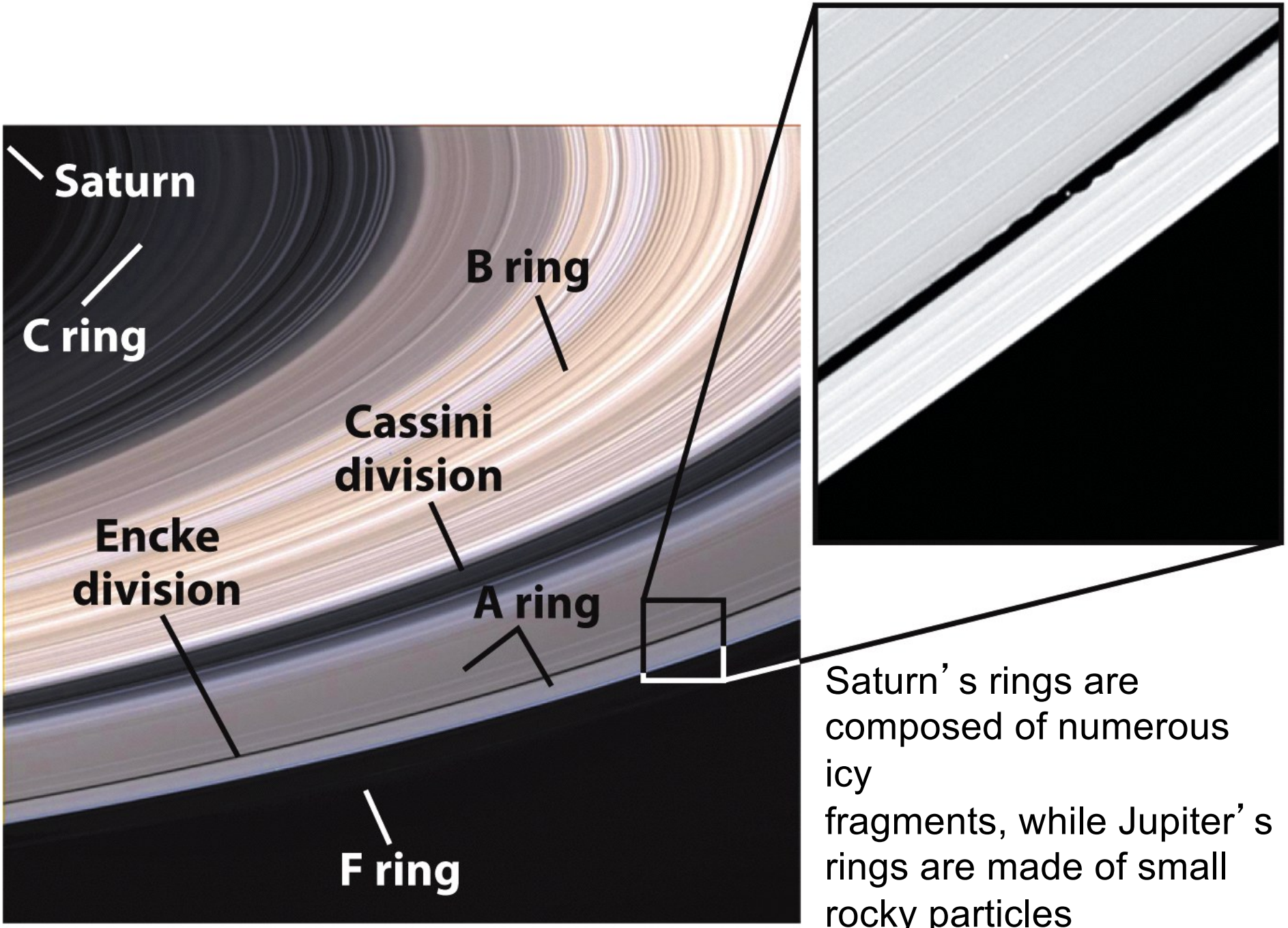
- Saturn is circled by a system of thin, broad rings lying in the plane of the planet's equator
- This system is tilted away from the plane of Saturn's orbit, which causes the rings to be seen at various angles by an Earth-based observer over the course of a Saturnian year



Saturn's rings are composed of numerous icy fragments, while Jupiter's rings are made of small rocky particles

Figure 8-24
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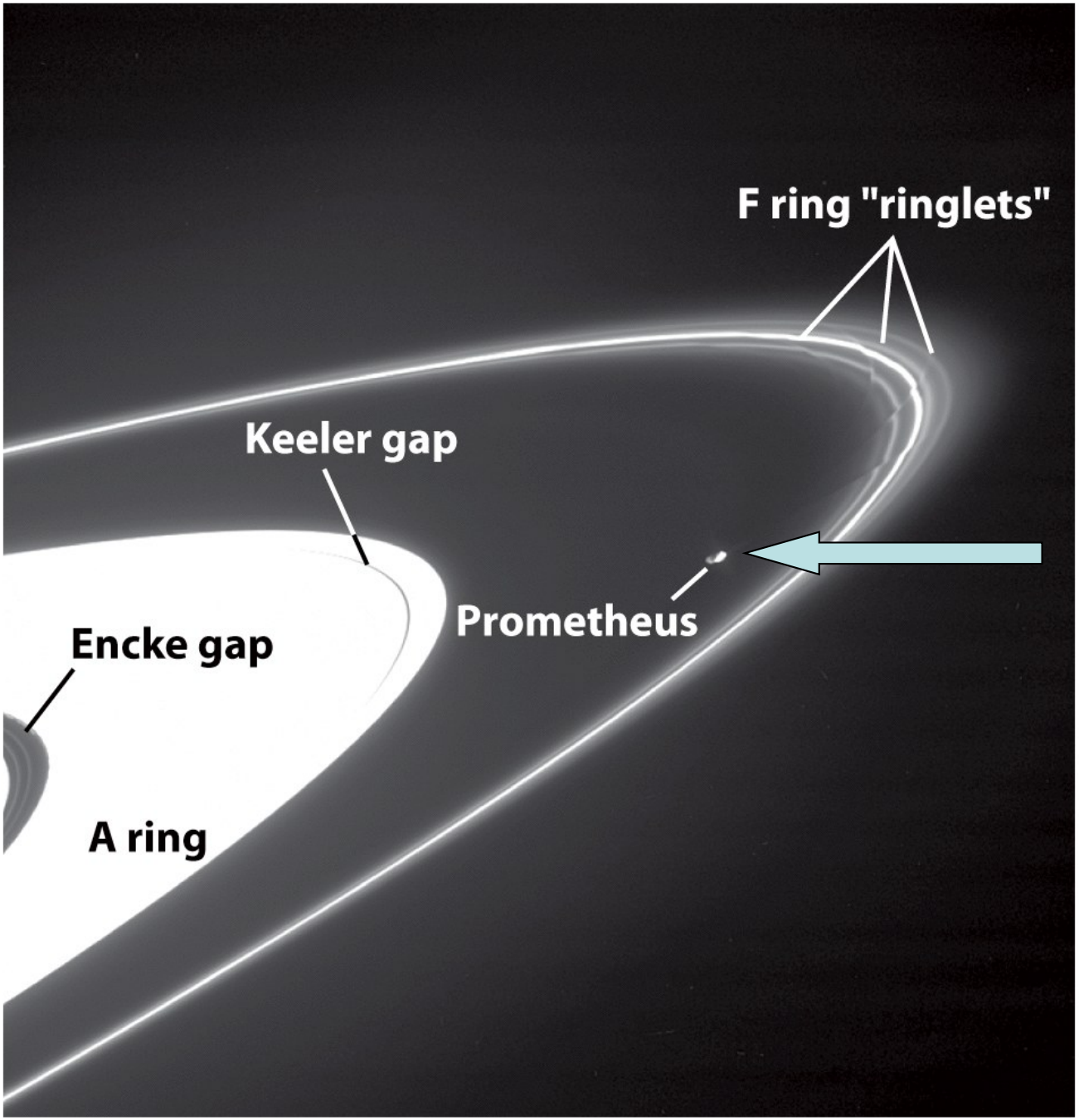

Shepherds shape the rings

Figure 8-25
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Titan has a thick, opaque atmosphere rich in methane, nitrogen, and hydrocarbons

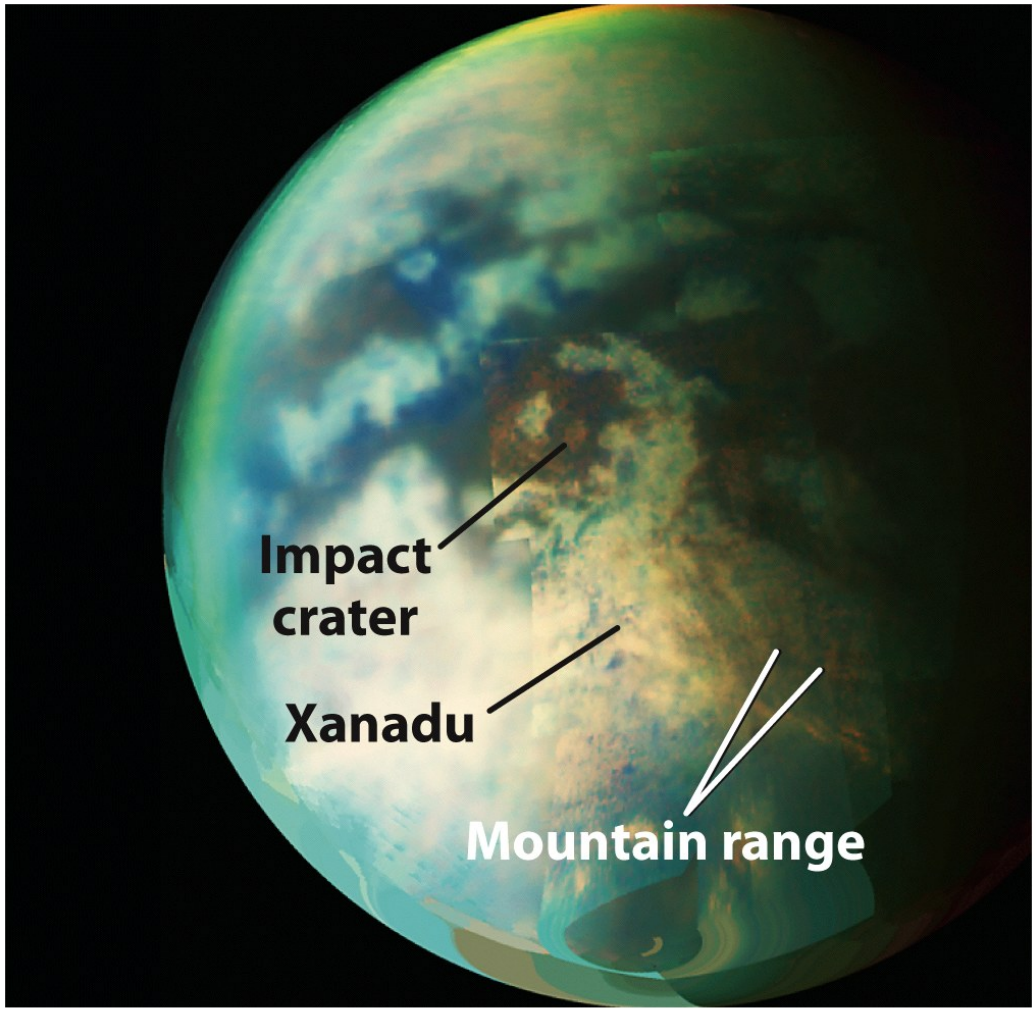

Figure 8-29b
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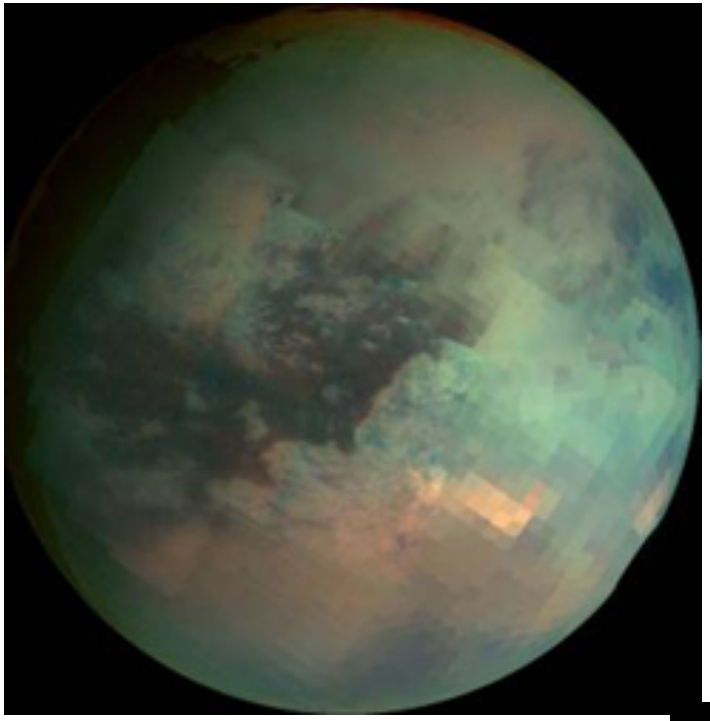
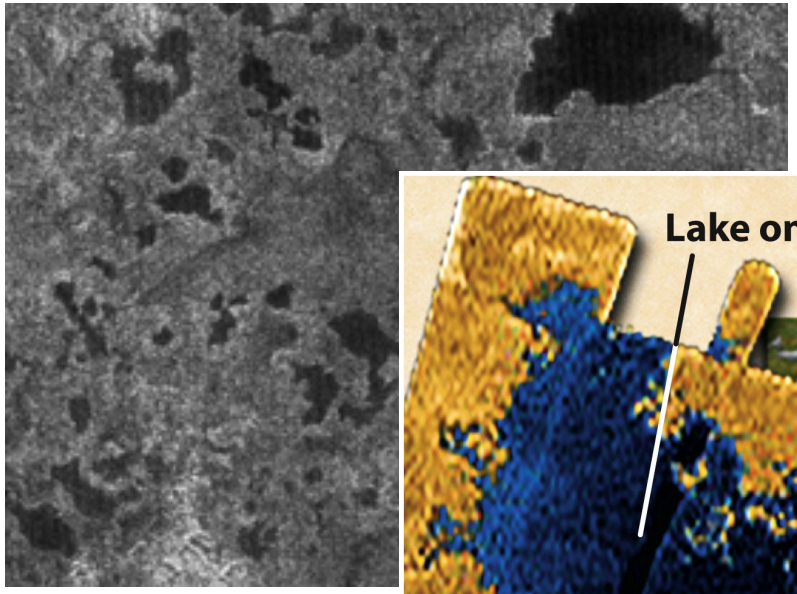
The largest Saturnian satellite, Titan, is a terrestrial world with a dense nitrogen atmosphere

A variety of hydrocarbons are produced there by the interaction of sunlight with methane

These compounds form an aerosol layer in Titan's atmosphere and possibly cover some of its surface with lakes of ethane

Cassini and the methane lakes of Titan





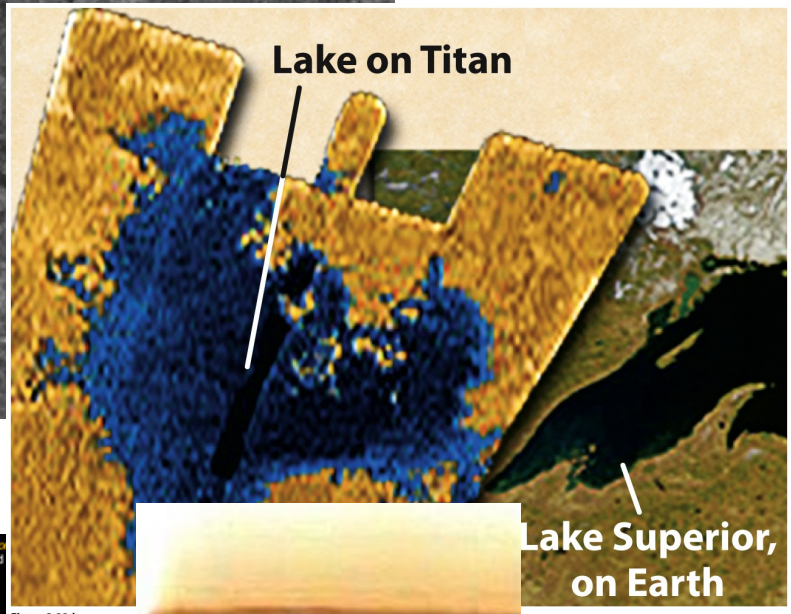


Figure 8-29d
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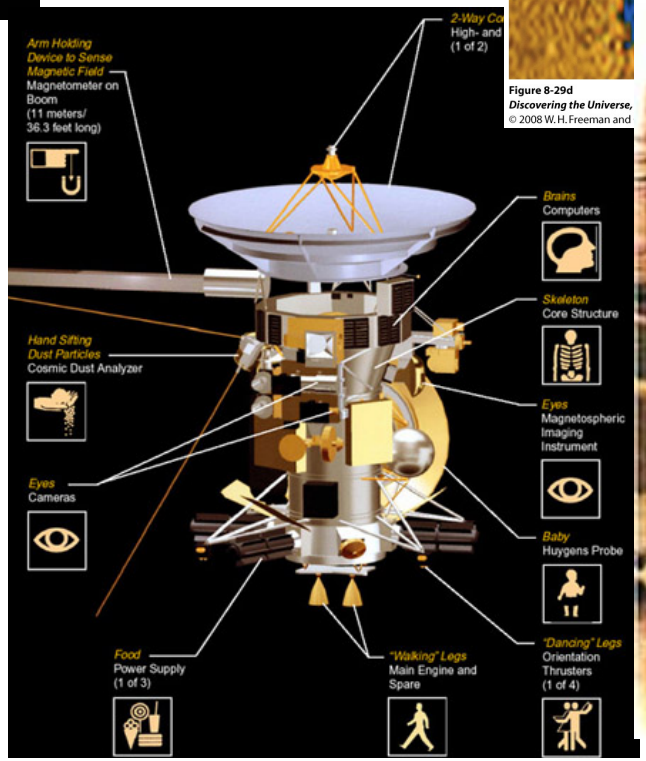
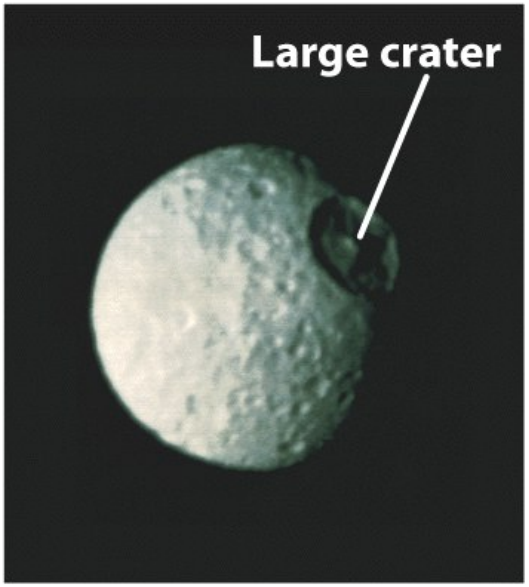
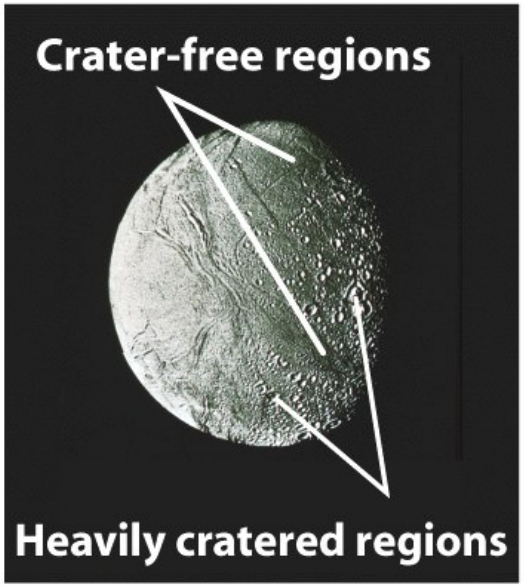
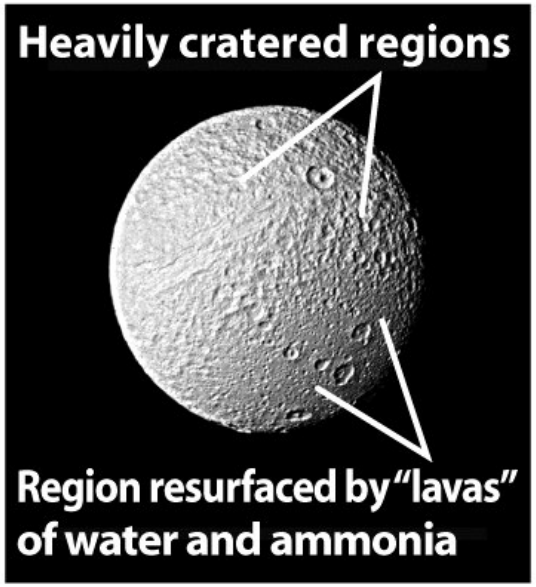




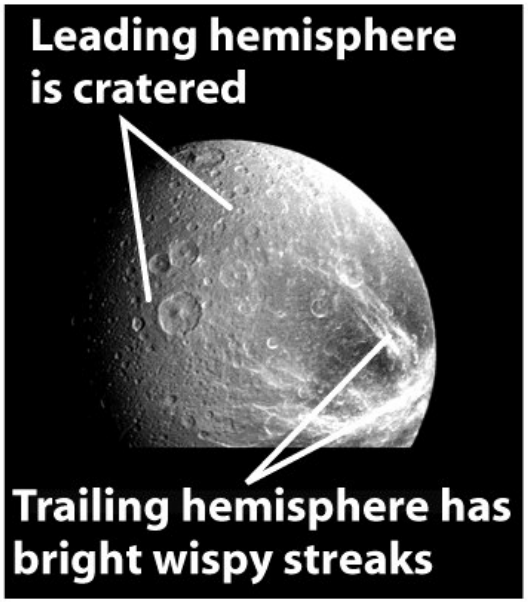
(a) Mimas
(diameter 392 km)



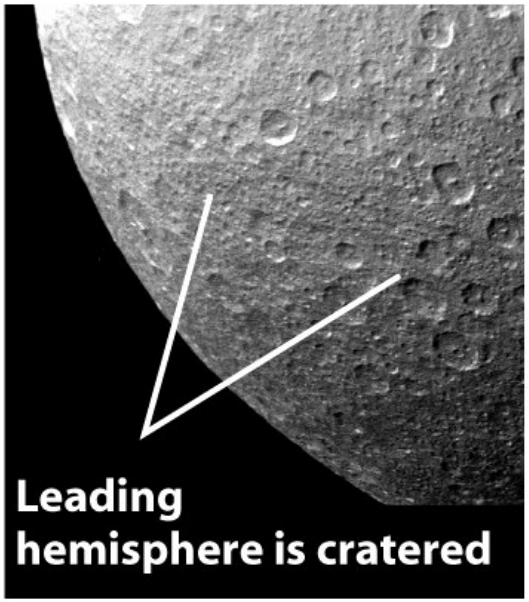
(b) Enceladus
(diameter 500 km)



(c) Tethys
(diameter 1060 km)



(d) Dione
(diameter 1120 km)



(e) Rhea
(diameter 1530 km)

(f) Iapetus
(diameter 1460 km)

The Outer Worlds

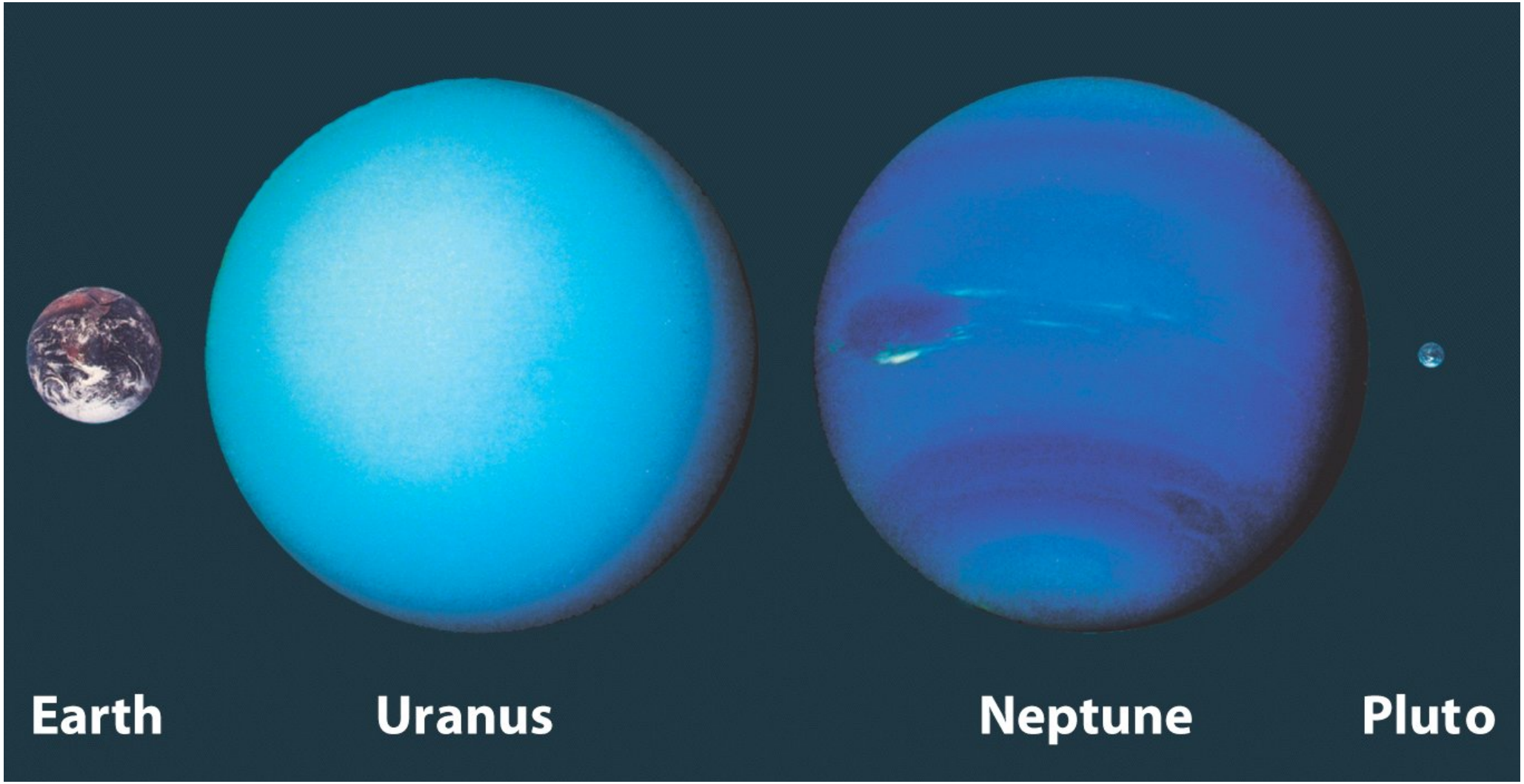


table 16-1 | Uranus Data

Average distance from Sun:	19.194 AU = 2.871×10^9 km
Maximum distance from Sun:	20.017 AU = 2.995×10^9 km
Minimum distance from Sun:	18.371 AU = 2.748×10^9 km
Eccentricity of orbit:	0.0429
Average orbital speed:	6.83 km/s
Orbital period:	84.099 years
Rotation period (internal):	17.24 hours
Inclination of equator to orbit:	97.86°
Inclination of orbit to ecliptic:	0.77°
Diameter:	51,118 km = 4.007 Earth diameters (equatorial)
Mass:	8.682×10^{25} kg = 14.53 Earth masses
Average density:	1318 kg/m^3
Escape speed:	21.3 km/s
Surface gravity (Earth = 1):	0.90
Albedo:	0.56
Average temperature at cloudtops:	–218°C = –360°F = 55 K
Atmospheric composition (by number of molecules):	82.5% hydrogen (H_2), 15.2% helium (He), 2.3% methane (CH_4)

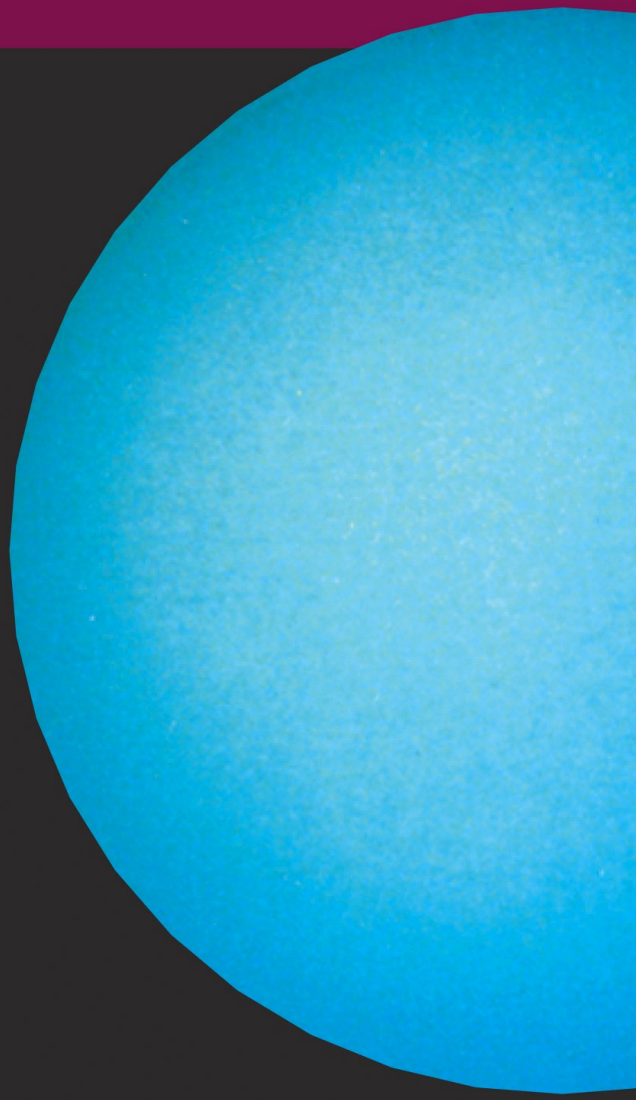
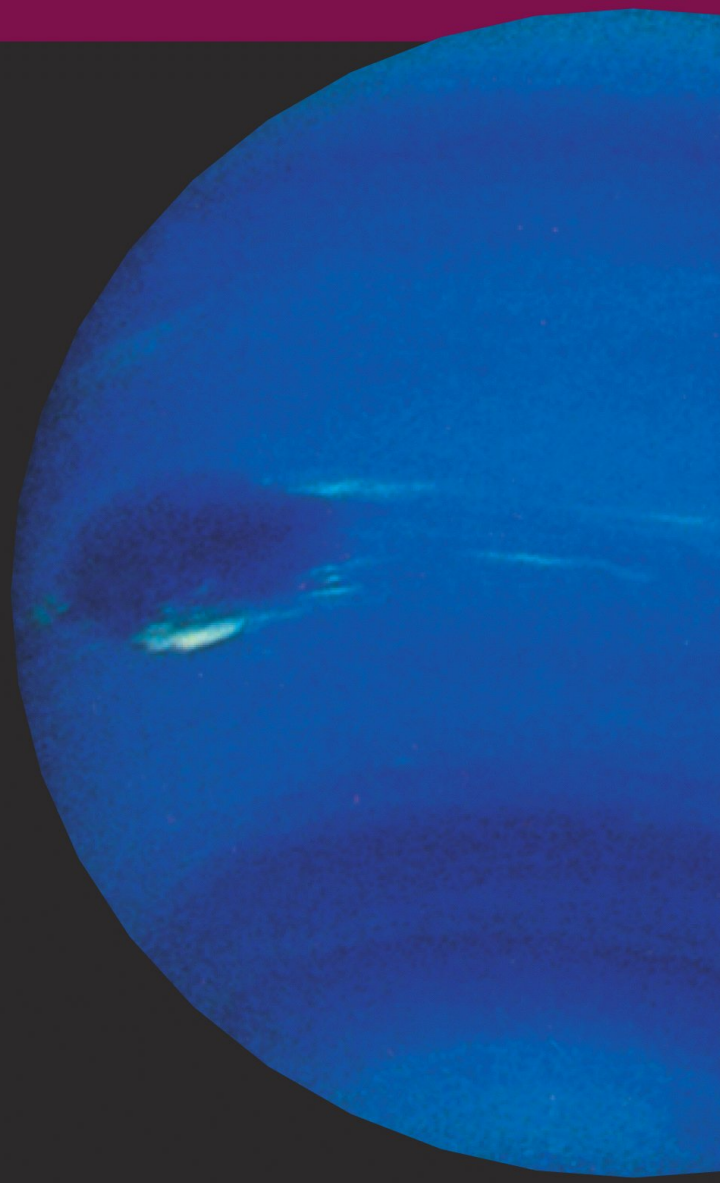


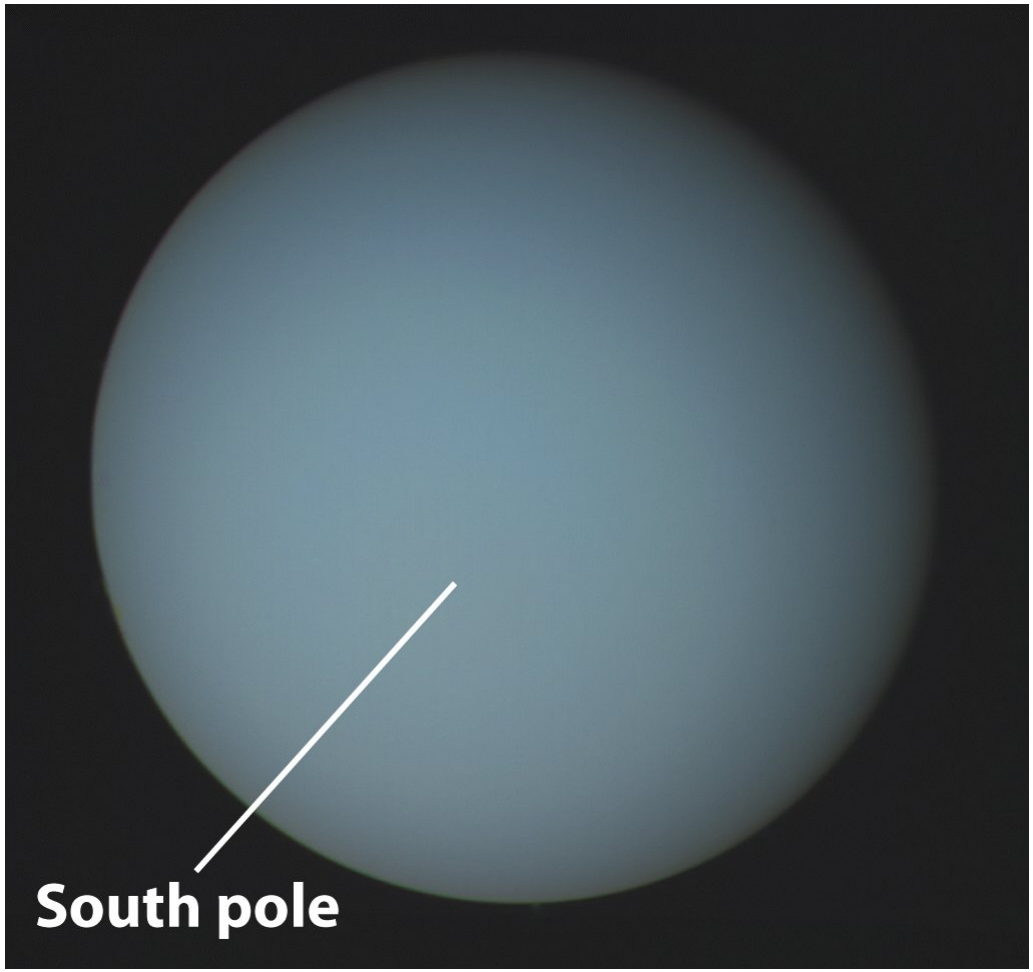
table 16-2 Neptune Data

Average distance from Sun:	30.066 AU = 4.498×10^9 km
Maximum distance from Sun:	30.367 AU = 4.543×10^9 km
Minimum distance from Sun:	29.765 AU = 4.453×10^9 km
Eccentricity of orbit:	0.010
Minimum distance from Sun:	29.765 AU = 4.453×10^9 km
Eccentricity of orbit:	0.010
Average orbital speed:	5.5 km/s
Orbital period:	164.86 years
Rotation period (internal):	16.11 hours
Inclination of equator to orbit:	29.56°
Inclination of orbit to ecliptic:	1.77°
Diameter:	49,528 km = 3.883 Earth diameters (equatorial)
Mass:	1.024×10^{26} kg = 17.15 Earth masses
Average density:	1638 kg/m^3
Escape speed:	23.5 km/s
Surface gravity (Earth = 1):	1.1
Albedo:	0.51
Average temperature at cloudtops:	−218°C = −360°F = 55 K
Atmospheric composition (by number of molecules):	79% hydrogen (H_2), 18% helium (He), 3% methane (CH_4)



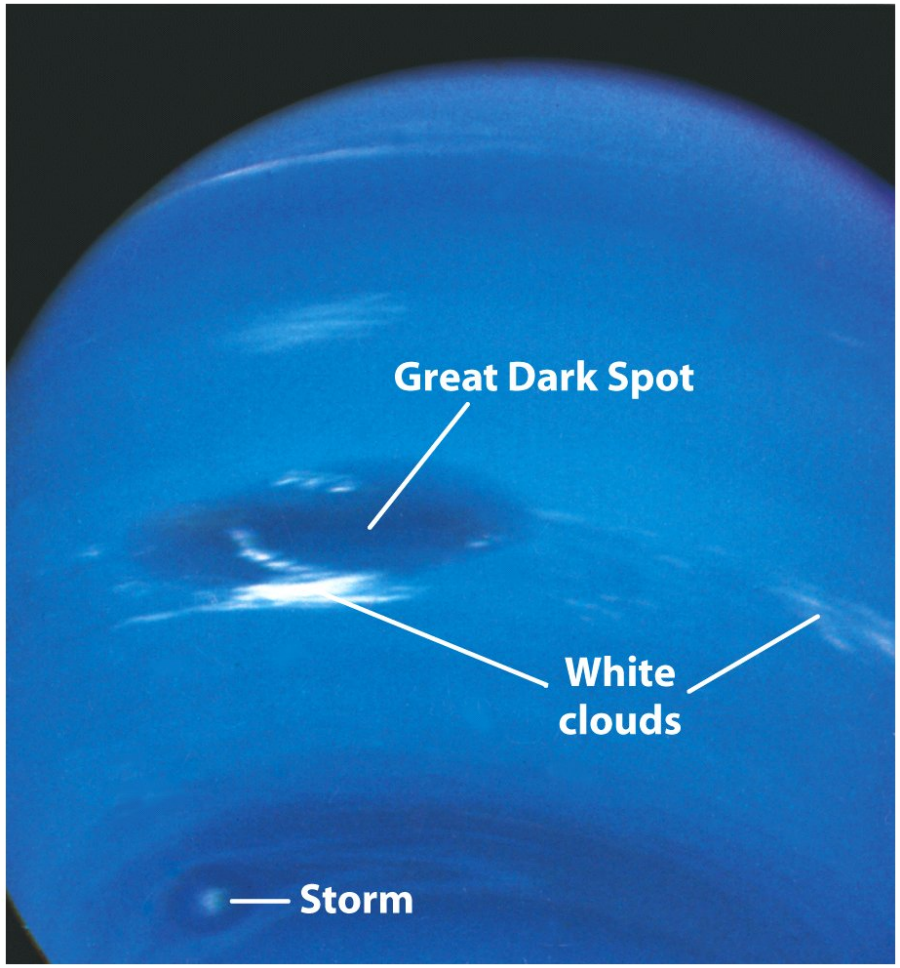
Uranus was discovered by chance, but Neptune’s existence was predicted by applying Newtonian mechanics

Uranus is nearly featureless and has an unusually tilted axis of rotation

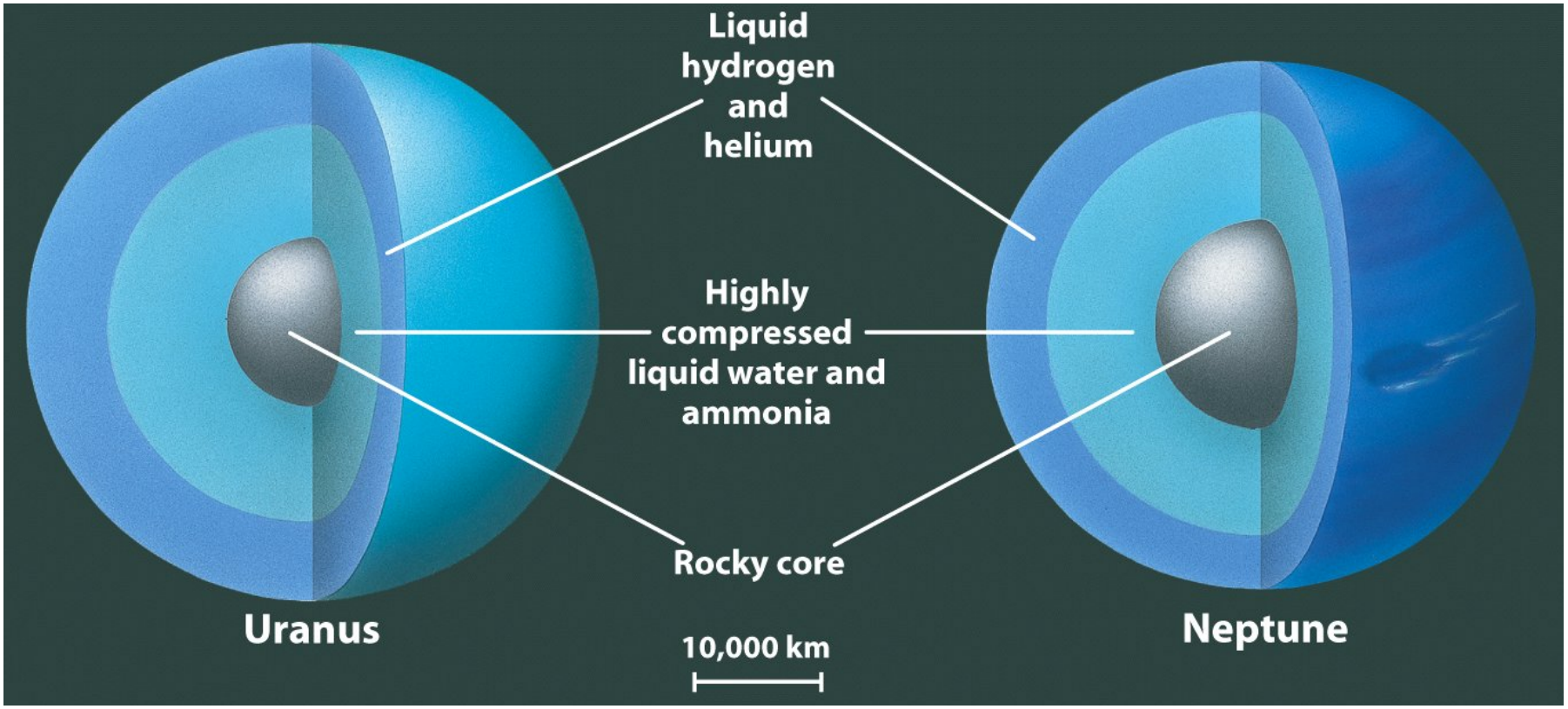


- Both Uranus and Neptune have atmospheres composed primarily of hydrogen, helium, and a few percent methane
- Methane absorbs red light, giving Uranus and Neptune their greenish-blue color

Neptune is a cold, bluish world with Jupiterlike atmospheric features

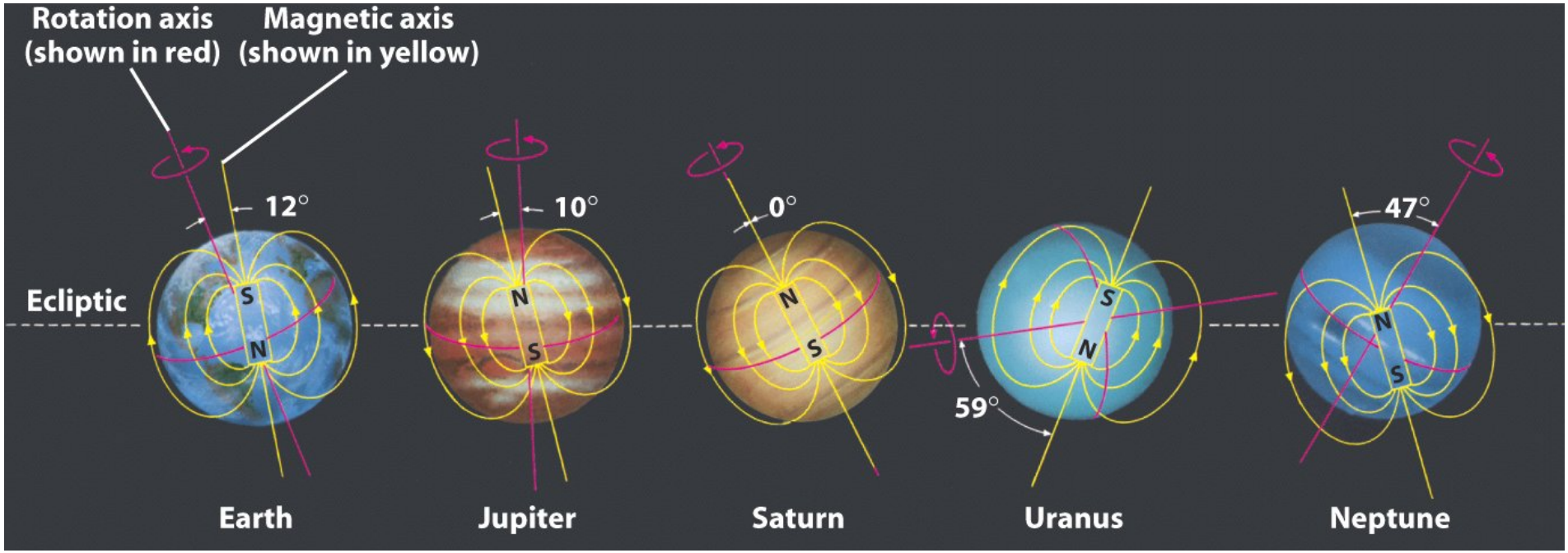


Uranus and Neptune contain a higher proportion of heavy elements than Jupiter and Saturn



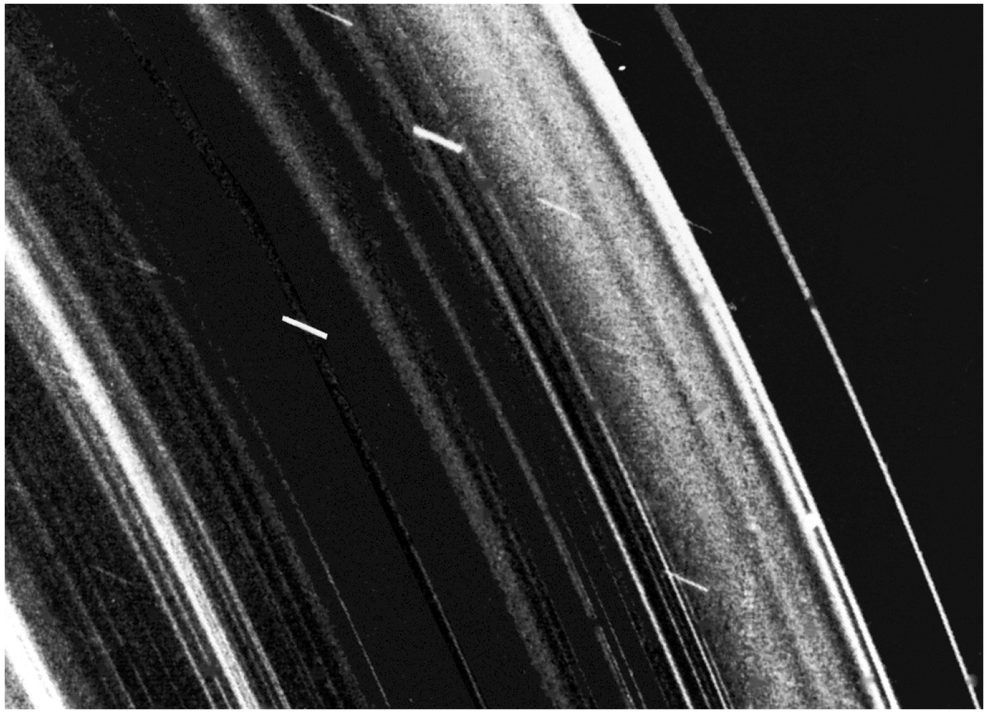
- Both Uranus and Neptune may have a rocky core surrounded by a mantle of water and ammonia
- Electric currents in the mantles may generate the magnetic fields of the planets

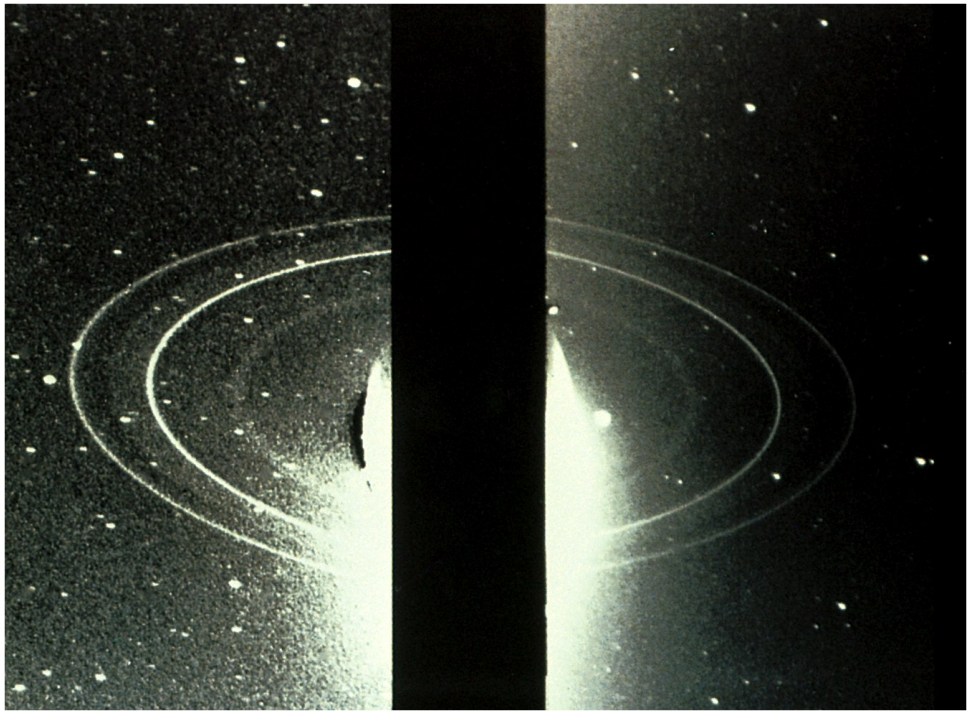
The magnetic fields of both Uranus and Neptune are oriented at unusual angles



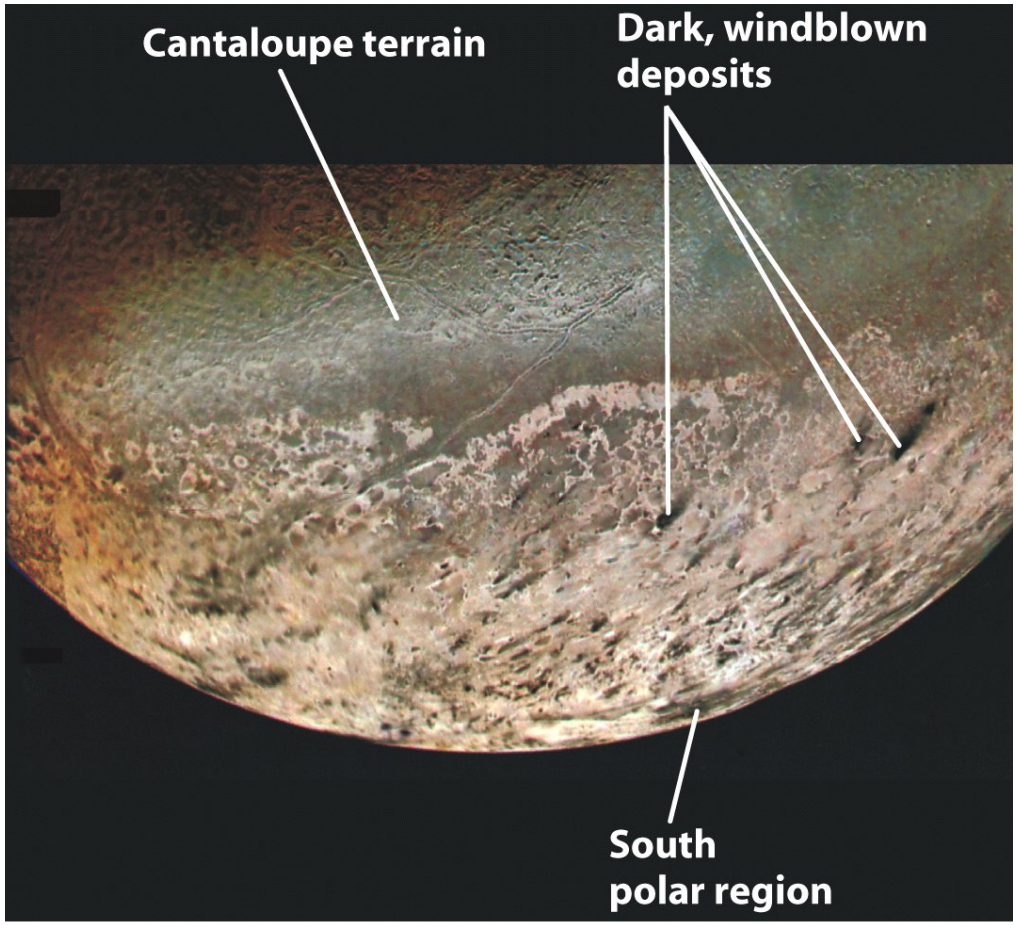
- The magnetic axes of both Uranus and Neptune are steeply inclined from their axes of rotation
- The magnetic and rotational axes of all the other planets are more nearly parallel
- The magnetic fields of Uranus and Neptune are also offset from the centers of the planets

Uranus and Neptune each have a system of thin, dark rings





Triton is a frigid, icy world with a young surface and a tenuous atmosphere



- Neptune has 13 satellites, one of which (Triton) is comparable in size to our Moon or the Galilean satellites of Jupiter
- Triton has a young, icy surface indicative of tectonic activity
- The energy for this activity may have been provided by tidal heating that occurred when Triton was captured by Neptune's gravity into a retrograde orbit
- Triton has a tenuous nitrogen atmosphere

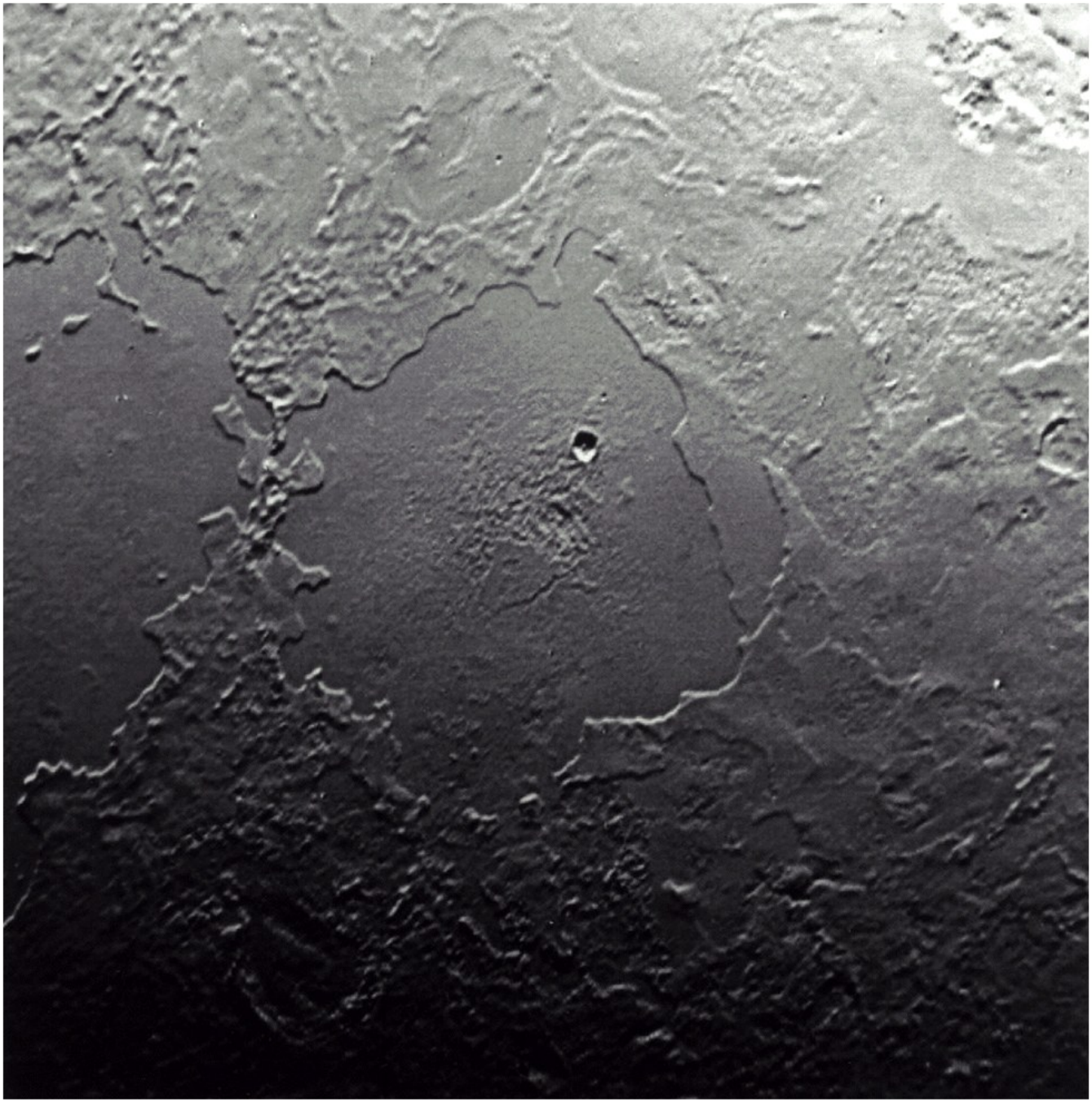


Figure 8-42
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The capture and destruction of Triton

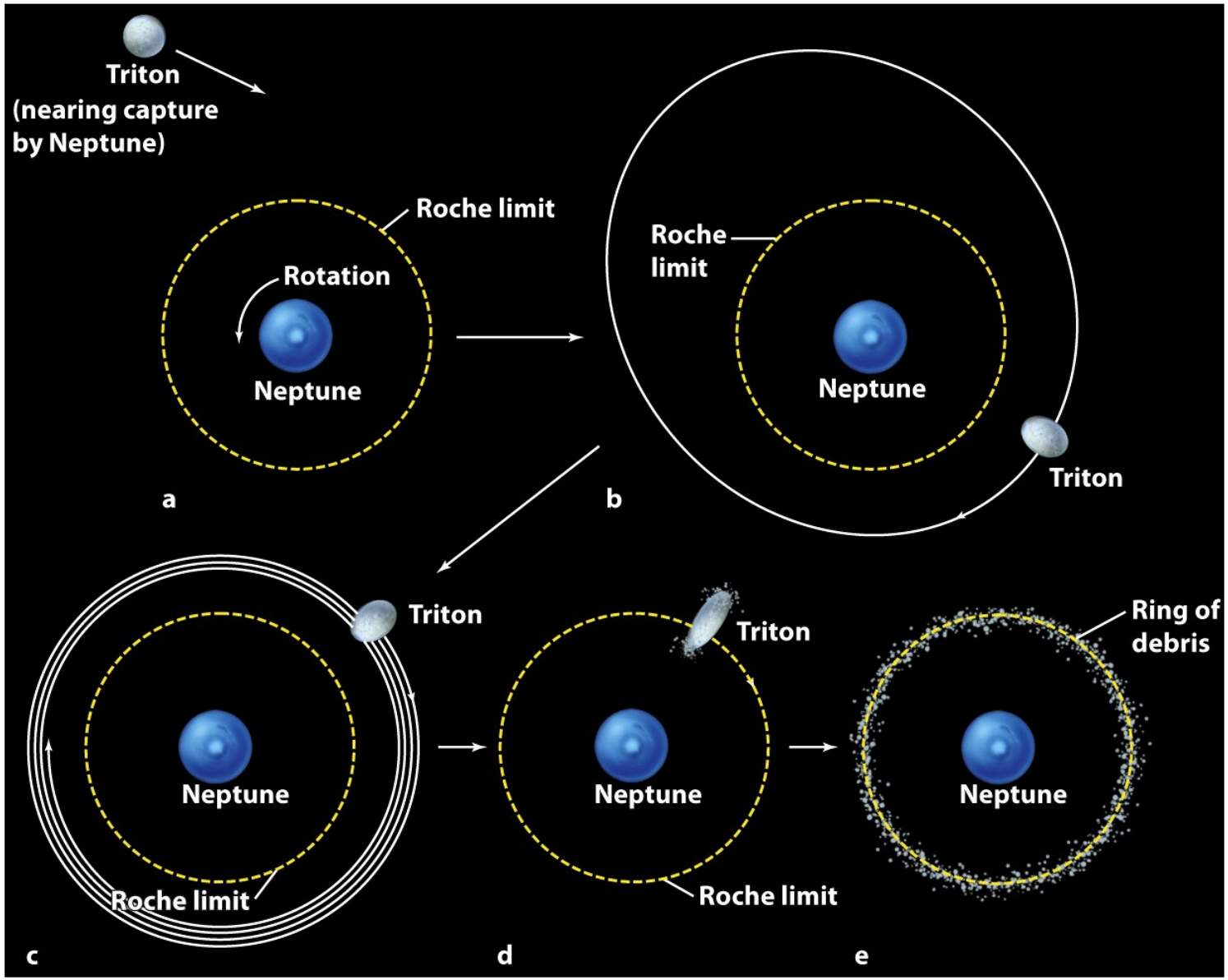

Figure 8-43
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The Outer Planets: A Comparison

	Interior	Surface	Rings	Atmosphere	Magnetic Field
Jupiter	Terrestrial core, liquid metallic hydrogen shell, liquid hydrogen mantle	No solid surface, atmosphere gradually thickens to liquid state, belt and zone structure, hurricane-like features	Yes	Primarily H, He	19,000 × Earth's total field; at its cloud layer, 14 × stronger than Earth's surface field
Saturn	Similar to Jupiter, with bigger terrestrial core and less metallic hydrogen	No solid surface, less distinct belt and zone structure than Jupiter	Yes	Primarily H, He	570 × Earth's total field; at its cloud layer, ⅔ × Earth's surface field
Uranus	Terrestrial core, liquid water shell, liquid hydrogen and helium mantle	No solid surface, weak belt and zone system, hurricane-like features, color from methane absorption of red, orange, yellow	Yes	Primarily H, He, some CH_4	50 × Earth's total field; at its cloud layer, 0.73 Earth's surface field
Neptune	Similar to Uranus	Like Uranus	Yes	Primarily H, He, some CH_4	35 × Earth's total field; at its cloud layer, 0.4 × Earth's surface field

For detailed numerical comparisons between planets, see Appendix Tables E-1 and E-2.
***To see the orientations of these magnetic fields relative to the rotation axes of the planets, see Figure 8-34.**

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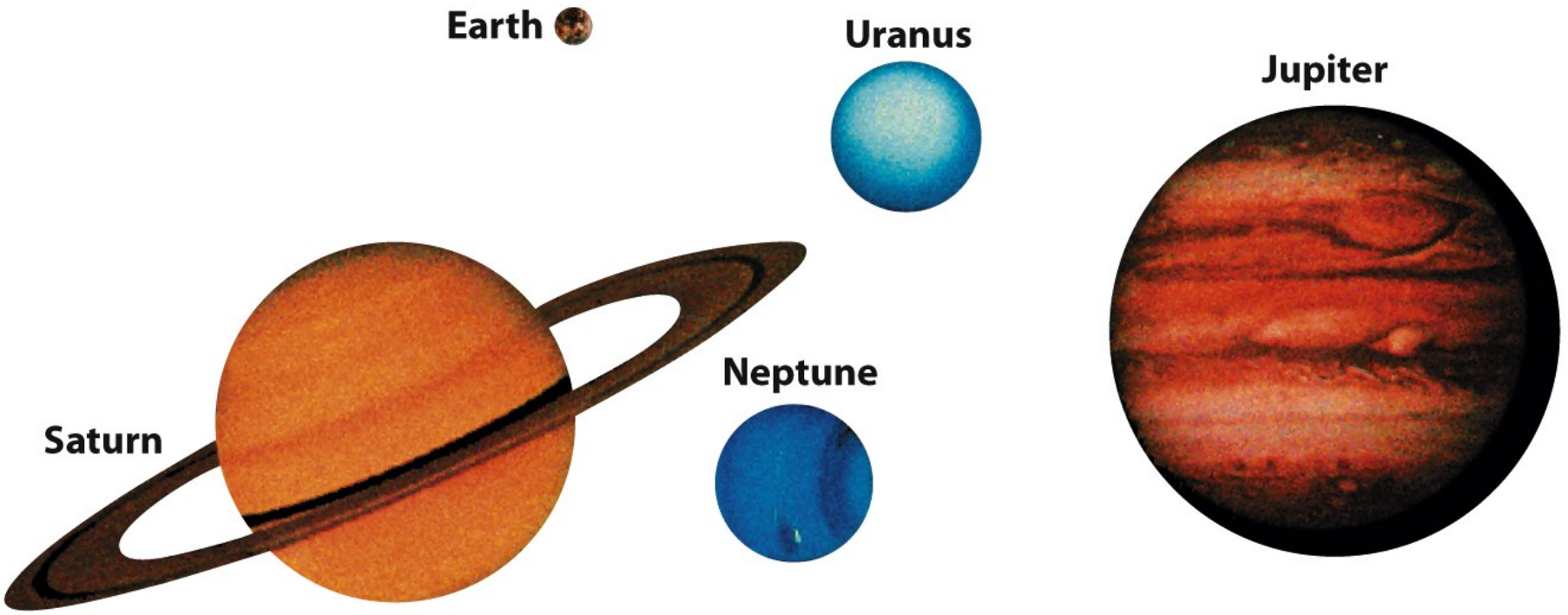

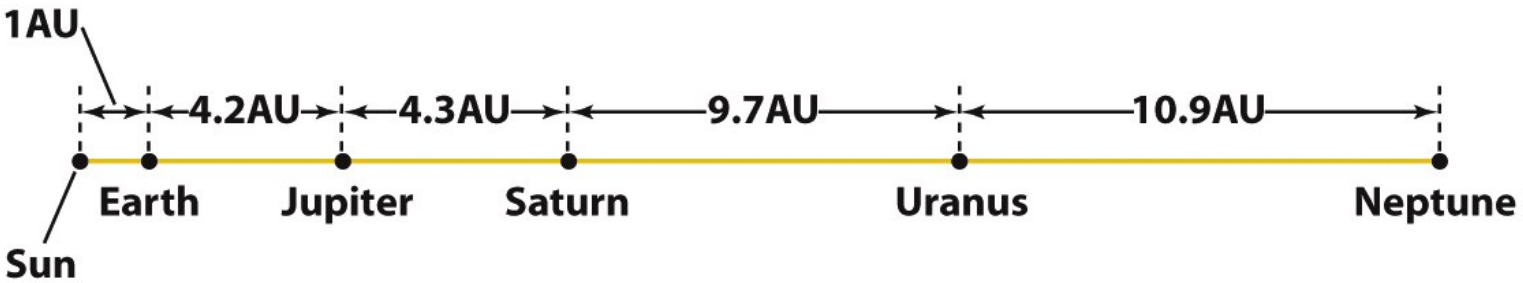

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