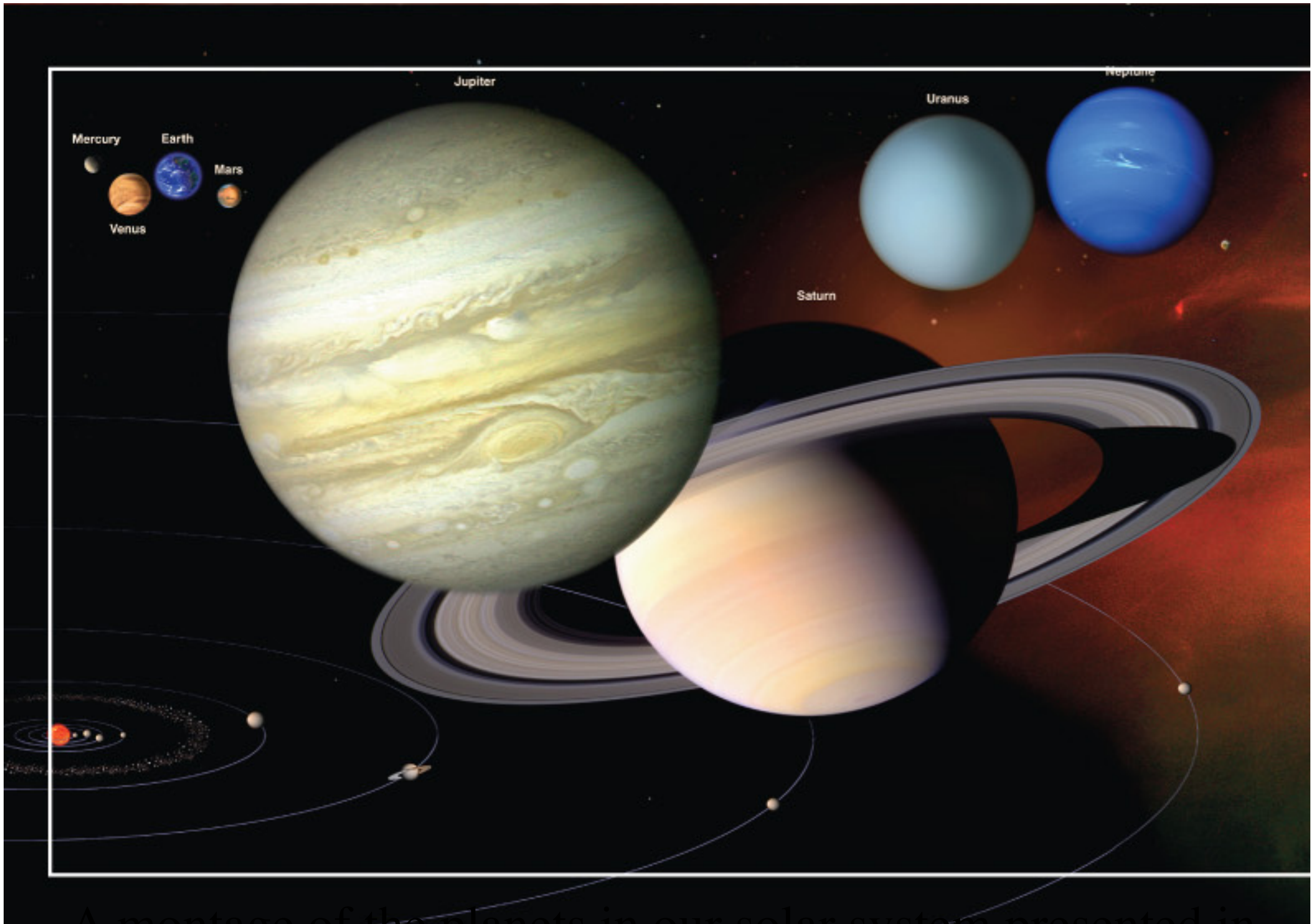

Neil F. Comins
Discovering the Essential Universe
Ninth Edition
CHAPTER 6
The Terrestrial Planets and Their Moons

Orbital Characteristics of the Planets

	Average distance from Sun		Orbital period	Orbital eccentricity	Orbital inclination
	(AU)	(10^6 km)	(year)	(*e*)	
Mercury	0.39	58	0.24	0.206	7.01°
Venus	0.72	108	0.62	0.007	3.39°
Earth	1.00	150	1.00	0.017	0°
Mars	1.52	228	1.88	0.093	1.85°
Jupiter	5.20	778	11.86	0.048	1.30°
Saturn	9.54	1427	29.46	0.054	2.48°
Uranus	19.19	2871	84.01	0.047	0.77°
Neptune	30.06	4497	164.79	0.009	1.77°



A montage of the planets in our solar system presented in correct relative sizes. The orbits in the background are also drawn to scale.

table 9-1 | Earth Data

Average distance from the Sun:	1.000 AU = 1.496×10^8 km
Maximum distance from the Sun:	1.017 AU = 1.521×10^8 km
Minimum distance from the Sun:	0.983 AU = 1.471×10^8 km
Eccentricity of orbit:	0.017
Average orbital speed:	29.79 km/s
Orbital period:	365.256 days
Rotation period:	23.9345 hours
Inclination of equator to orbit:	23.45°
Diameter (equatorial):	12,756 km
Mass:	5.974×10^{24} kg
Average density:	5515 kg/m^3
Escape speed:	11.2 km/s
Albedo:	0.39
Surface temperature range:	Maximum: 60°C = 140°F = 333 K Mean: 14°C = 57°F = 287 K Minimum: –90°C = –130°F = 183 K
Atmospheric composition (by number of molecules):	78.08% nitrogen (N_2) 20.95% oxygen (O_2) 0.035% carbon dioxide (CO_2) about 1% water vapor

Temperature profile of Earth's atmosphere

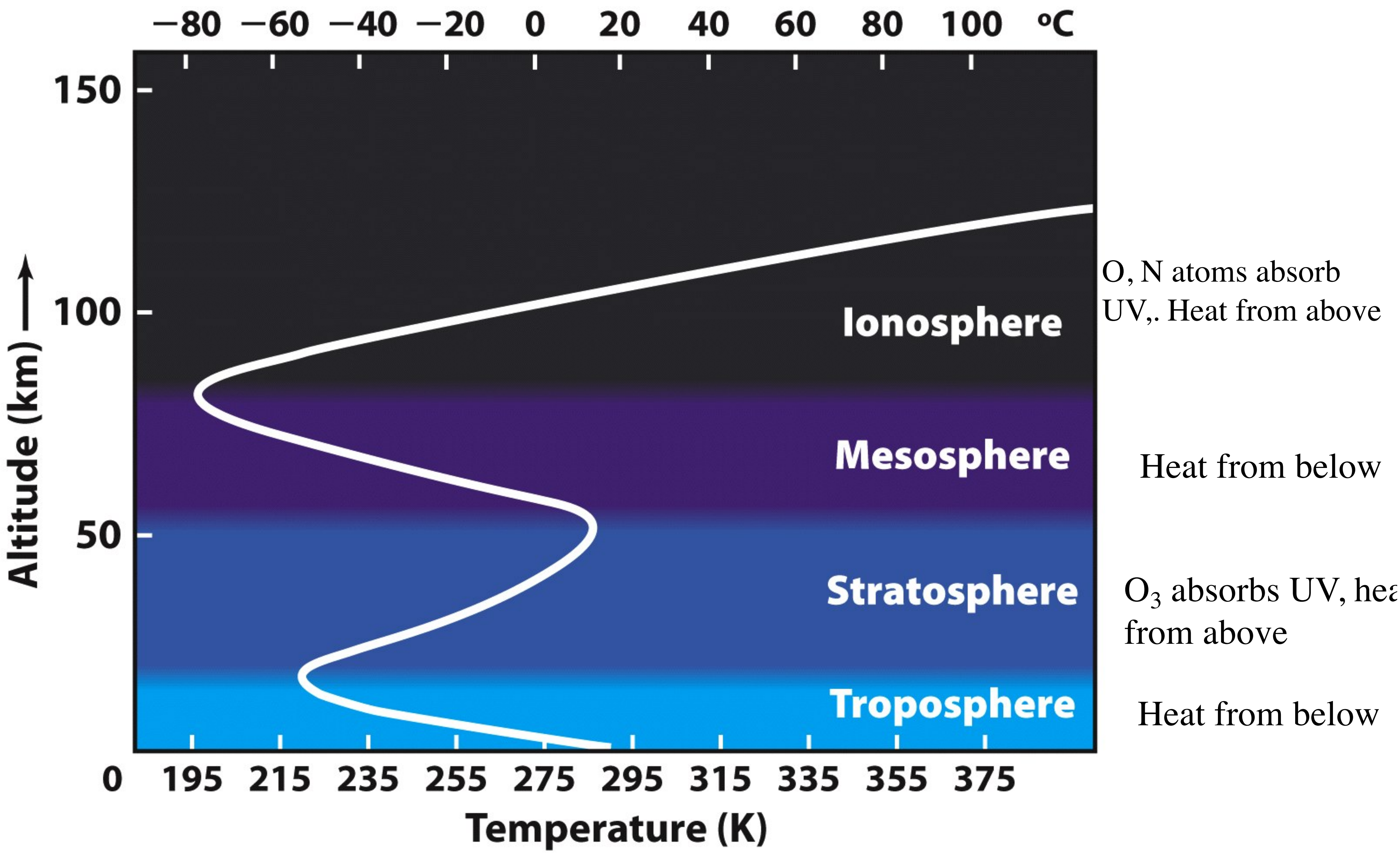


Figure 6-2

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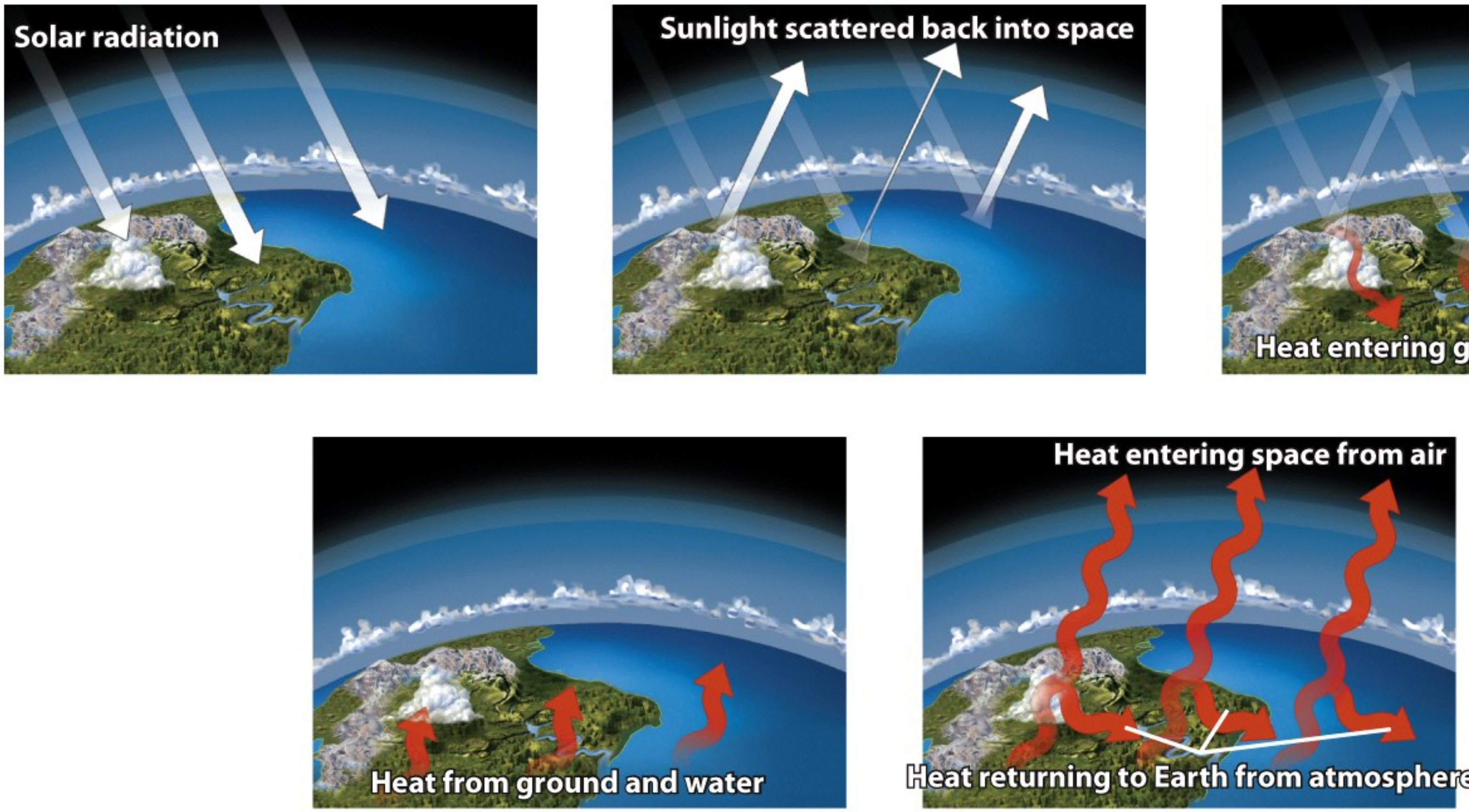

Figure 6-4a
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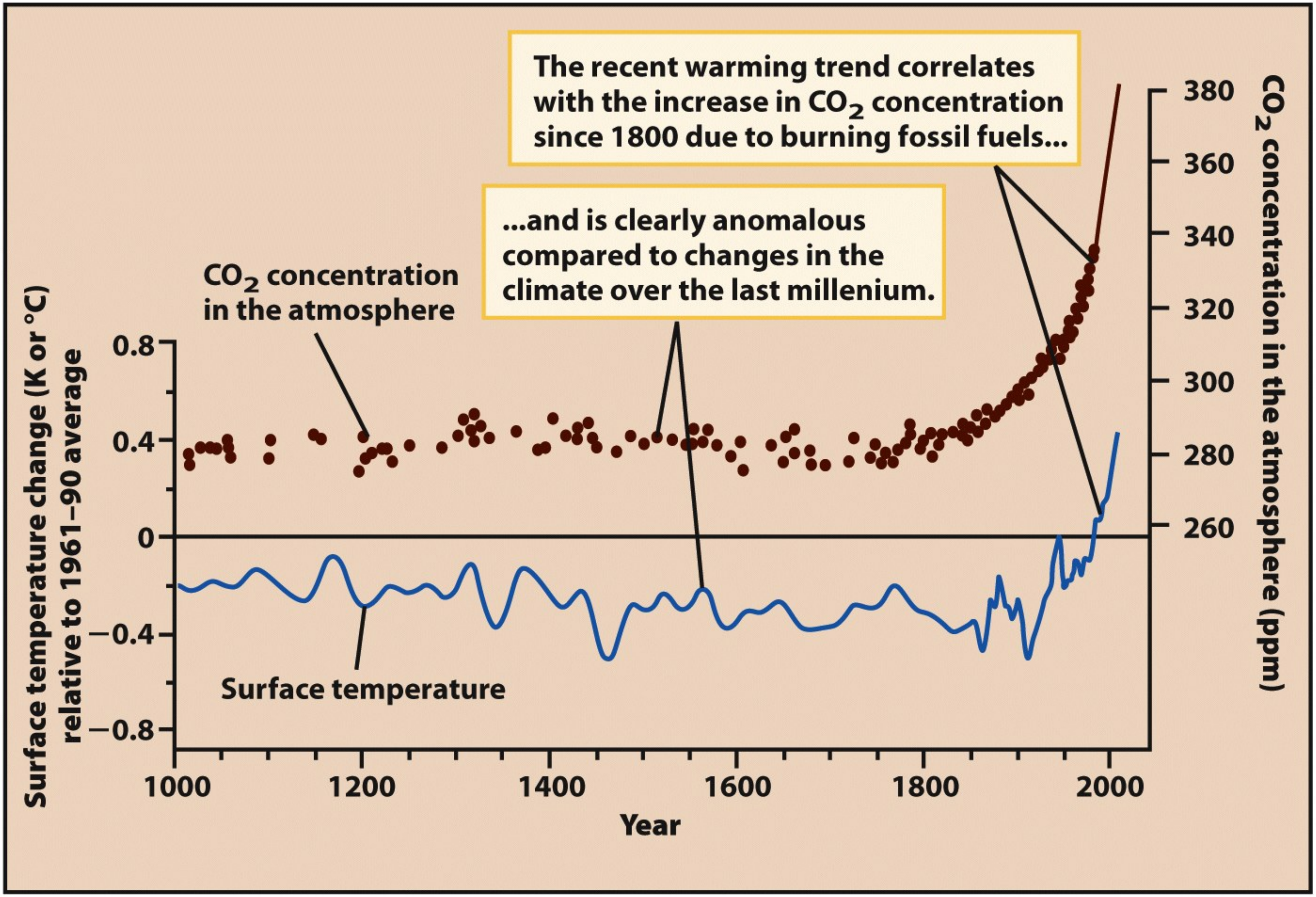

Figure 6-4b
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Average surface temperature of planet

$P_{abs}=(L/4\pi d^2) \times \pi r_p^2\ (1\text{-albedo})$

$P_{em}=4\pi r_p^2\ \sigma T_p^4$

If no atmosphere then for thermal equilibrium:

$P_{abs} = P_{em}$

$T_p = [L/(4\pi d^2) \times (1\text{-albedo})/(4\sigma)]^{1/4}$

Example for Earth:

$L=3.86 \times 10^{26}$ W, $d=1.5 \times 10^{11}$ m, albedo = 0.37,
$\sigma=5.67\times10^{-8}$ J $m^{-2}K^{-4}s^{-1}$

$\mathbf{T_p = 247\ K}$

With average T=290K ➔ 43K due to greenhouse effect

Surface of Earth (crust),
Floating on a layer
of denser material.

Alfred Wegener
1912-1915 observations
Africa and South America fit

Hypothesis:
Continental drift

Figure 6-5
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237 million years ago: the supercontinent Pangaea

Figure 6-6a
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152 million years ago: the breakup of Pangaea

Figure 6-6b
Discovering the Universe, Eighth Edition

The continents today

Figure 6-6c
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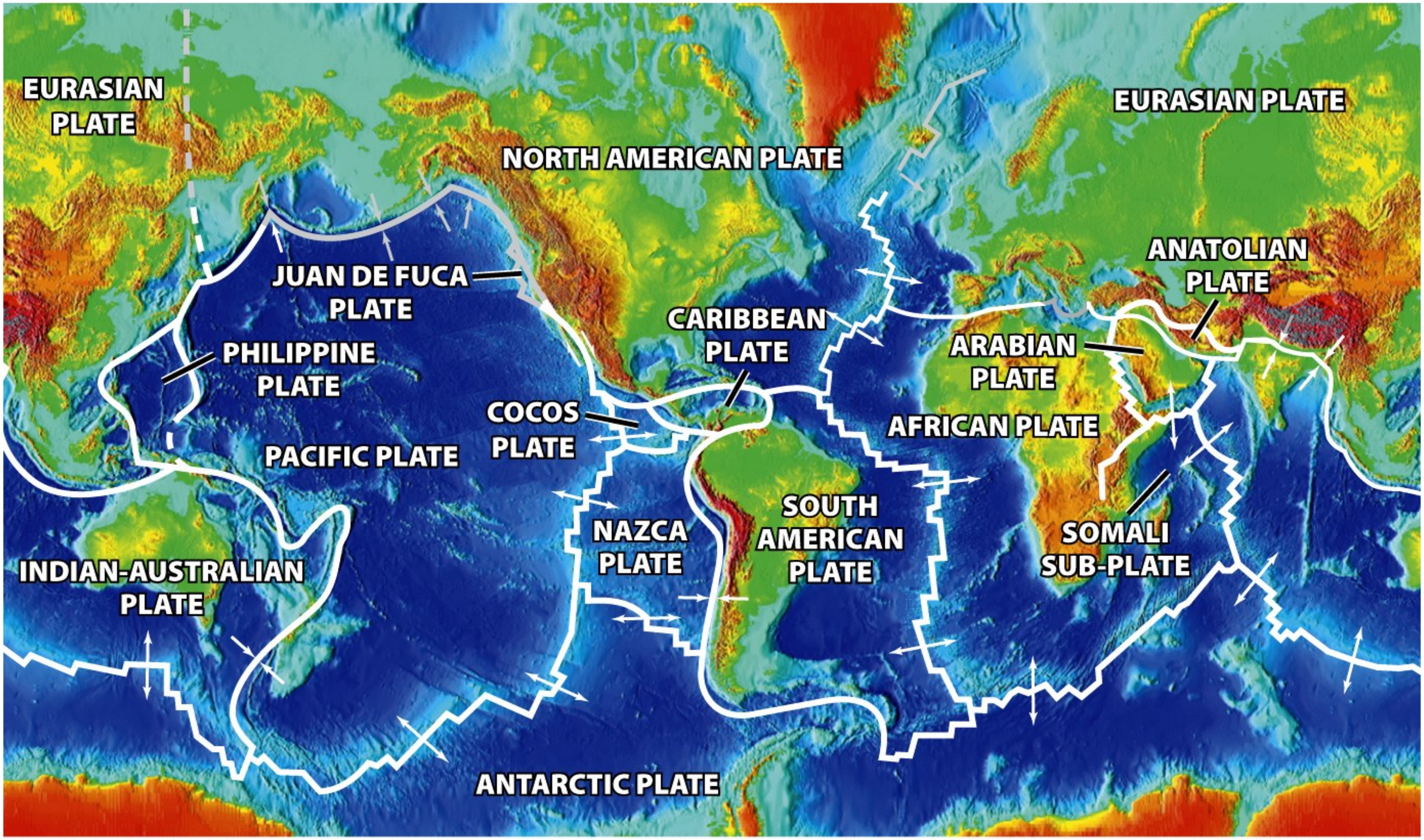

Figure 6-7a
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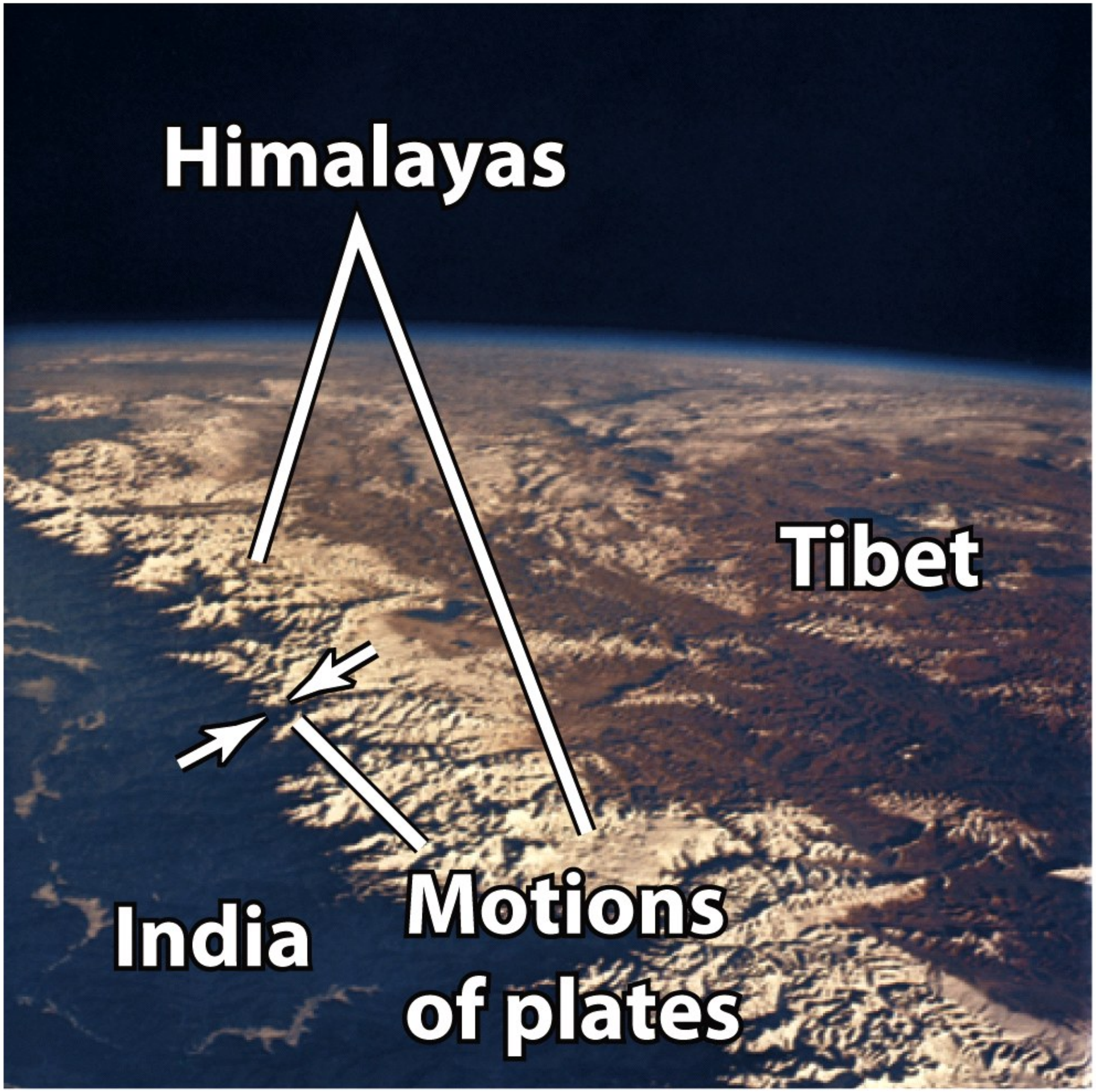

Figure 6-7d
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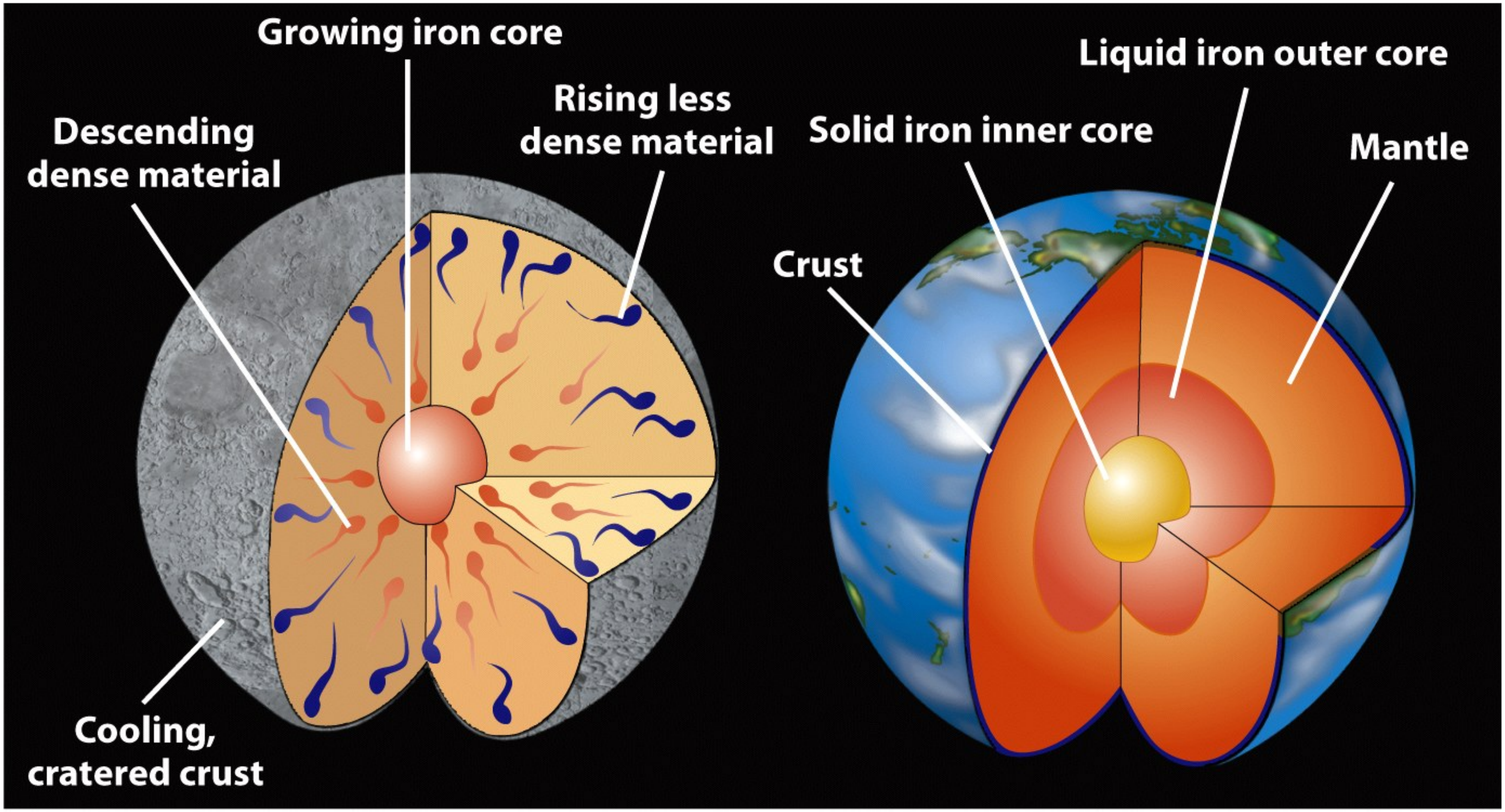
HONDA



As a result of differentiation, the Earth has the layered structure that we see today

Figure 6-8
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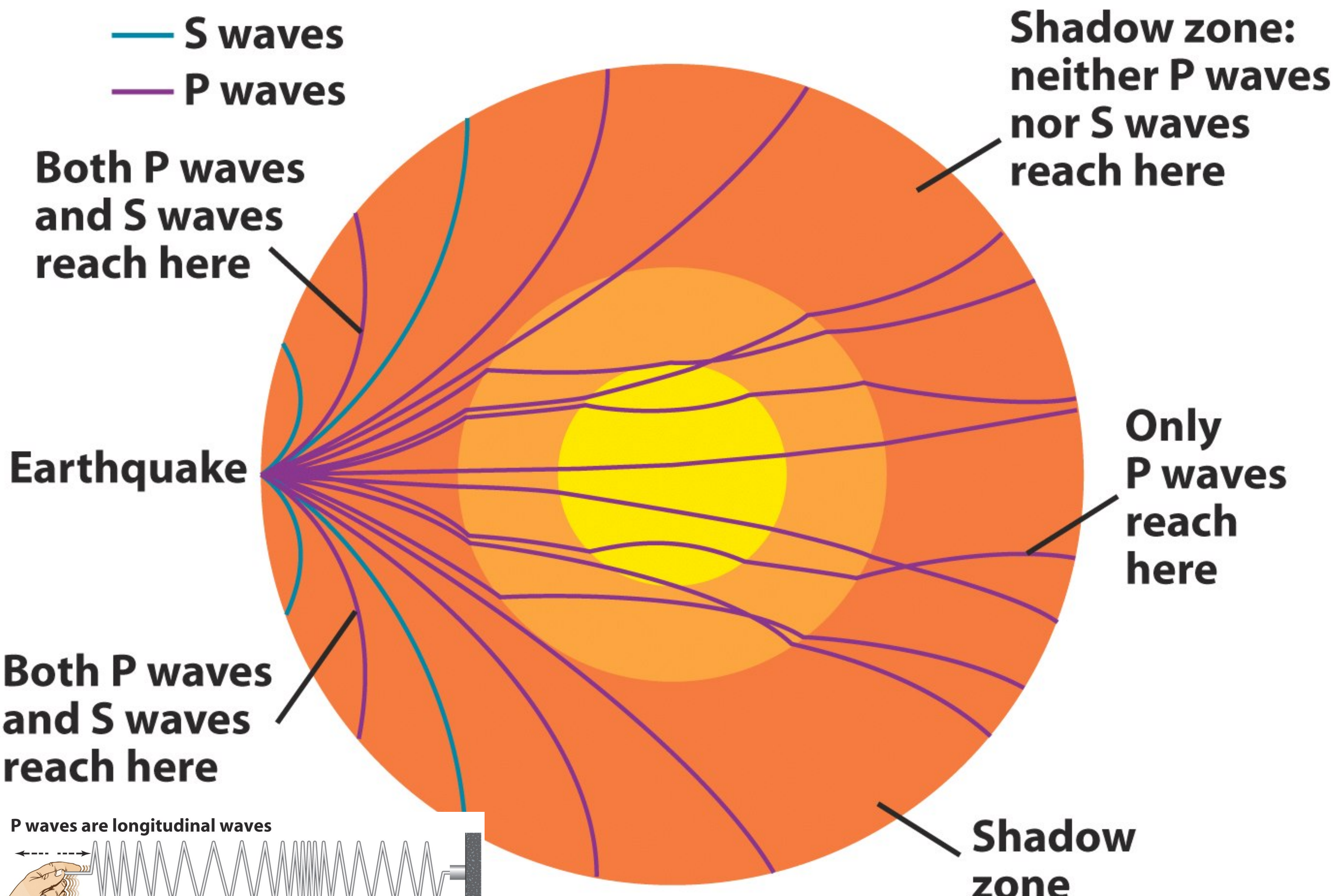

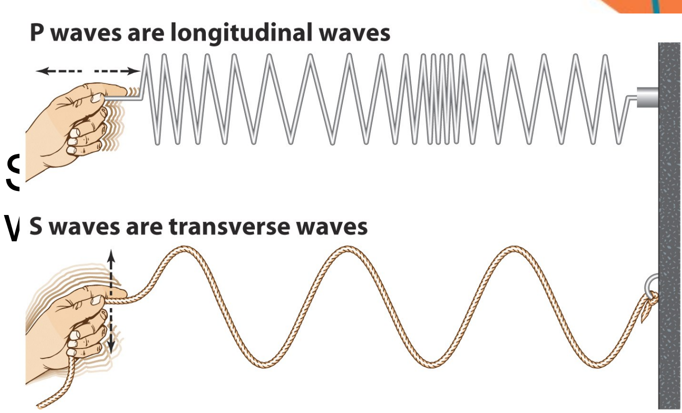

S… th’s interior structure by studying how longitudinal P
W… s travel through the Earth’s interior

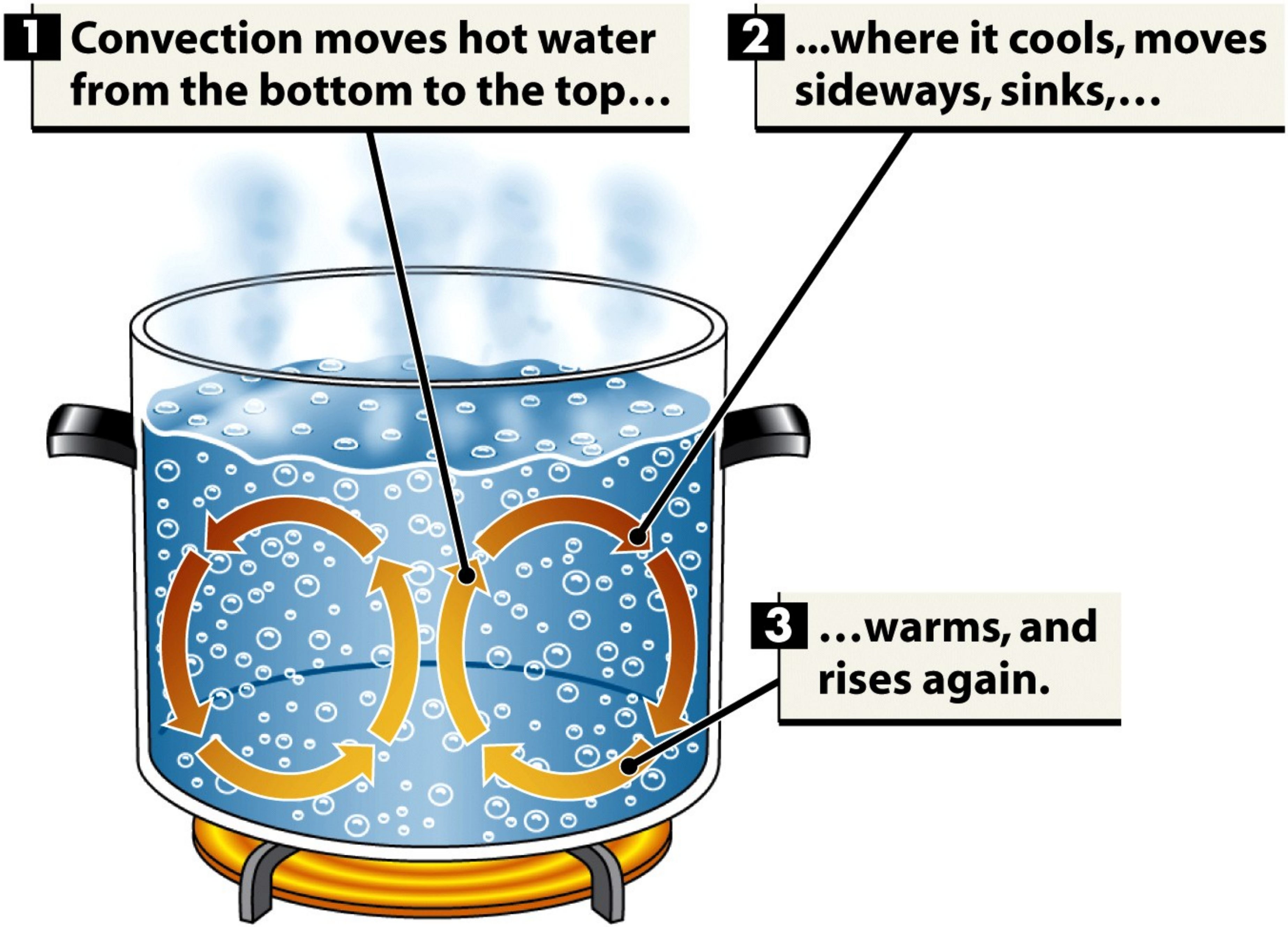

Figure 6-9a
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The Mechanism of plate techtonics

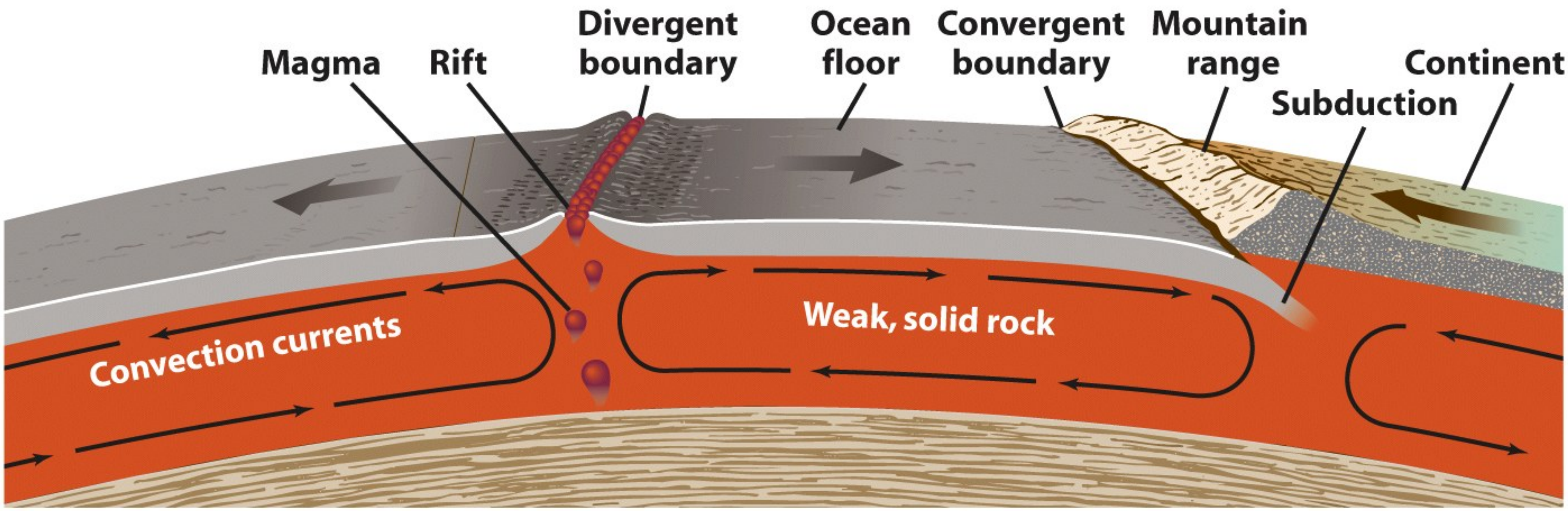

Figure 6-9b
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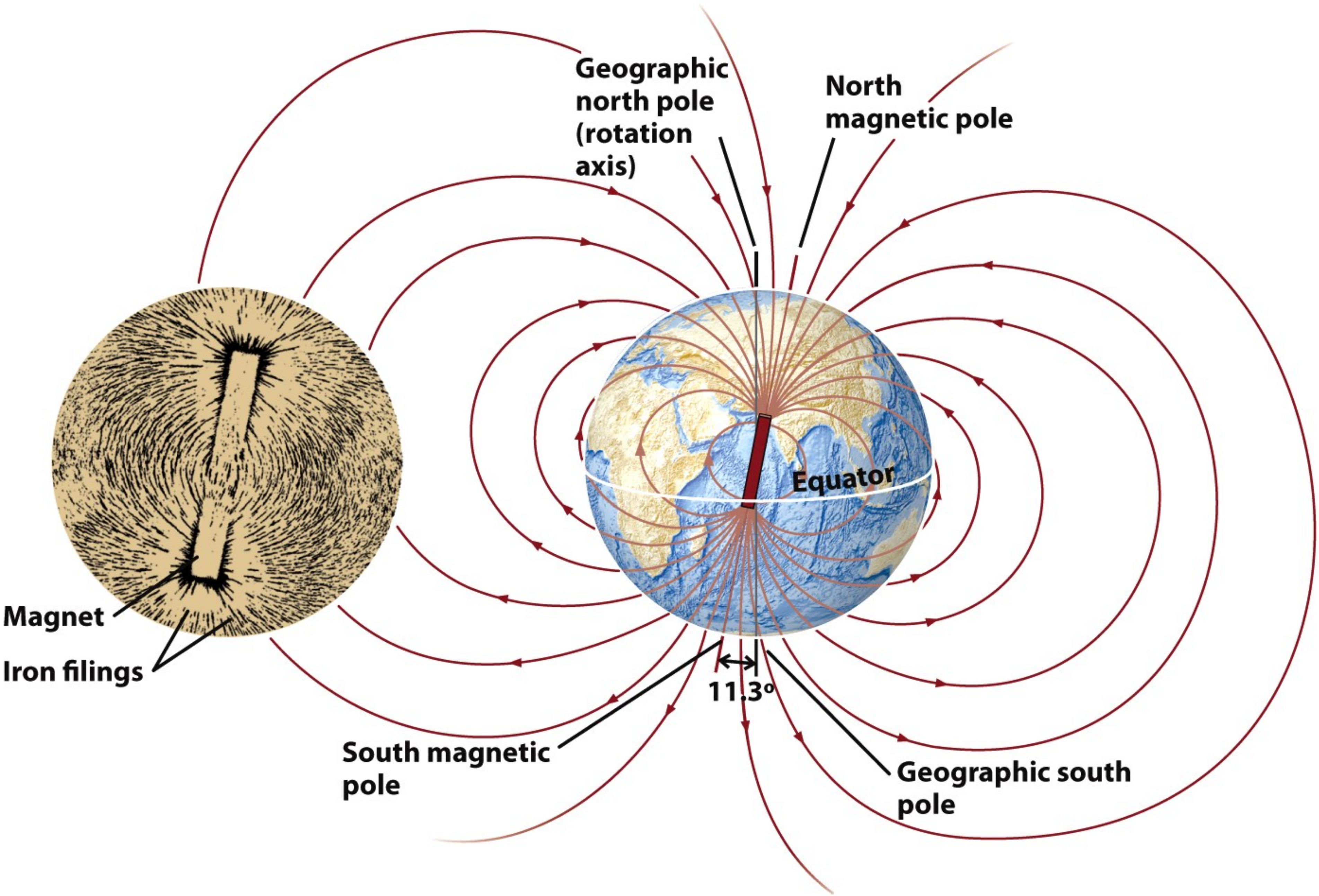

Figure 6-10
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Earth’s magnetosphere

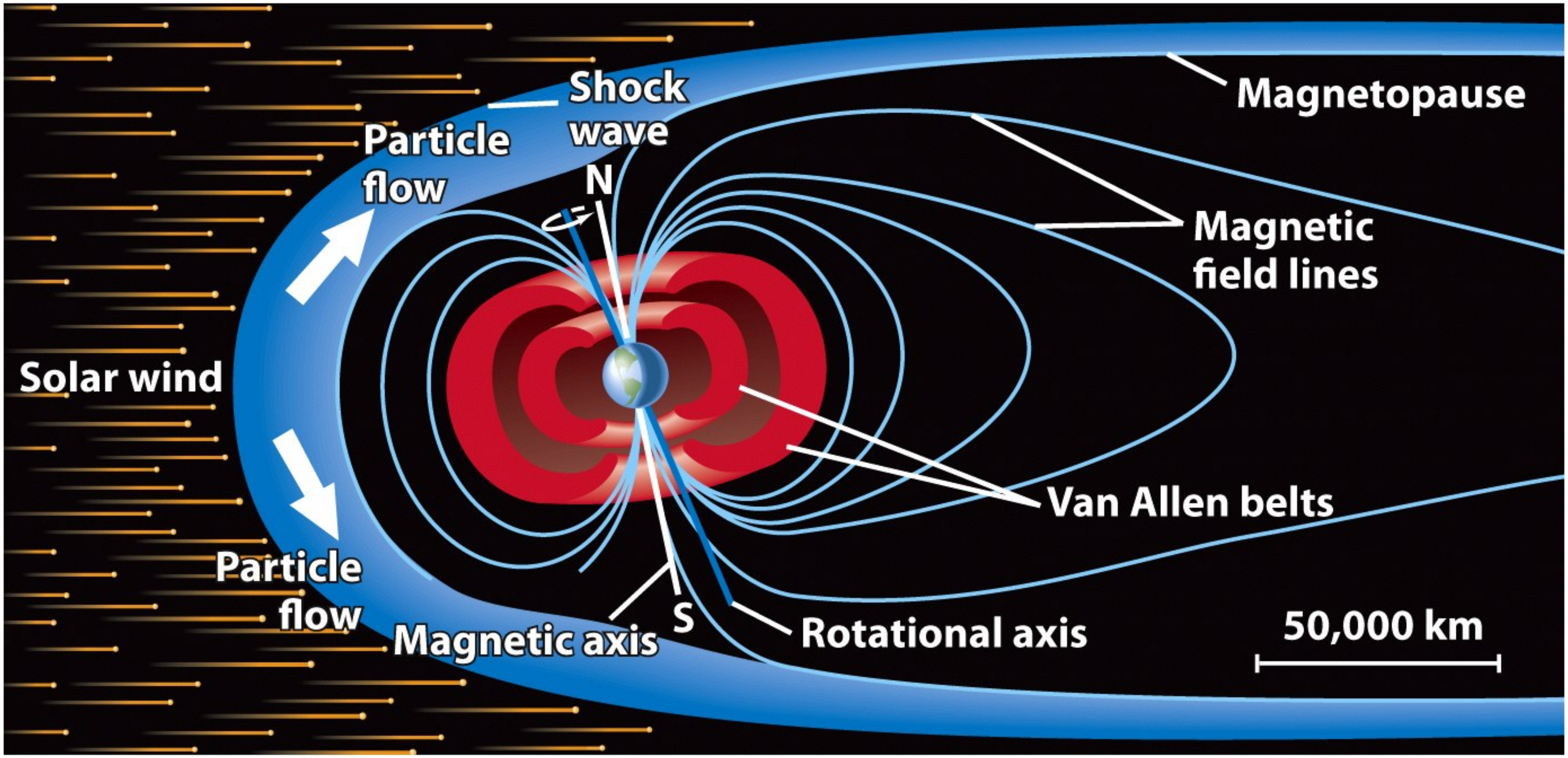

Figure 6-11
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Aurora Borealis

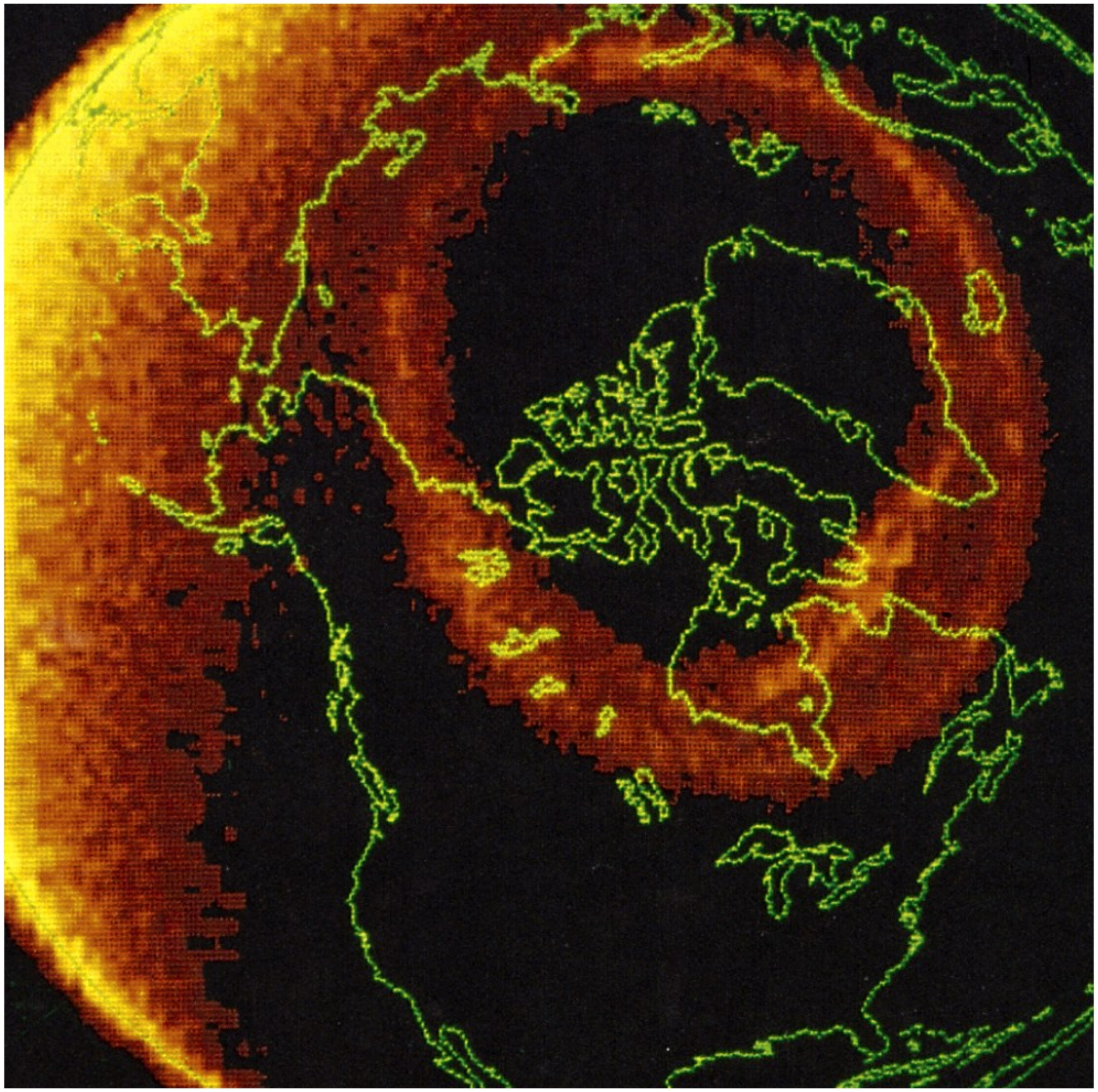

Figure 6-12a
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Figure 6-12c
Discovering the Universe, Eighth Edition

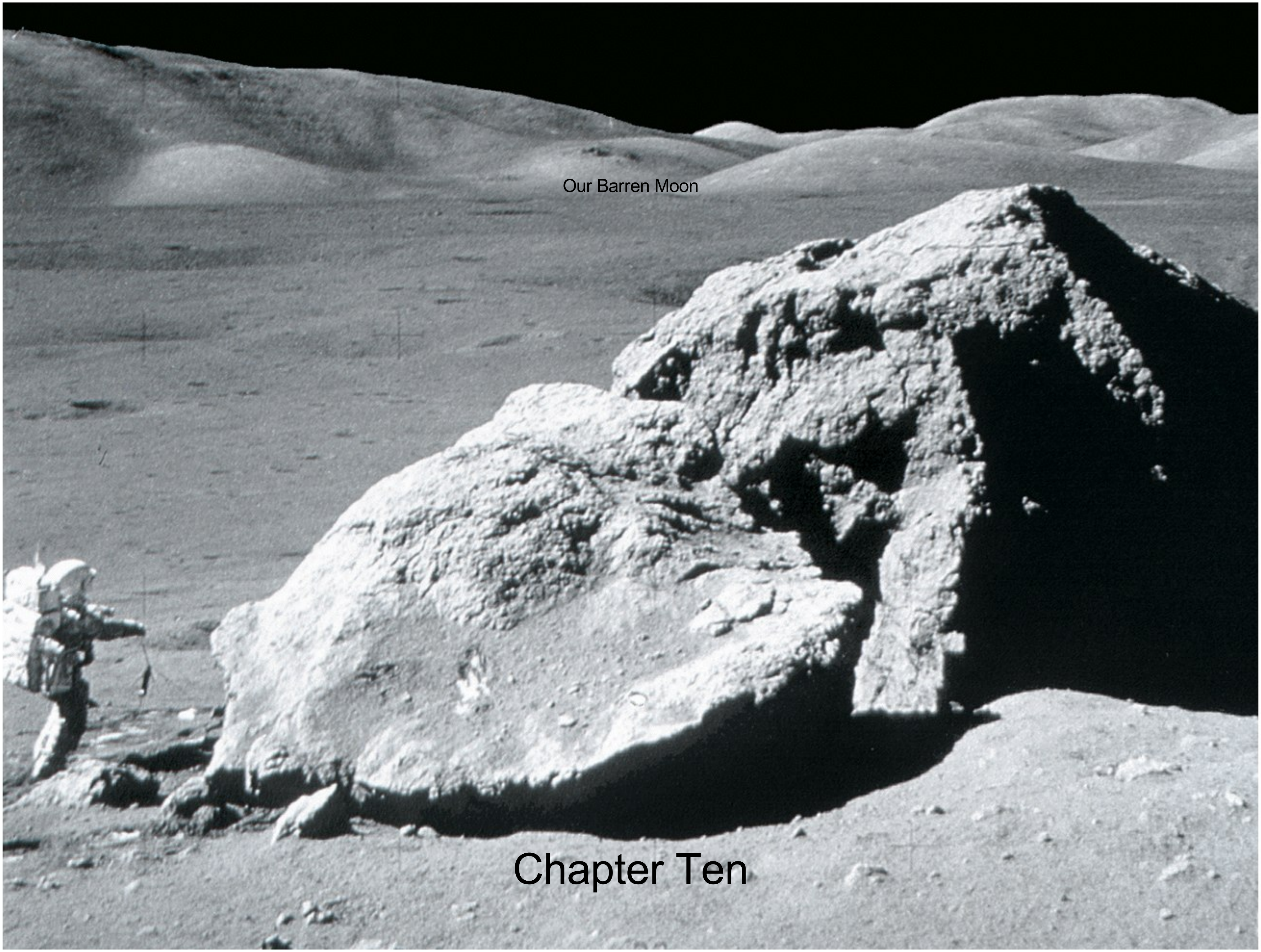
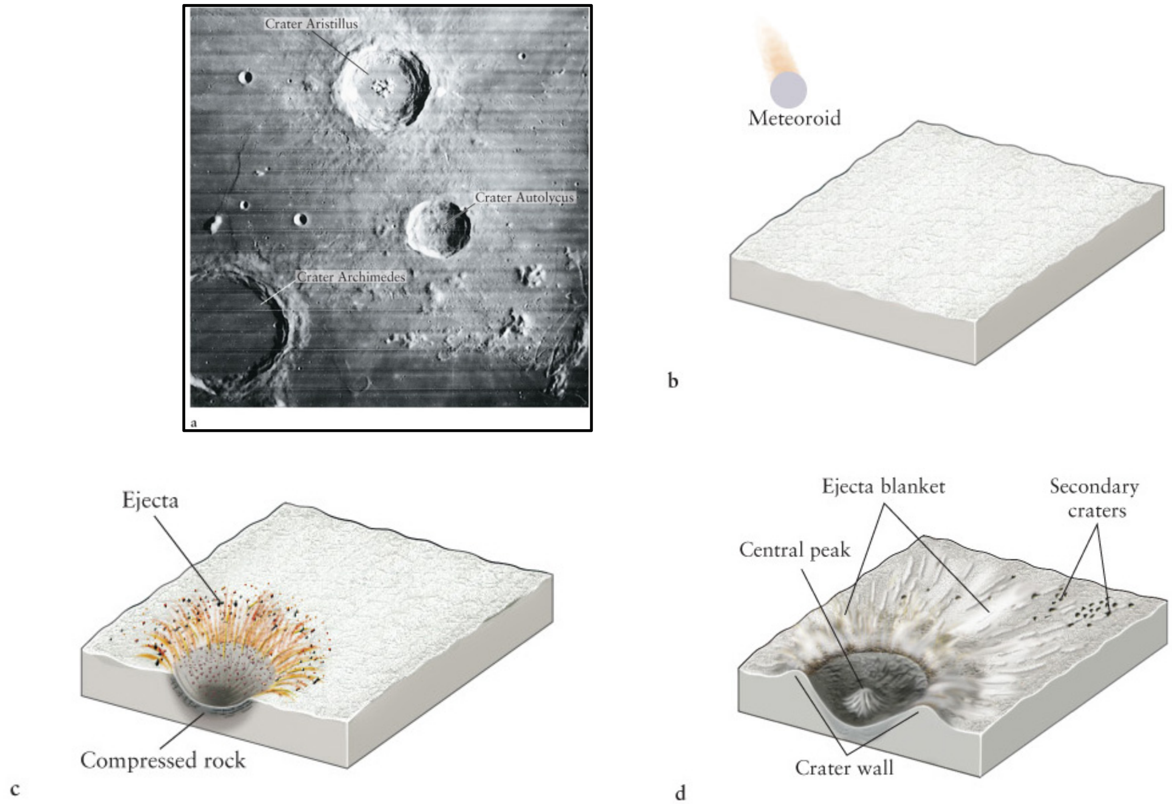

Our Barren Moon
Chapter Ten

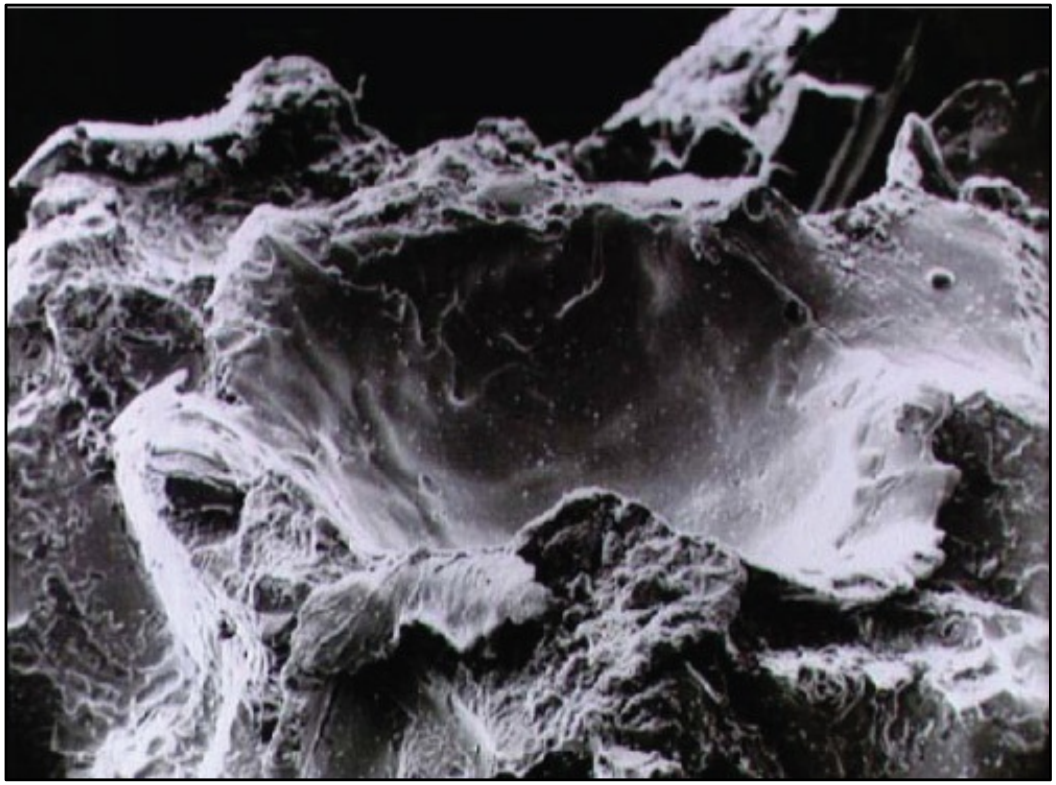
table 10-1 Moon Data

Distance from Earth (center to center):	Average: 384,400 km = 238,900 mi Maximum (apogee): 405,500 km Minimum (perigee): 363,300 km
Eccentricity of orbit:	0.0549
Average orbital speed:	3680 km/h
Sidereal period (relative to fixed stars):	27.322 days
Synodic period (new moon to new moon):	29.531 days
Inclination of lunar equator to orbit:	6.68°
Inclination of orbit to ecliptic:	5.15°
Diameter (equatorial):	3476 km = 2160 mi = 0.272 Earth diameter
Mass:	7.349×10^{22} kg = 0.0123 Earth mass
Average density:	3344 kg/m^3
Escape speed:	2.4 km/s
Surface gravity (Earth = 1):	0.17
Albedo:	0.11
Average surface temperatures:	Day: 130°C = 266°F = 403 K Night: −180°C = −292°F = 93 K
Atmosphere:	Essentially none

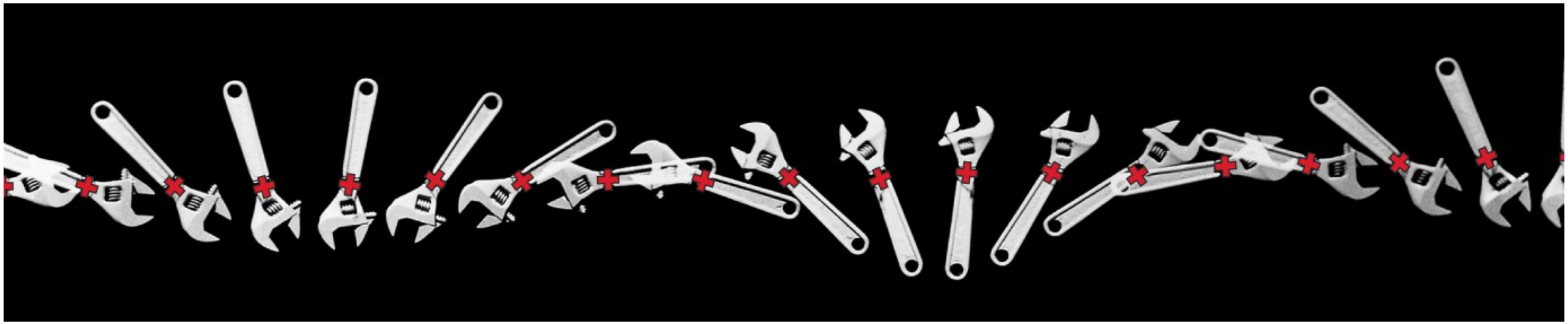


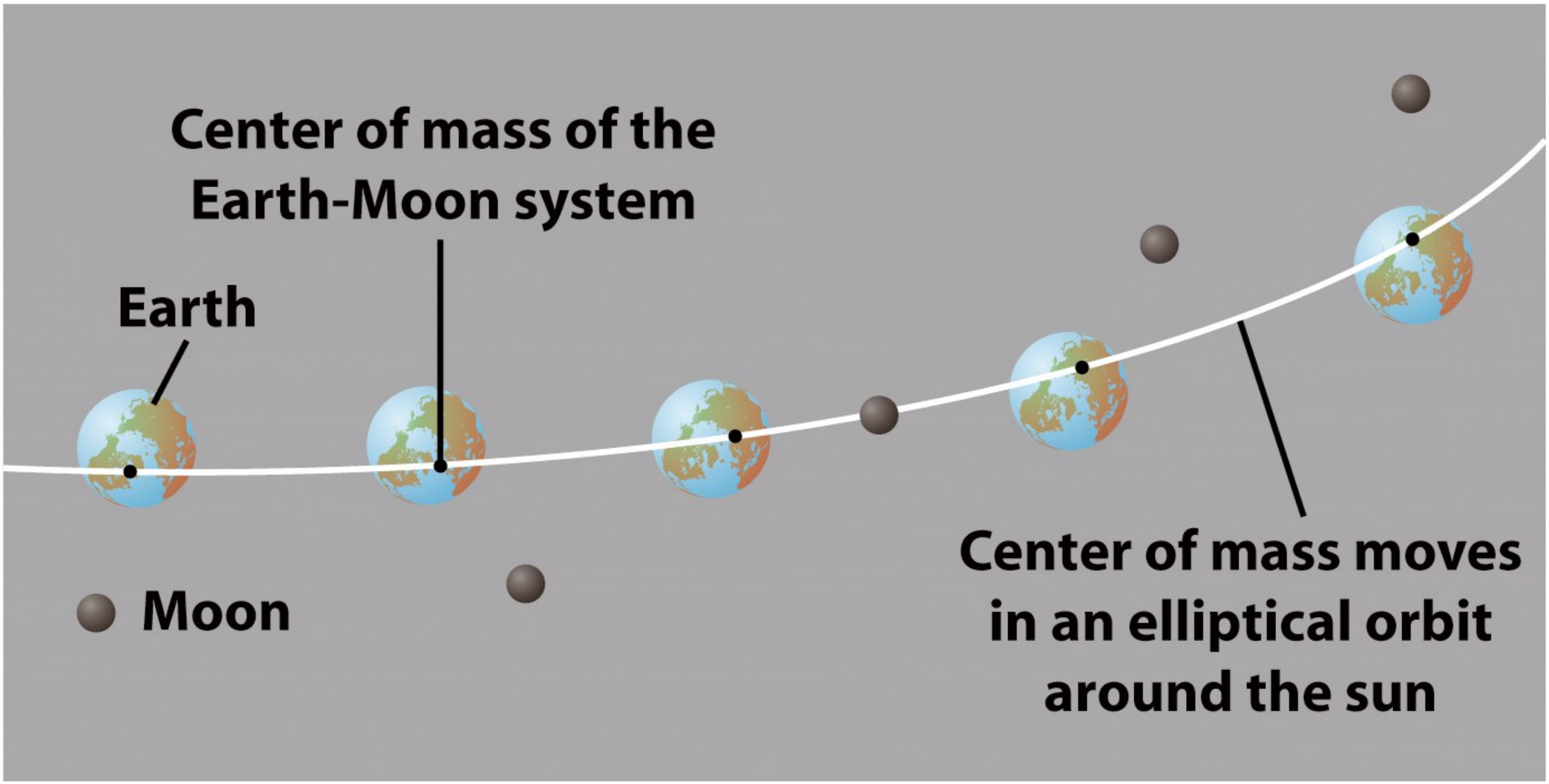
(b) An incoming meteoroid, (c) upon impact, is pulverized and the surface explodes outward and downward. (d) After the impact, the ground rebounds, creating the central peak and causing the crater walls to collapse. The lighter region is the ejecta blanket.

A Microscopic Lunar Crater



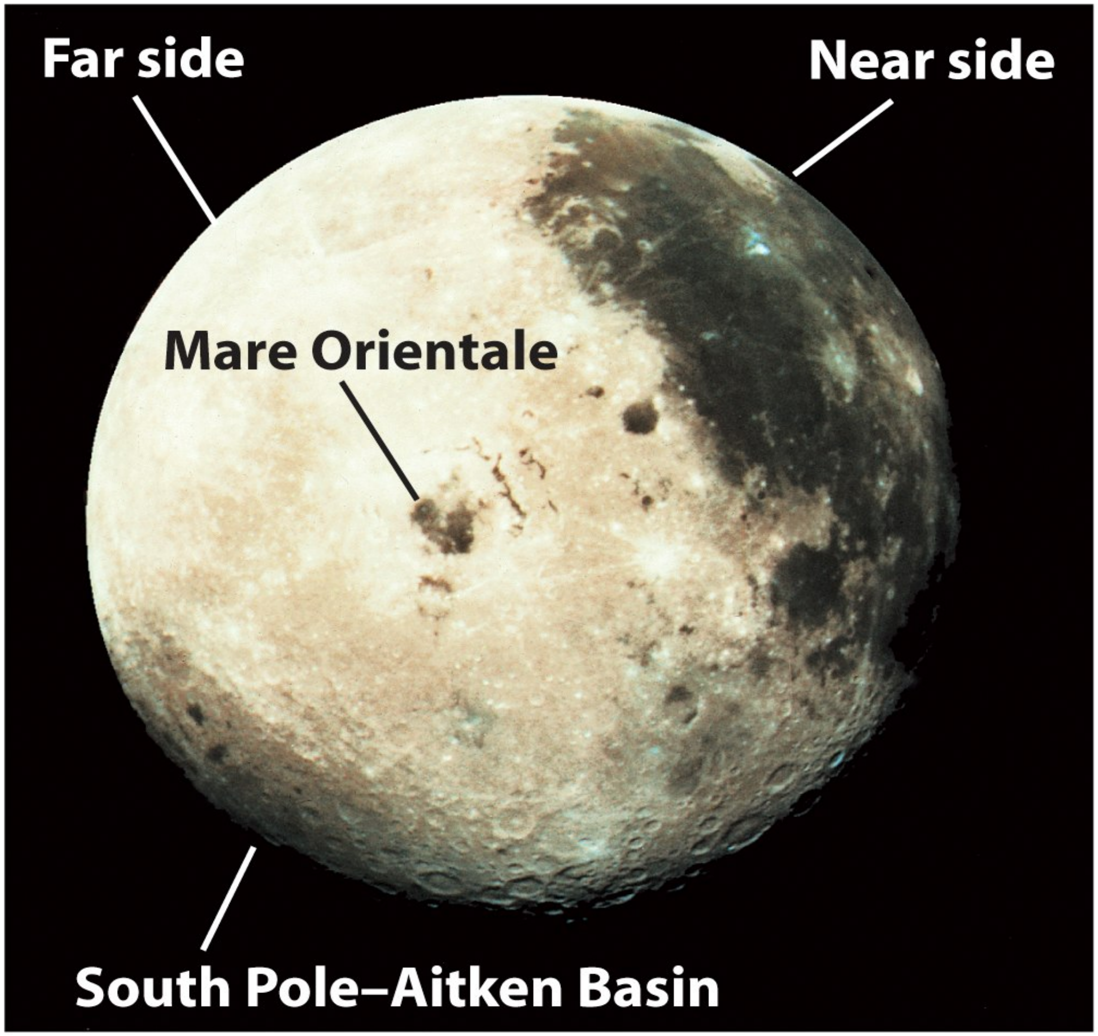
This photograph, made with a microscope, shows tiny microcraters less than 1 mm across on a piece of Moon rock.





Center of mass of the
Earth-Moon system
Earth
Moon
Center of mass moves
in an elliptical orbit
around the sun

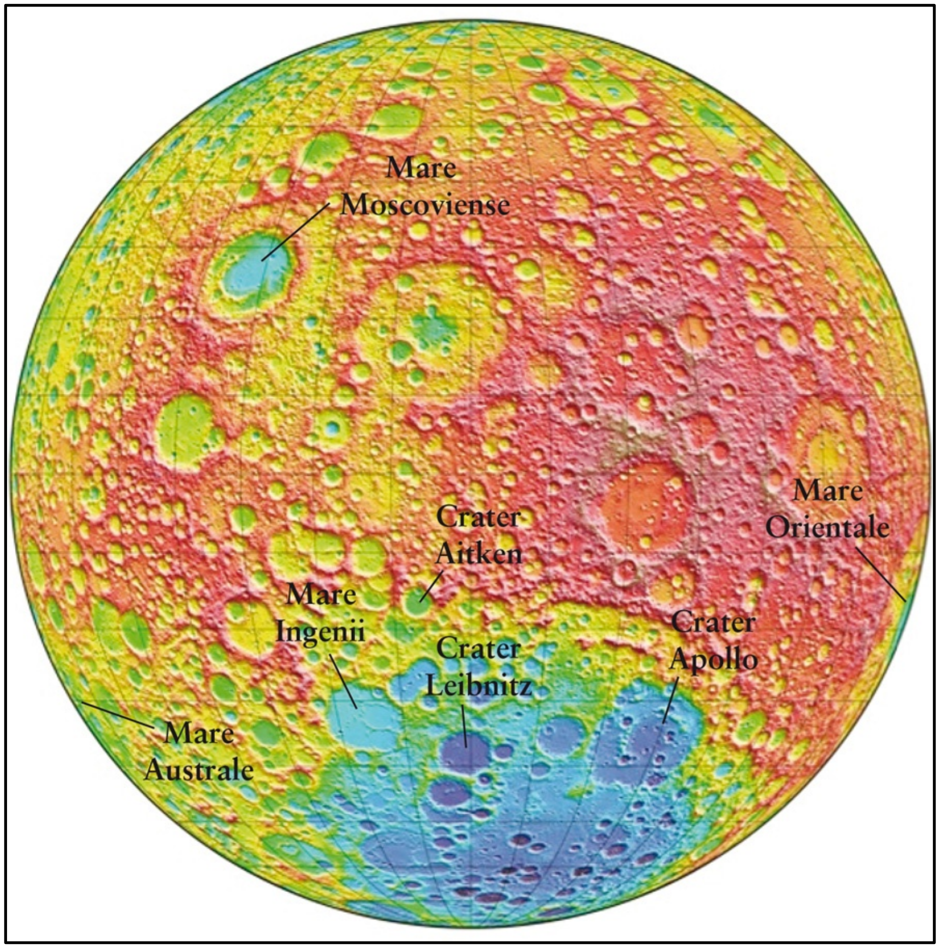
The Moon's airless, dry surface is covered with plains and craters



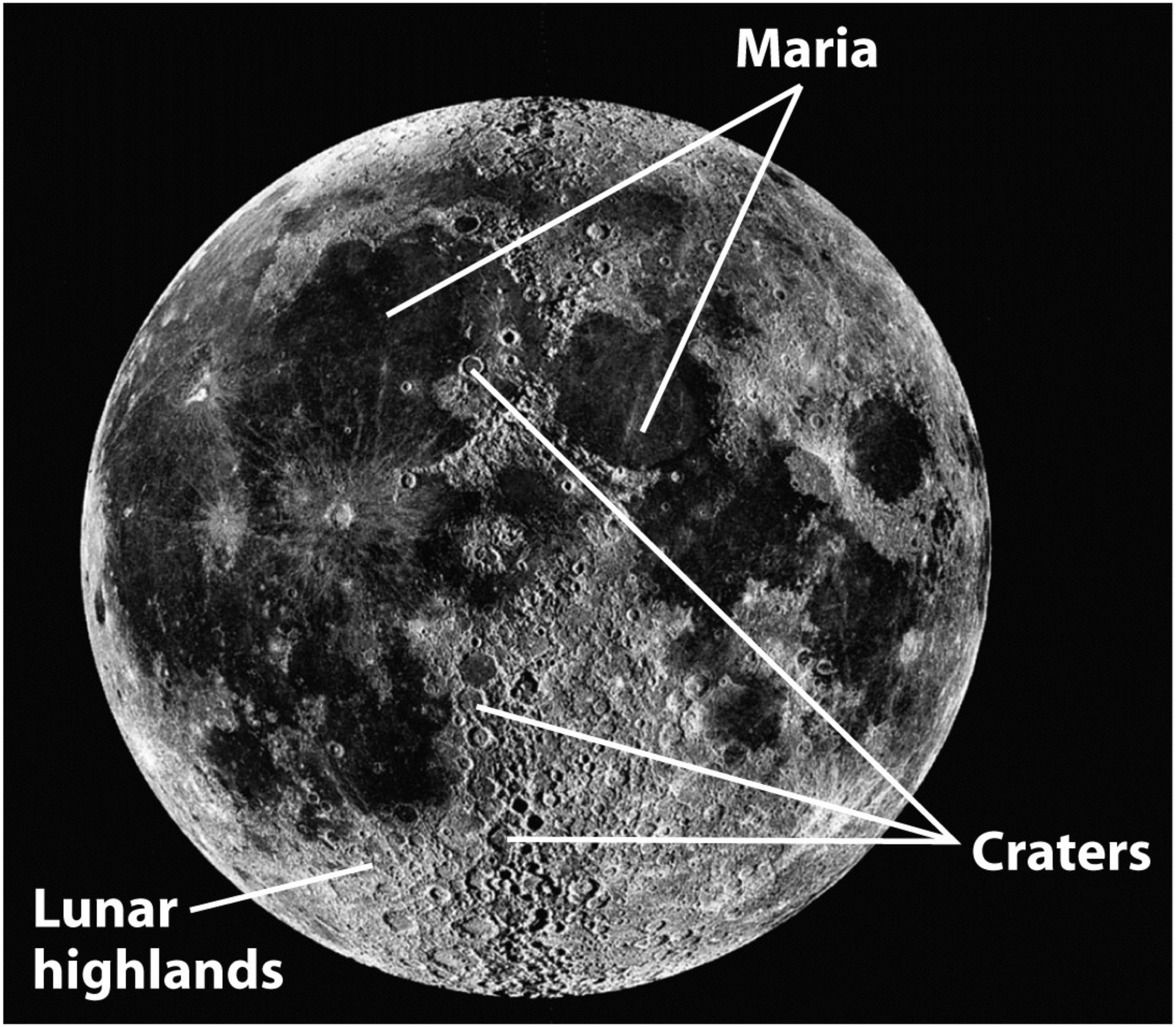
The Earth-facing side of the Moon displays light-colored, heavily cratered highlands and dark-colored, smooth-surfaced maria

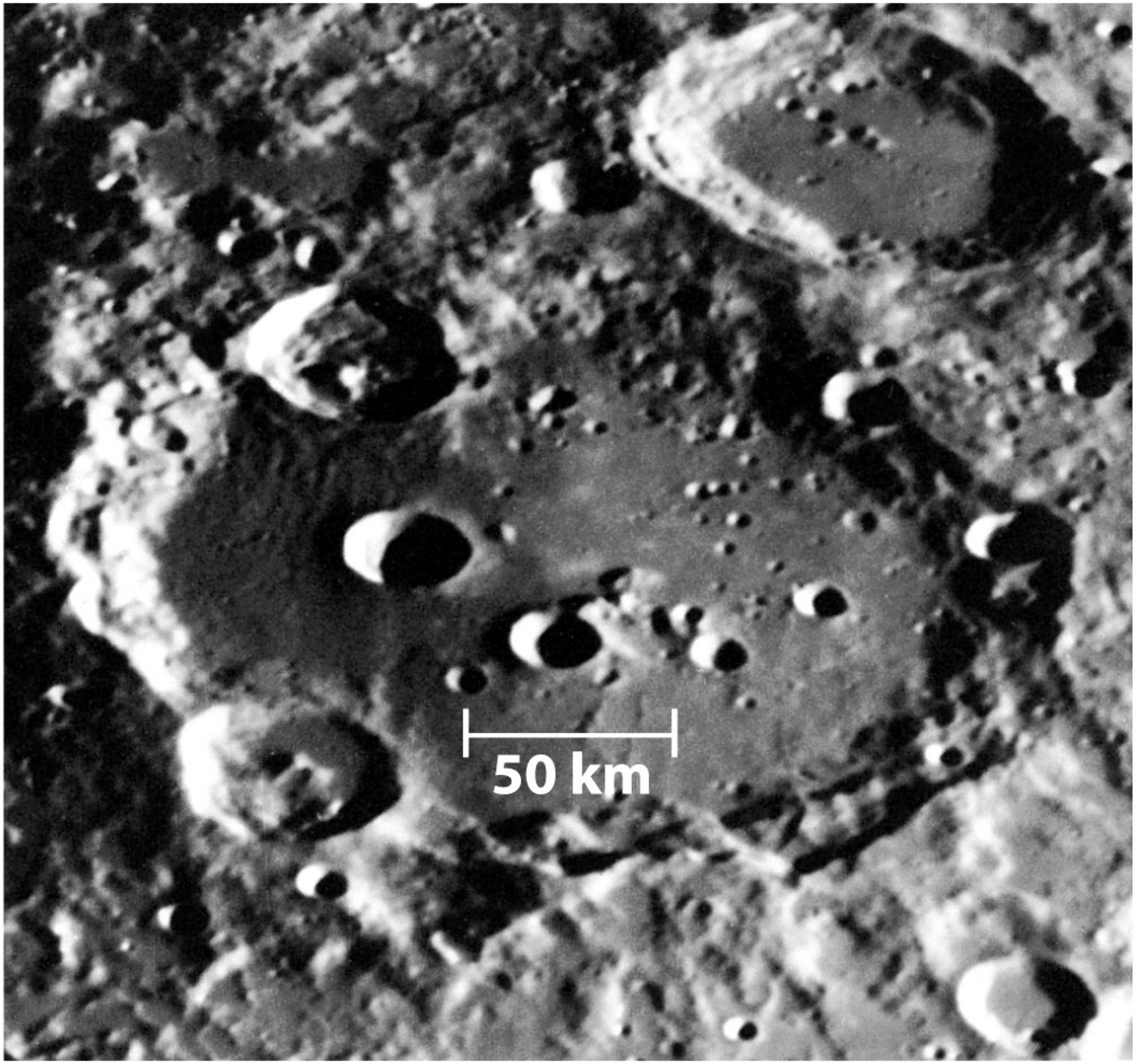
The Moon's far side has almost no maria

The Far Side of the Moon



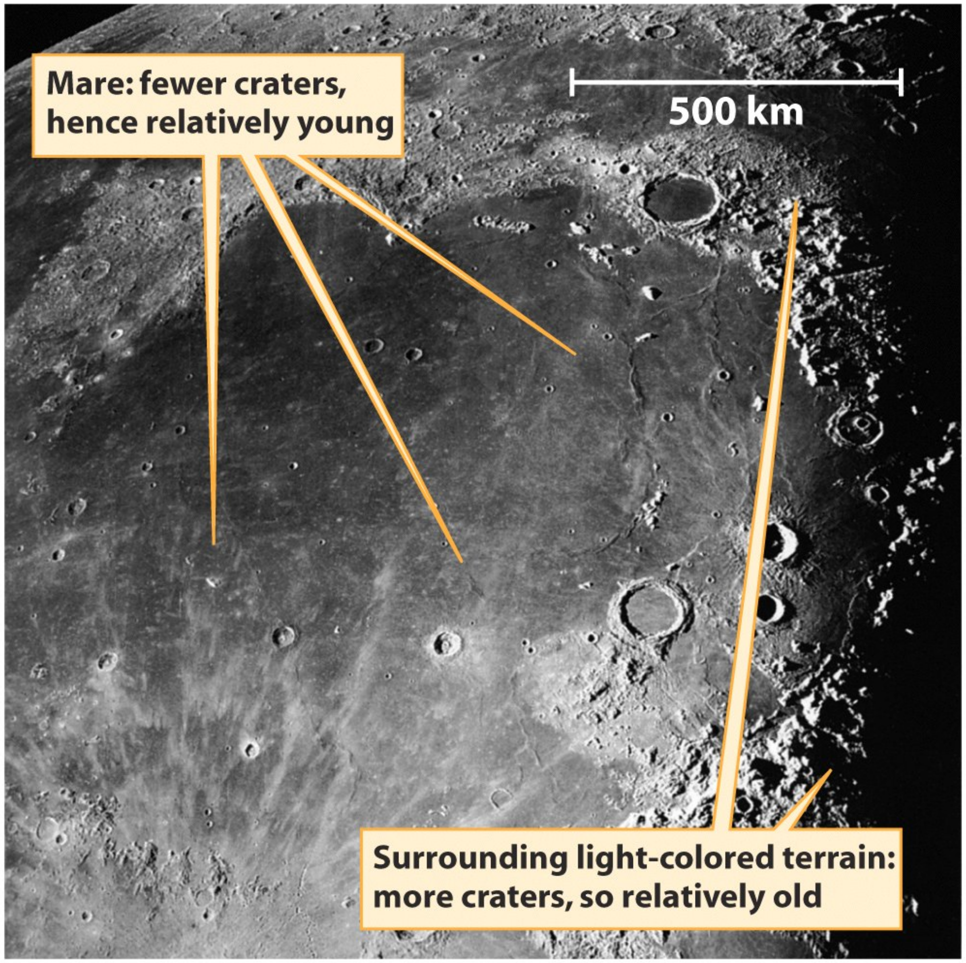
Using a laser mounted on the *Lunar Reconnaissance Orbiter*, this detailed image of the lunar far side was made in 2010. Going by the colors of the rainbow, violet indicates lowest terrain, while red indicates highest.

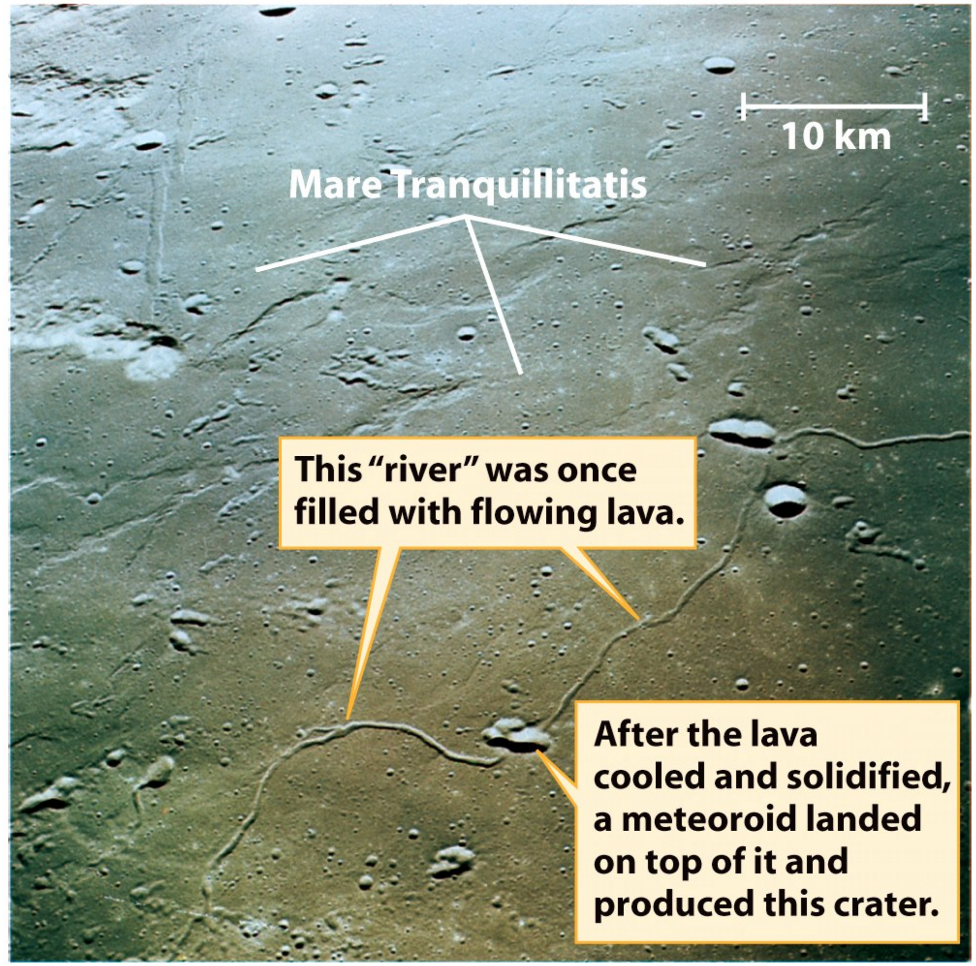

Maria
Craters
Lunar
highlands

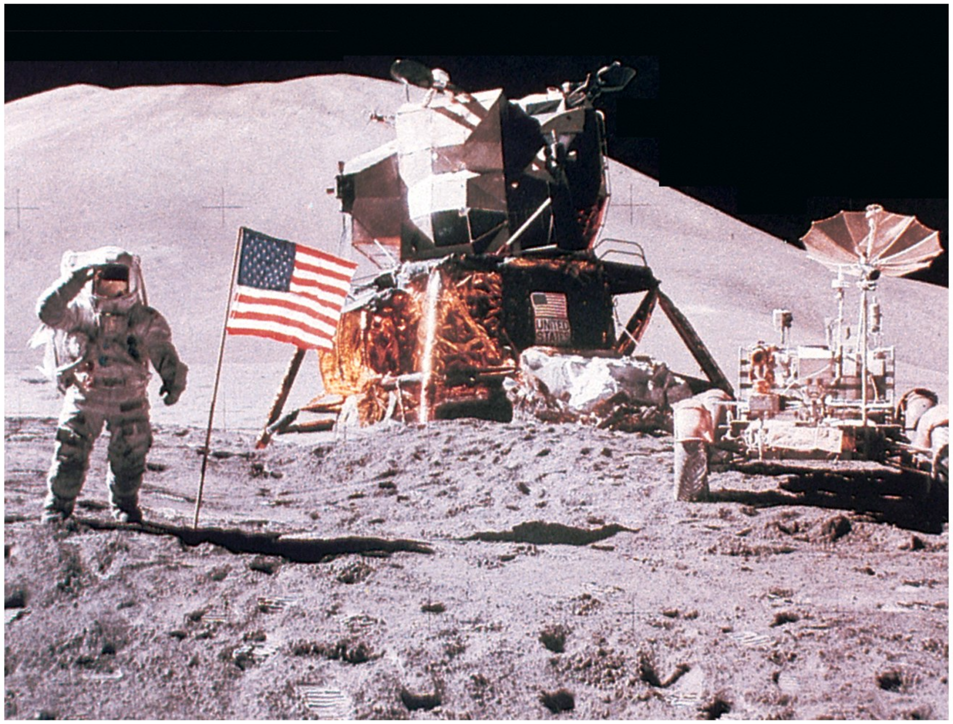


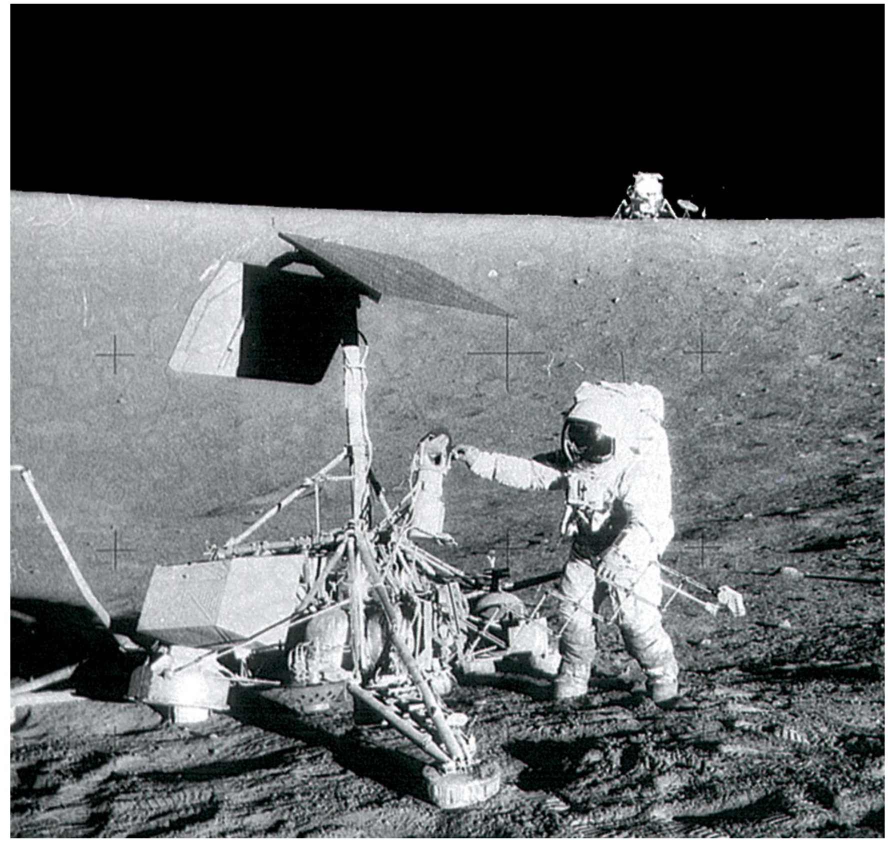
Virtually all lunar craters were caused by space debris striking the surface

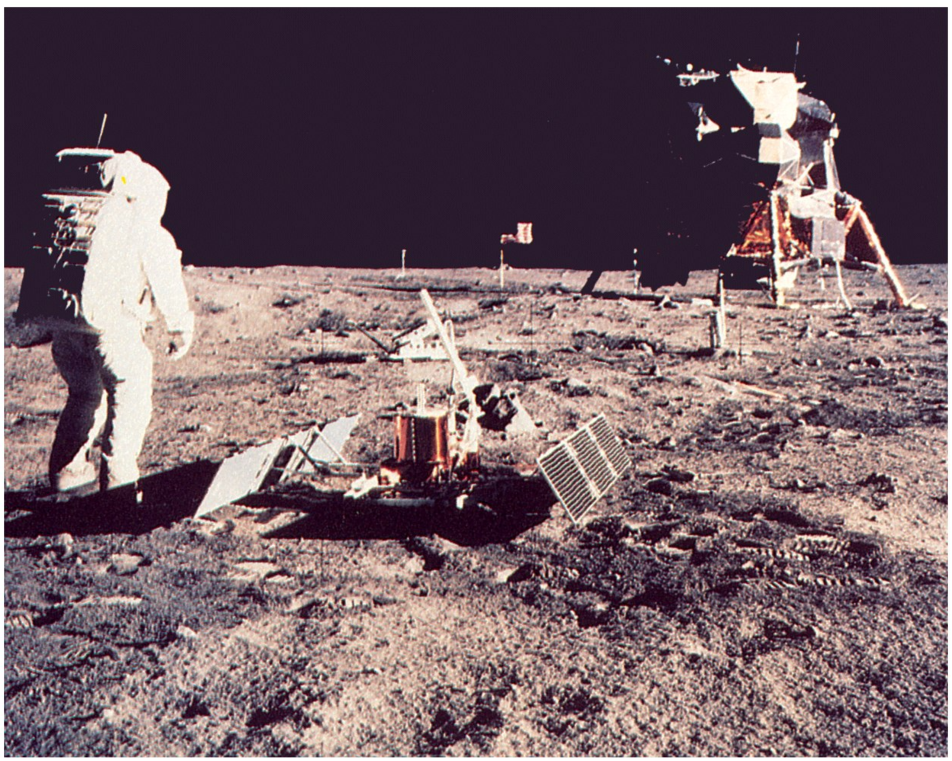
There is no evidence of plate tectonic activity on the Moon


Mare: fewer craters, hence relatively young
500 km
Surrounding light-colored terrain: more craters, so relatively old


10 km
Mare Tranquillitatis
This "river" was once filled with flowing lava.
After the lava cooled and solidified, a meteoroid landed on top of it and produced this crater.

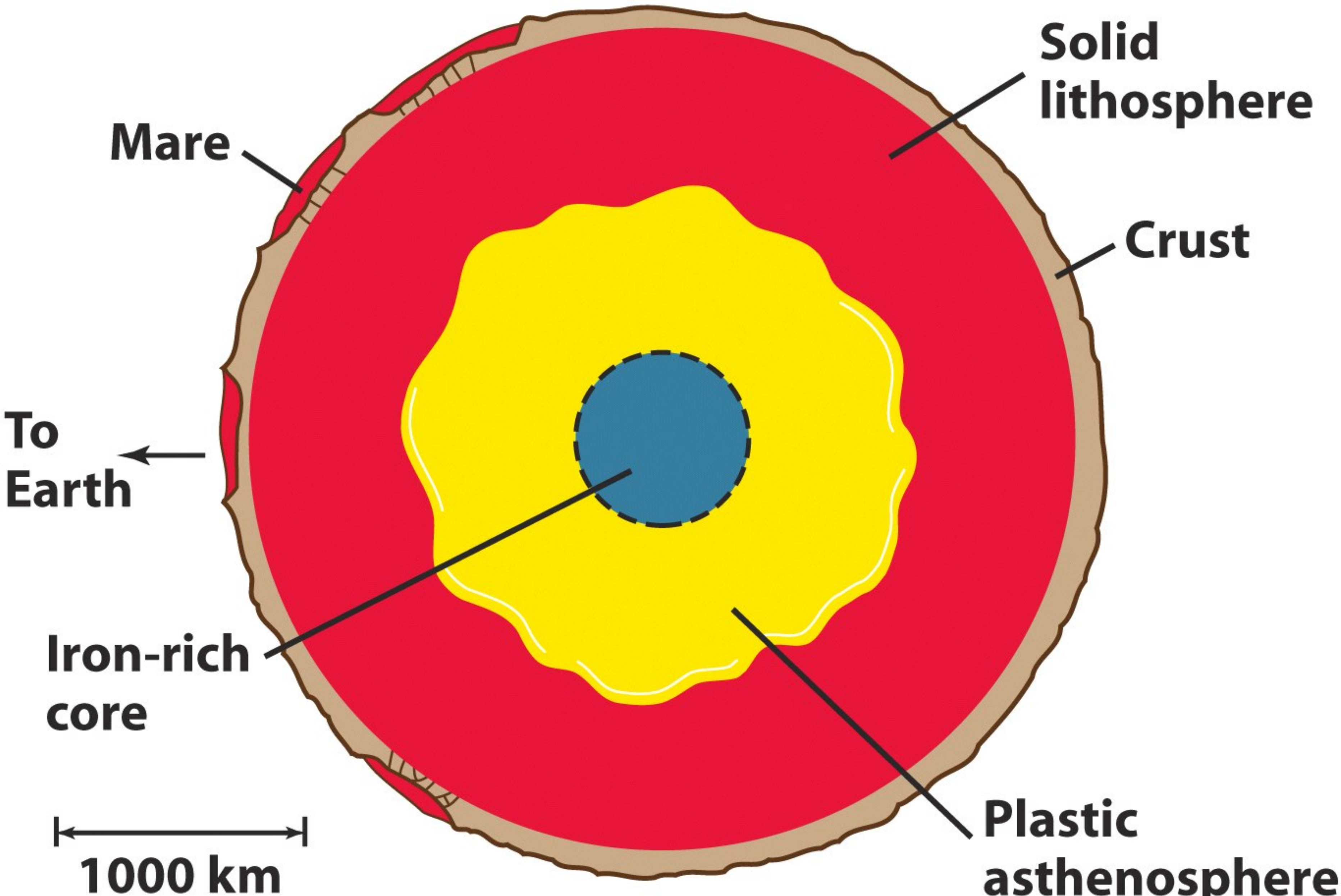






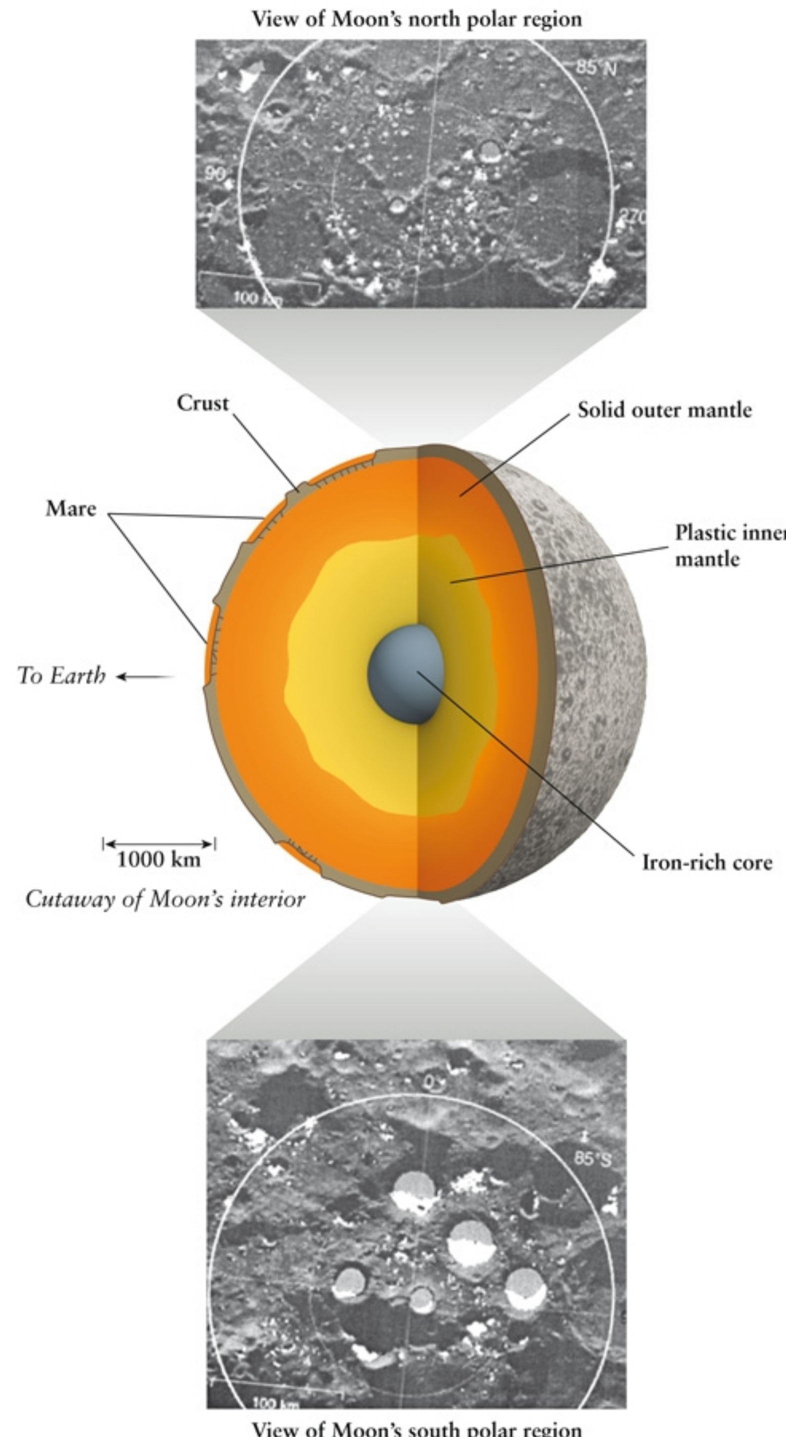
Much of our knowledge about the Moon has come from human exploration in the 1960s and early 1970s and from more recent observations by unmanned spacecraft

The Moon has no global magnetic field but has a small core beneath a thick mantle



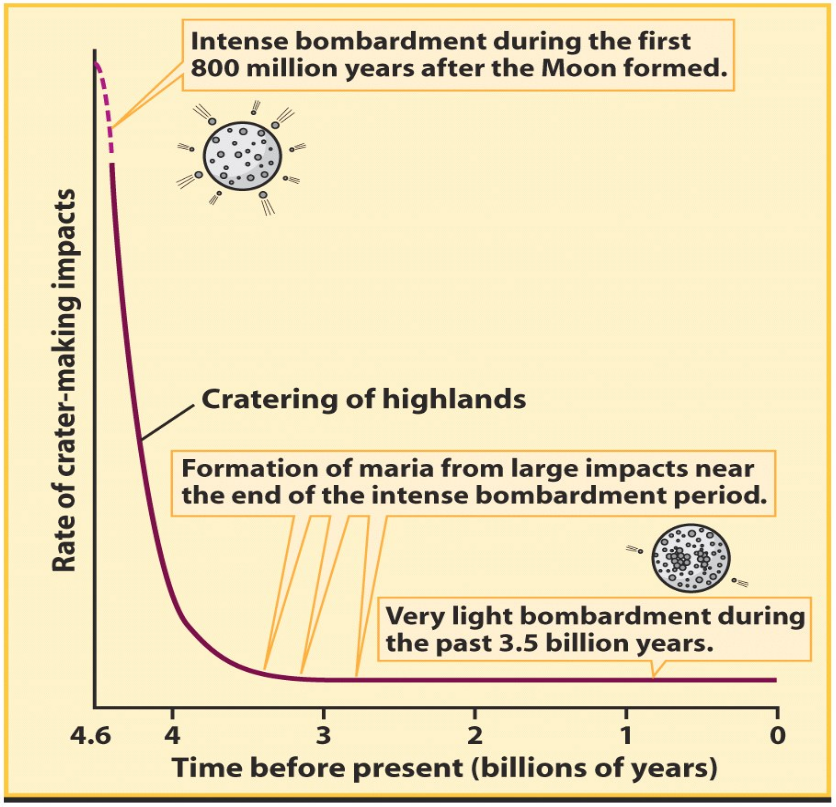
Seismic experiments revealed that the main regions of the Moon's interior mimic those of Earth, but in different proportions.

Water ice may exist in the polar craters, where the energy received from the Sun is insufficient to melt it.

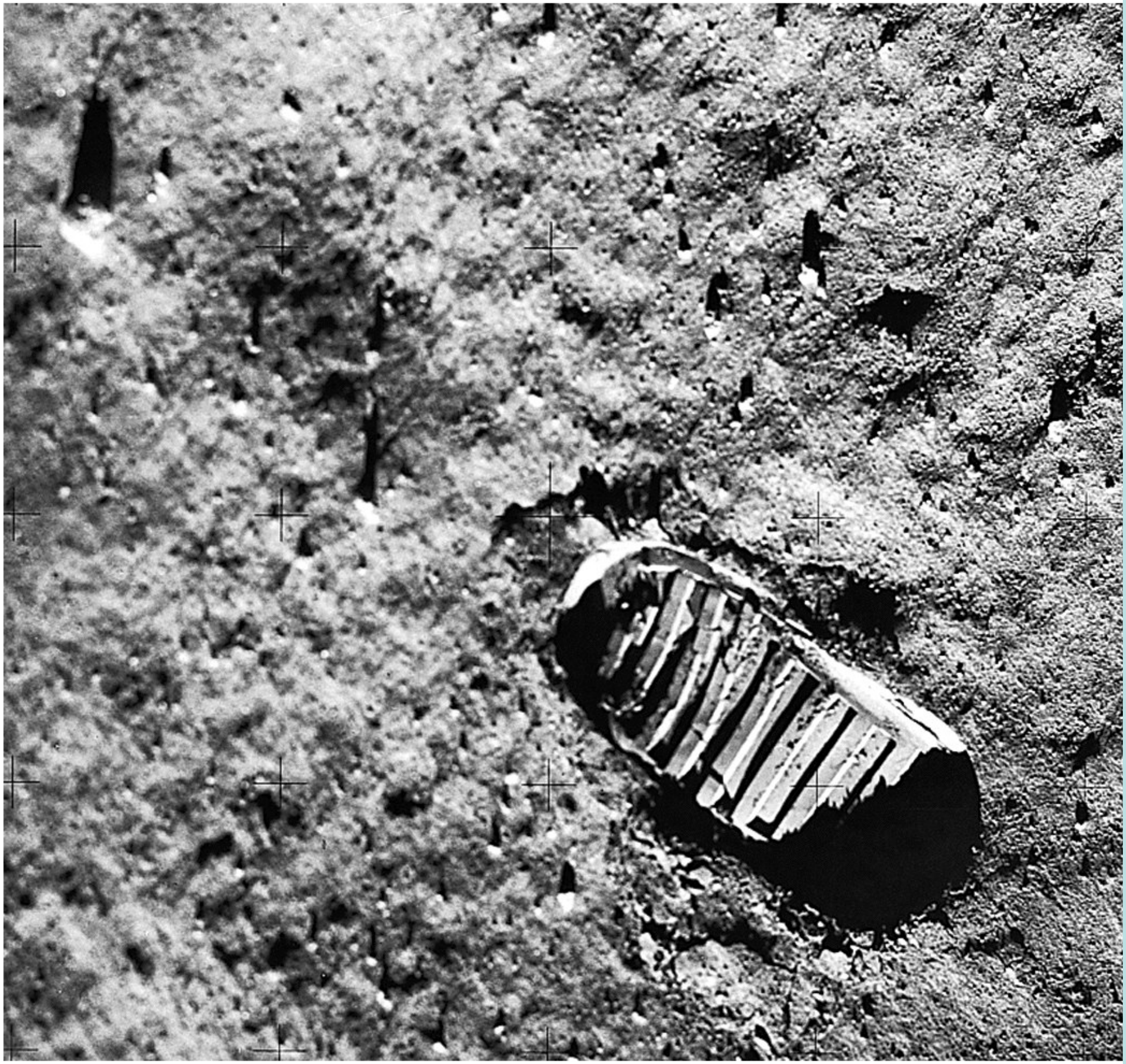


b

Lunar rocks reveal a geologic history quite unlike that of Earth

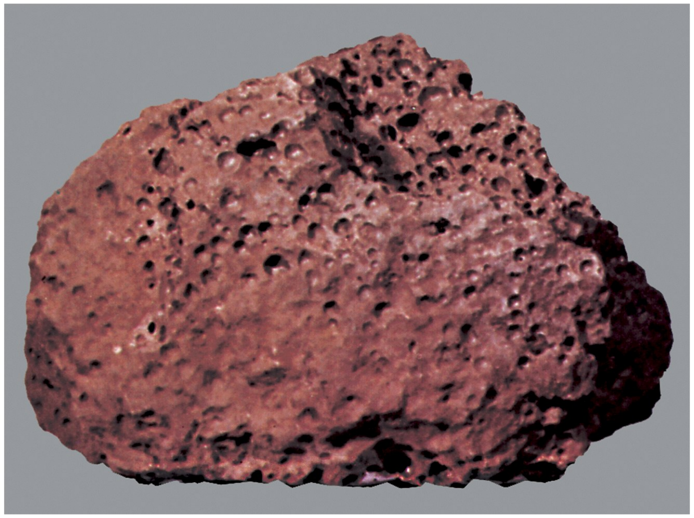


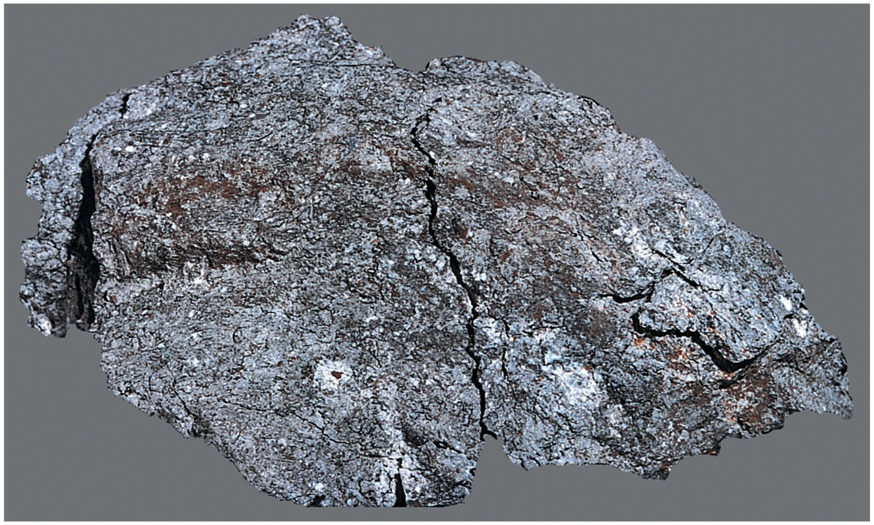
- The anorthositic crust exposed in the highlands was formed between 4.0 and 4.3 billion years ago
- The mare basalts solidified between 3.1 and 3.8 billion years ago
- The Moon's surface has undergone very little change over the past 3 billion years



- Meteoroid impacts have been the only significant “weathering” agent on the Moon
- The Moon’s regolith, or surface layer of powdered and fractured rock, was formed by meteoritic action

All of the lunar rock samples are rocks formed largely of minerals found in terrestrial rocks





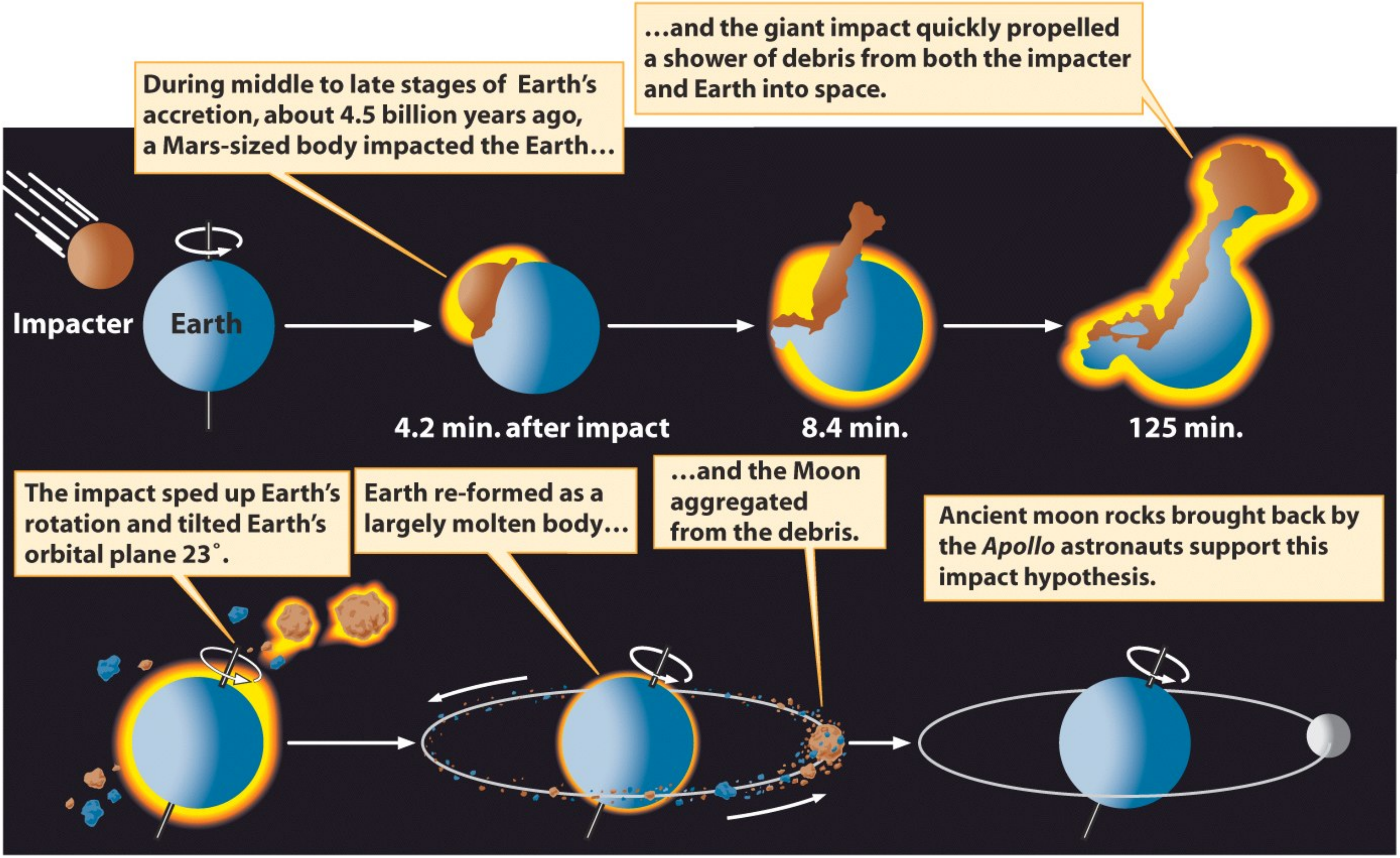
The lunar rocks contain no water

They differ from terrestrial rocks in being relatively enriched in the refractory elements and depleted in the volatile elements

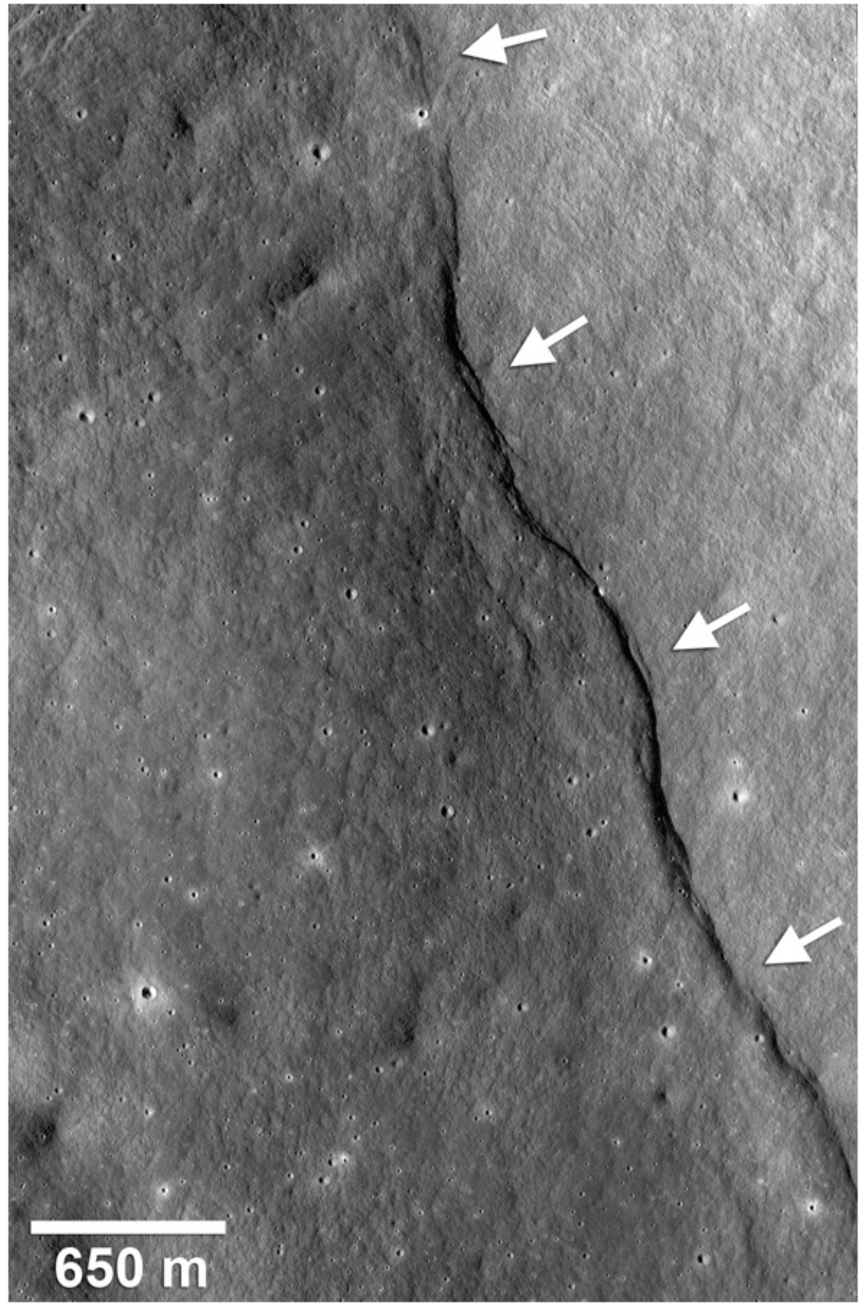
The Moon probably formed from debris cast into space when a huge planetesimal struck the proto-Earth

- The collisional-ejection theory holds that the proto-Earth was struck by a Mars-sized protoplanet and that debris from this collision coalesced to form the Moon
- This theory successfully explains most properties of the Moon
- The Moon was molten in its early stages, and the anorthositic crust solidified from low-density magma that floated to the lunar surface
- The mare basins were created later by the impact of planetesimals and filled with lava from the lunar interior

The Moon probably formed from debris cast into space when a huge planetesimal struck the proto-Earth

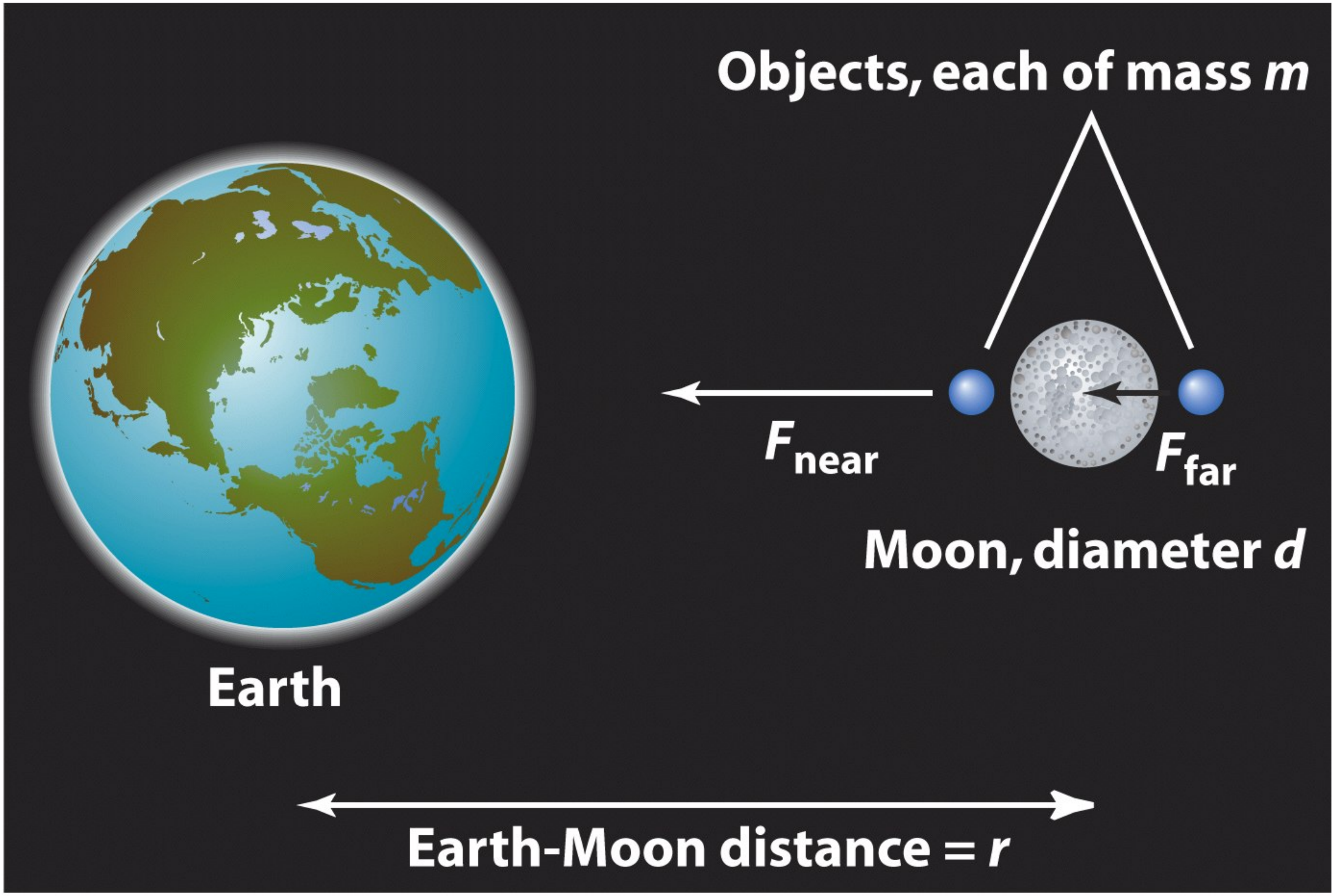


As the Moon's interior shrank, the surface settled irregularly, creating long lines of cliffs called scarps.



a

Tidal Forces



Tidal forces depend very strongly on the distance between two celestial bodies. They are very strong for the Earth-Moon system. Here is the math:

$$F_{near} - F_{far} = F_{tidal}$$

$$F_{tidal} = \frac{dF}{dr}\Delta r = \frac{d}{dr}\frac{GM_{Earth}m_{bulge}}{r^2}\Delta r$$

Tidal forces

$$F_{tidal} = -\frac{2GM_{Earth}m_{bulge}}{r^3}\Delta r$$

$$m_{bulge} = \frac{A}{r^3}$$

$$\Delta r = -d$$

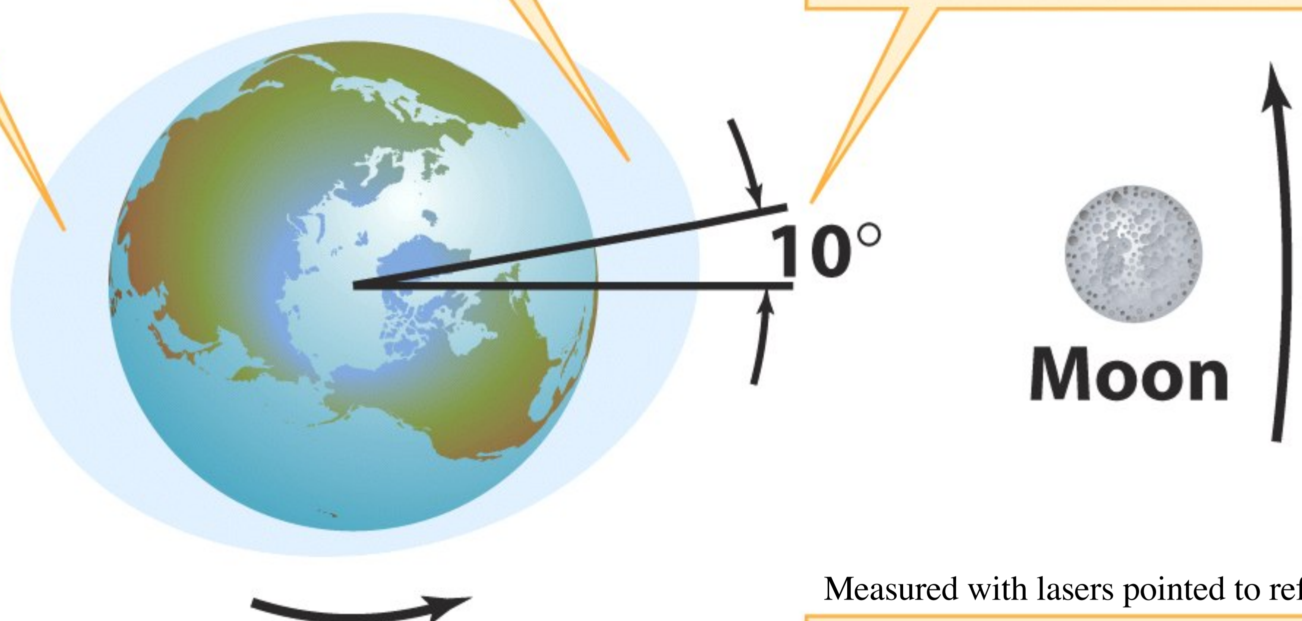
$$F_{tidal-net} = A\frac{2GM_{Earth}}{r^6}d$$

$$\frac{F_{tidal-net-perigee}}{F_{tidal-net-apogee}} = \left(\frac{r_{perigee}}{r_{apogee}}\right)^{-6} = \left(\frac{363{,}300}{405{,}500}\right)^{-6} = 1.93$$

Tidal forces are slowing the Earth's rotation and pushing the Moon away from Earth

1. The Moon's tidal forces elongate Earth's oceans along an Earth-Moon line.

2. Friction between the spinning Earth and its oceans drags the tidal bulge about 10° ahead of alignment with the moon.



Measured with lasers pointed to reflectors stationed on the Moon

3. Friction between Earth and its oceans also makes the Earth rotate more slowly, increasing the length of the day. By 0.02 ms/yr!!!

4. The tidal bulge on the side nearest the Moon exerts a small forward force on the Moon, making it spiral slowly away from Earth. By 3.8 cm/yr!!!

Why do we see only one side of the moon from earth?

Tidal forces cause the moon to be in synchronous rotation.

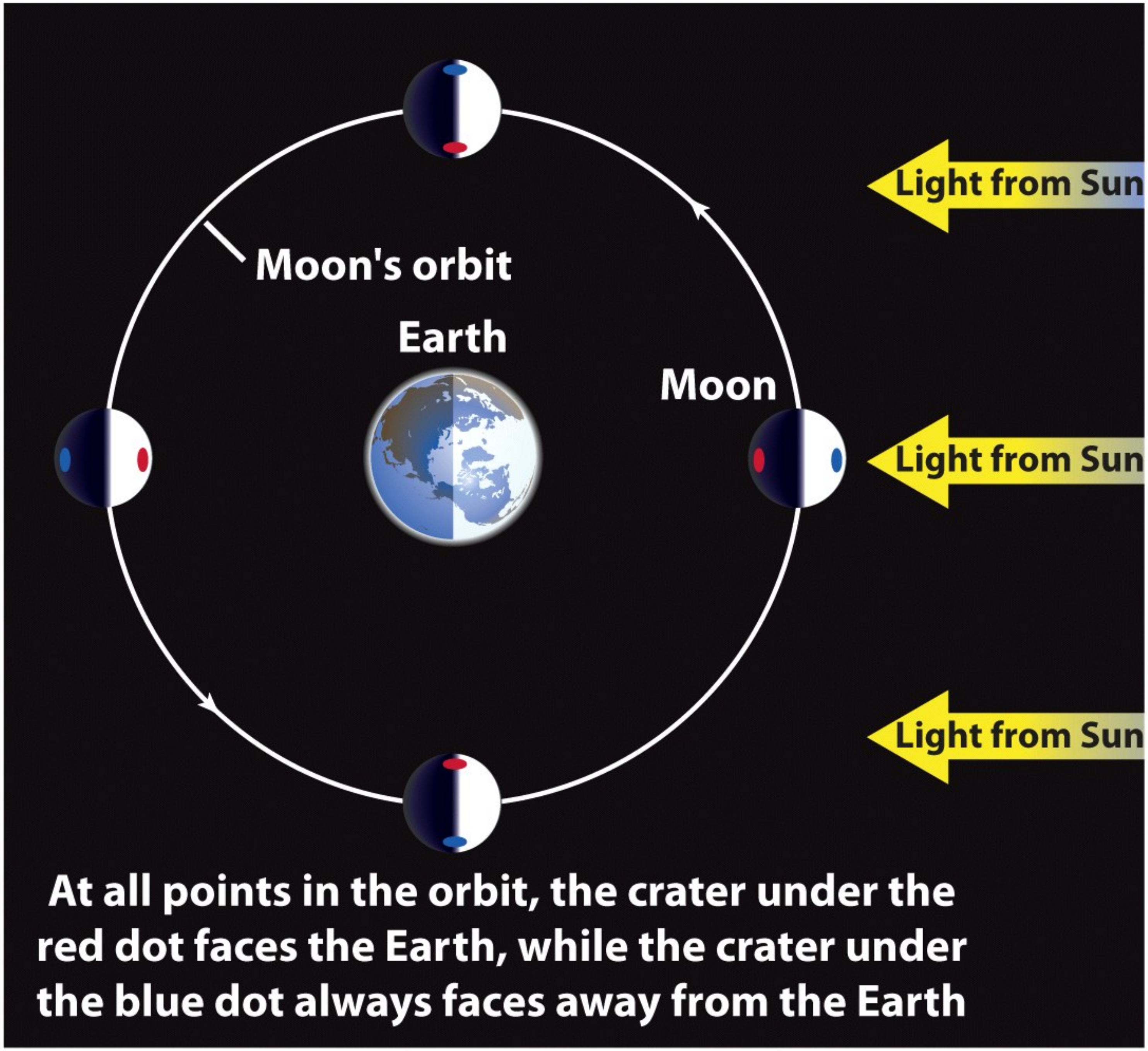


Figure 6-29
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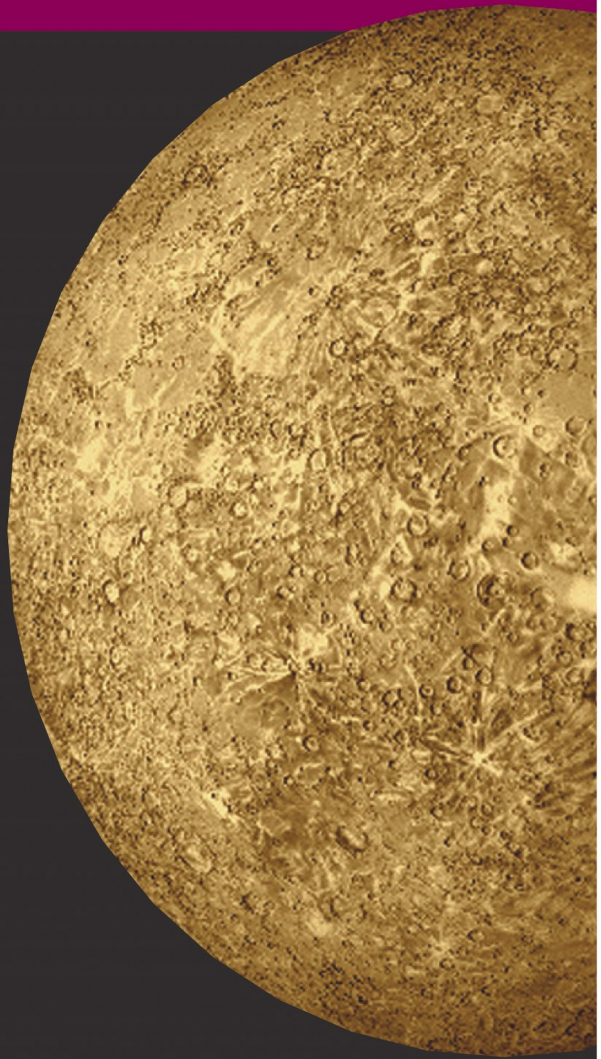
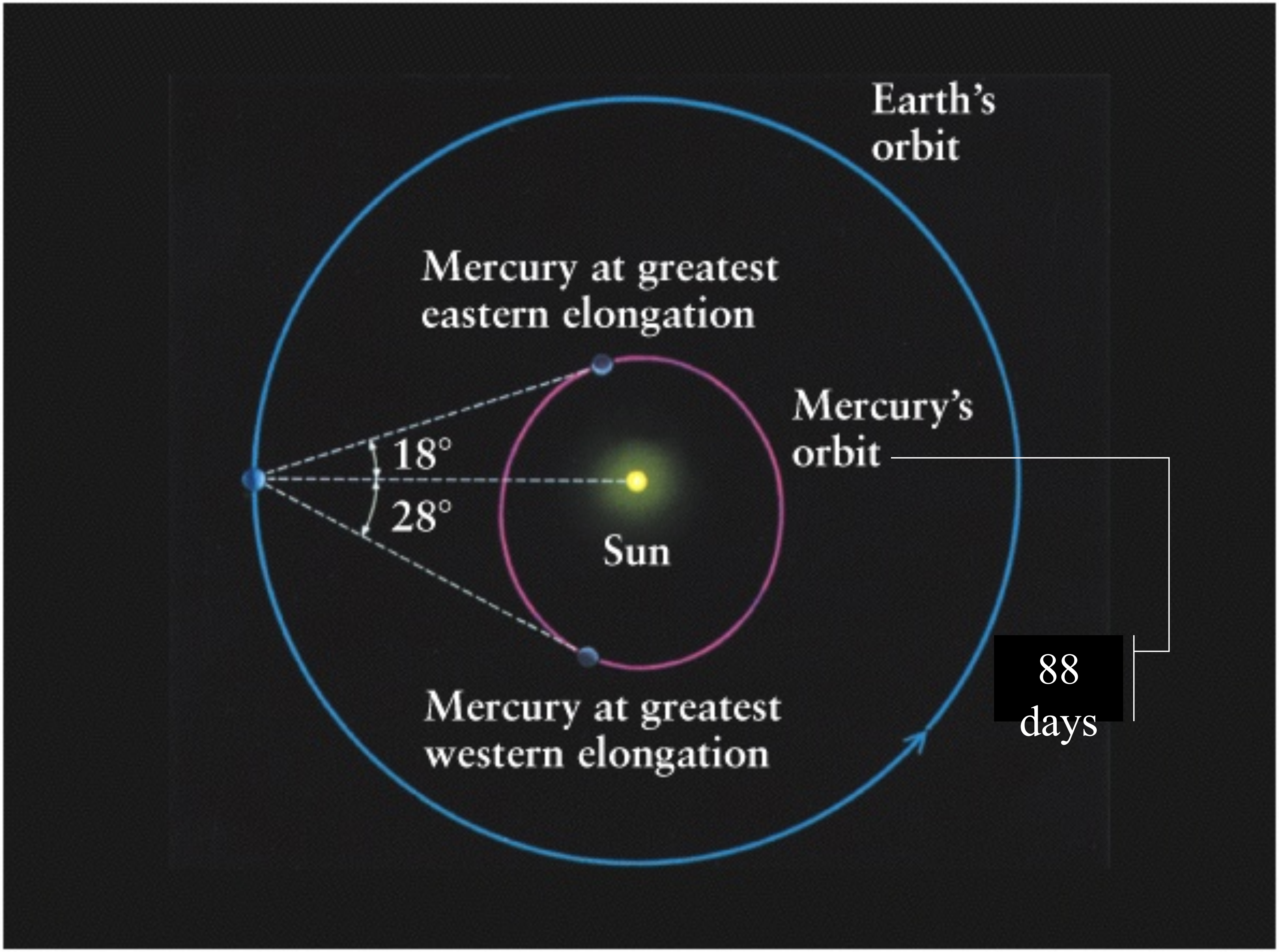
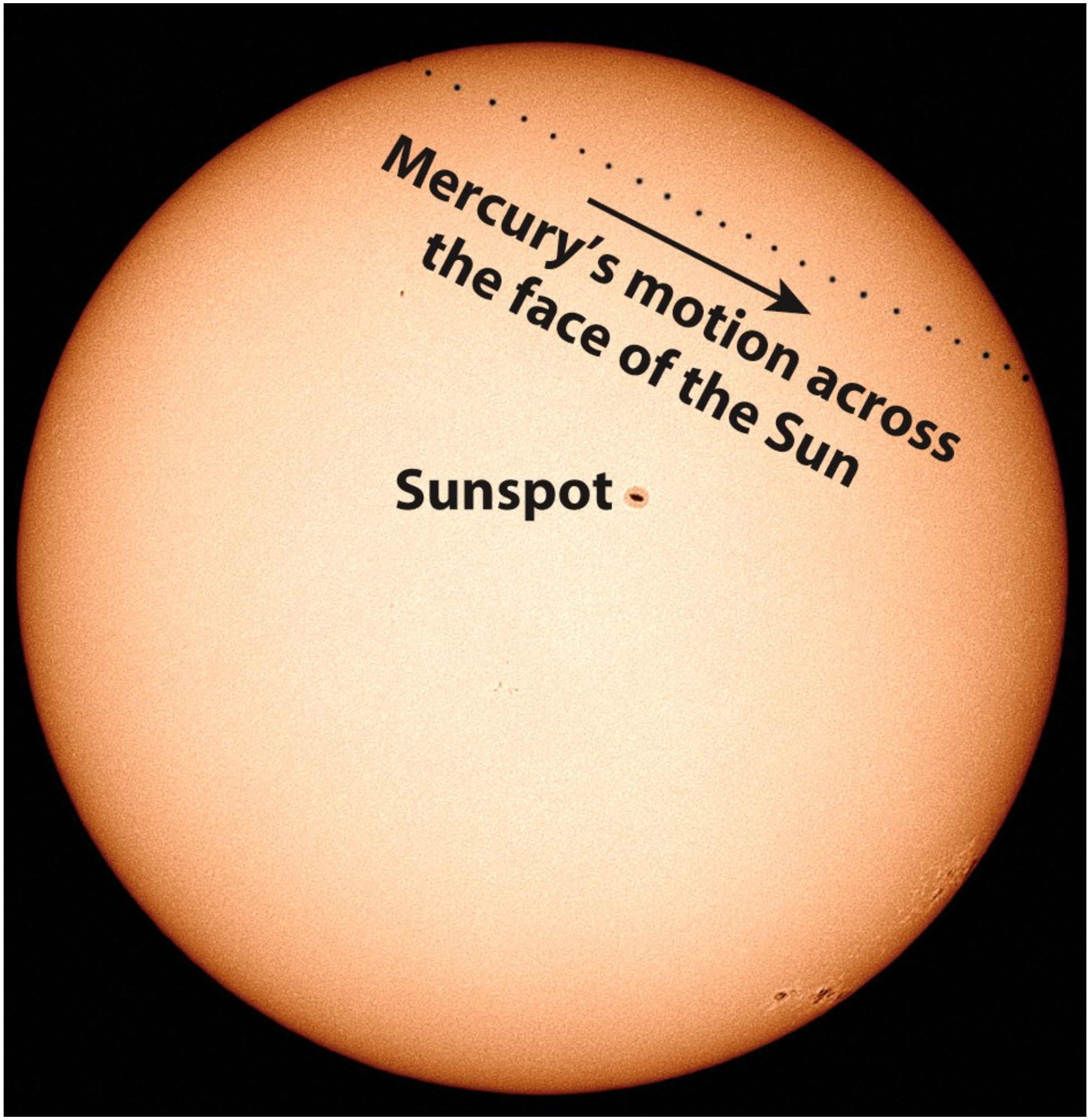
table 11-1 | Mercury Data

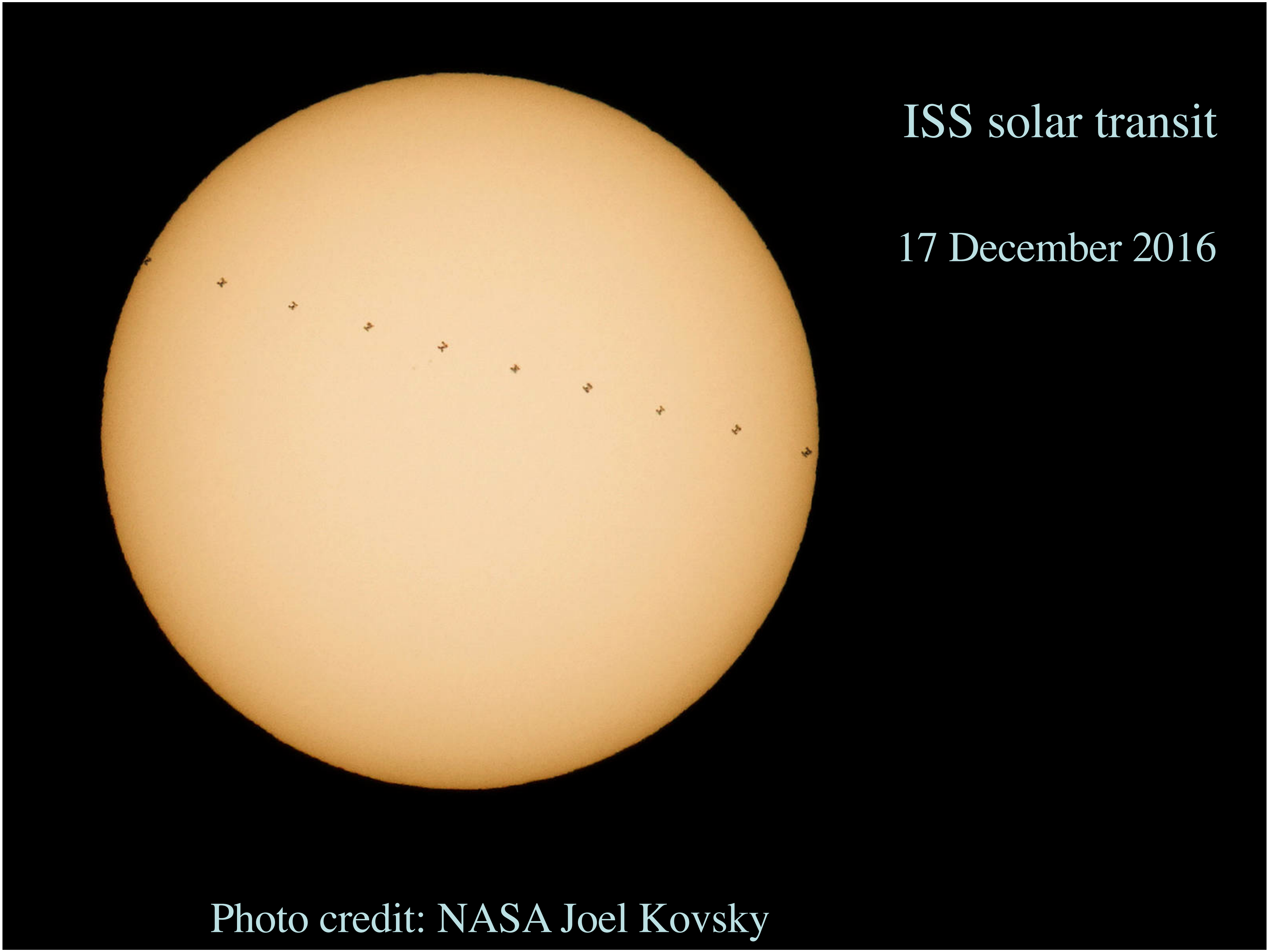
Average distance from Sun:	0.387 AU = 5.79×10^7 km
Maximum distance from Sun:	0.467 AU = 6.98×10^7 km
Minimum distance from Sun:	0.307 AU = 4.60×10^7 km
Eccentricity of orbit:	0.206
Average orbital speed:	47.9 km/s
Orbital period:	87.969 days
Rotation period:	58.646 days
Inclination of equator to orbit:	0.5°
Inclination of orbit to ecliptic:	7° 00′ 16″
Diameter (equatorial):	4880 km = 0.383 Earth diameter
Mass:	3.302×10^{23} kg = 0.0553 Earth mass
Average density:	5430 kg/m^3
Escape speed:	4.3 km/s
Surface gravity (Earth = 1):	0.38
Albedo:	0.12
Average surface temperatures:	Day: 350°C = 662°F = 623 K
	Night: −170°C = −274°F = 103 K
Atmosphere:	Essentially none




Earth's orbit
Mercury at greatest eastern elongation
Mercury's orbit
18°
28°
Sun
88 days
Mercury at greatest western elongation

Solar Transit




ISS solar transit
17 December 2016
Photo credit: NASA Joel Kovsky

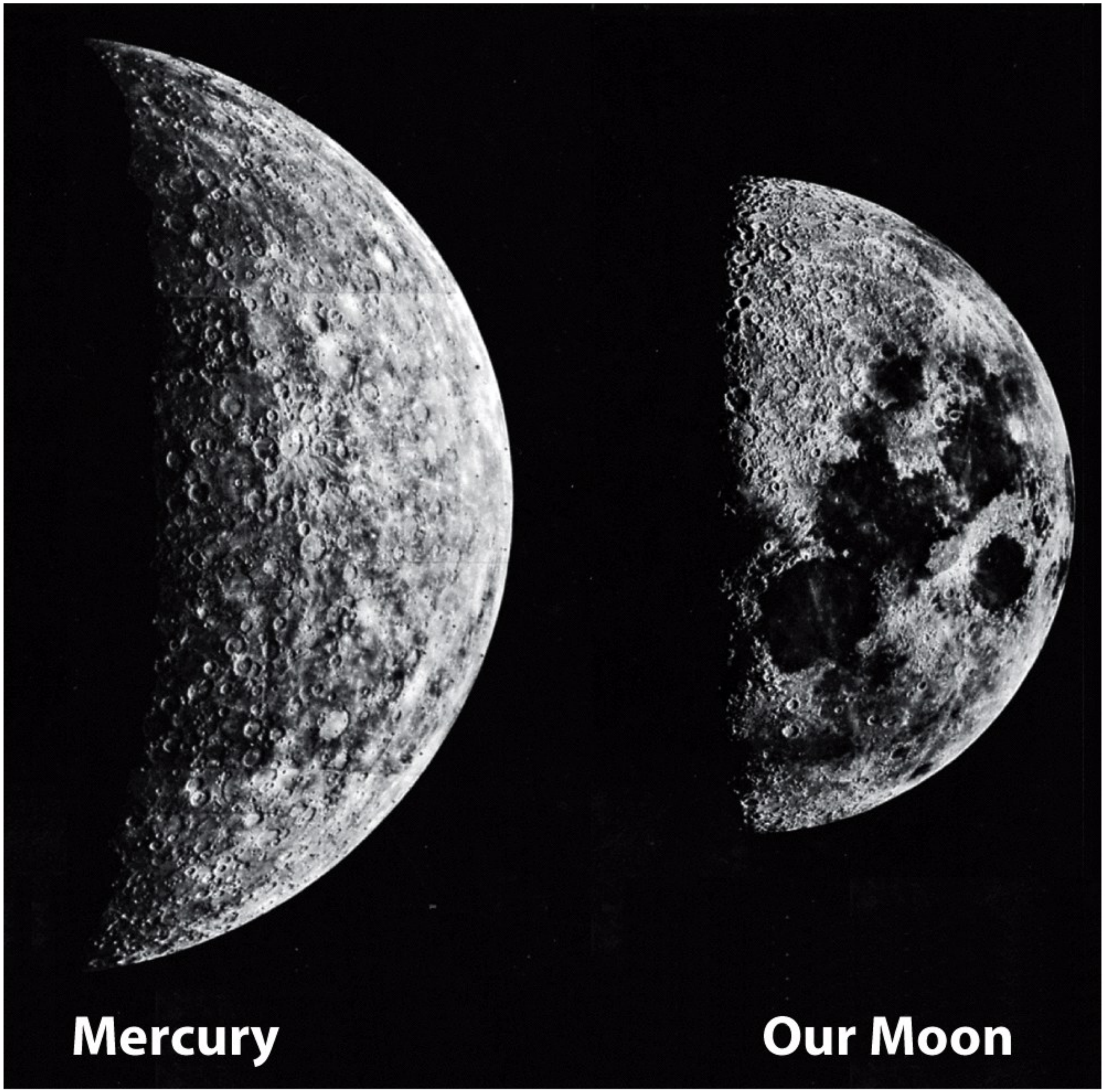


Figure 7-2
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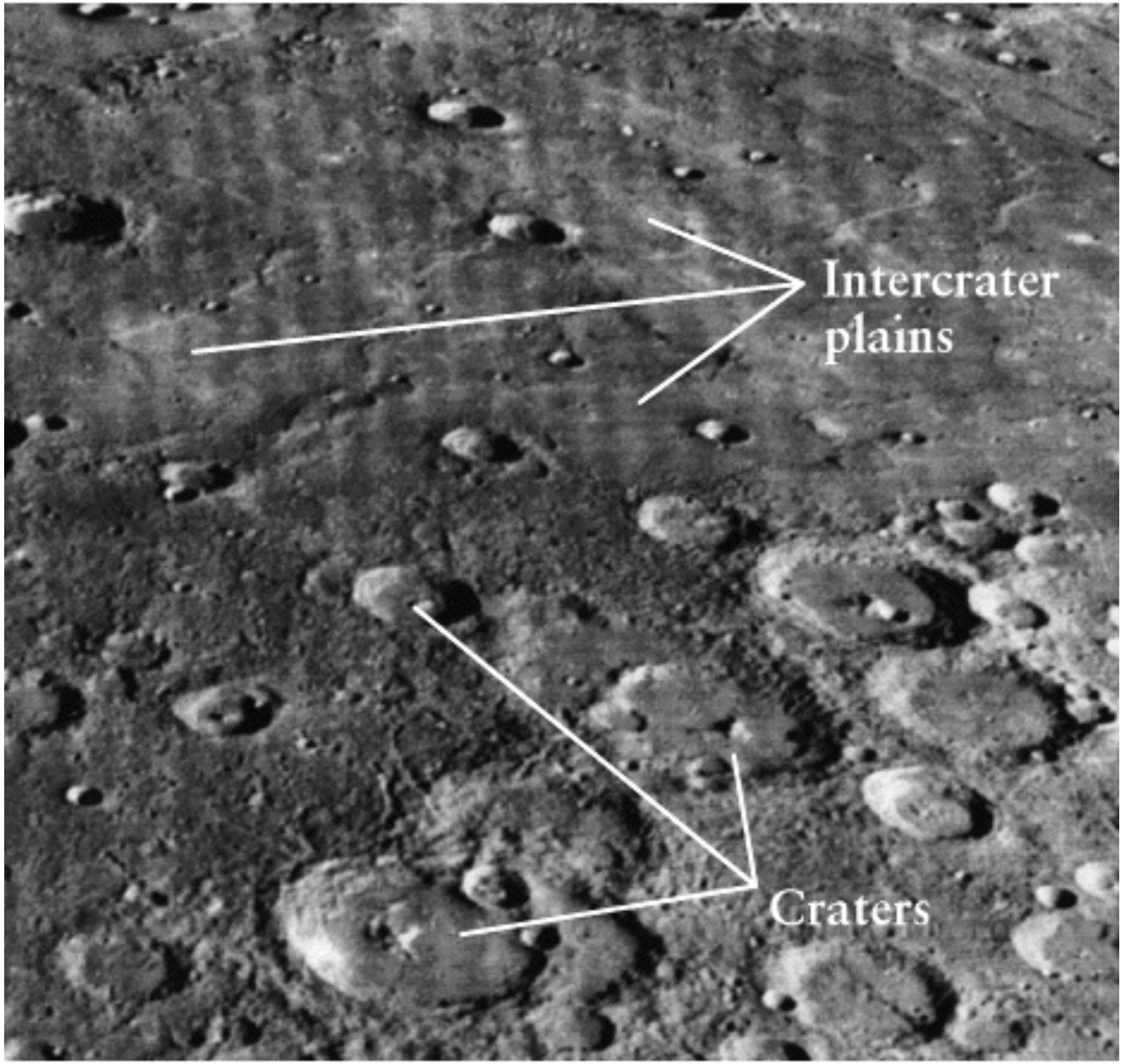
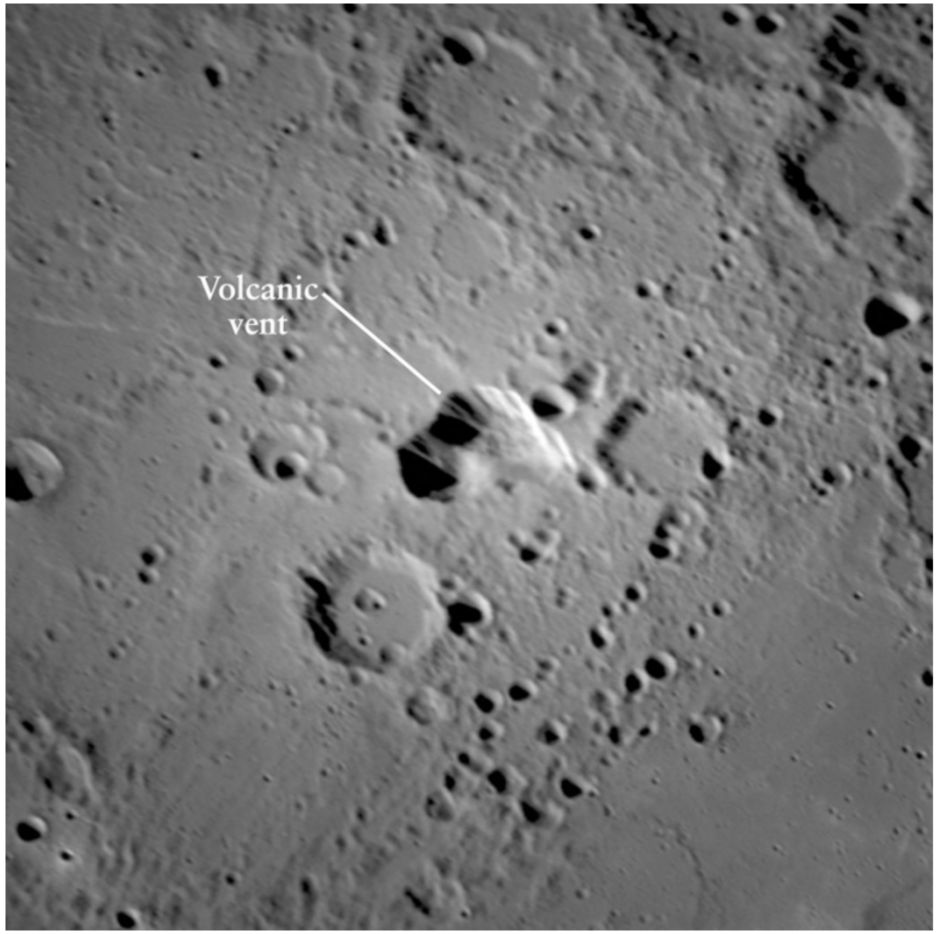
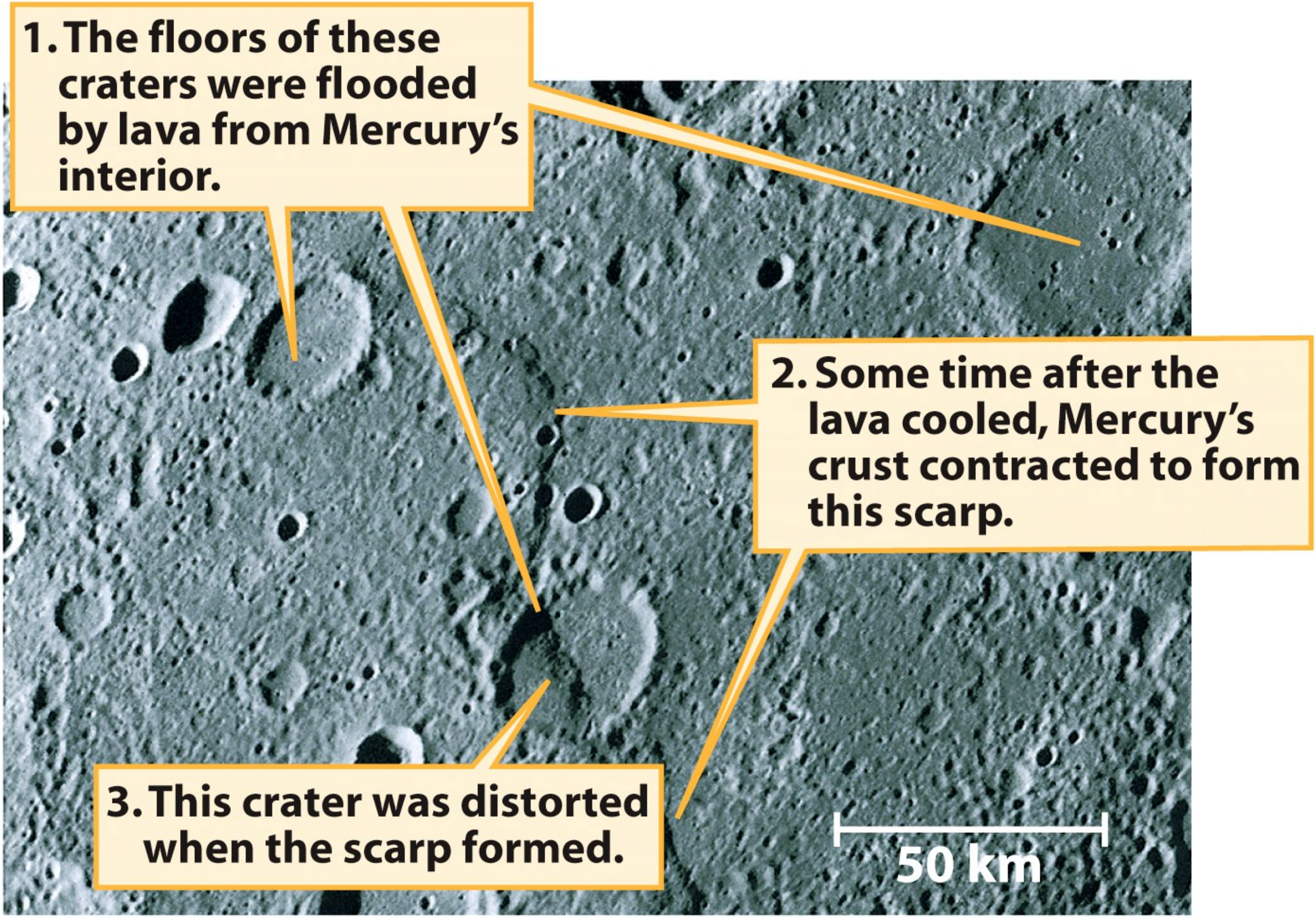
- Heavily cratered surface
- Less dense cratering than moon
- Gently rolling plains
- Scarps
- No evidence of tectonics

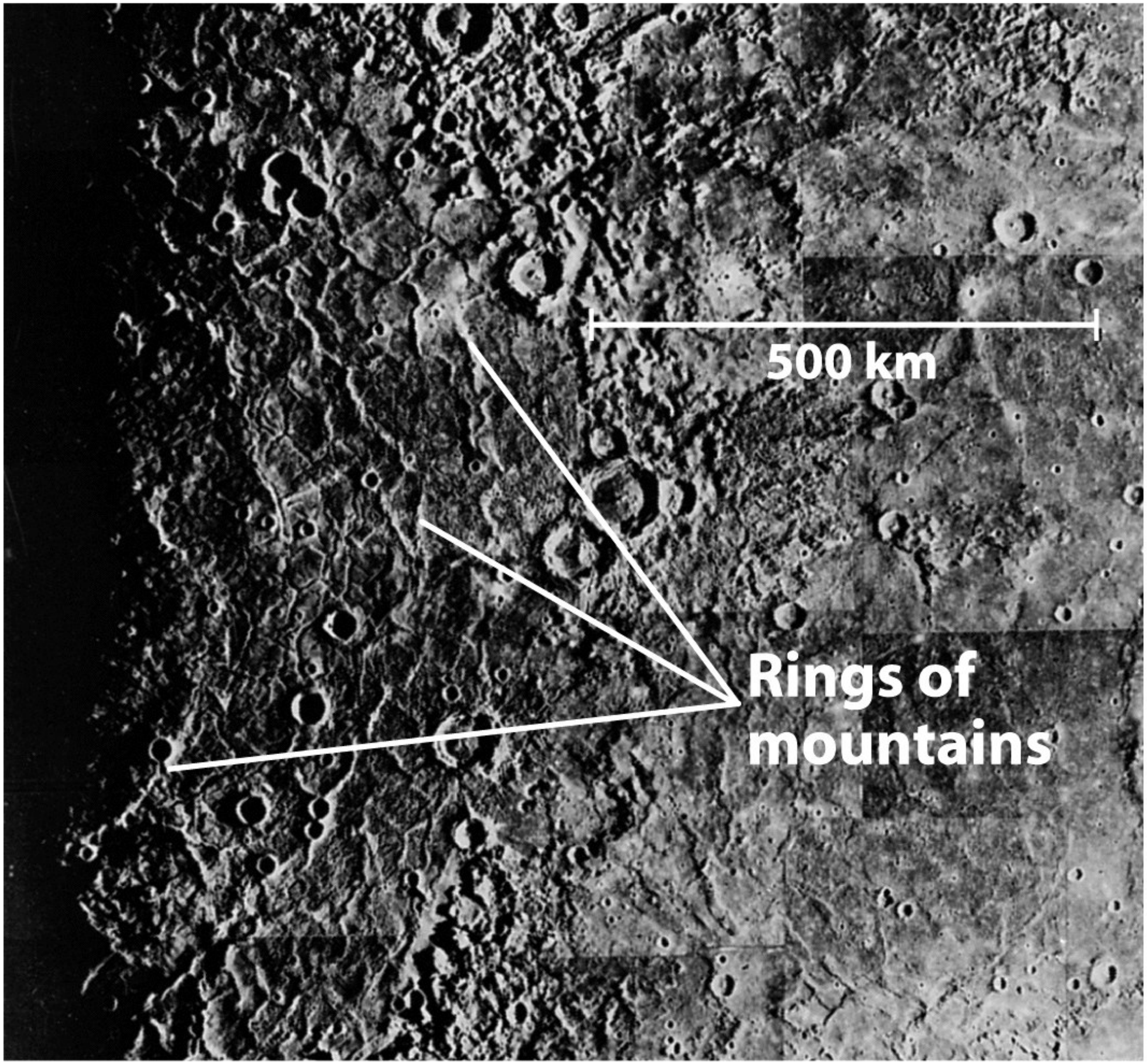


Possible Volcanic Vent



The central indentation in this *Messenger* image from 2009 is believed to be a caldera (sunken vent) of an explosive volcano on Mercury. It is unlikely to be an impact crater, as it completely lacks a raised crater wall.

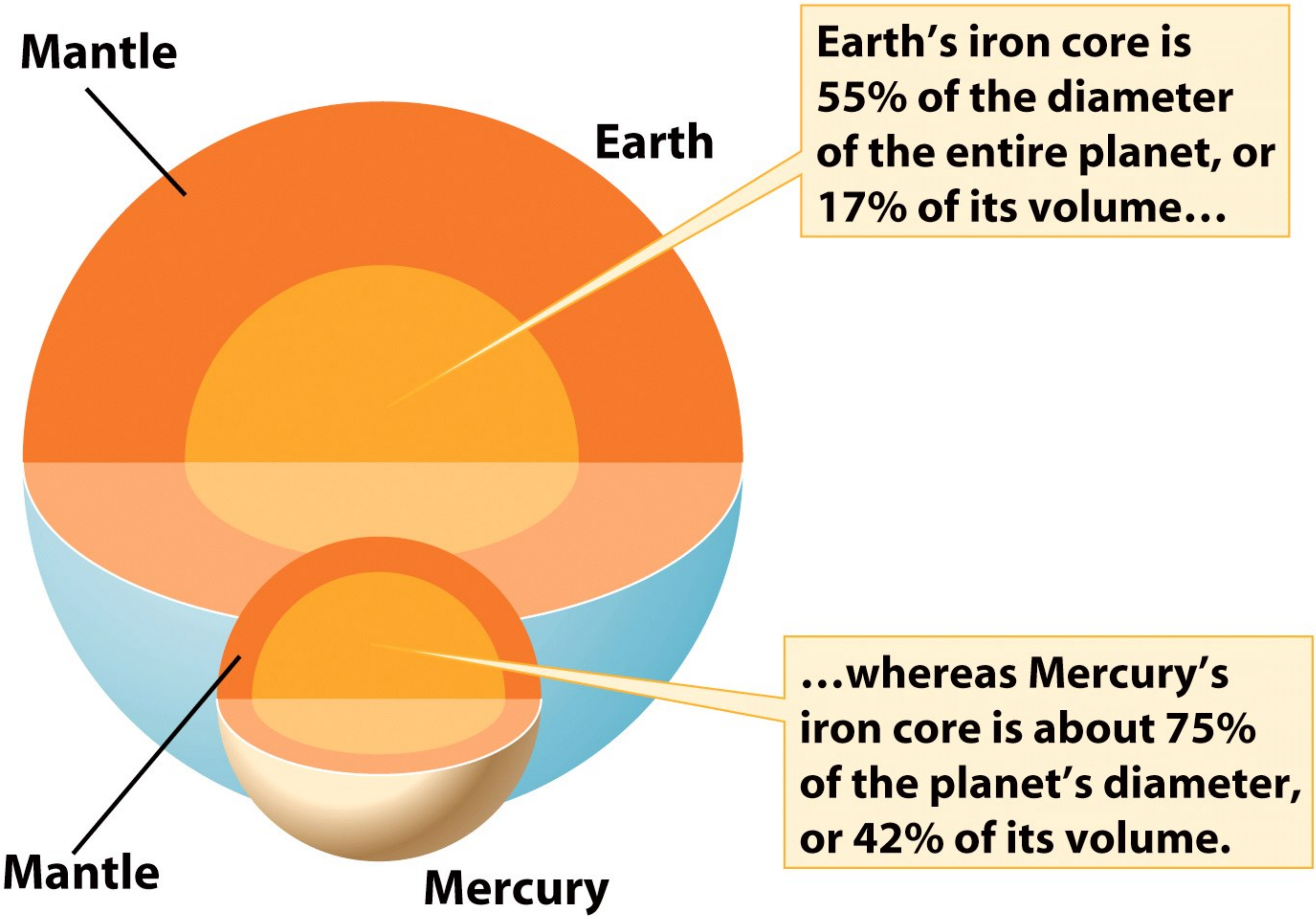

1. The floors of these craters were flooded by lava from Mercury's interior.
2. Some time after the lava cooled, Mercury's crust contracted to form this scarp.
3. This crater was distorted when the scarp formed.
50 km



The Caloris Basin
is evidence of a
large impact

Mercury has an iron core and a surprising magnetic field

- Most iron-rich (relative to mass) planet in the solar system with a core that is 75% of the diameter
- The earth's core is 55% of its diameter and the moon's core is 20% of its diameter
- Among highest density for the planets
- Weak magnetic field indicating part of the core is liquid
- Magnetic field causes a magnetosphere similar to Earth's but weaker



Mantle
Earth
Earth's iron core is 55% of the diameter of the entire planet, or 17% of its volume…
…whereas Mercury's iron core is about 75% of the planet's diameter, or 42% of its volume.
Mantle
Mercury

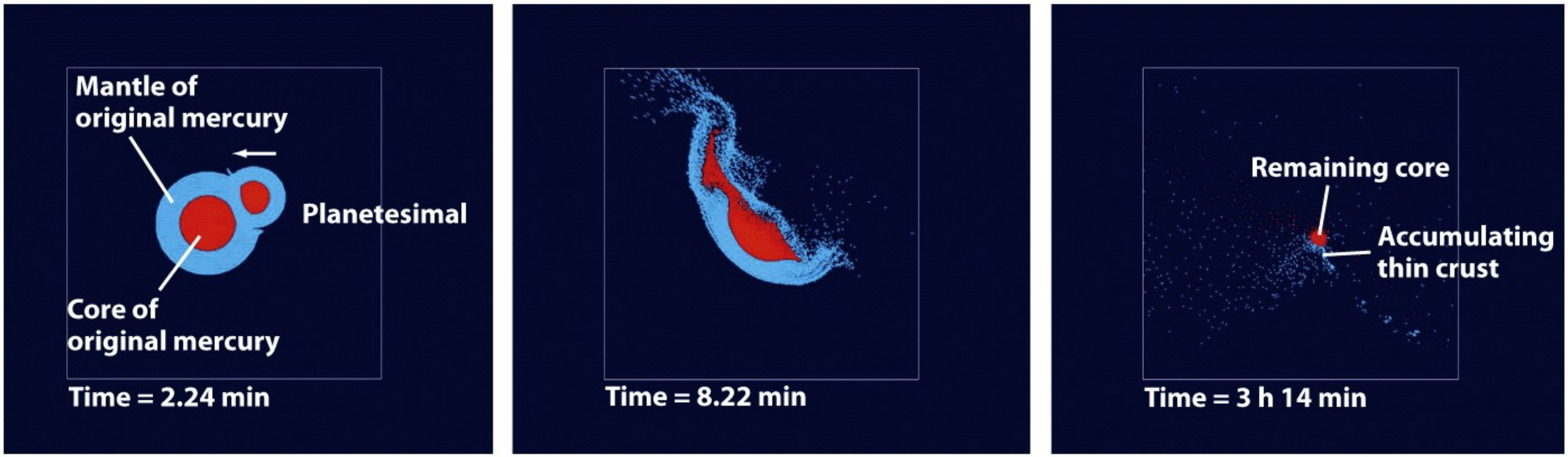
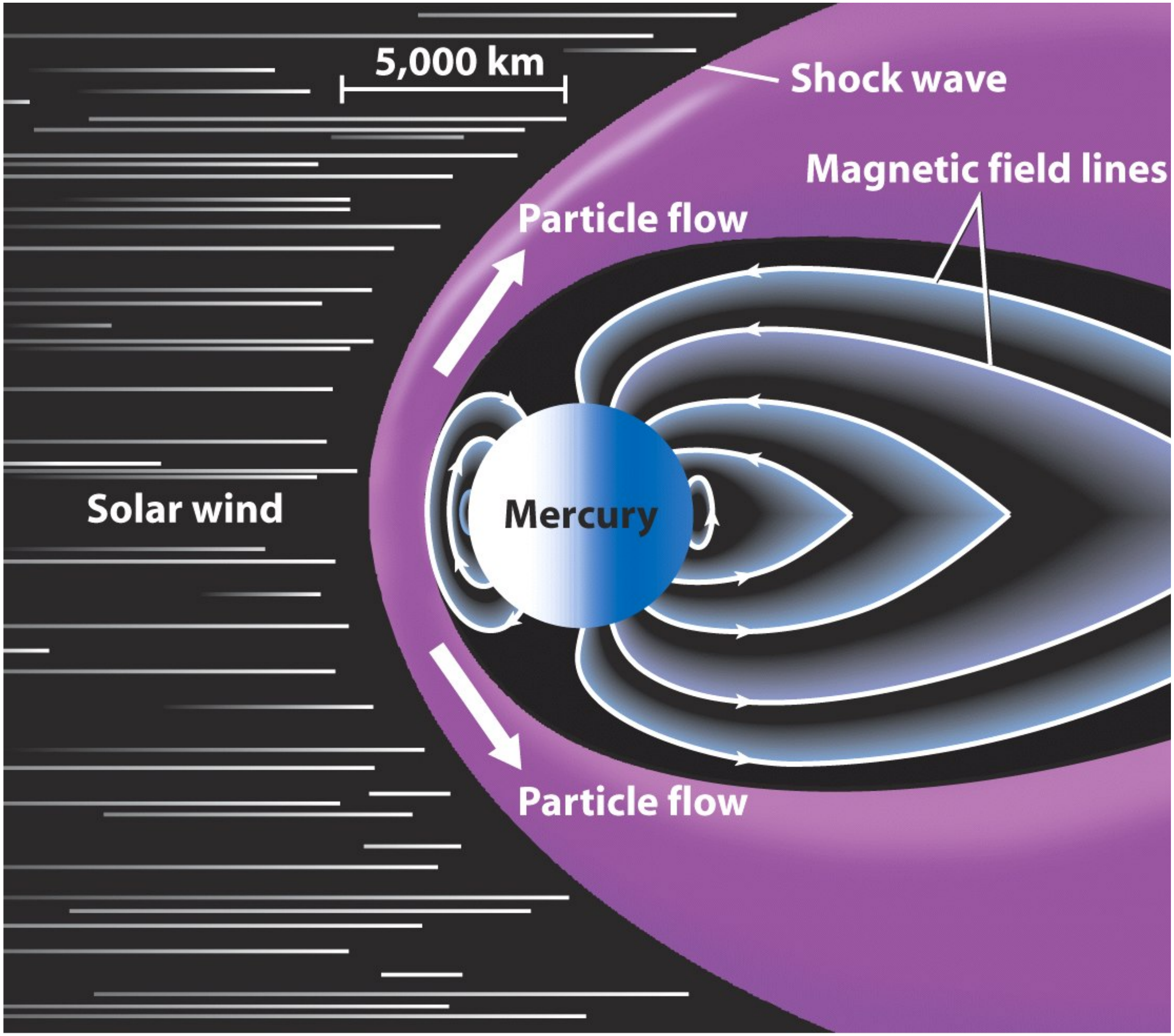
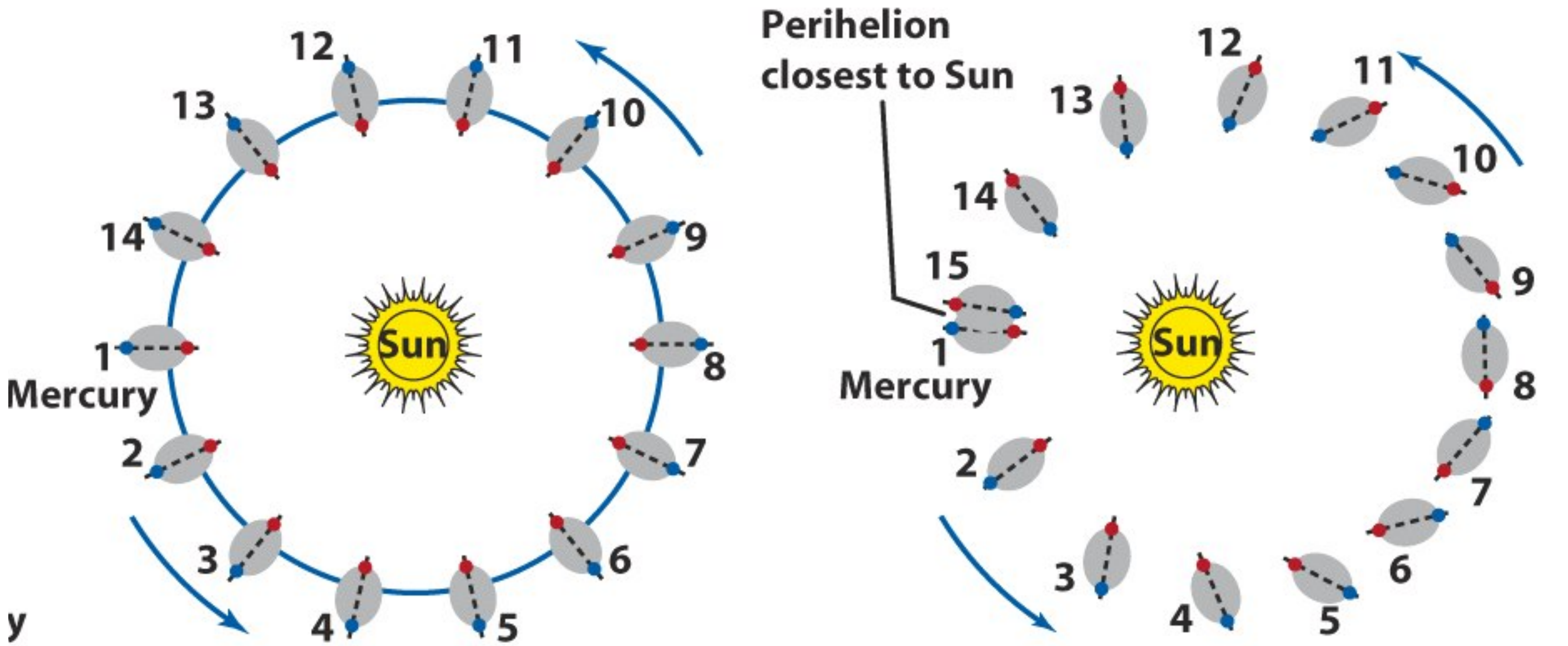


Figure 7-7
Discovering the Universe, Eighth Edition

The (weak) magnetosphere blocks the solar wind from reaching the surface of the planet



Mercury rotates slowly and has a 3-to-2 spin-orbit coupling



(b) If Mercury were in a circular orbit, its long axis would always point toward the Sun: Mercury would be in synchronous rotation (1-to-1 spin-orbit coupling).

(c) In fact Mercury is in an elliptical orbit, and its long axis only points toward the Sun at perihelion: Mercury spins on its axis 1½ times during each complete orbit (3-to-2 spin-orbit coupling).

table 12-1 Venus Data

Average distance from Sun:	0.723 AU = 1.082×10^8 km
Maximum distance from Sun:	0.728 AU = 1.089×10^8 km
Minimum distance from Sun:	0.718 AU = 1.075×10^8 km
Eccentricity of orbit:	0.0068
Average orbital speed:	35.0 km/s
Orbital period:	224.70 days
Rotation period:	243.01 days (retrograde)
Inclination of equator to orbit:	177.4°
Inclination of orbit to ecliptic:	3.39°
Diameter (equatorial):	12,104 km = 0.949 Earth diameter
Mass:	4.868×10^{24} kg = 0.815 Earth mass
Average density:	5243 kg/m^3
Escape speed:	10.4 km/s
Surface gravity (Earth = 1):	0.91
Albedo:	0.59
Average surface temperature:	460°C = 860°F = 733 K
Atmospheric composition (by number of molecules):	96.5% carbon dioxide (CO_2) 3.5% nitrogen (N_2), 0.003% water vapor (H_2O)

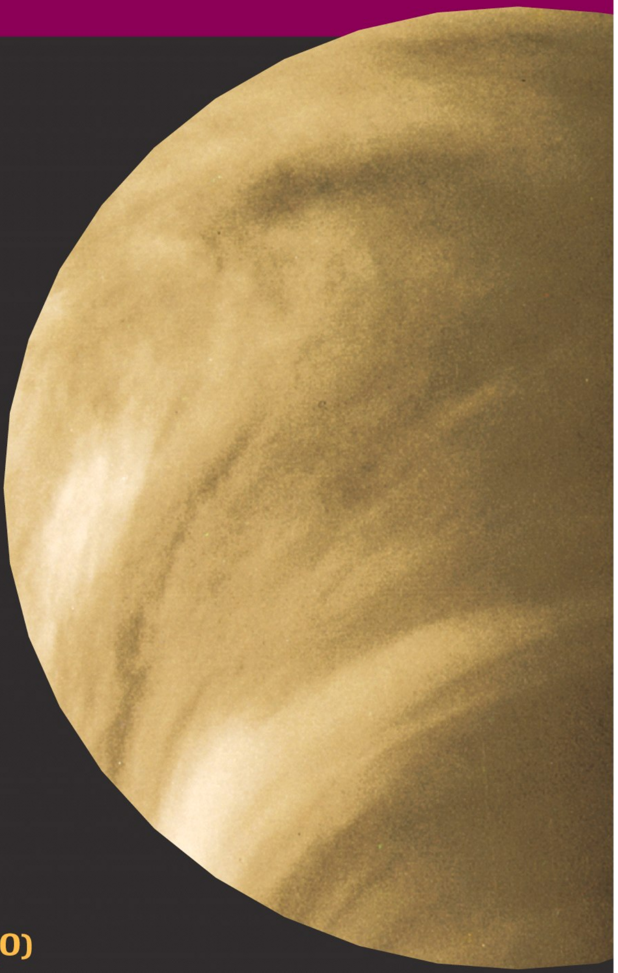
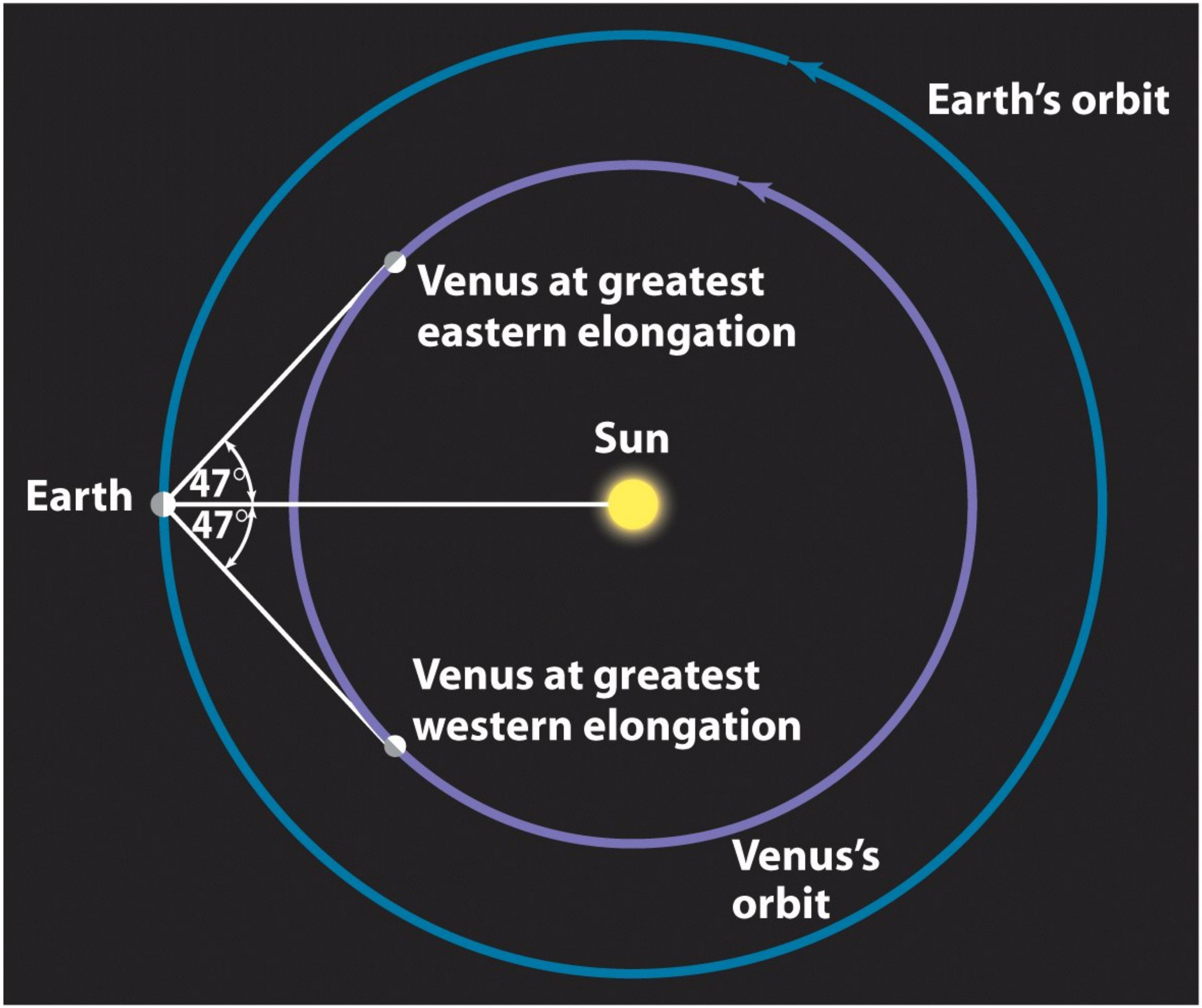
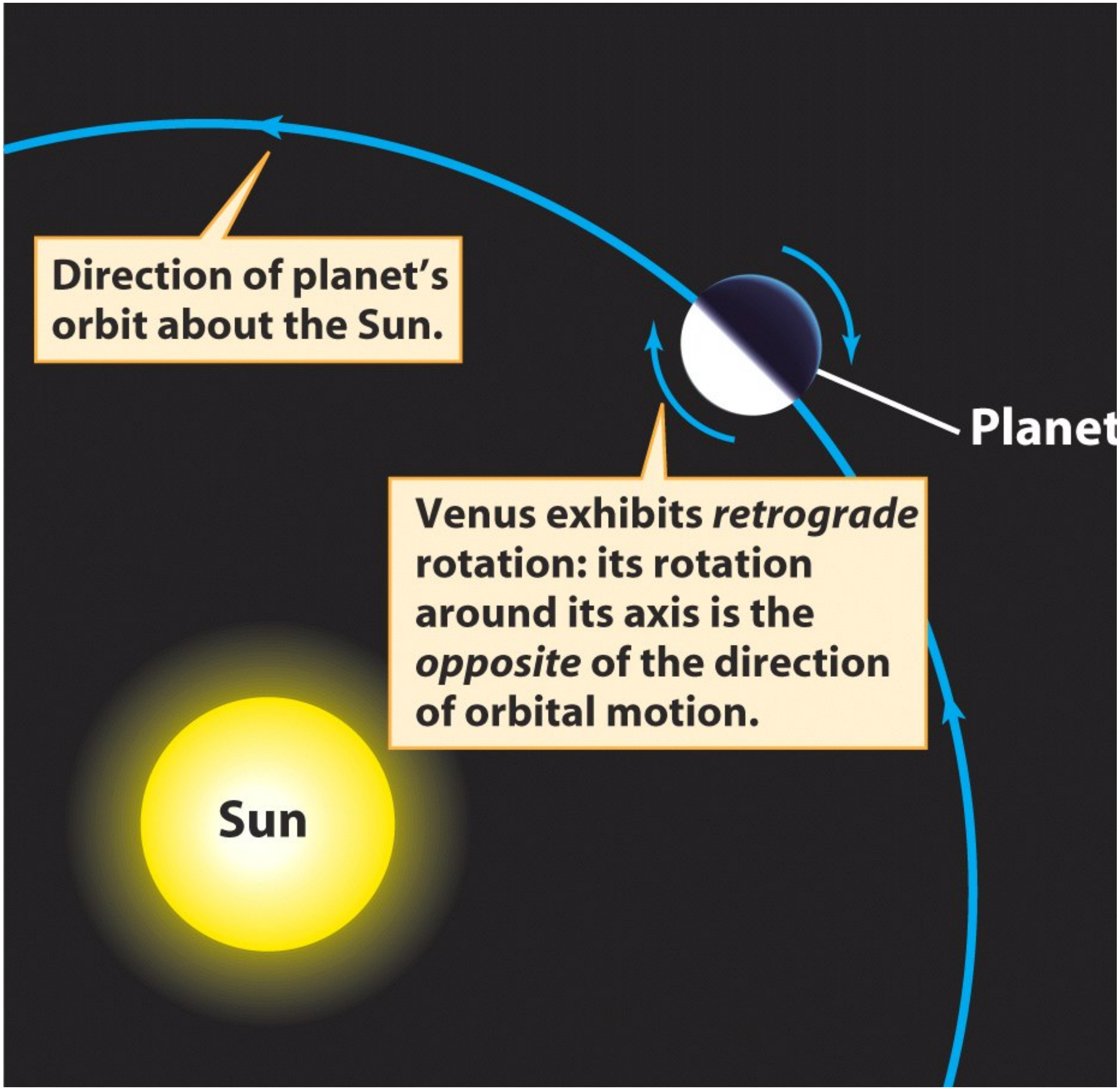


Figure 7-9
Discovering the Universe, Eighth Edition


Earth's orbit
Venus at greatest
eastern elongation
Sun
Earth
47°
47°
Venus at greatest
western elongation
Venus's
orbit



- Venus rotates slowly in a retrograde direction with a solar day of 117 Earth days and a rotation period of 243 Earth days
- There are approximately two Venusian solar days in a Venusian year.

Venus has a hot, dense atmosphere and highly reflective corrosive cloud layers

- Spacecraft measurements reveal that 96.5% of the Venusian atmosphere is carbon dioxide
- Most of the balance of the atmosphere is nitrogen.
- Venus's clouds consist of droplets of concentrated sulfuric acid.
- The surface pressure on Venus is 90 atm, and the surface temperature is 460° C
- Both temperature and pressure decrease as altitude increases

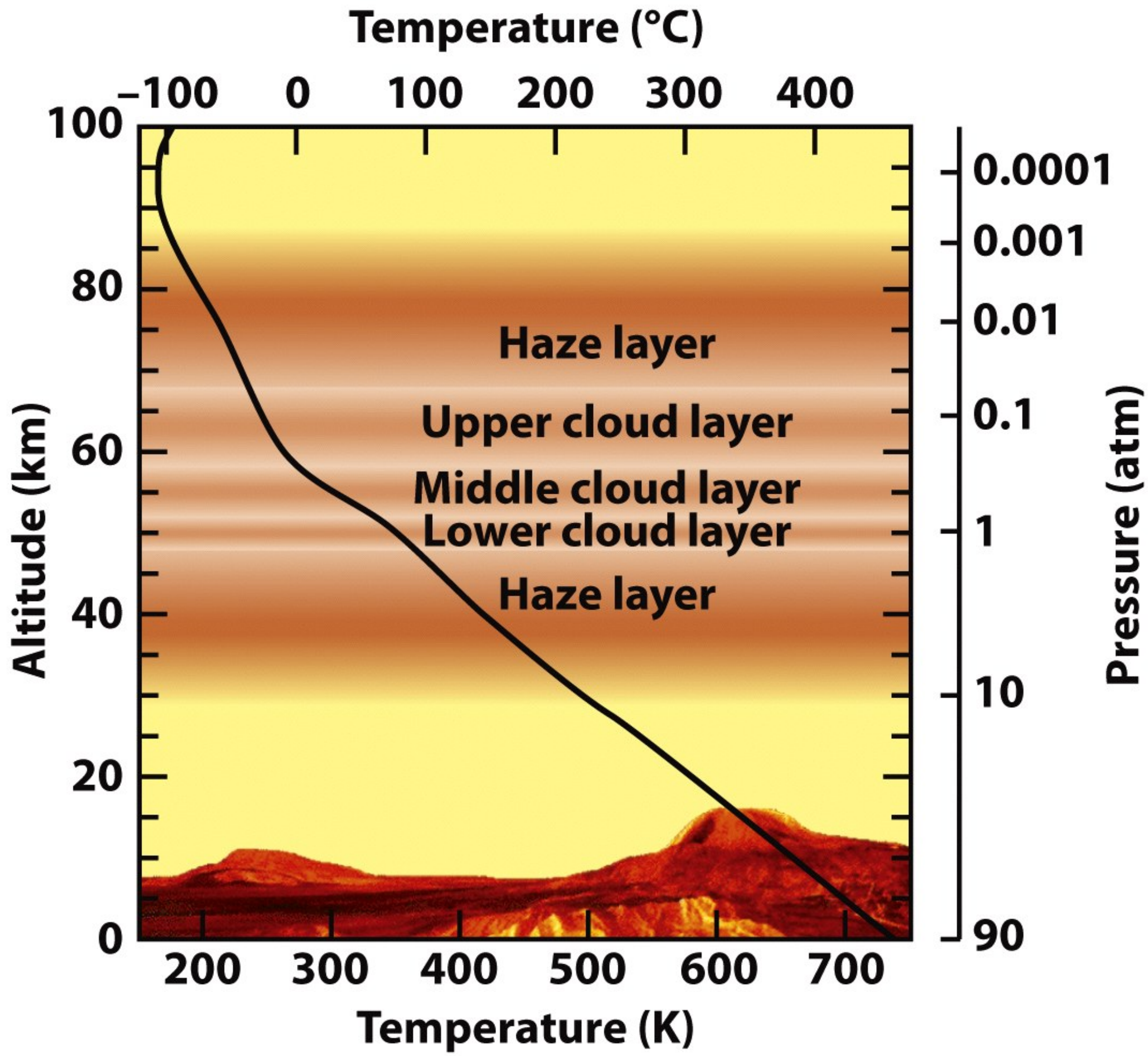


Figure 7-11
Discovering the Universe, Eighth Edition

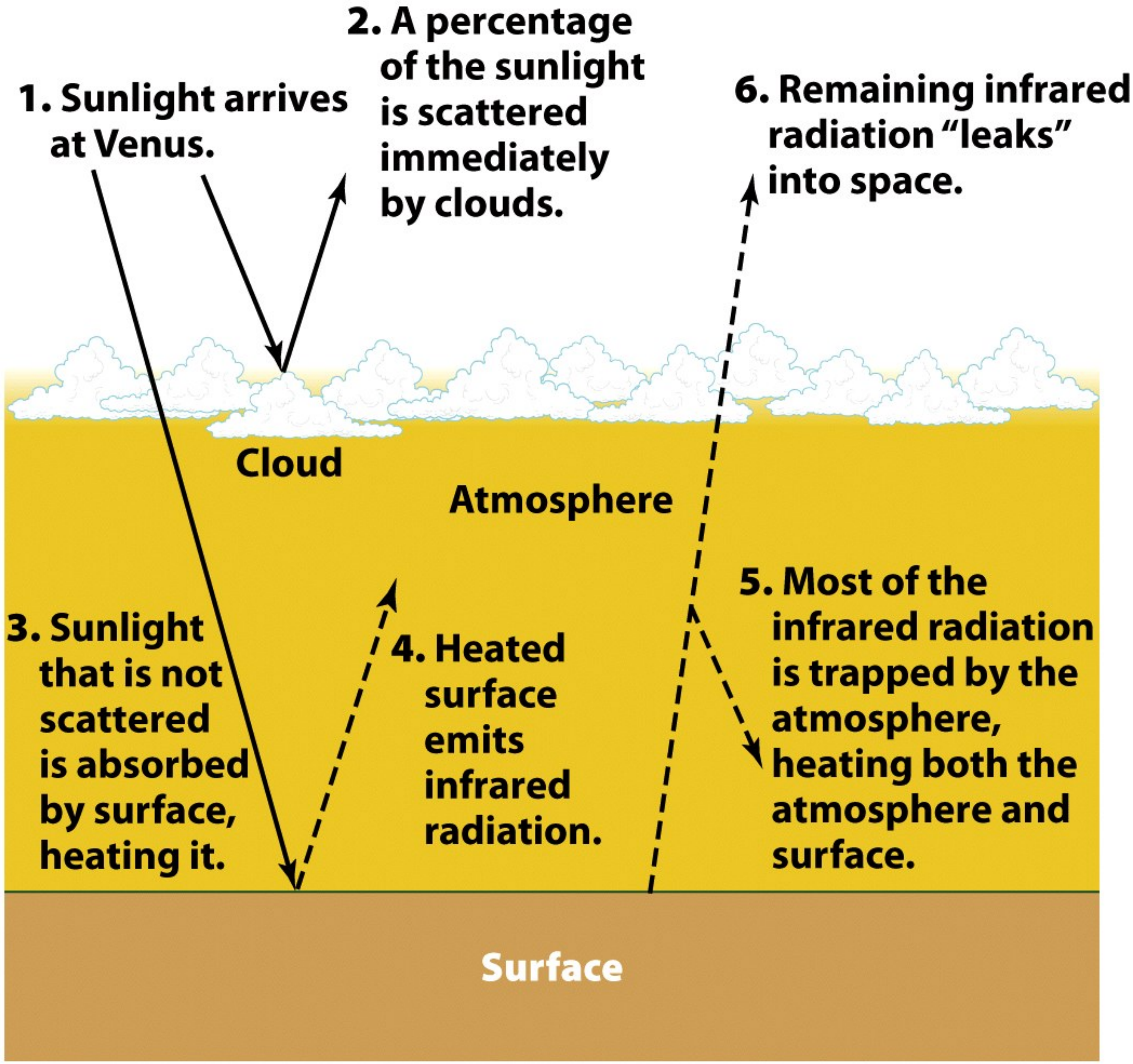


Figure 7-12
Discovering the Universe, Eighth Edition

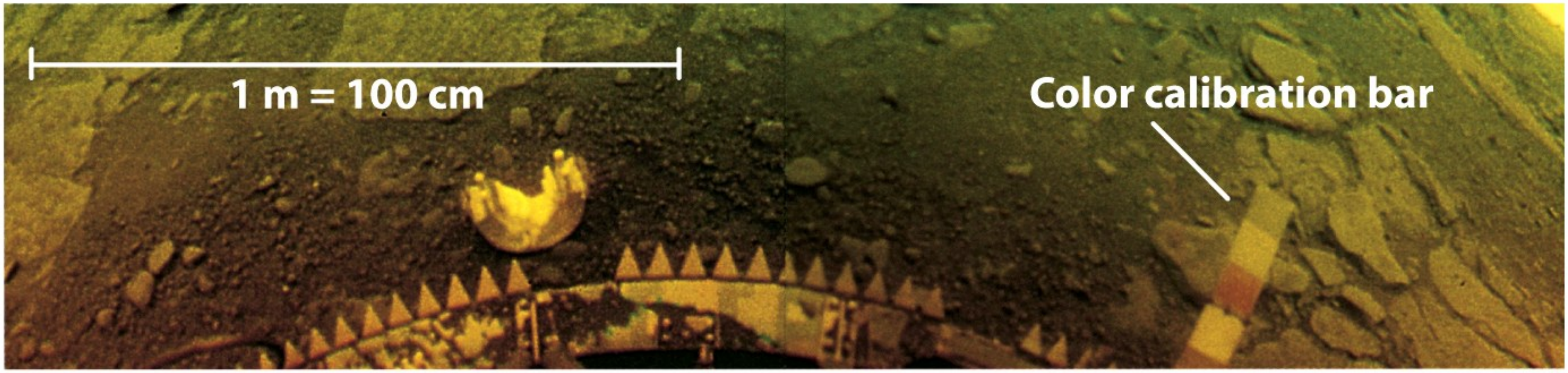
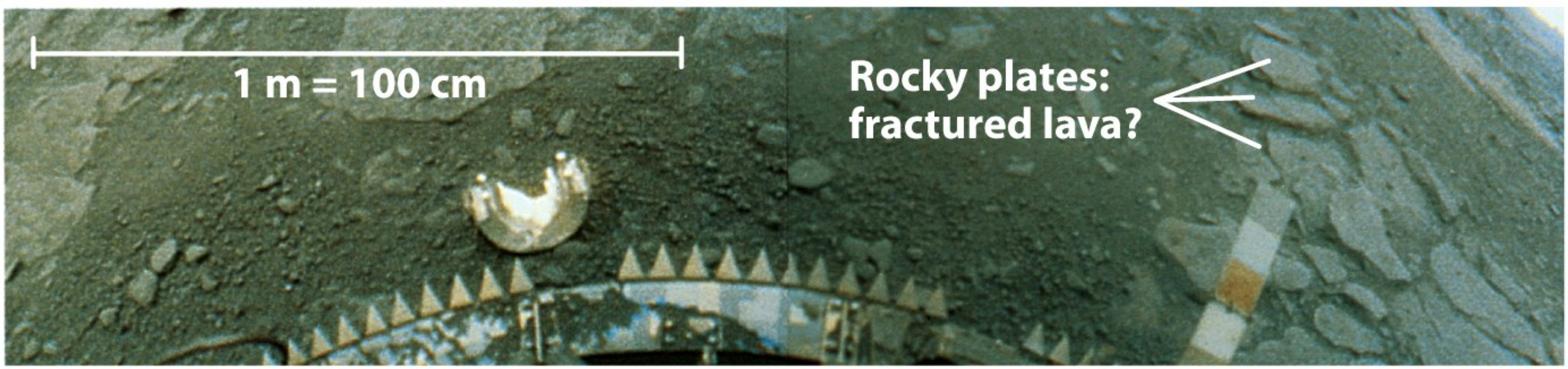


Image from *Venera 13*



Color-corrected image

Figure 7-13ab
Discovering the Universe, Eighth Edition

Figure 7-13c
Discovering the Universe, Eighth Edition

Recent observations indicate evidence for phospine, PH_3 , in the atmosphere of Venus. Evidence for life in the atmosphere perhaps? Results are controversial.

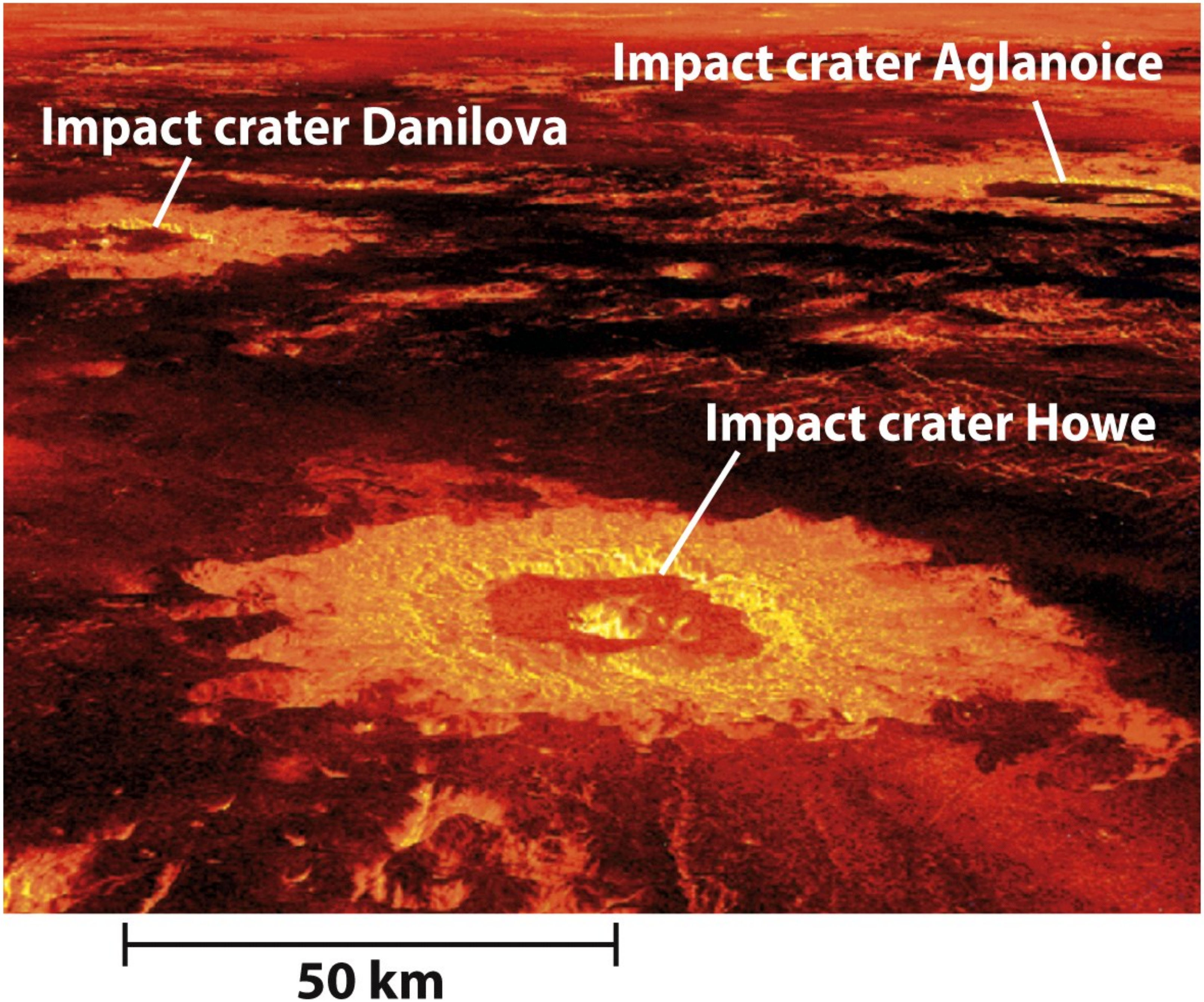


Figure 7-17
Discovering the Universe, Eighth Edition

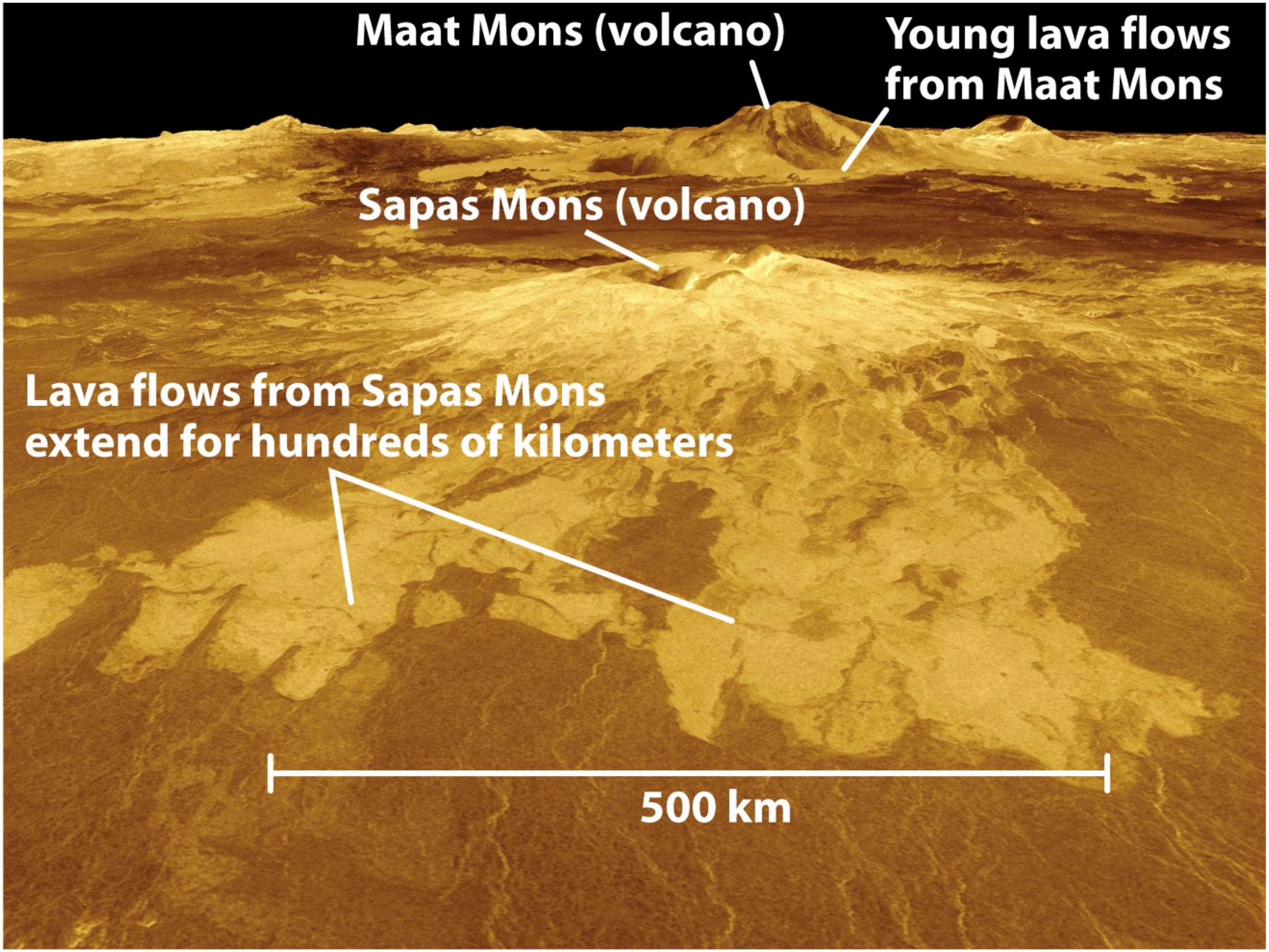


Figure 7-14
Discovering the Universe, Eighth Edition

Topography of Venus

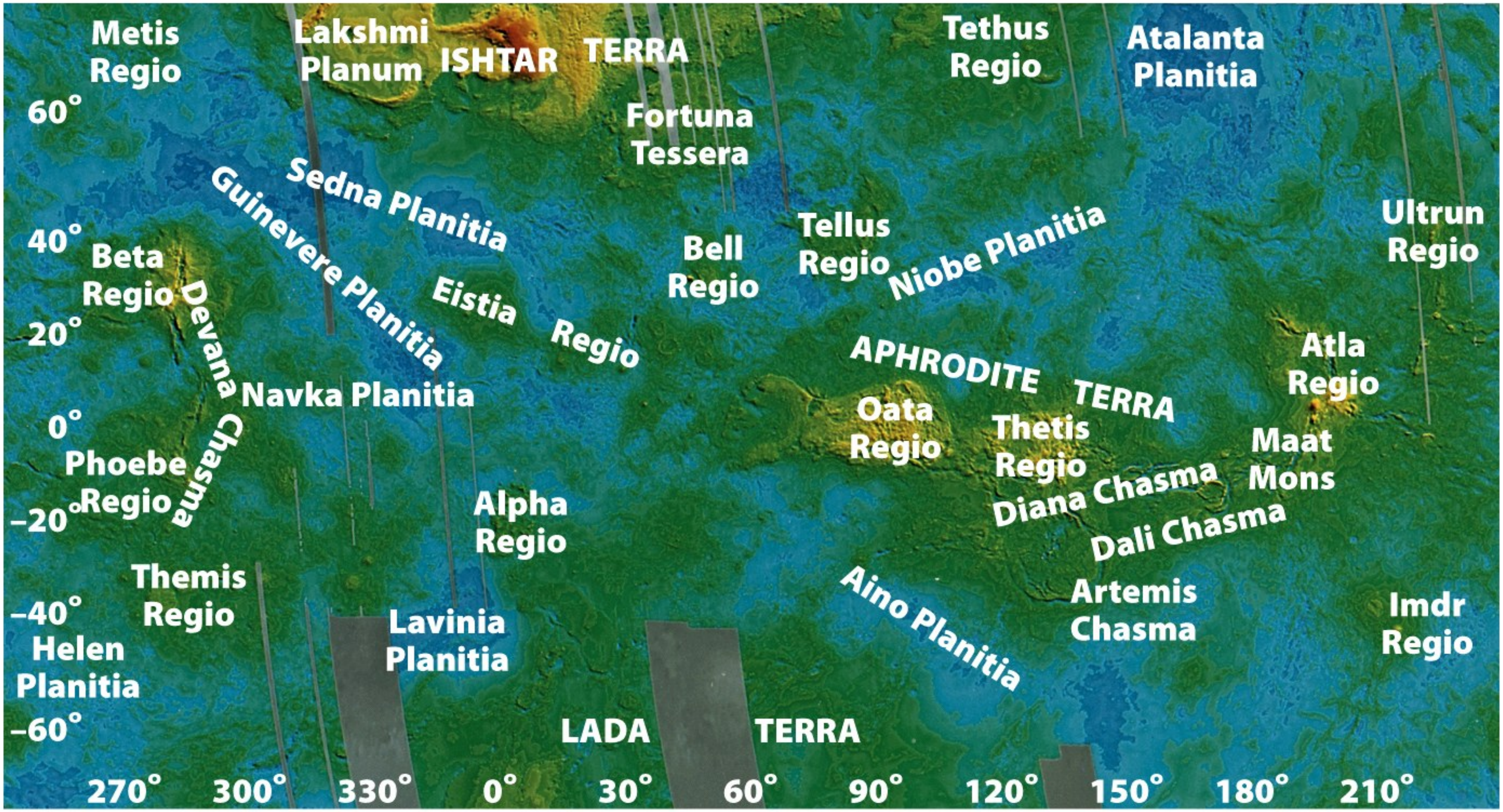


Figure 7-15

Discovering the Universe, Eighth Edition

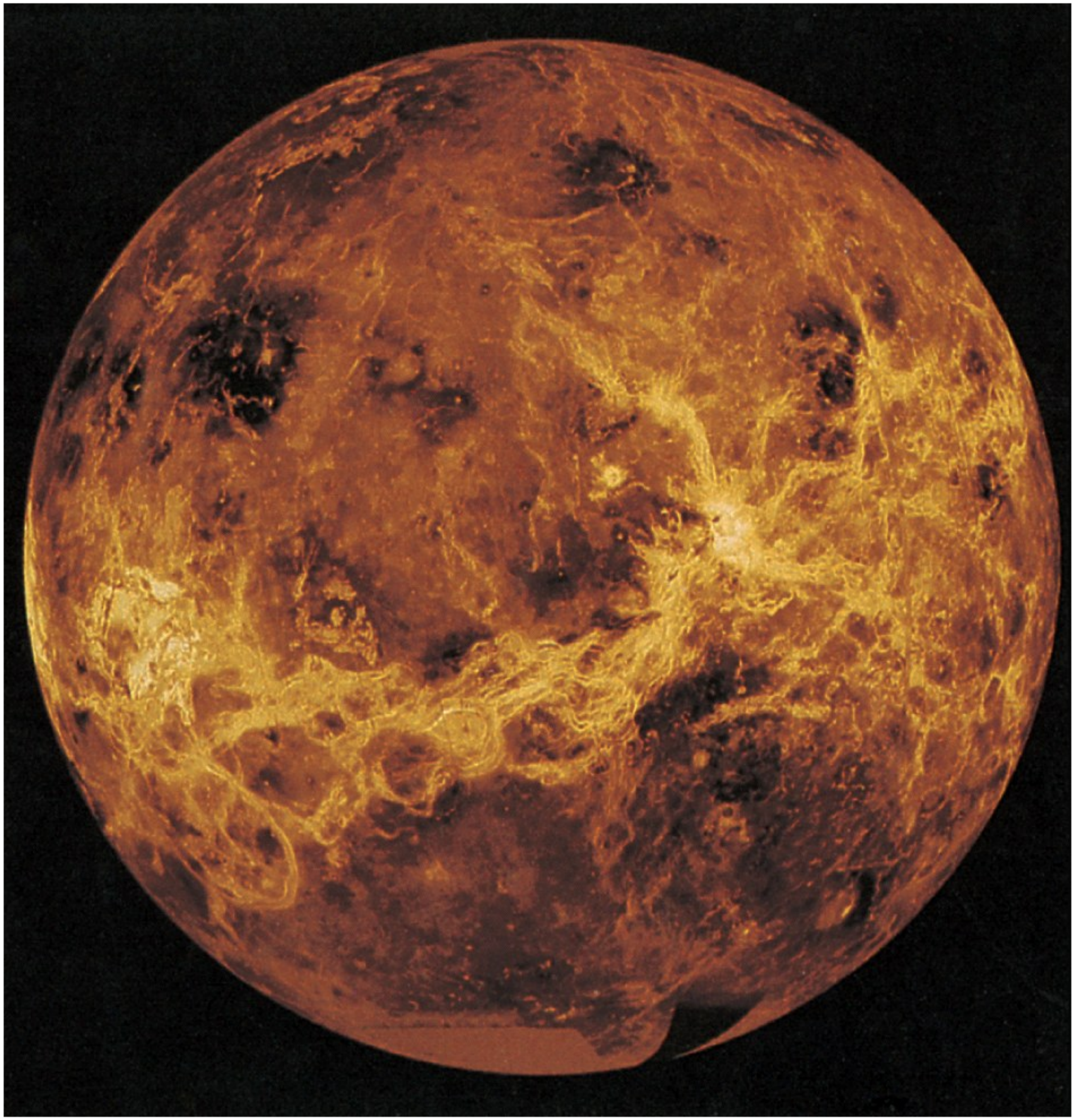
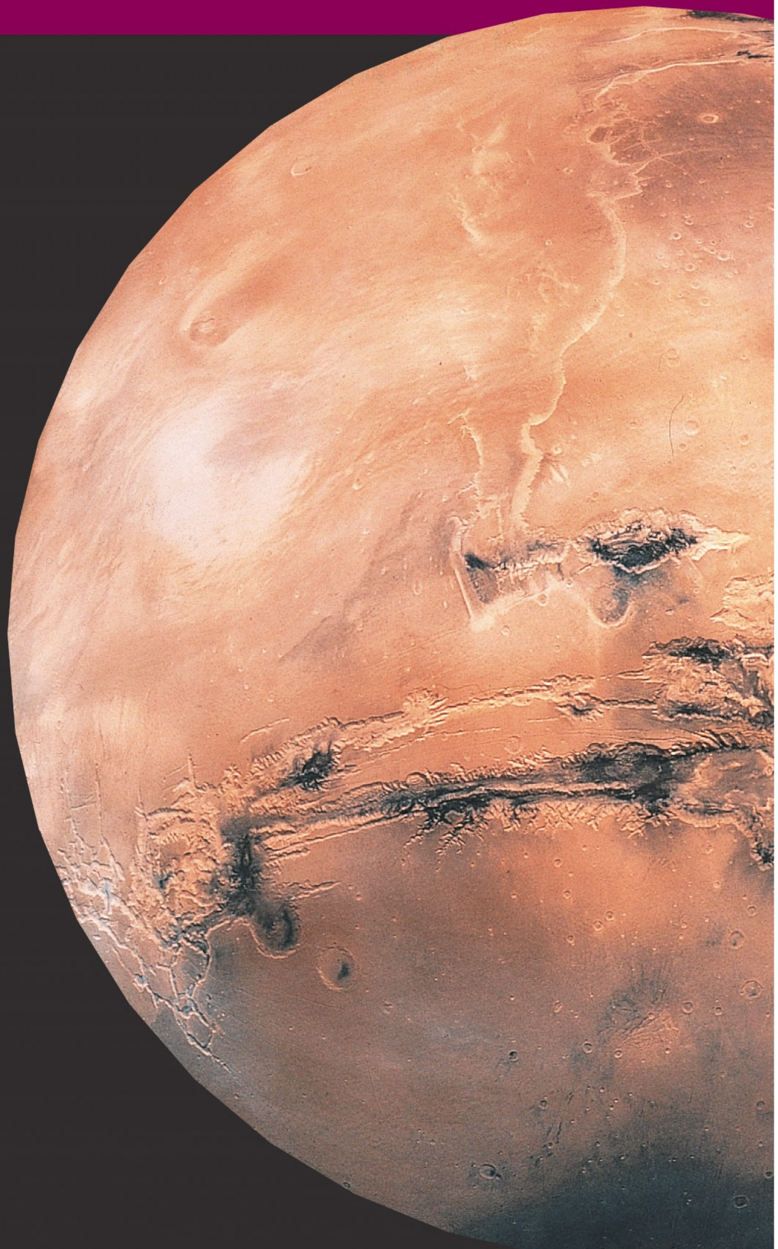


Figure 7-16
Discovering the Universe, Eighth Edition

Radar picture of Venus

table 13-1 Mars Data



Average distance from Sun:	1.524 AU = 2.279×10^8 km
Maximum distance from Sun:	1.666 AU = 2.492×10^8 km
Minimum distance from Sun:	1.381 AU = 2.067×10^8 km
Eccentricity of orbit:	0.093
Average orbital speed:	24.1 km/s
Orbital period:	686.98 days = 1.88 years
Rotation period:	$24^h\ 37^m\ 22^s$
Inclination of equator to orbit:	25.19°
Inclination of orbit to ecliptic:	1.85°
Diameter (equatorial):	6794 km = 0.533 Earth diameter
Mass:	6.418×10^{23} kg = 0.107 Earth mass
Average density:	3934 kg/m^3
Escape speed:	5.0 km/s
Surface gravity (Earth = 1):	0.38
Albedo:	0.15
Surface temperatures:	Maximum: 20°C = 70°F = 293 K Mean: −53°C = −63°F = 220 K Minimum: −140°C = −220°F = 133 K
Atmospheric composition (by number of molecules):	95.3% carbon dioxide (CO_2) 2.7% nitrogen (N_2) 0.03% water vapor (H_2O) 2% other gases

The Martian surface has numerous craters, several huge volcanoes, a vast rift valley, and dried-up riverbeds— but no canals.

Martian volcanoes and the Valles Marineris rift valley were formed by upwelling plumes of magma in the mantle.

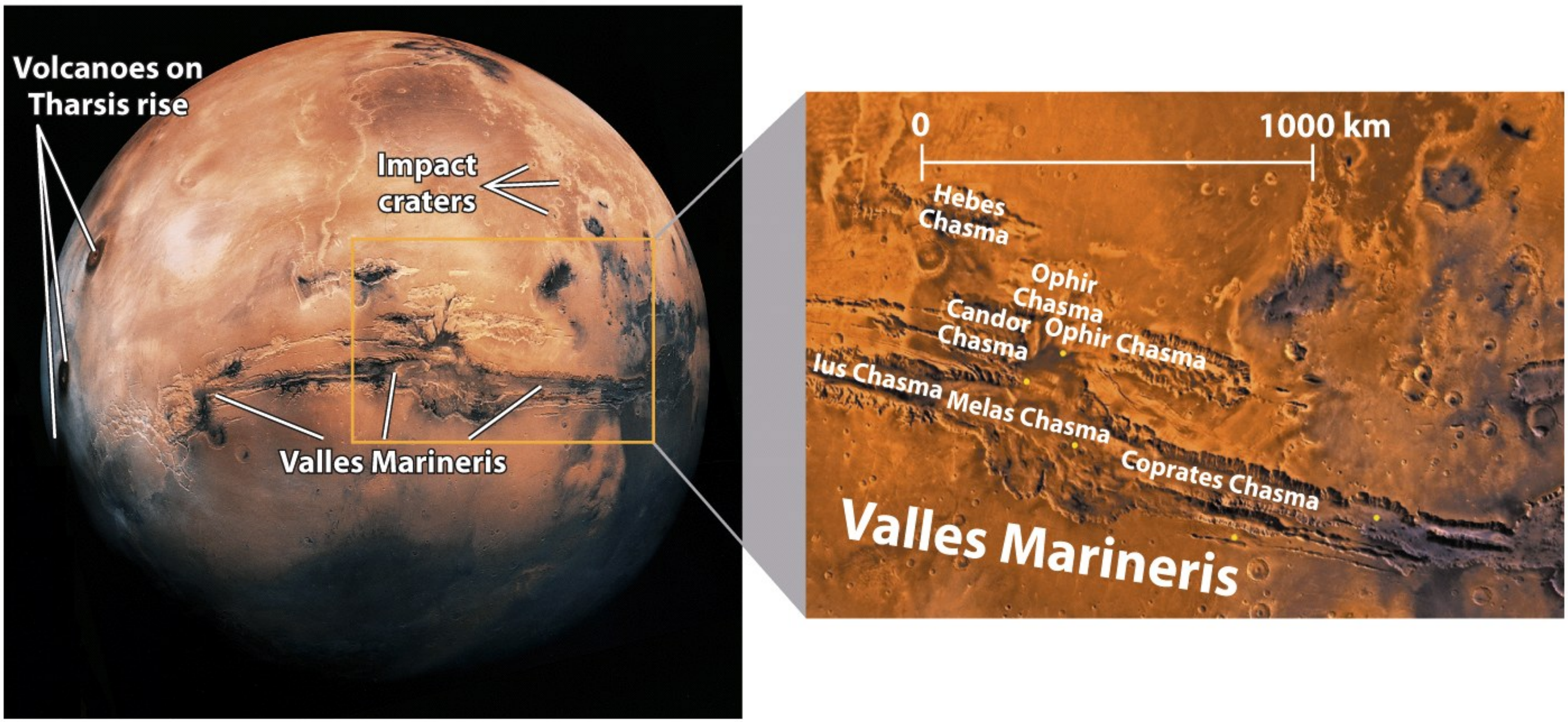
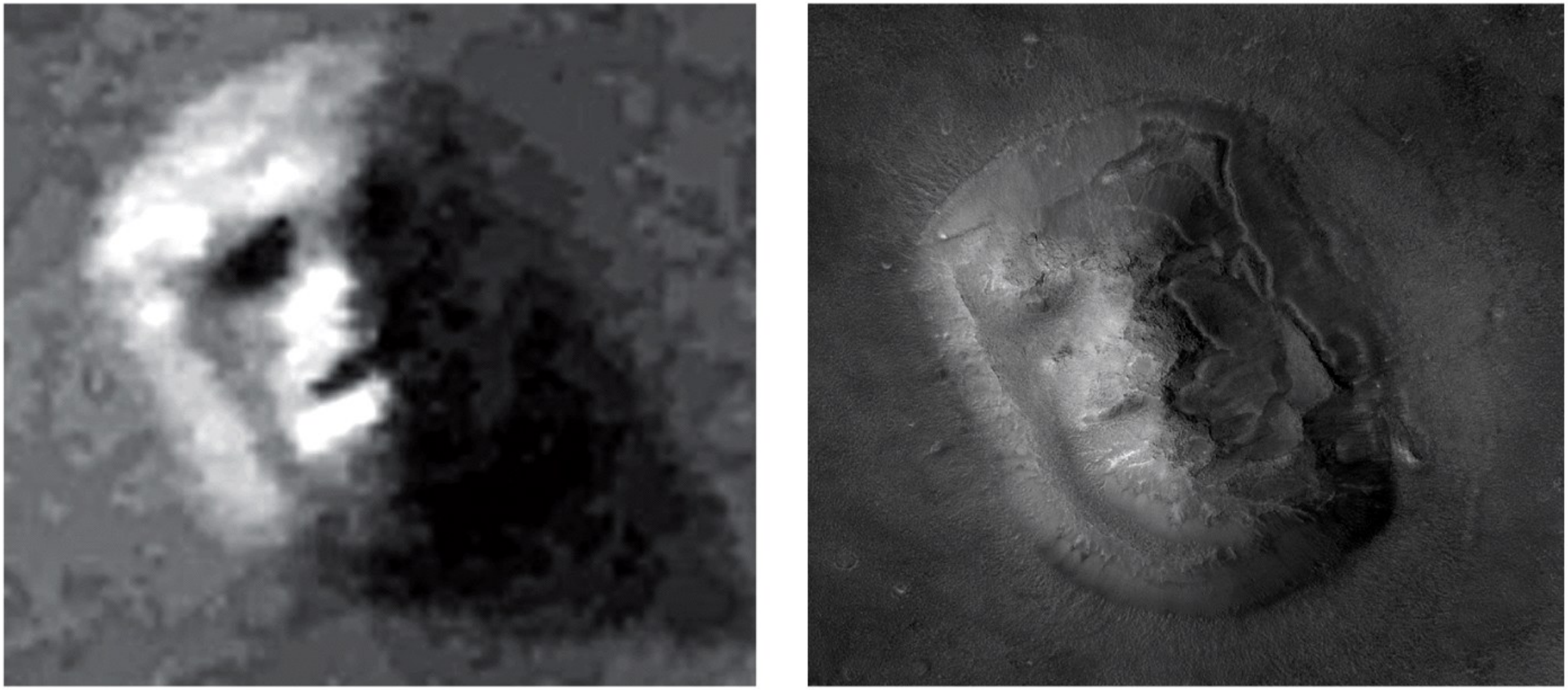


Figure 7-21
Discovering the Universe, Eighth Edition



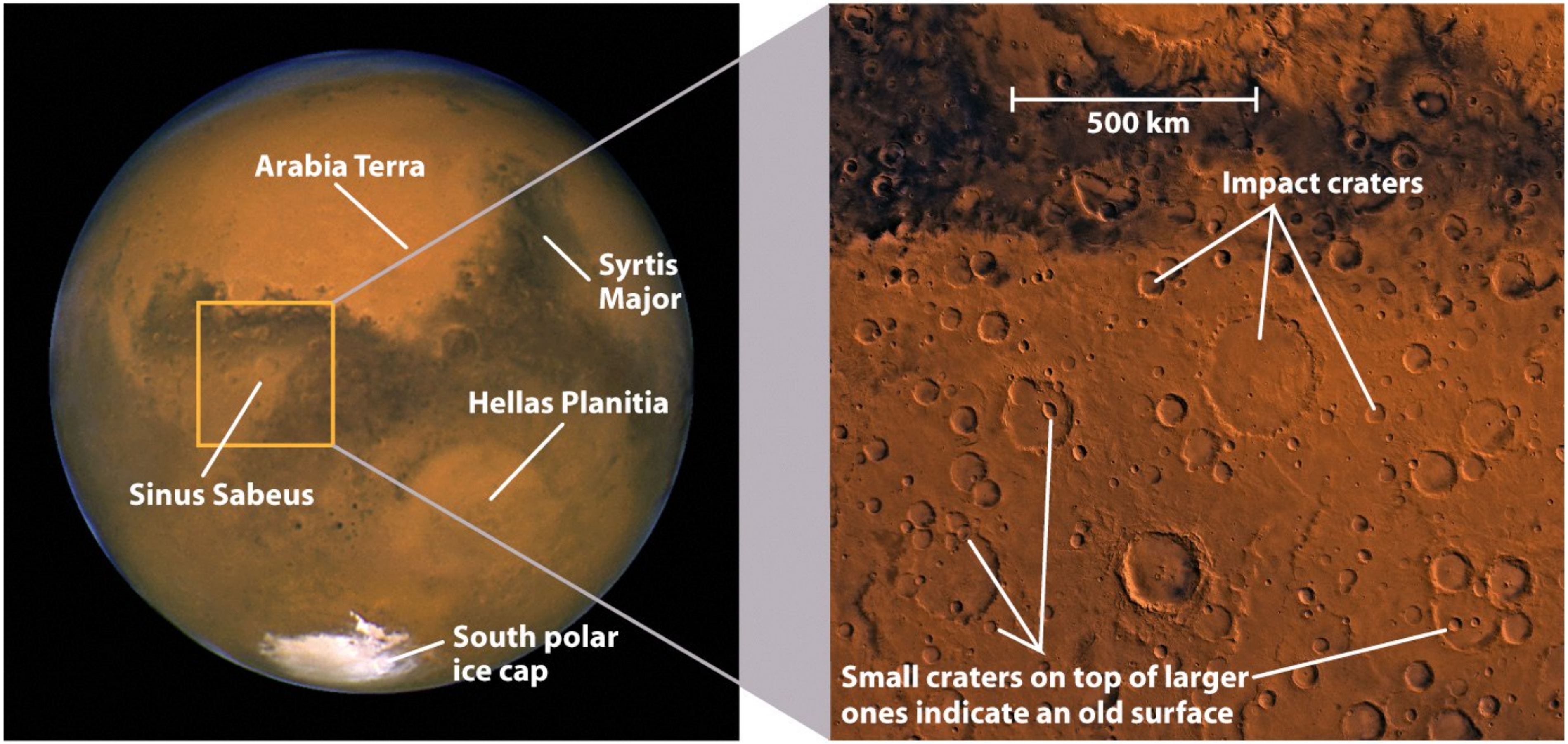
a **b**

Figure 7-24ab
Discovering the Universe, Eighth Edition

Illusion

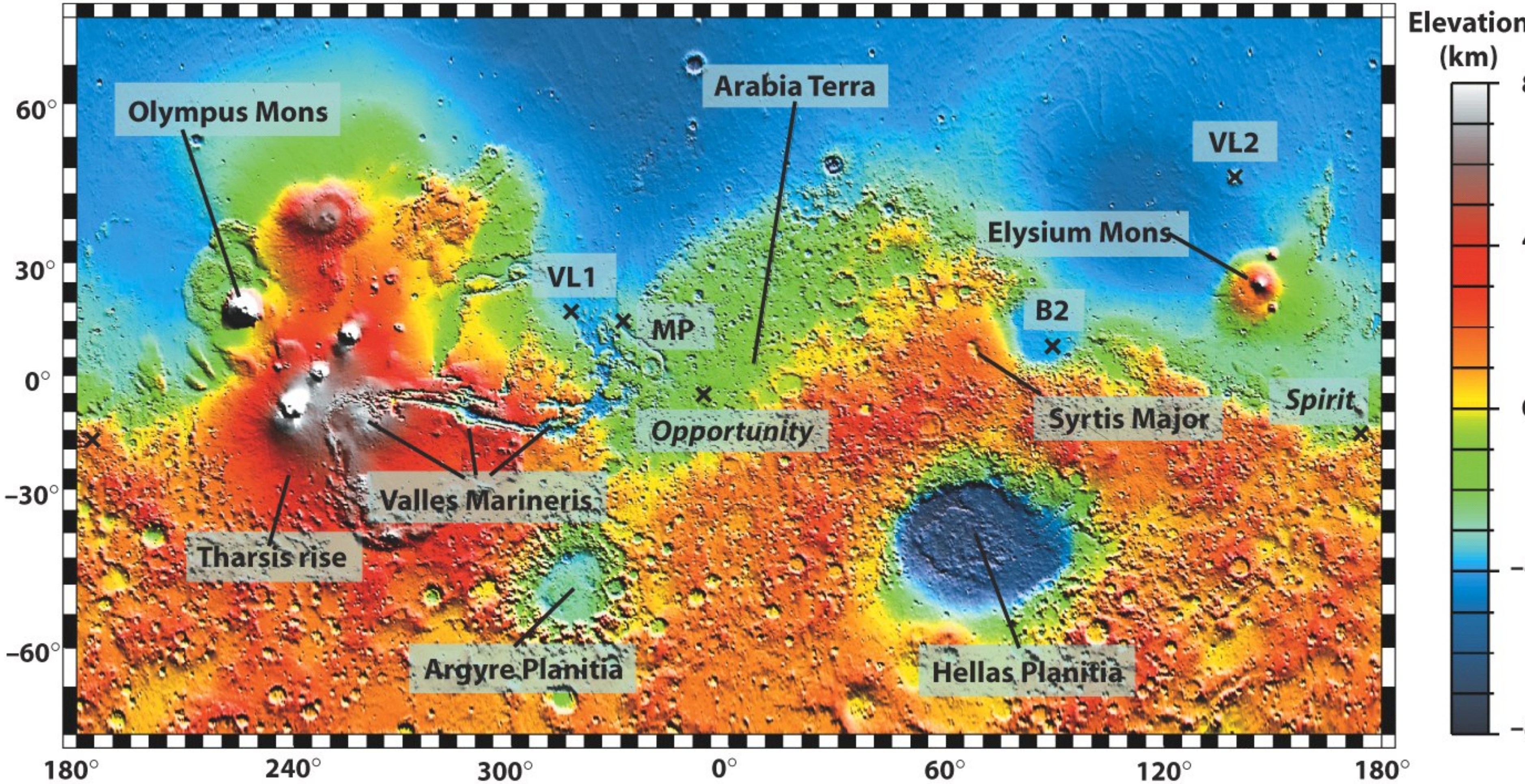
A Mars rat?

Illusion! (Image credit: NASA/JPL-Caltech)



(a) Mars from the Hubble Space Telescope (b) Closeup of Sinus Sabeus region

- For reasons that are not understood, the chemical composition of ancient Martian lava is different from that of more recent lava
- Mars has no planet wide magnetic field at present but may have had one in the ancient past



The heavily cratered southern highlands are older and about 5 km higher in elevation than the smooth northern lowlands

The origin of this crustal dichotomy is not completely understood

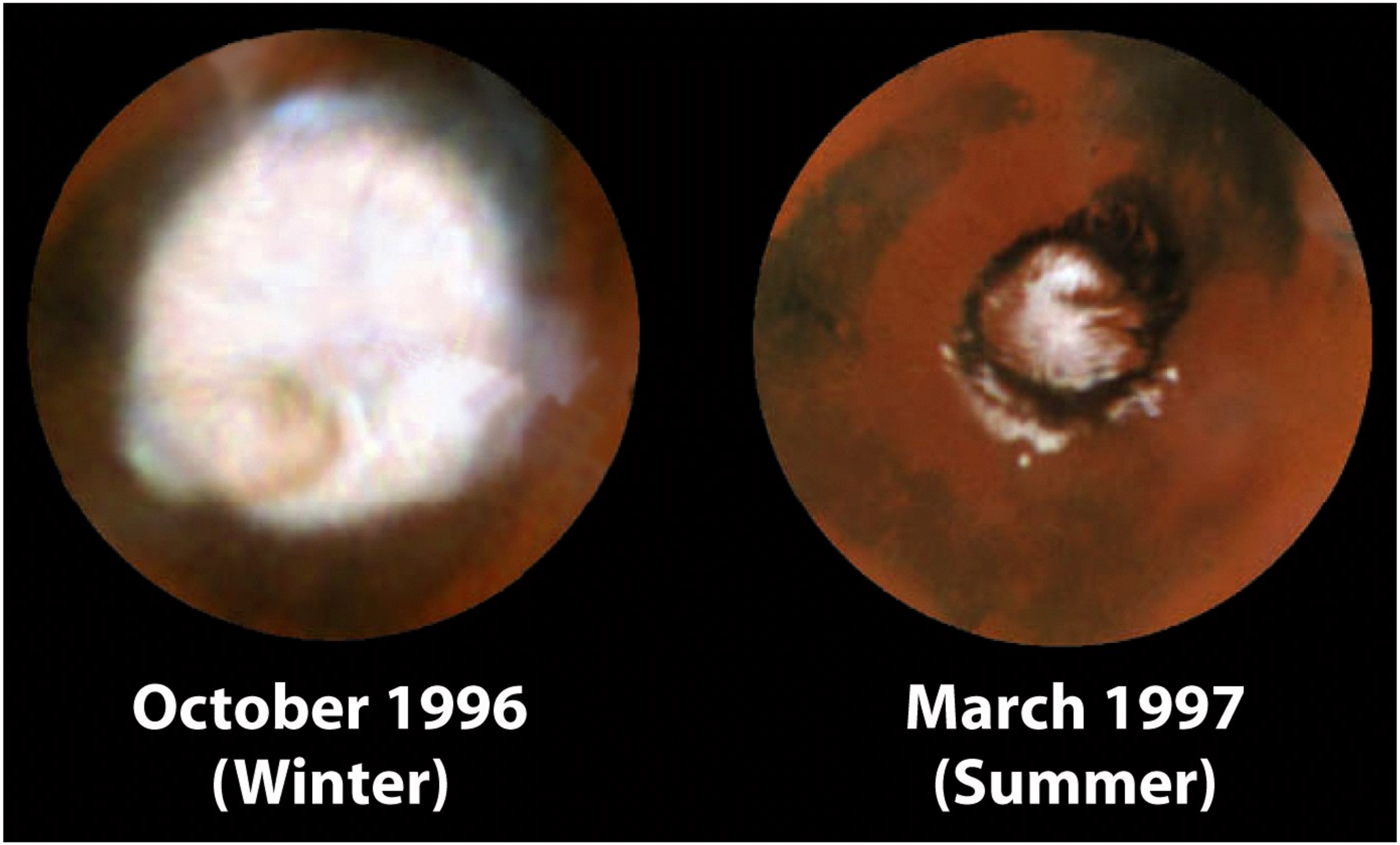
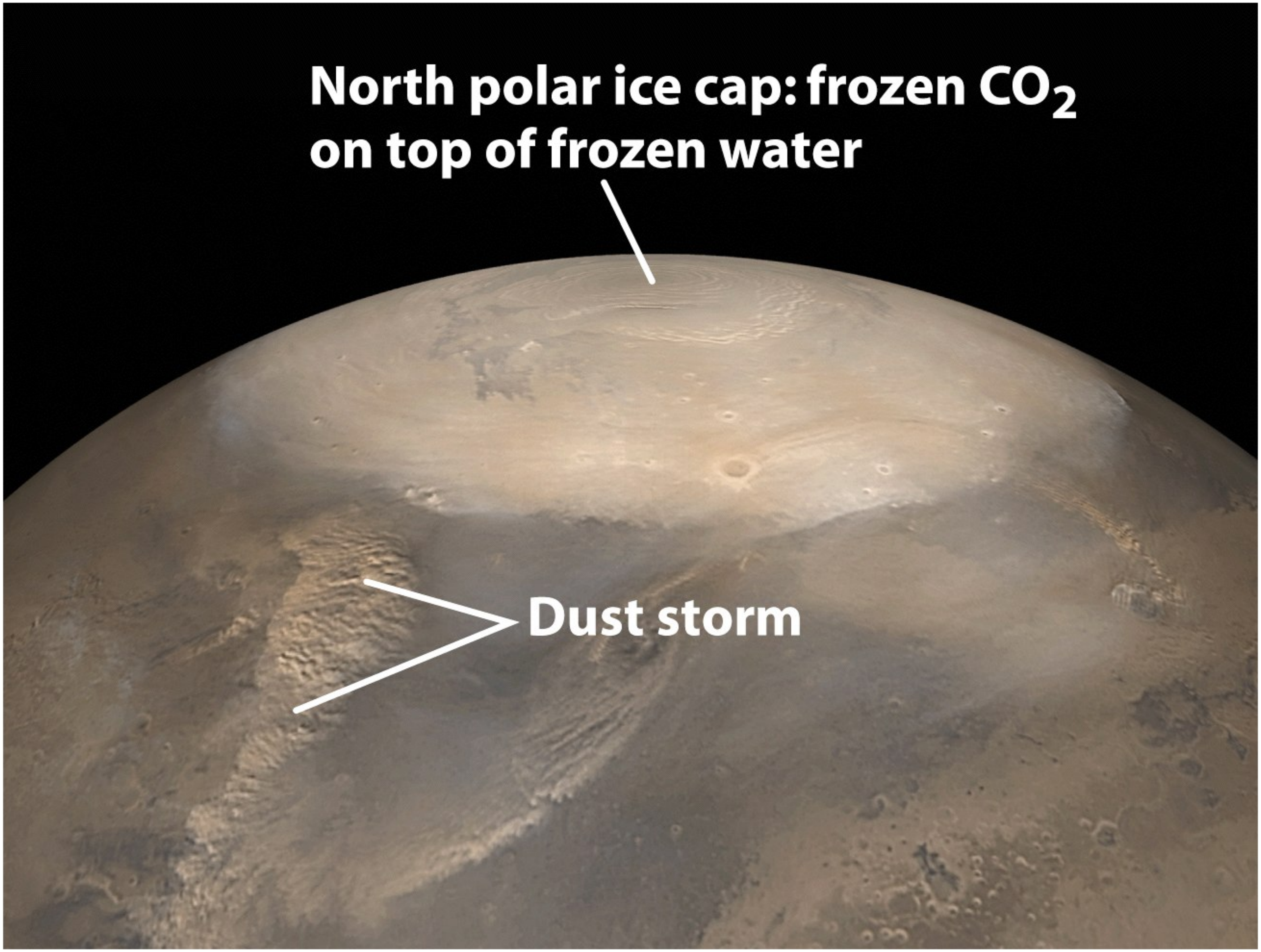
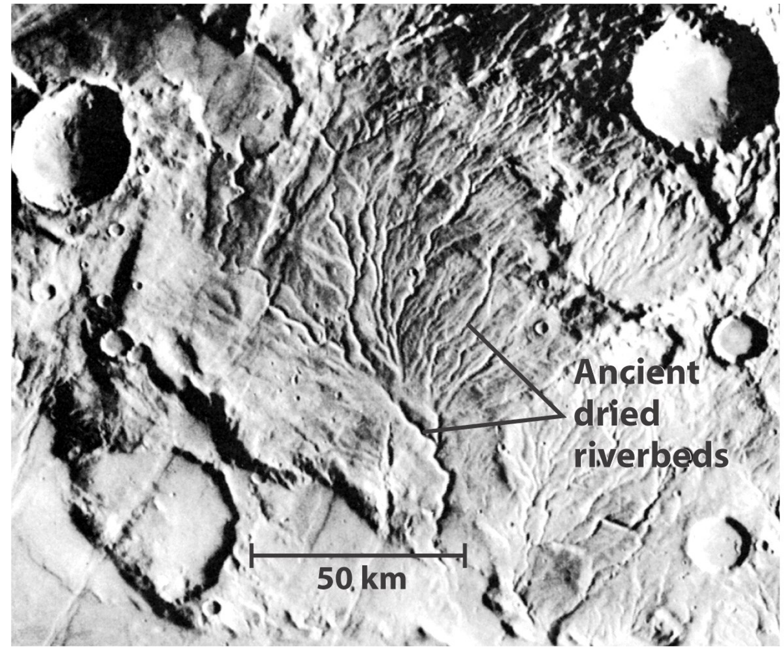


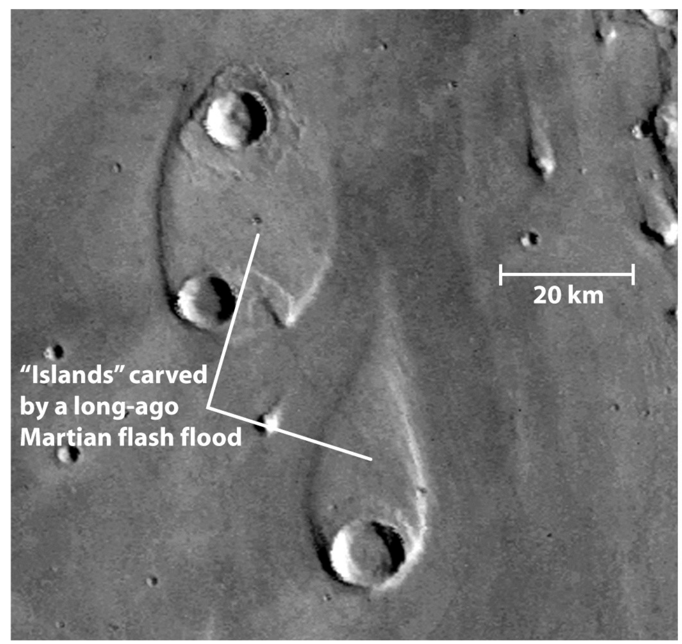
Figure 7-25
Discovering the Universe, Eighth Edition

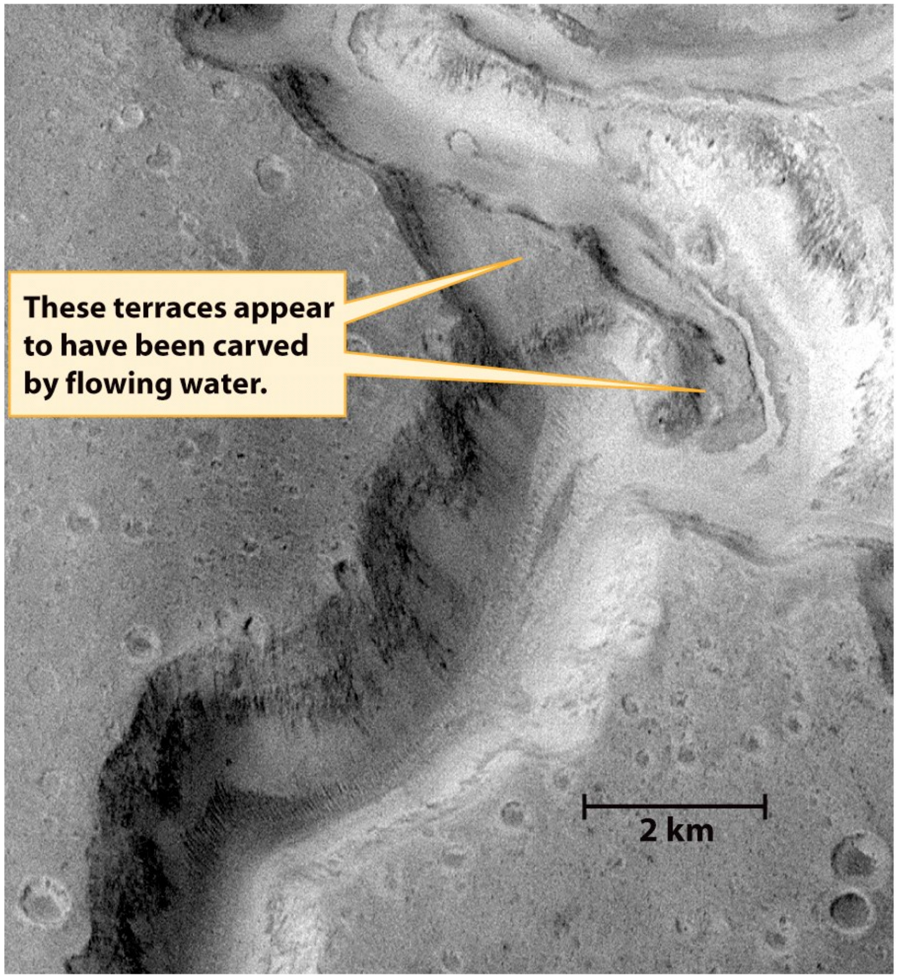

North polar ice cap: frozen CO_2 on top of frozen water
Dust storm

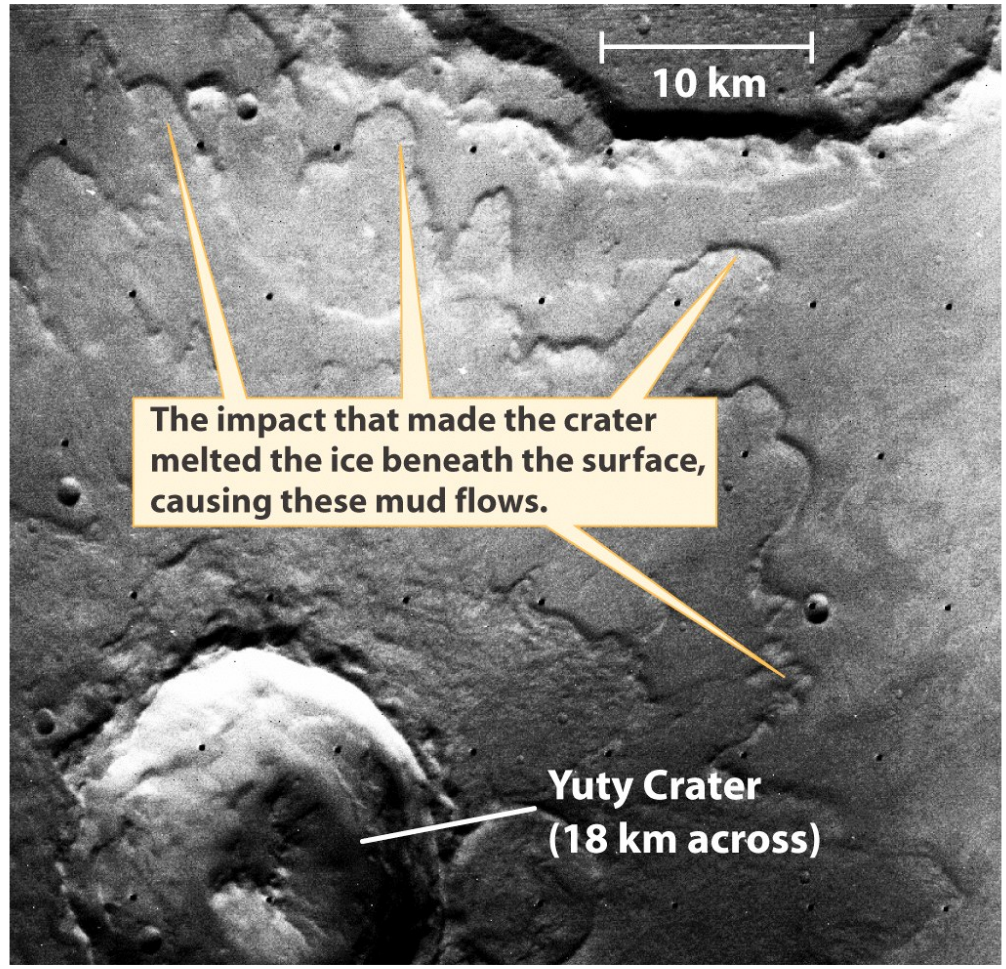
Flash-flood features and dried riverbeds on the Martian surface indicate that water has flowed on Mars at least occasionally

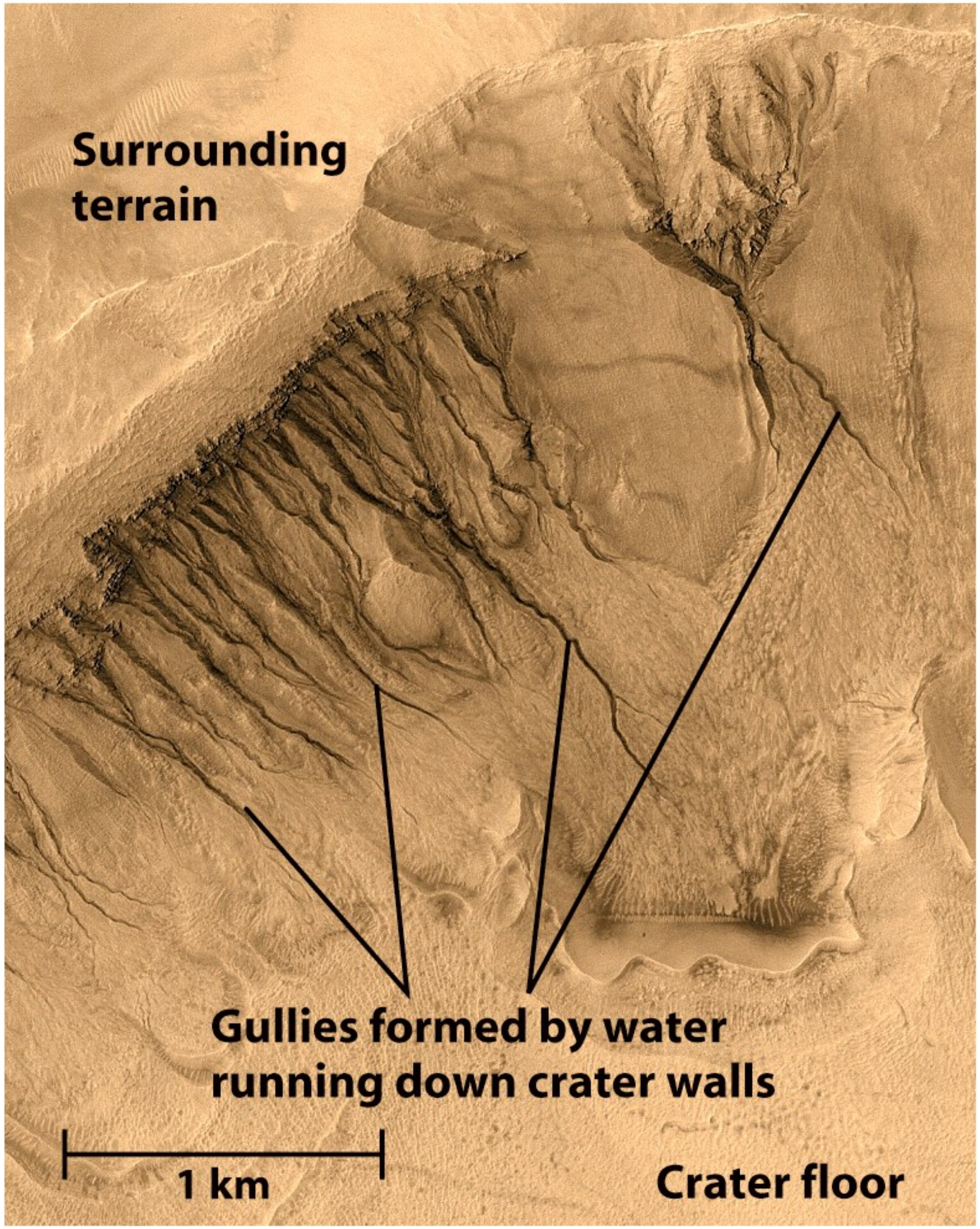
No liquid water can exist on the Martian surface today






These terraces appear to have been carved by flowing water.
2 km


10 km
The impact that made the crater melted the ice beneath the surface, causing these mud flows.
Yuty Crater (18 km across)



Surrounding terrain
Gullies formed by water running down crater walls
1 km
Crater floor

Ancient Riverbed on Mars

Figure 7-29a
Discovering the Universe, Eighth Edition

River in China

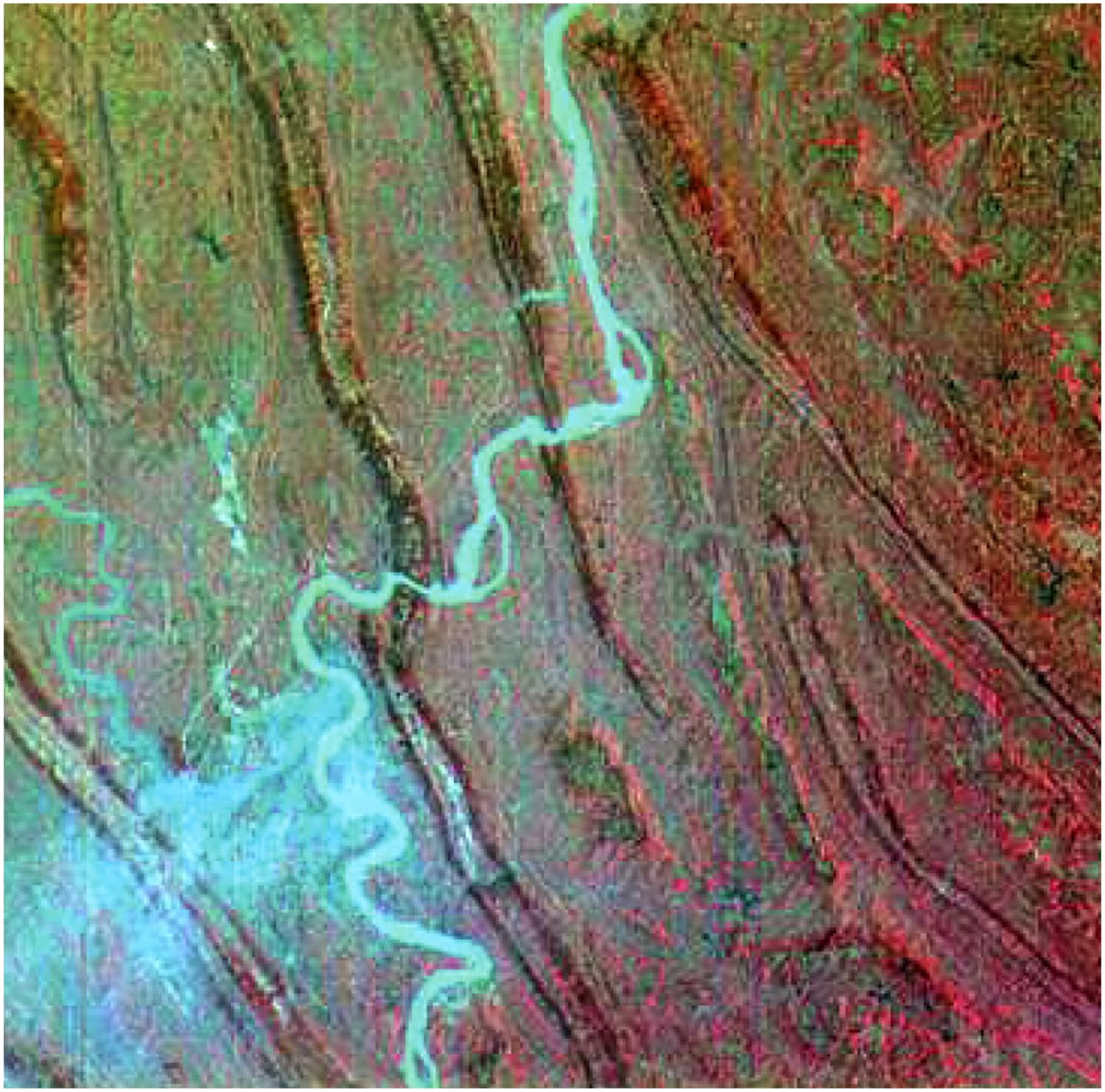


Figure 7-29b
Discovering the Universe, Eighth Edition

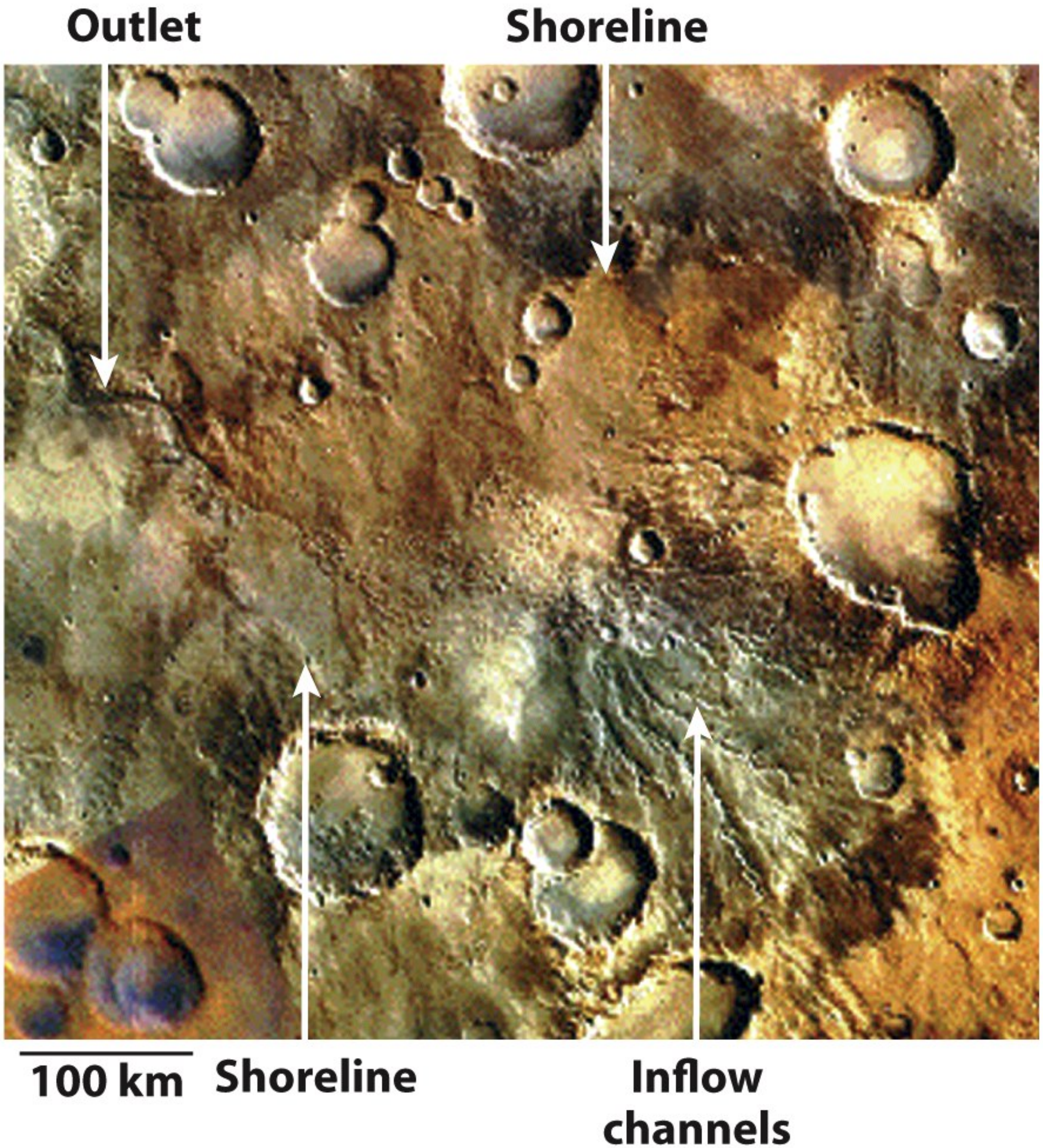


Figure 7-30a
Discovering the Universe, Eighth Edition

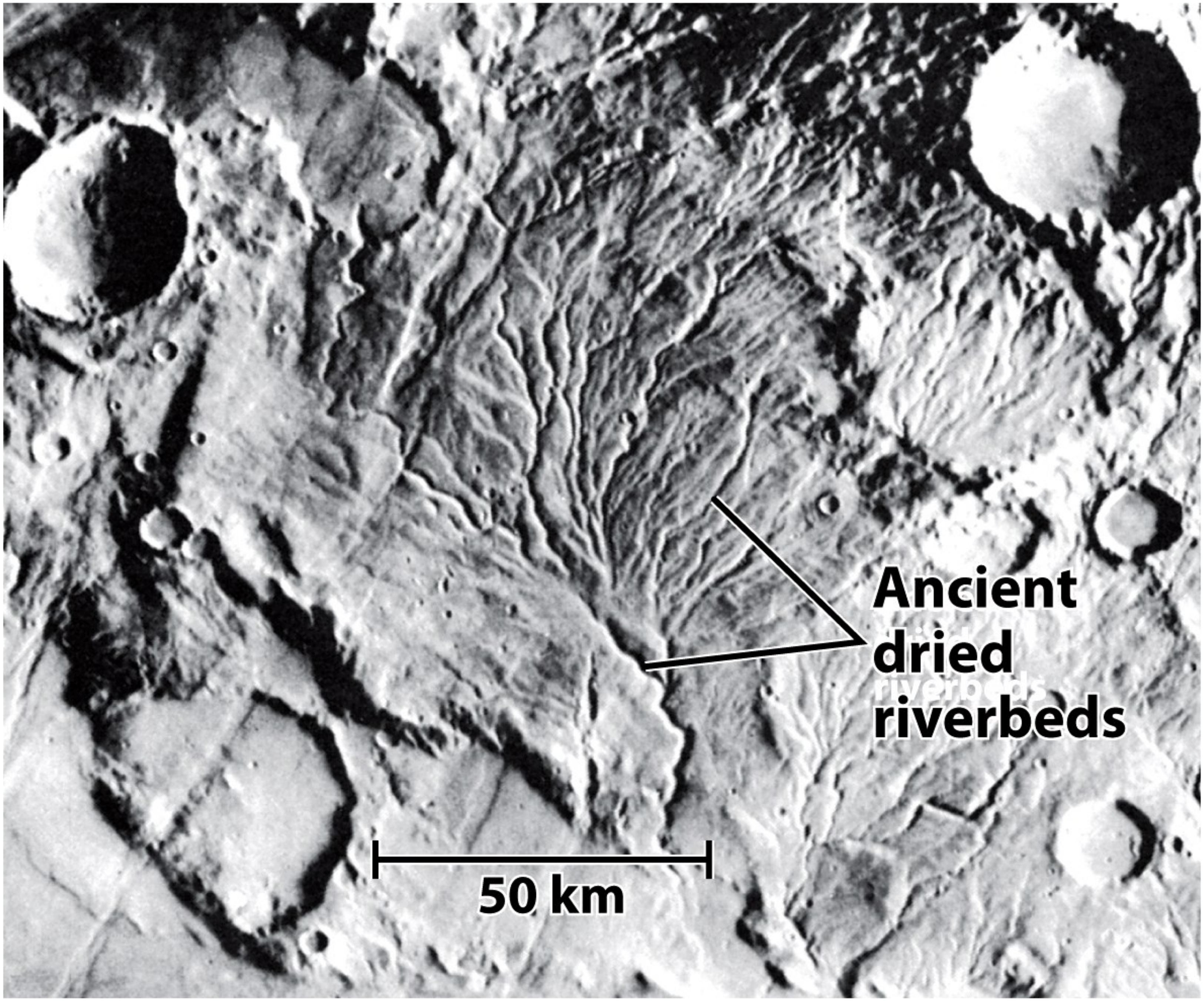
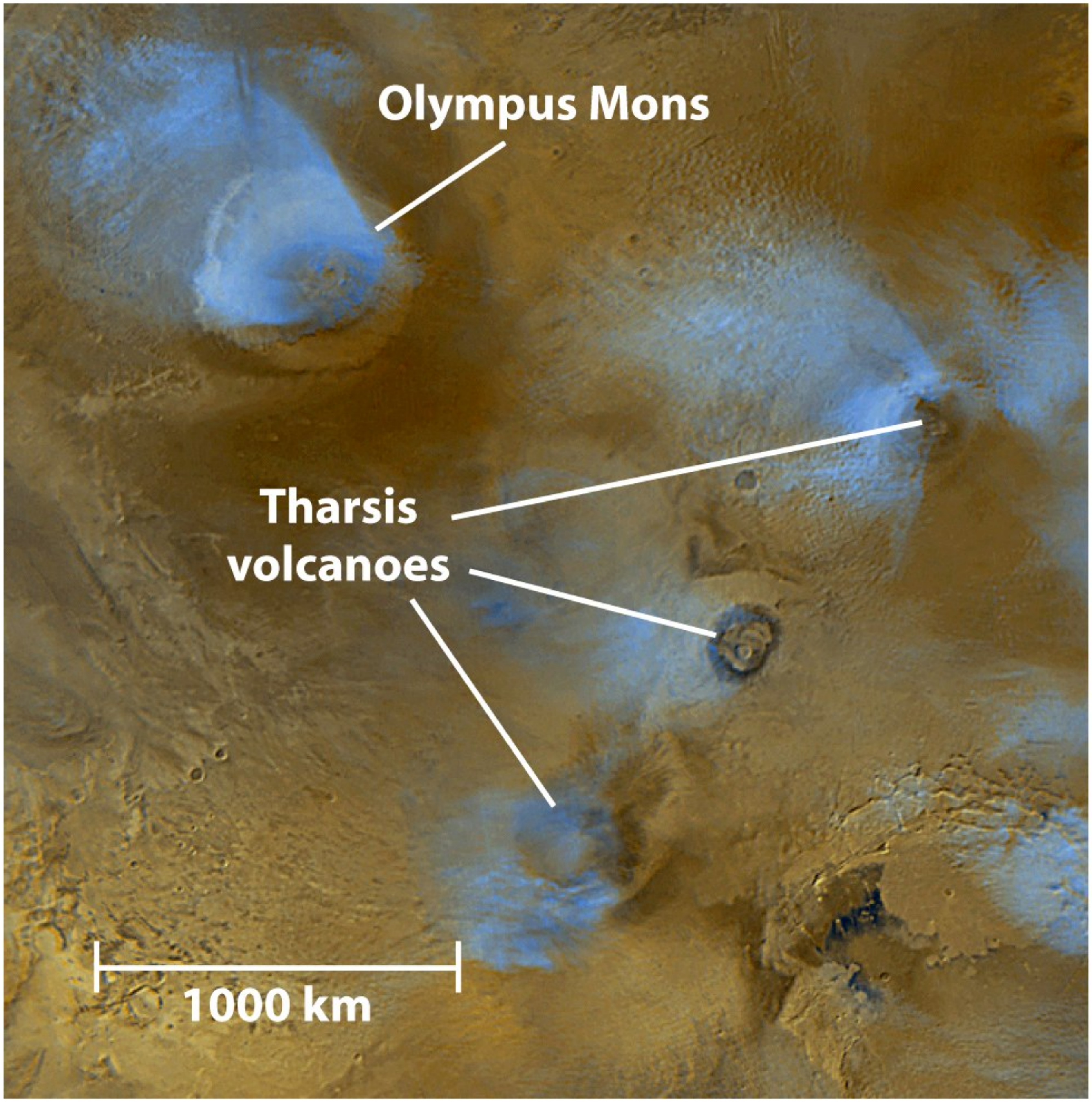
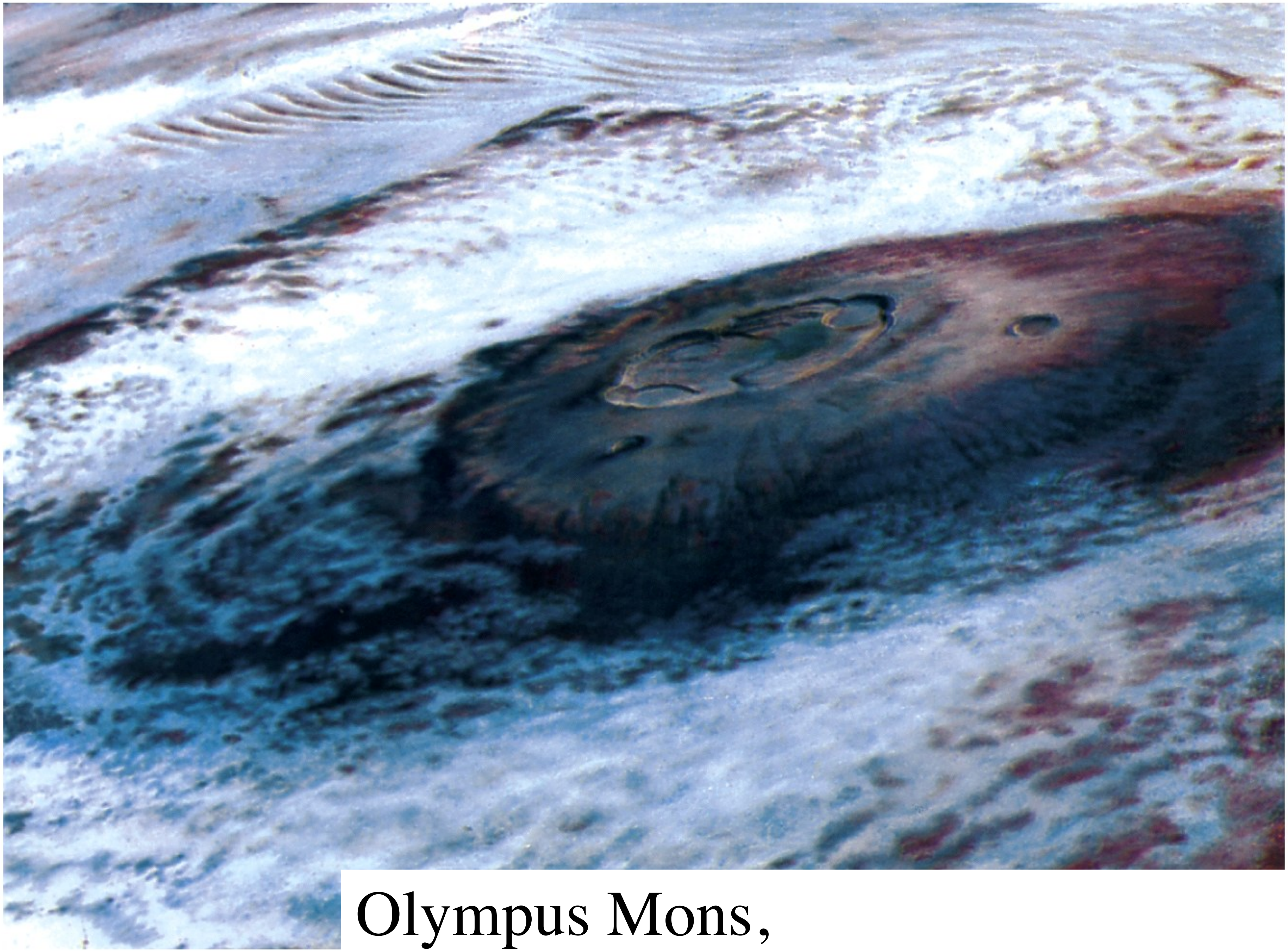


Figure 7-30b

Discovering the Universe, Eighth Edition

Clouds Above Mars' Mountains





Olympus Mons,

the larges volcano on Mars and in the solar system

Figure 7-23a
Discovering the Universe, Eighth Edition

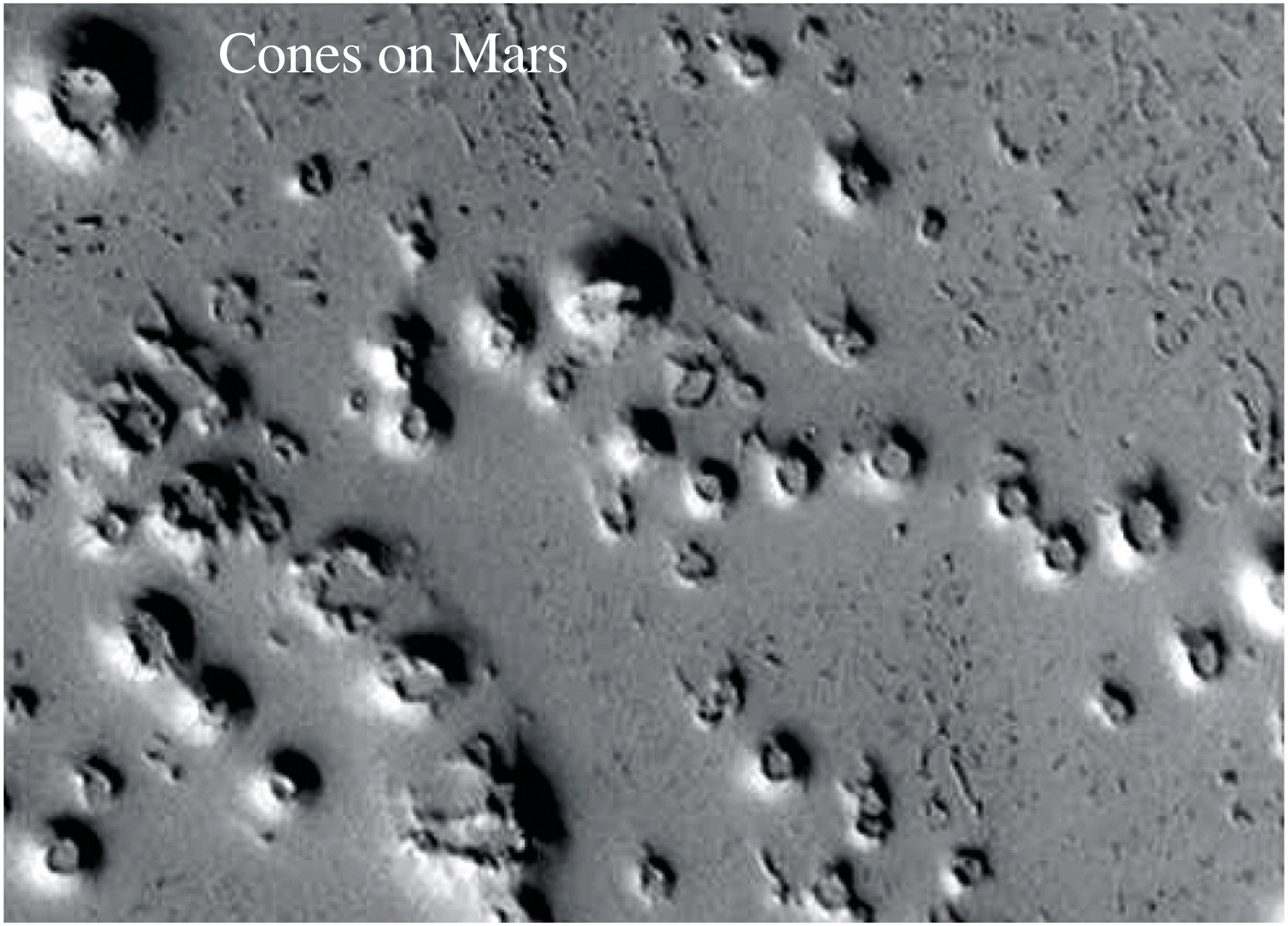
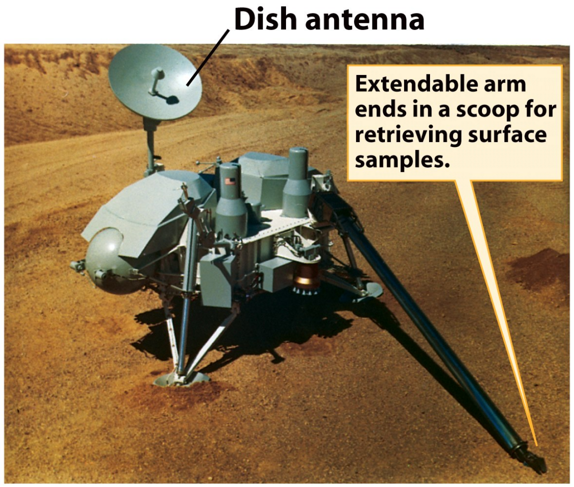
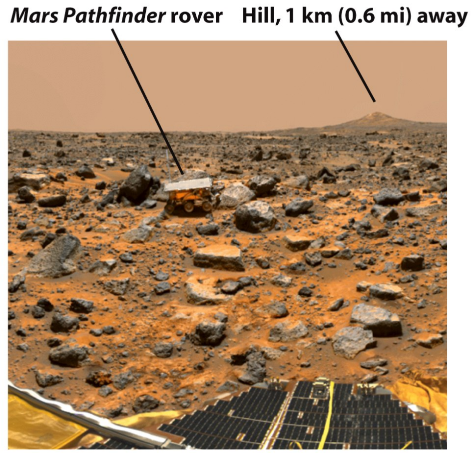


Figure 7-23b
Discovering the Universe, Eighth Edition

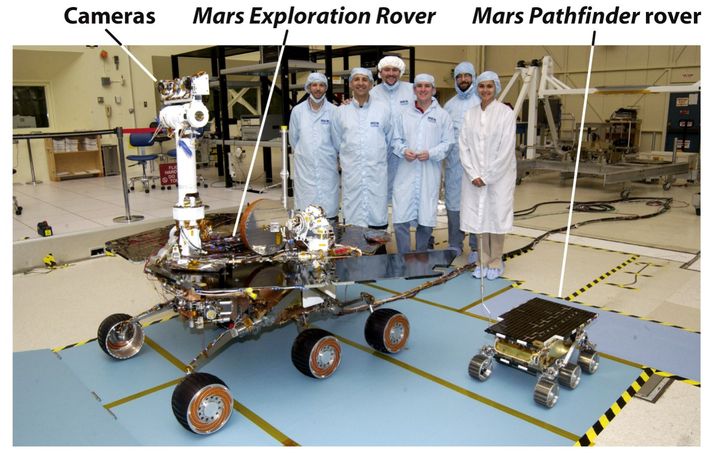
Cones may have originated from lava from Olympus Mons that heated underground ice causing the water and vapor coming to the surface

Landers have explored the surface of Mars

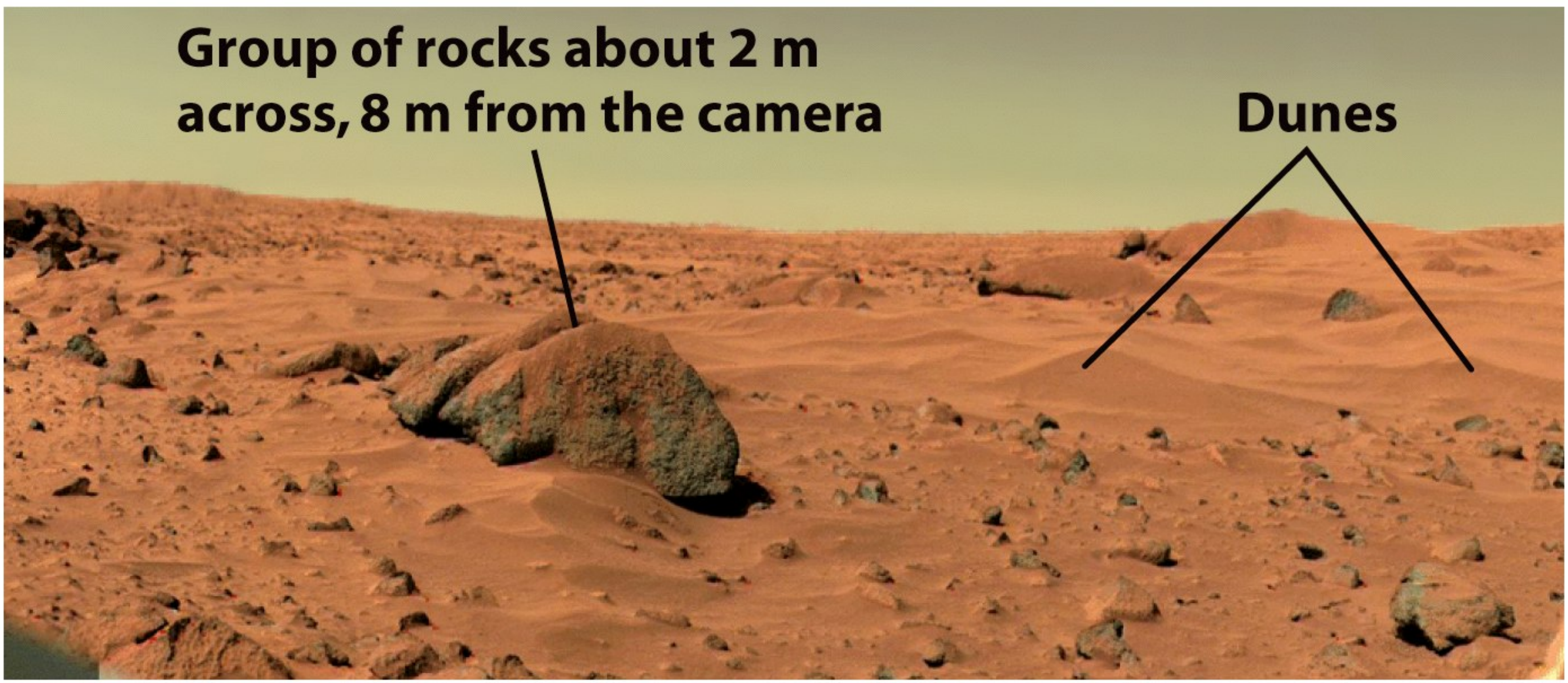




(a) A rover on Mars



Two generations of rovers



Atmosphere of Mars when free of dust

Figure 7-26a
Discovering the Universe, Eighth Edition

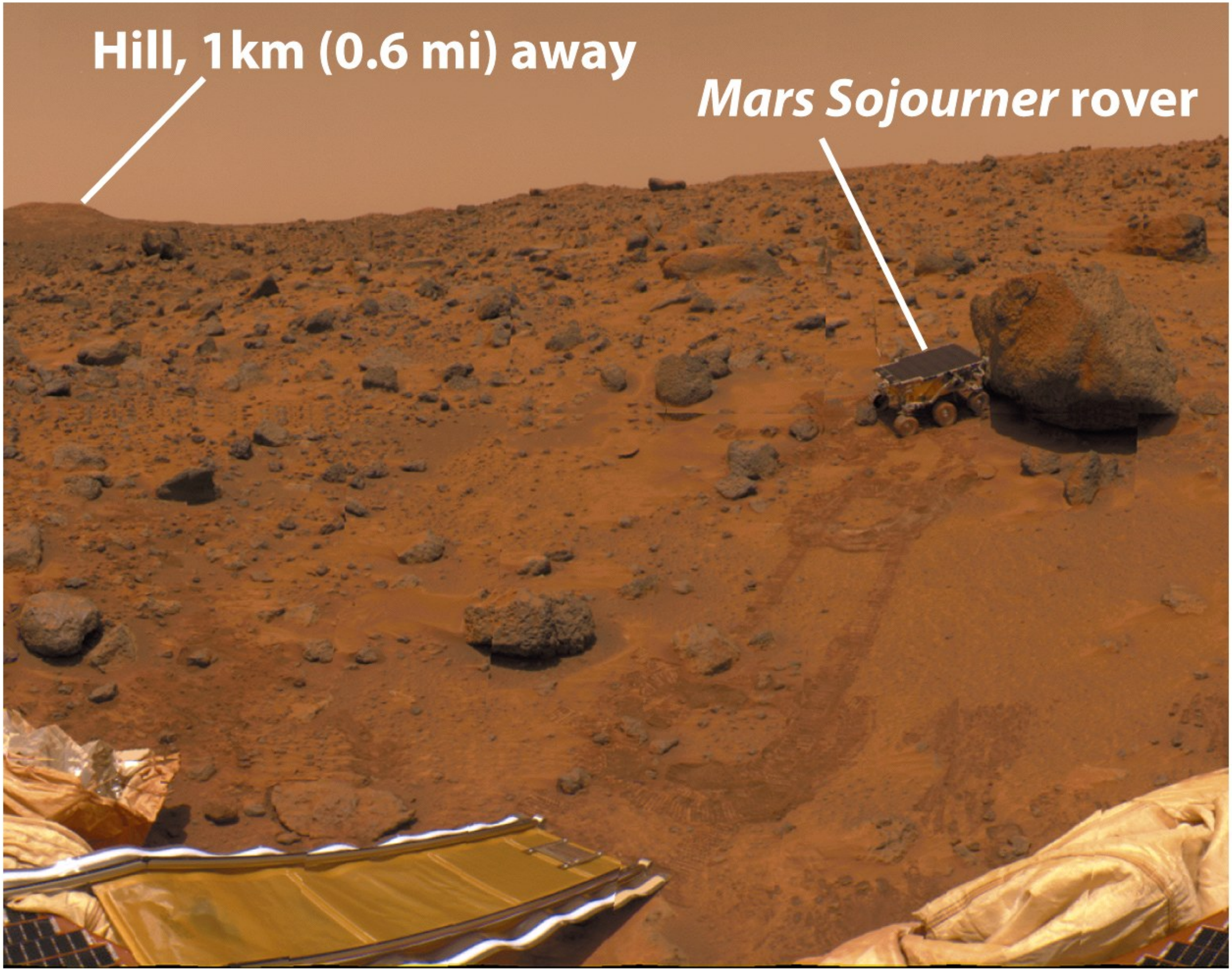


Figure 7-26b
Discovering the Universe, Eighth Edition

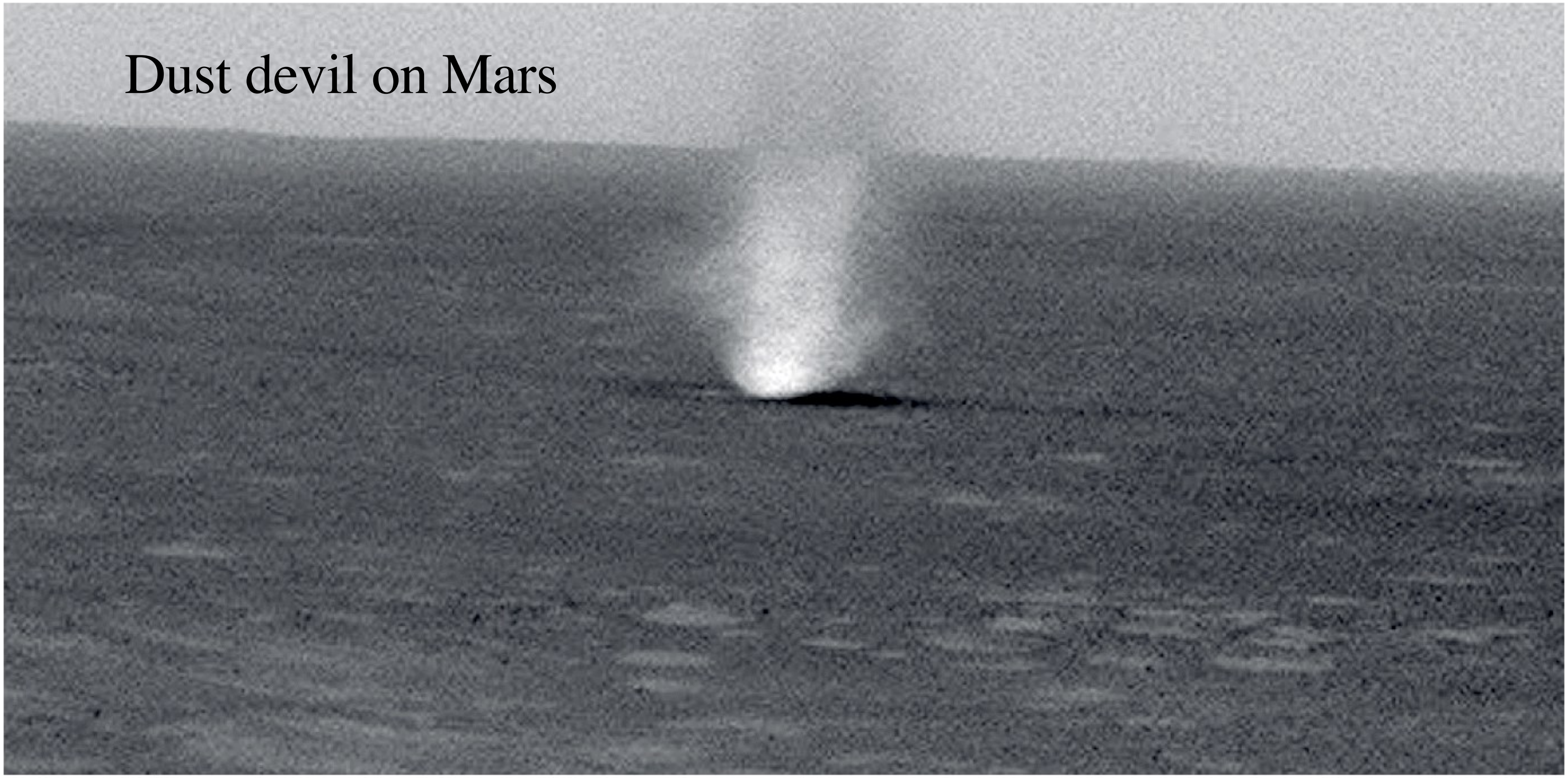


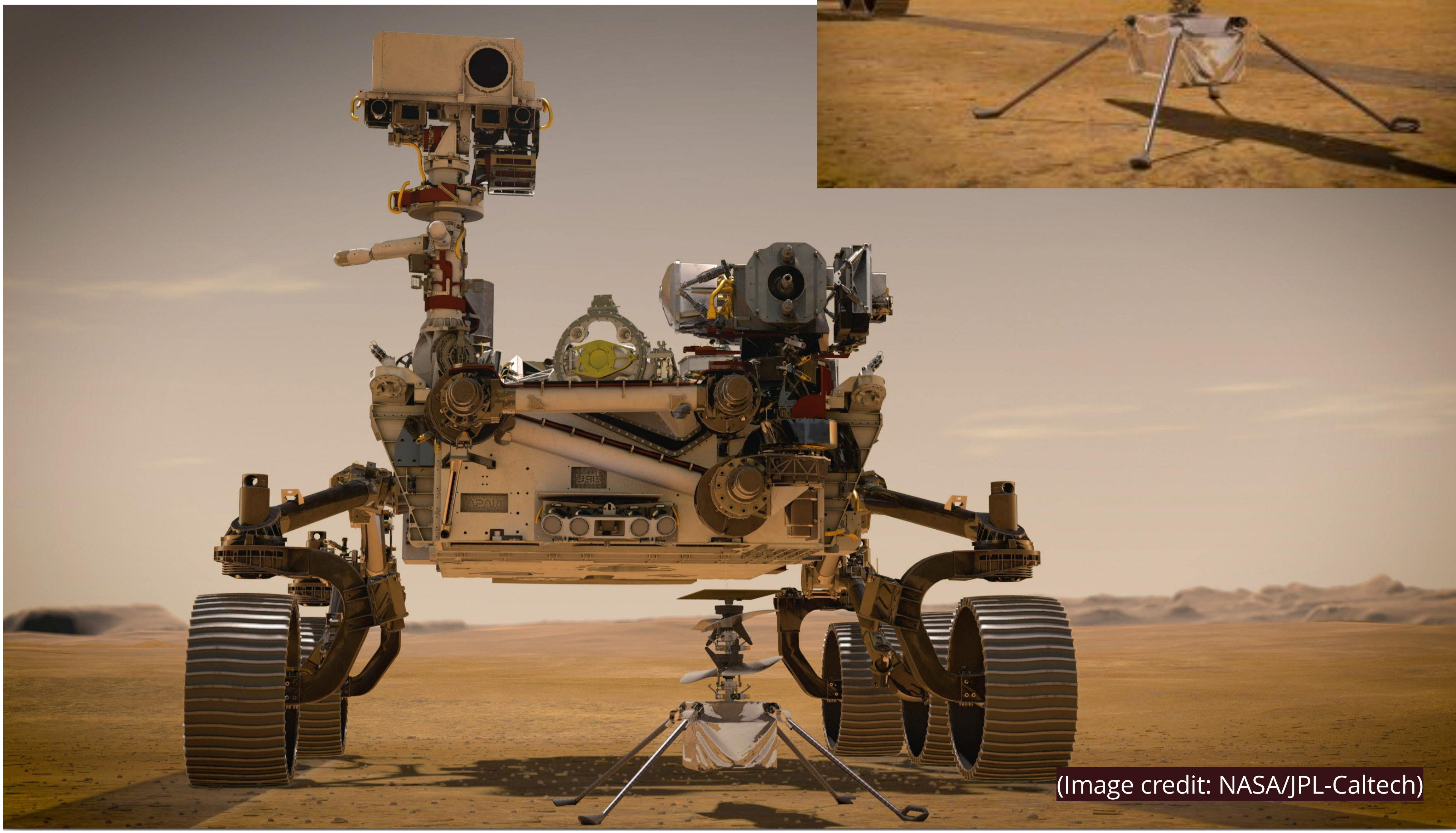
Figure 7-27a
Discovering the Universe, Eighth Edition

Panoramic view, Curiosity Mars rover, NASA

MISSION: RED PLANET

Feb, 2021: NASA's Perseverance rover has touched down on Mars, UAE's Hope mission and China's Tianwen-1 have entered Martian orbit. How are the three missions different from each other

Perseverance rover on Mars
Landed 18 February 2021

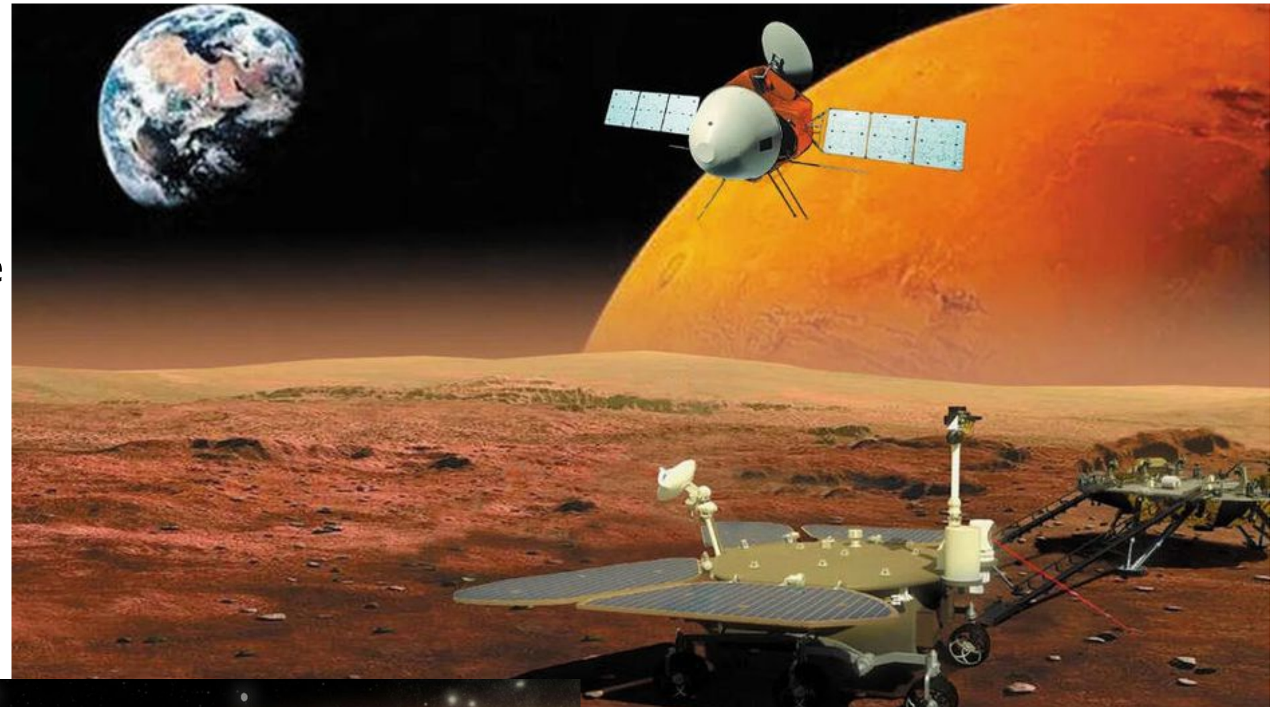


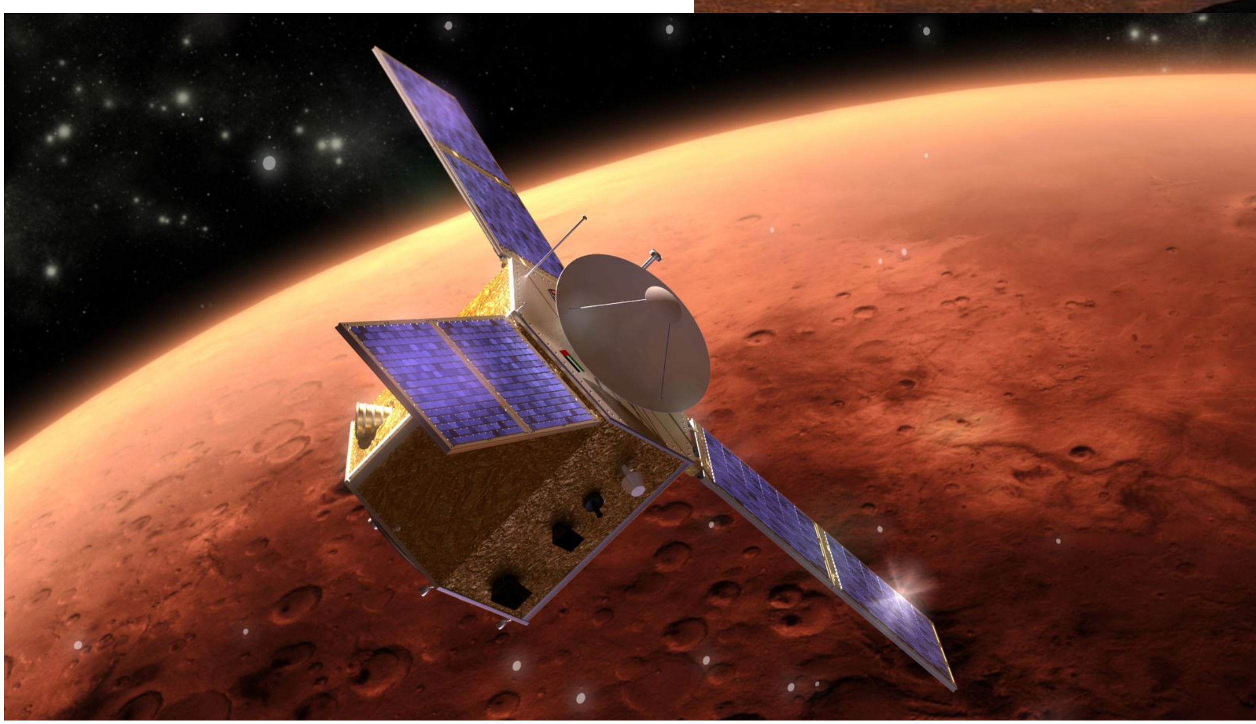
Perseverance will look for microbial life from 3 to 4 Bill. years ago

China’s Tianwen-1 Mars mission

Landing attempt,
later this year

An artist's impression of China’s three spacecraft ,   Nature Astronomy





Artist’s impression

UAE Mars mission
Mars orbiter

Source (WP:NFCC#4)

Life on Mars?

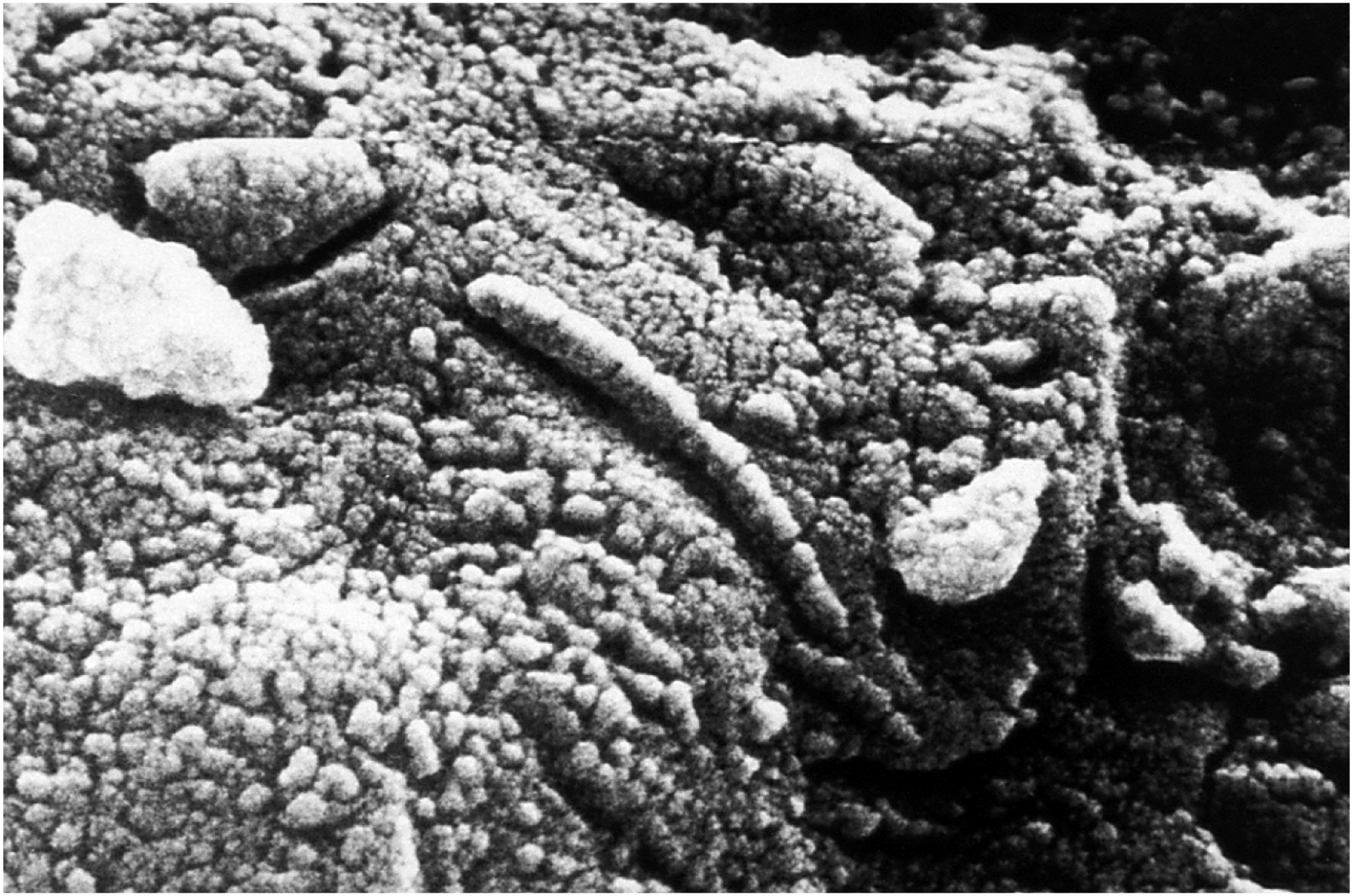
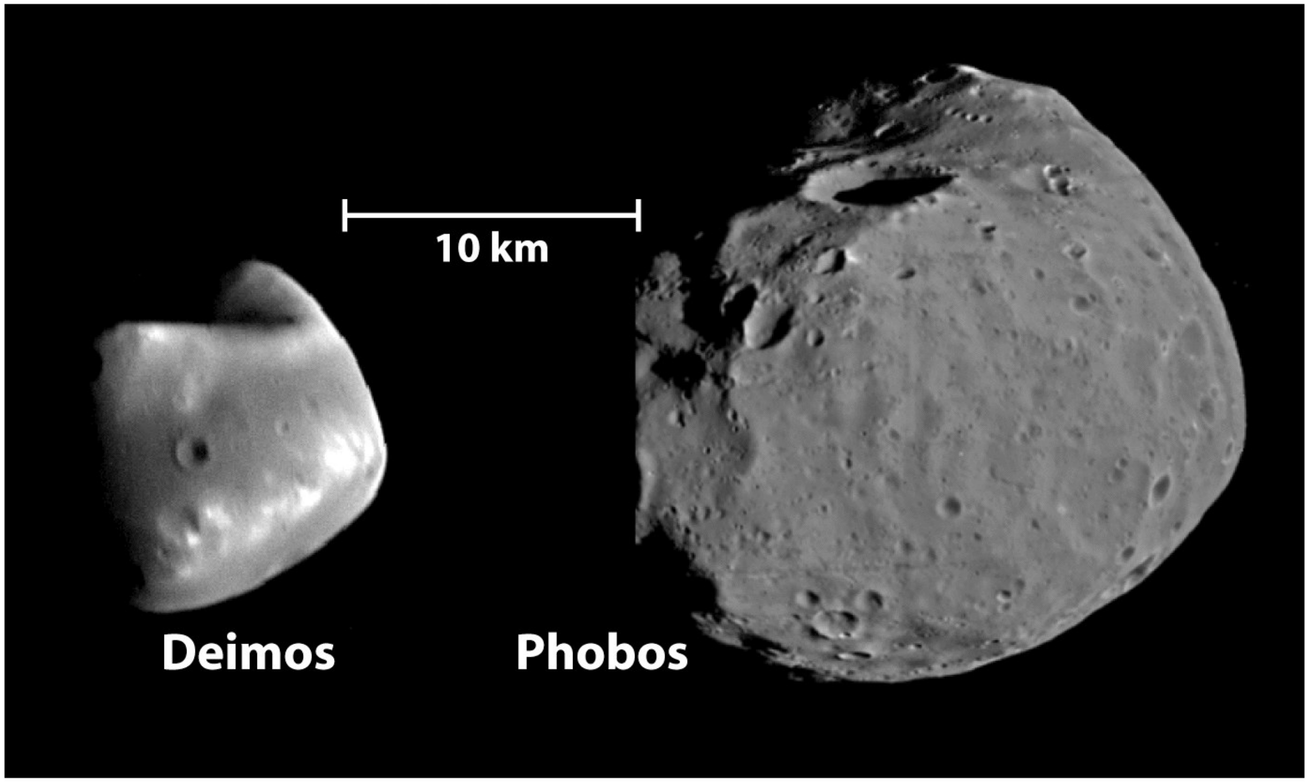
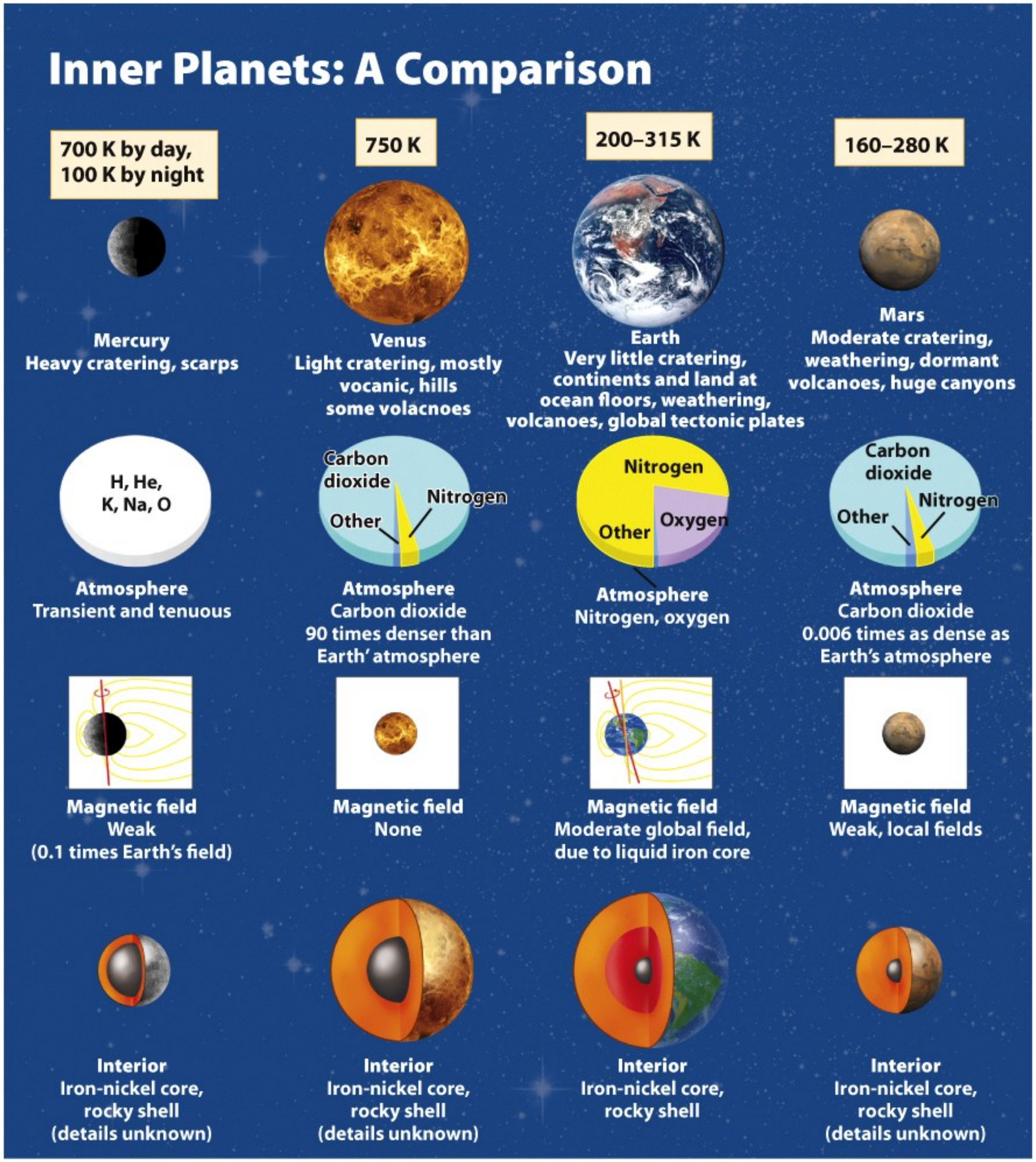


Figure 7-34b
Discovering the Universe, Eighth Edition

The two Martian moons resemble asteroids



- Mars has two small, football-shaped satellites that move in orbits close to the surface of the planet
- They may be captured asteroids or may have formed in orbit around Mars out of solar system debris



Unnumbered 7 p208

Discovering the Universe, Eighth Edition

Why is there no H_2 in the atmosphere of the inner planets?

$E_k=1/2mv^2$	J	Kinetic energy due to motion with velocity, v
$E_k=3/2kT$	J	Thermal kinetic energy of gas, atoms or molecules
$v=(3kT/m)^{1/2}$	m/s	Average speed of a gas, atom or molecule
$k=1.38\text{x}10^{-23}$	J/K	Boltzmann's constant
$m = \mathcal{M}$ x amu	kg	mass of atom or molecule
$\mathcal{M}$		mass number
amu= 1.66×10^{-27} kg		atomic mass unit

Example for Mars: T=220K, H_2 : $\mathcal{M}$=2, m= $2\text{x}1.66\text{x}10^{-27}$ kg

$v=[(3\text{x}1.38\text{x}10^{-23}\text{x}220/(2\text{x}1.66\text{x}10^{-27})]^{1/2}$ =1656 m/s

A planet or moon can retain a gas if the escape speed is at least 6 times greater than the average velocity of the gas.

What is the escape velocity for Mars?

$v^2_{escape} = 2GM/r$
M = 6.418×10^{23} kg (mass of Mars)
r=3397 km (radius of Mars)

$v^2_{escape} = 2 \times 6.673 \times 10^{-11} \times 6.418 \times 10^{23} / (3.397 \times 10^6) = 25.214 \times 10^6\ (m/s)^2$
$V_{escape} = 5021$ m/s = 5.021 km/s

Why is there no H_2 in the atmosphere of the inner planets?

$E_k=1/2mv^2$	J	Kinetic energy due to motion with velocity, v
$E_k=3/2kT$	J	Thermal kinetic energy of gas, atoms or molecules
$v=(3kT/m)^{1/2}$	m/s	Average speed of a gas, atom or molecule
$k=1.38\text{x}10^{-23}$	J/K	Boltzmann's constant
$m = \mathcal{M}$ x amu	kg	mass of atom or molecule
$\mathcal{M}$		mass number
amu= $1.66 \text{ x } 10^{-27}$ kg		atomic mass unit

Example for Mars: T=220K, H_2 : $\mathcal{M}$=2, m= $2\text{x}1.66\text{x}10^{-27}$ kg

$v=[(3\text{x}1.38\text{x}10^{-23}\text{x}220/(2\text{x}1.66\text{x}10^{-27})]^{1/2}$ =1656 m/s

A planet or moon can retain a gas if the escape speed is at least 6 times greater than the average velocity of the gas.

V_{esc}=5.02 km/s =3.0 x v ➔ H_2 cannot be retained by Mars.