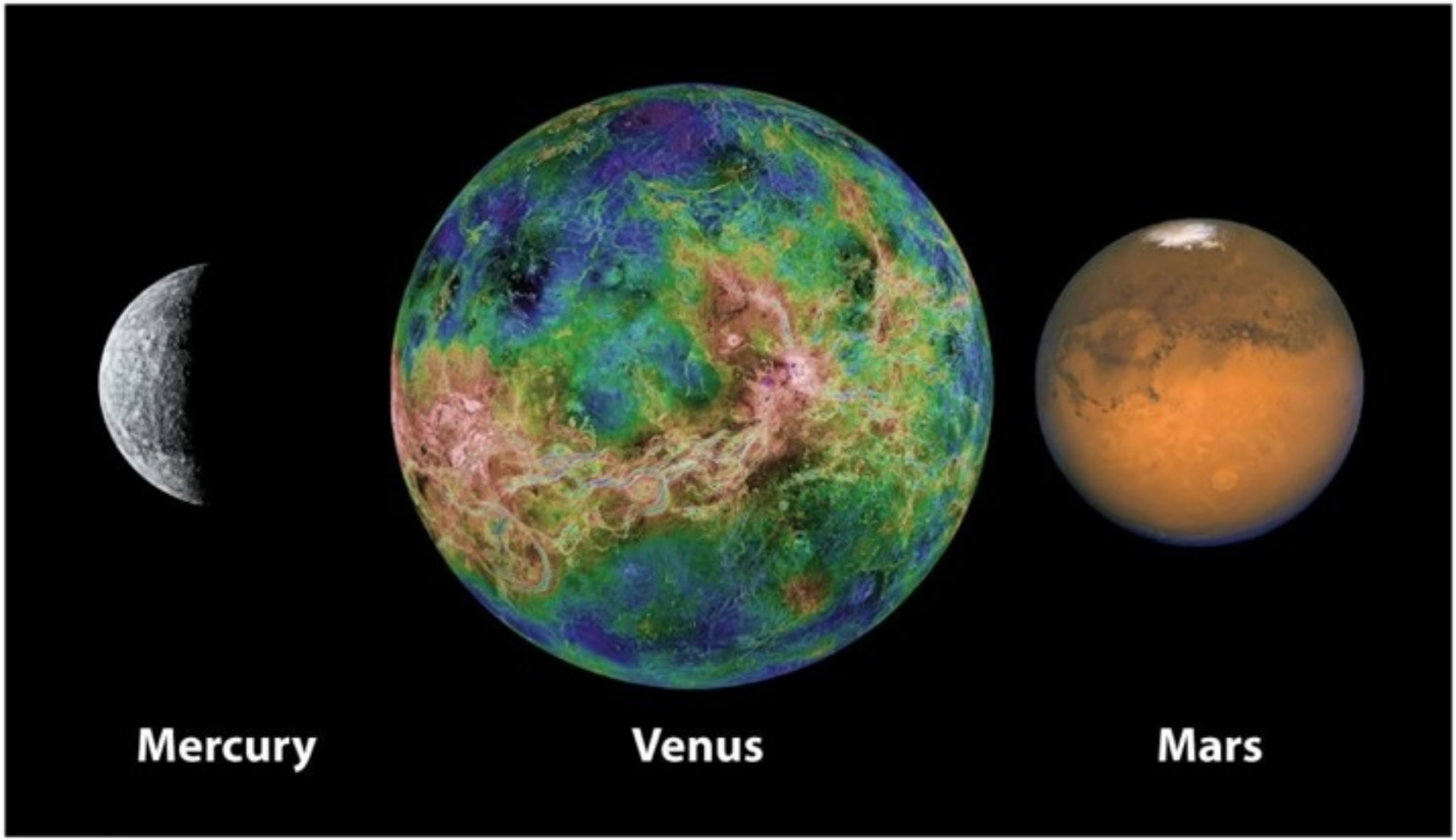
Roger Freedman • Robert Geller • William Kaufmann III

Universe

Tenth Edition

Chapter 11

Mercury, Venus, and Mars: Earthlike yet Unique



Chapter 11 Opener
Universe, Tenth Edition
Mercury: NASA; Venus: NASA/JPL, MIT, and USGS; Mars: NASA, J. Bell/Cornell University, and M. Wolff/SSI

By reading this chapter, you will learn

11-1 What astronomers have learned by observing the terrestrial planets from Earth

11-2 The radically different ways in which Mercury, Venus, and Mars rotate on their axes

11-3 The outstanding features of Mercury, and why its magnetic field came as a surprise

11-4 How the advent of the space age transformed our understanding of Venus and Mars

By reading this chapter, you will learn

11-5 How geologic activity took a very different form on Venus than on Earth, and why it essentially stopped on Mars

11-6 The key differences among the atmospheres of Earth, Venus, and Mars

11-7 How the atmospheres of Earth, Venus, and Mars evolved to their present states

11-8 The evidence that there was once liquid water on Mars

11-9 What we know about the two small satellites of Mars

11-1: Mercury, Venus and Mars can all be seen by the naked eye.

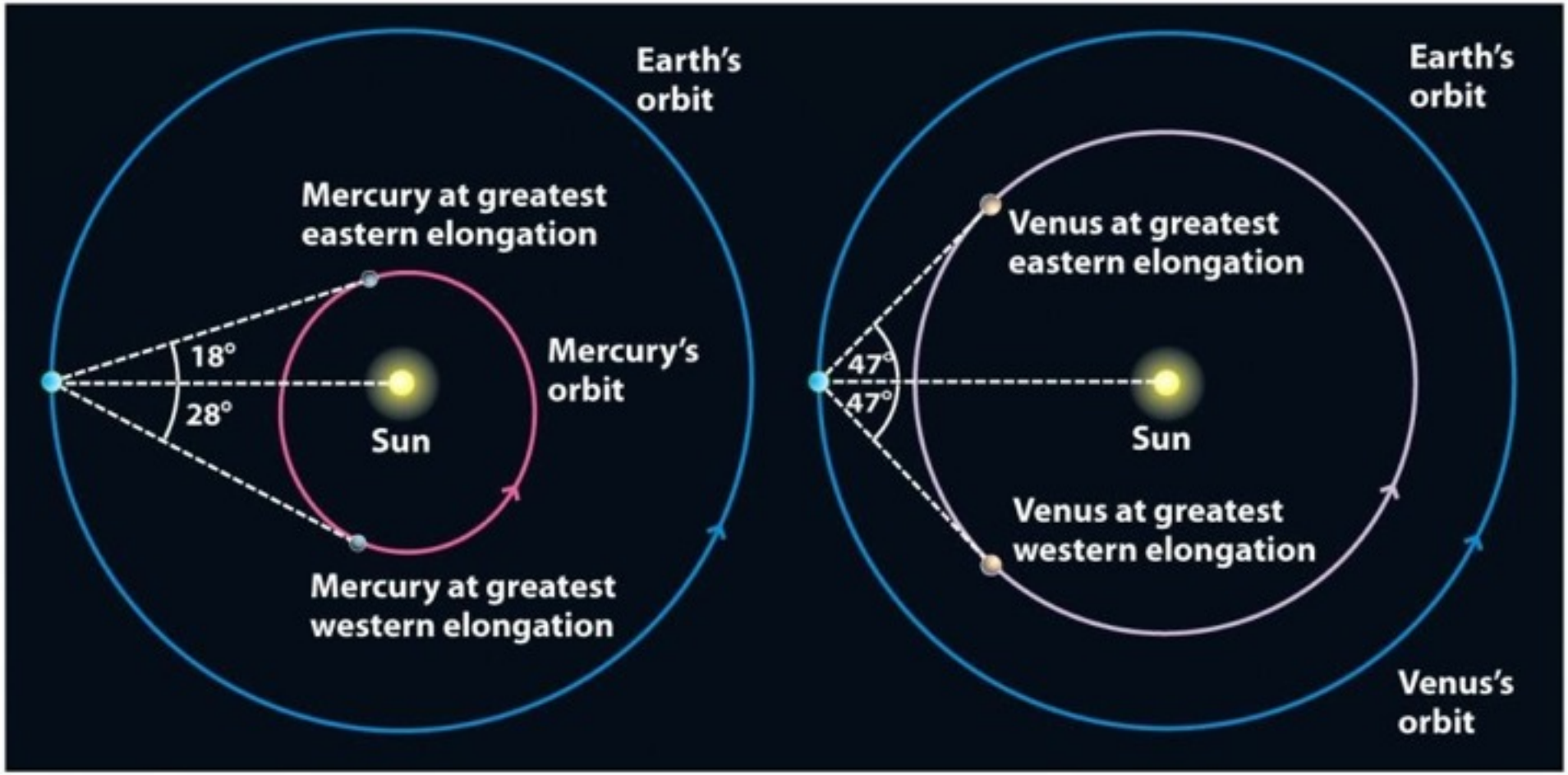
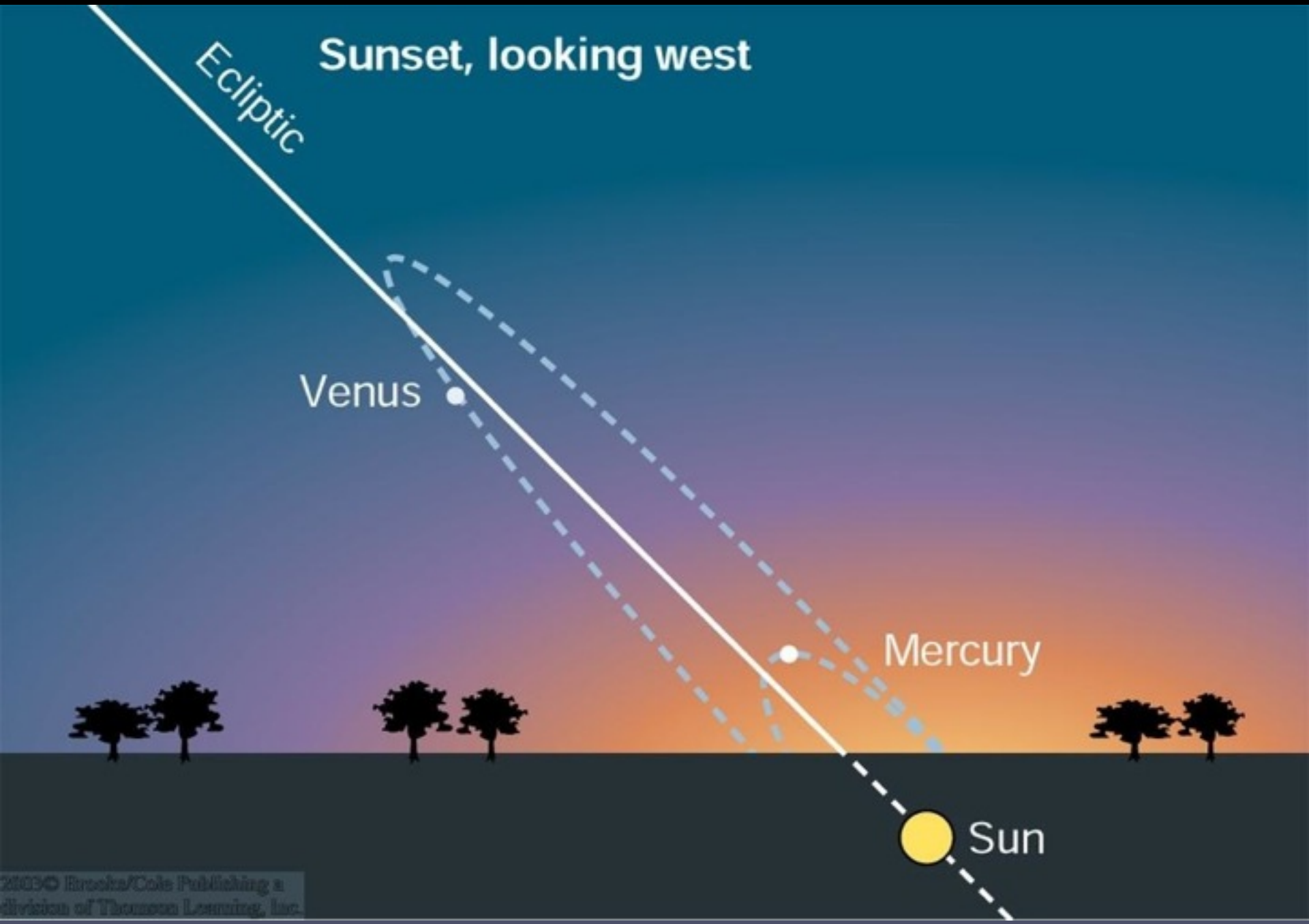
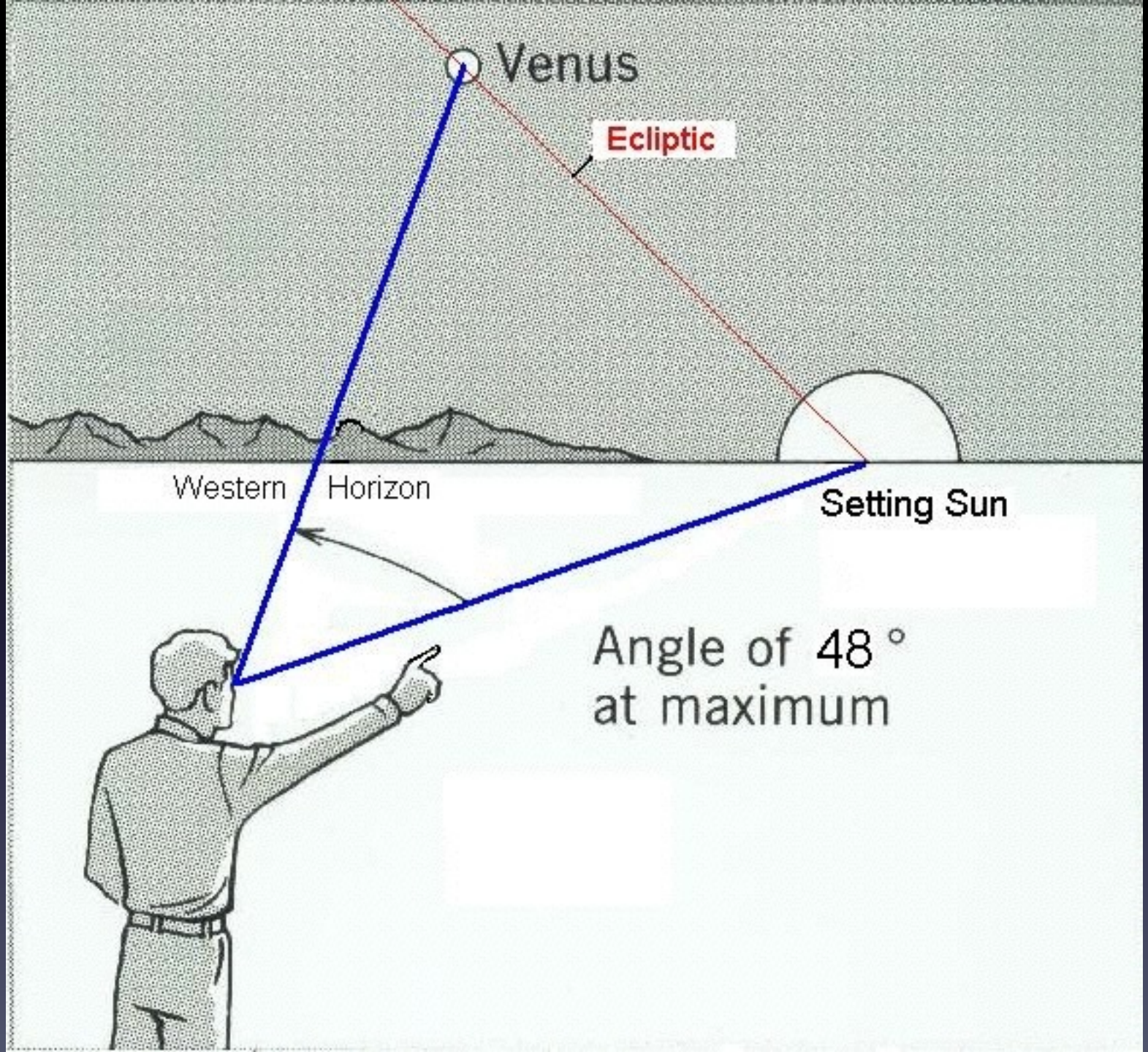
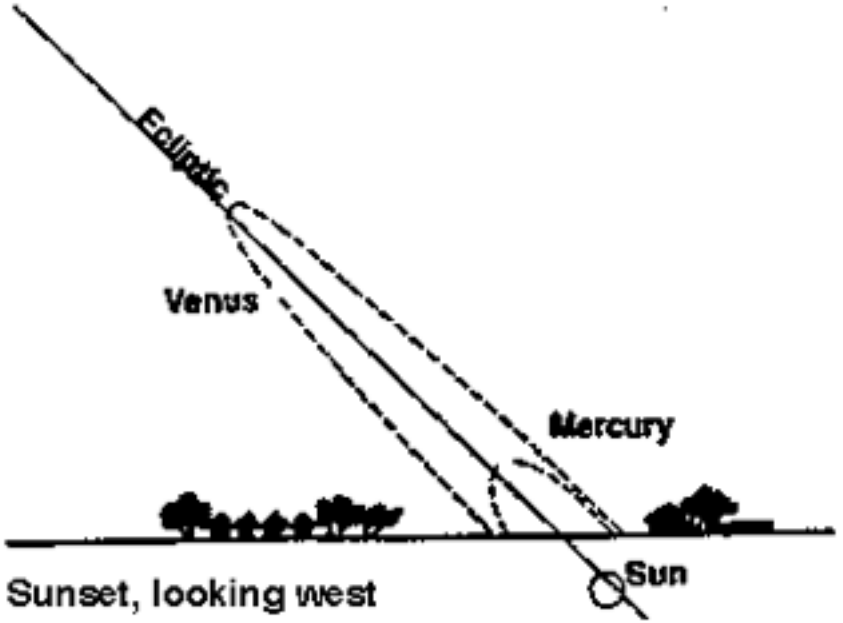


Figure 11-1
Universe, Tenth Edition

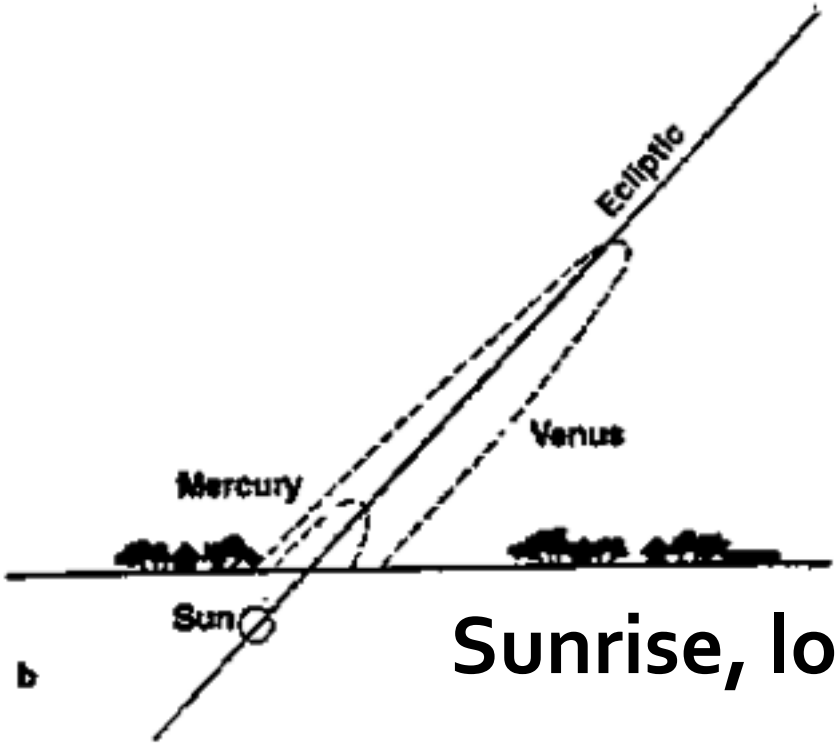
The Orbits of Mercury and Venus




Venus
Ecliptic
Western Horizon
Setting Sun
Angle of 48°
at maximum



Sunset, looking west



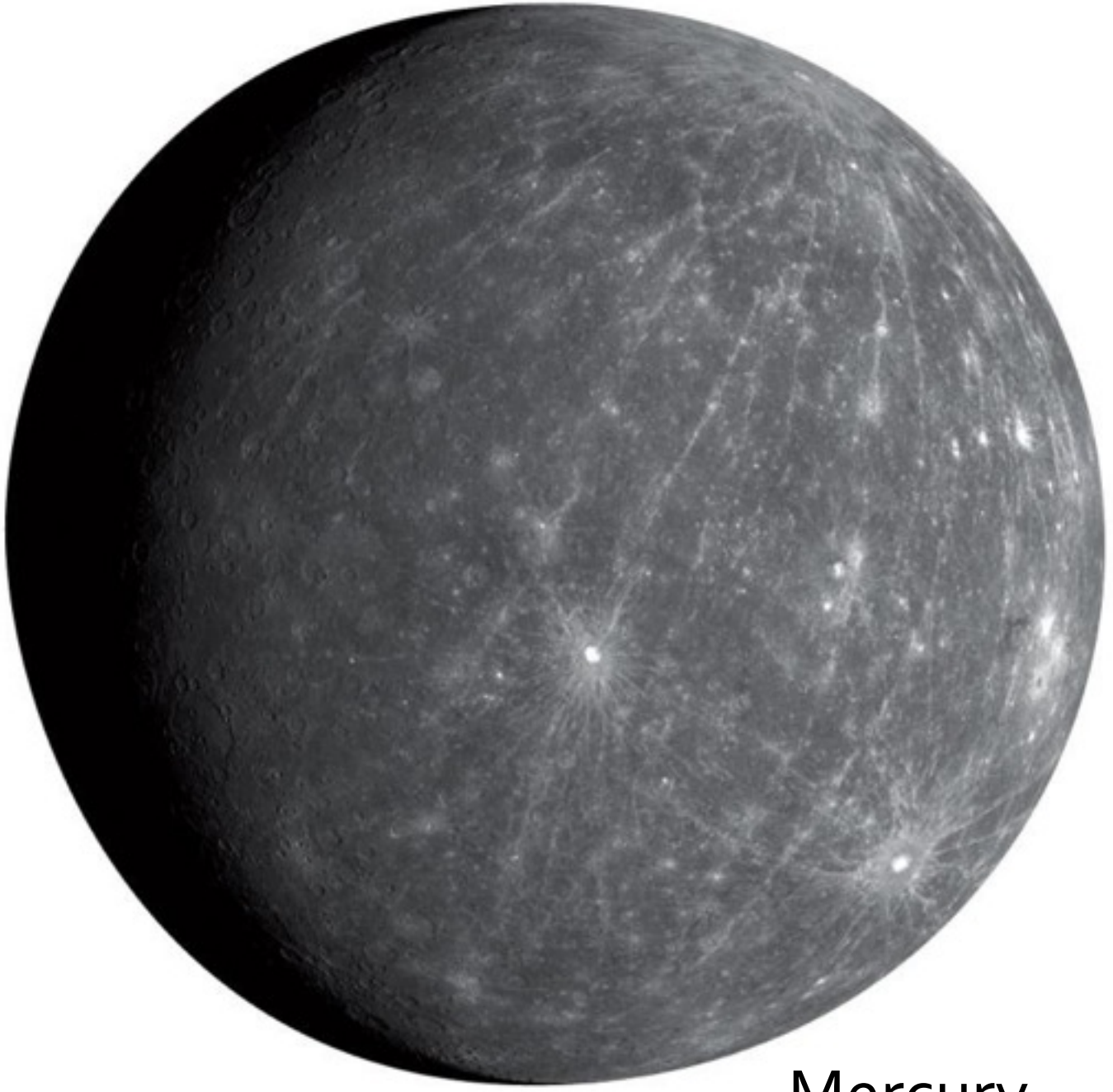
Sunrise, looking east

Table 11-3 photo
Universe, Tenth Edition
NASA, USGS

TABLE 11-3 Mars Data

Average distance from the Sun:	1.524 AU = 2.279×10^8 km
Maximum distance from the Sun:	1.666 AU = 2.492×10^8 km
Minimum distance from the 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/m³
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: −23°C = − 10°F = 250 K Minimum: −140°C = − 220°F = 133 K
Atmosphere 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

Table 11-3
Universe, Tenth Edition



Mercury

Table 11-1 photo
Universe, Tenth Edition
NASA/Johns Hopkins U. Applied Physics Laboratory/Carnegie Institution of Washington

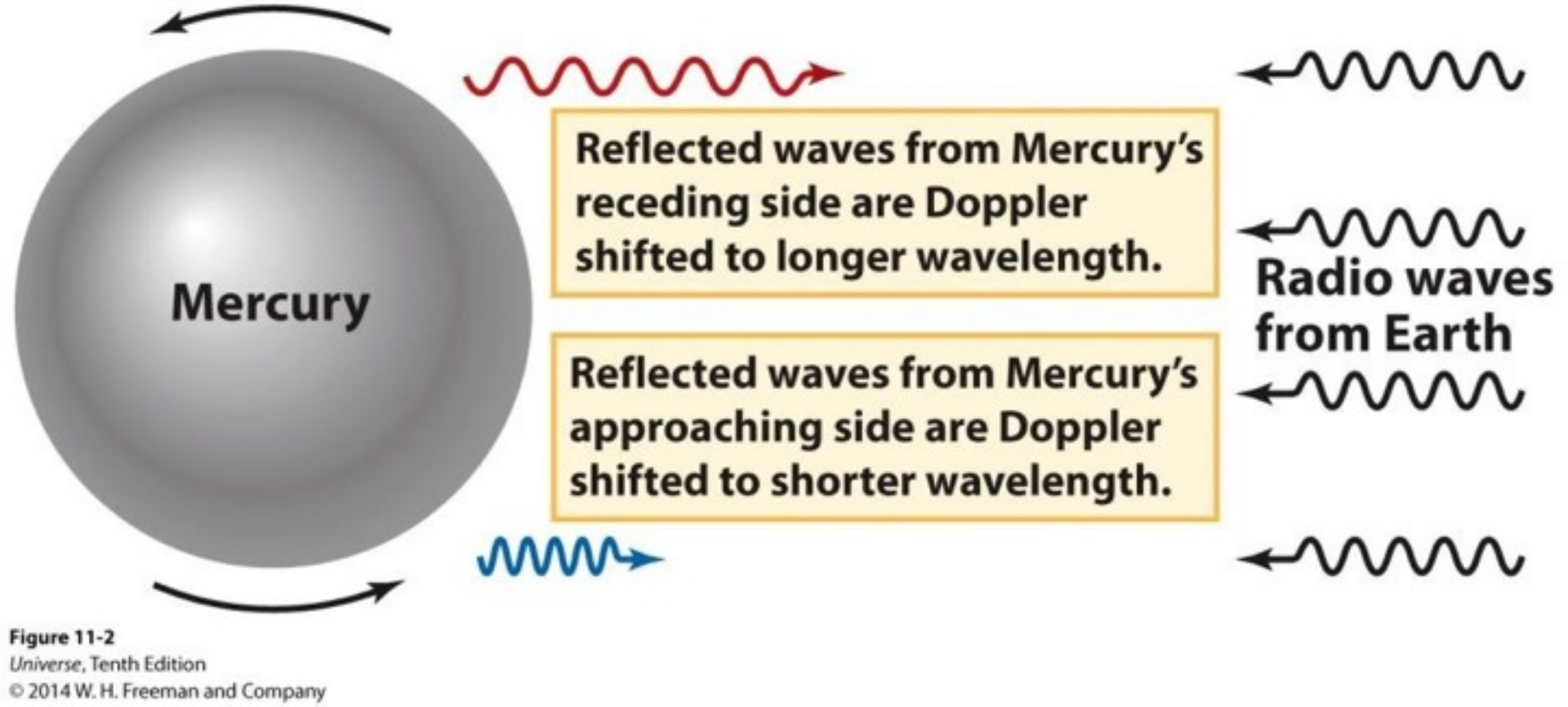


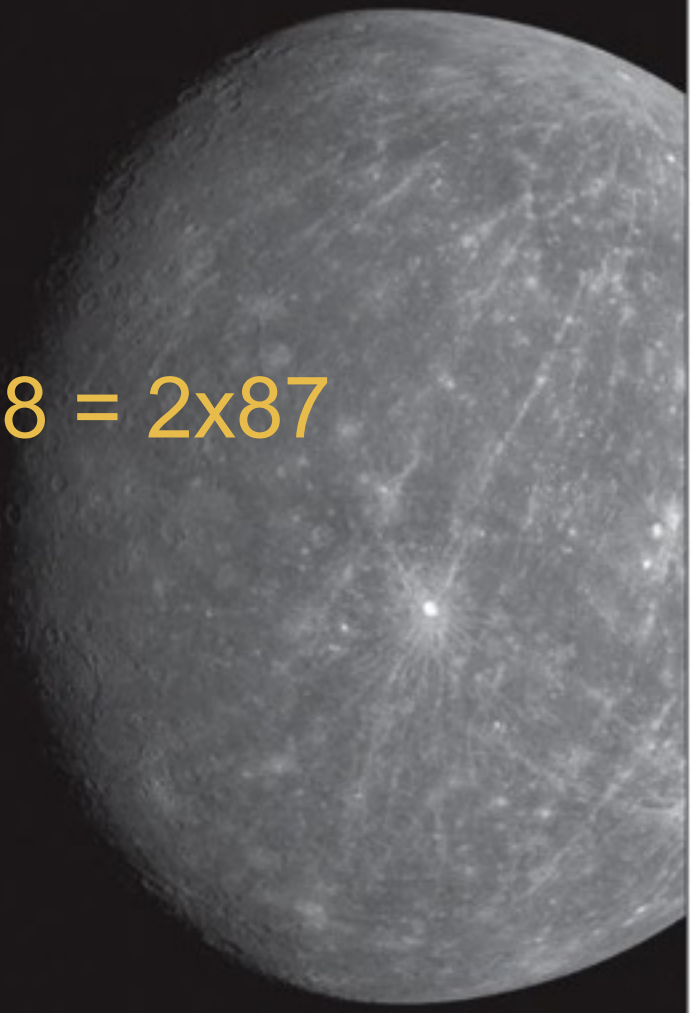
Figure 11-2
Universe, Tenth Edition

Measuring Mercury's Rotation Period

TABLE 11-1 Mercury Data

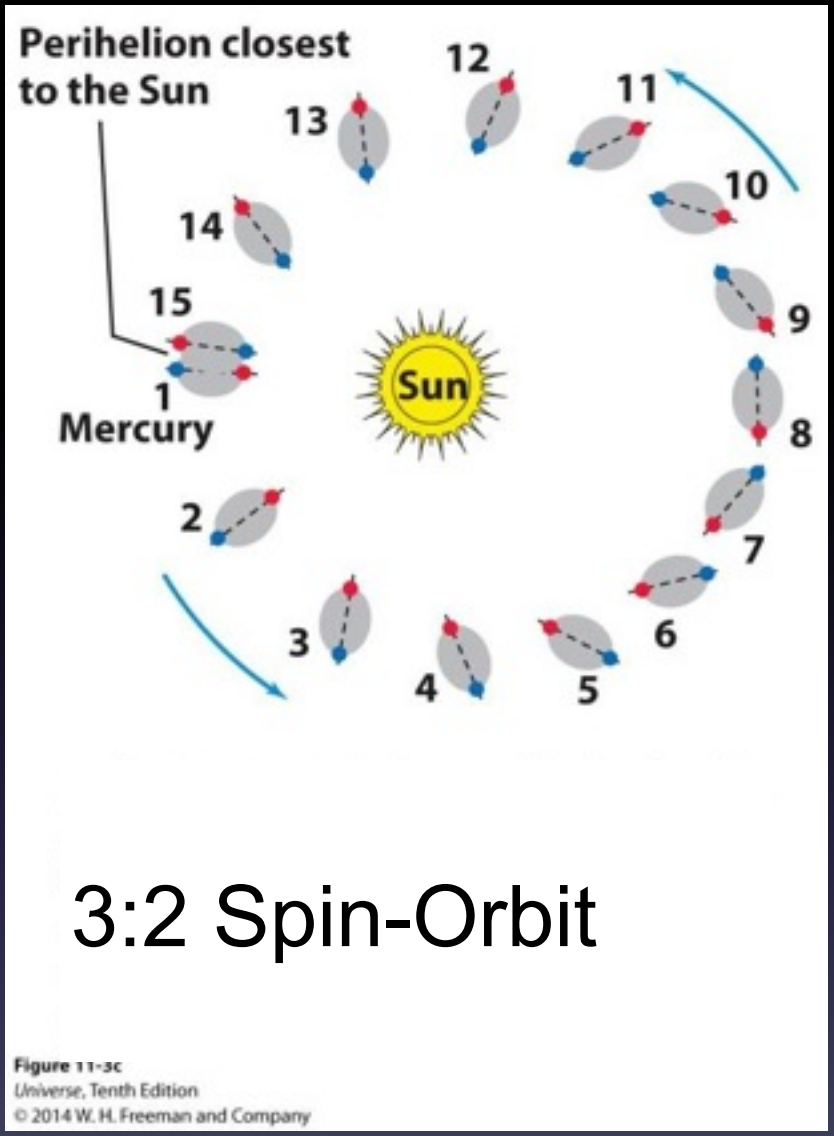
Average distance from the Sun:	0.387 AU = 5.79×10^7 km
Maximum distance from the Sun:	0.467 AU = 6.98×10^7 km
Minimum distance from the Sun:	0.307 AU = 4.60×10^7 km
Eccentricity of orbit:	0.206
Average orbital speed:	47.9 km/s
Orbital period:	87.969 days
Rotation period:	58.646 days
Inclination of equator 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

3x58 = 2x87



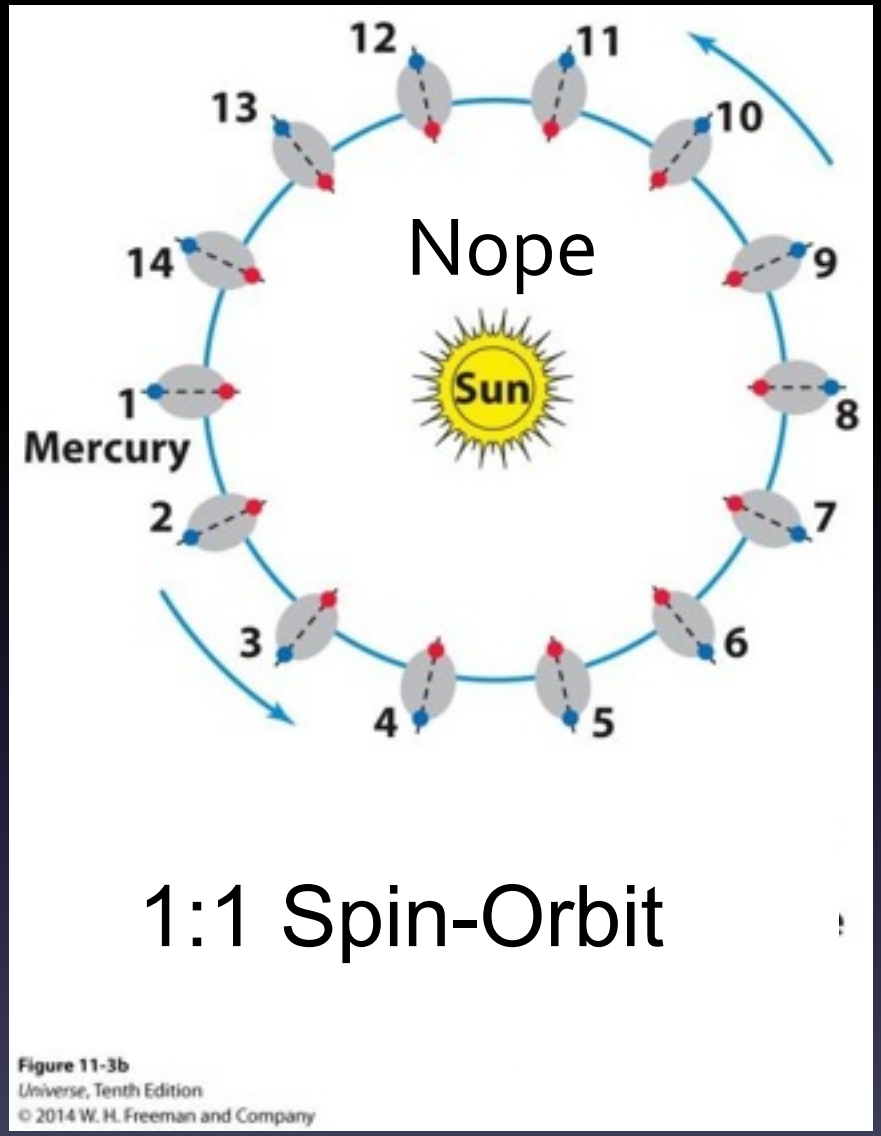
RIVUXG
(NASA/Johns Hopkins U. Applied Physics Laboratory/Carnegie Institution of Washington)

Table 11-1
Universe, Tenth Edition



3:2 Spin-Orbit

Figure 11-3c
Universe, Tenth Edition
© 2014 W. H. Freeman and Company



1:1 Spin-Orbit

Figure 11-3b
Universe, Tenth Edition
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Mercury's Spin-Orbit Coupling

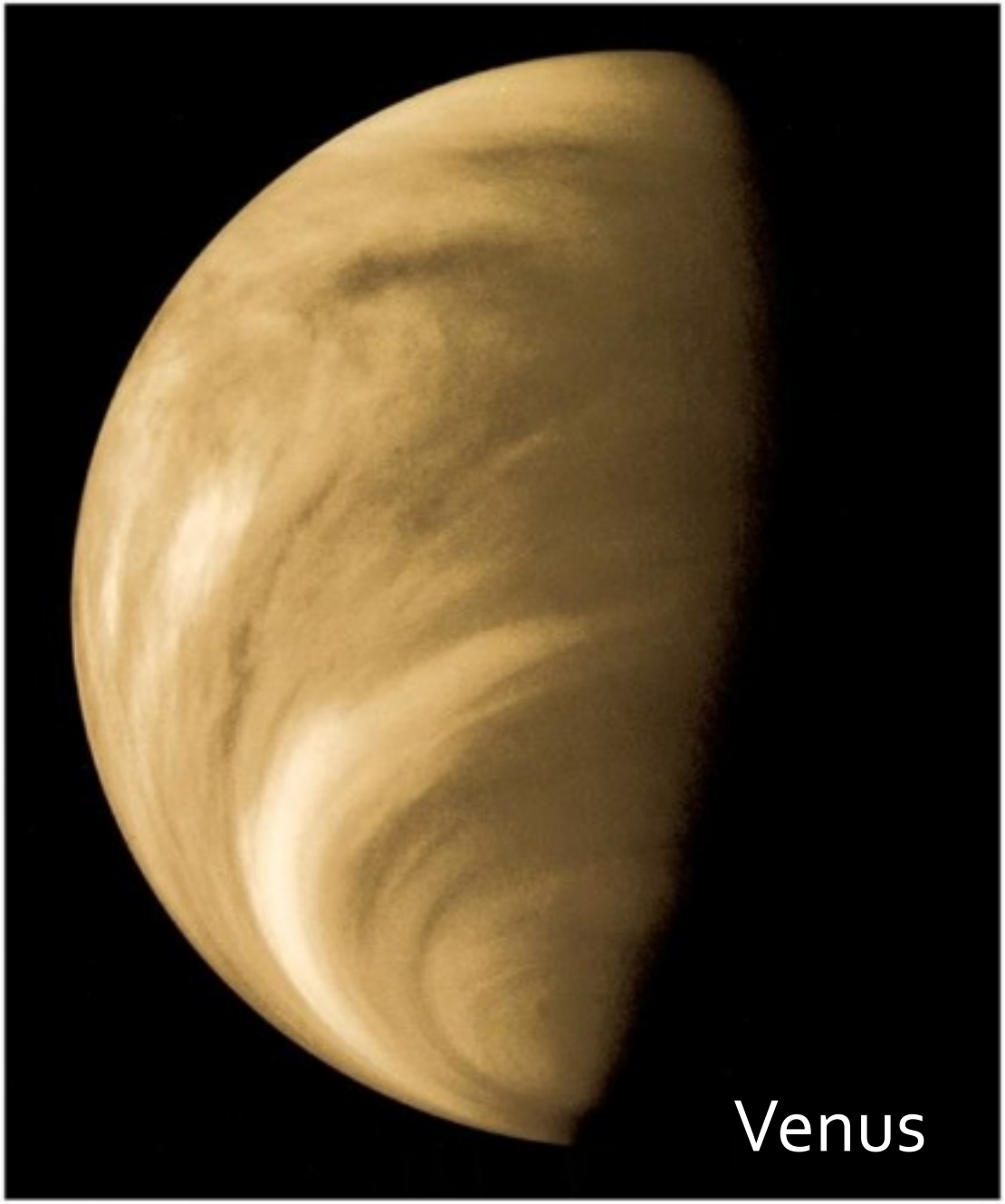


Table 11-2 photo
Universe, Tenth Edition
NASA

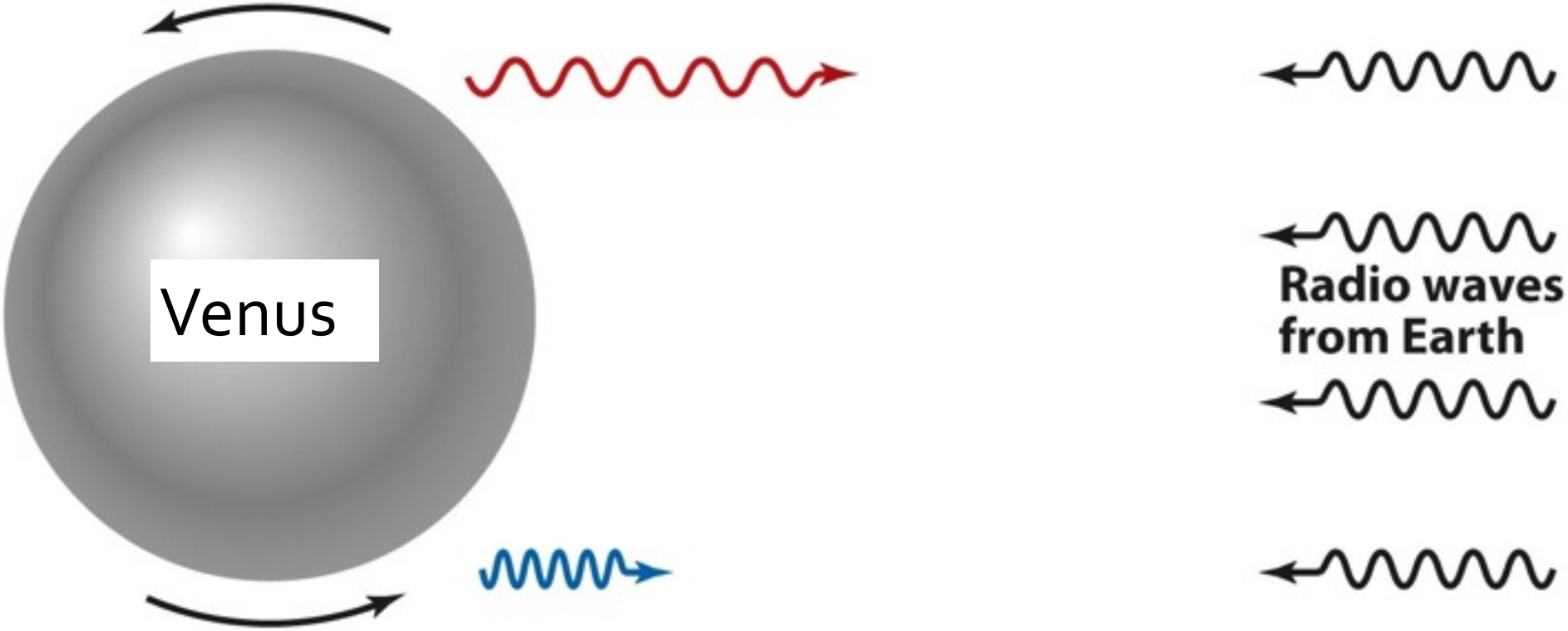


Figure 11-2
Universe, Tenth Edition

TABLE 11-2 Venus Data

Average distance from the Sun:	0.723 AU = 1.082×10^8 km
Maximum distance from the Sun:	0.728 AU = 1.089×10^8 km
Minimum distance from the 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
Atmosphere composition (by number of molecules):	96.5% carbon dioxide (CO_2) 3.5 nitrogen (N_2) 0.003% water vapor (H_2O)

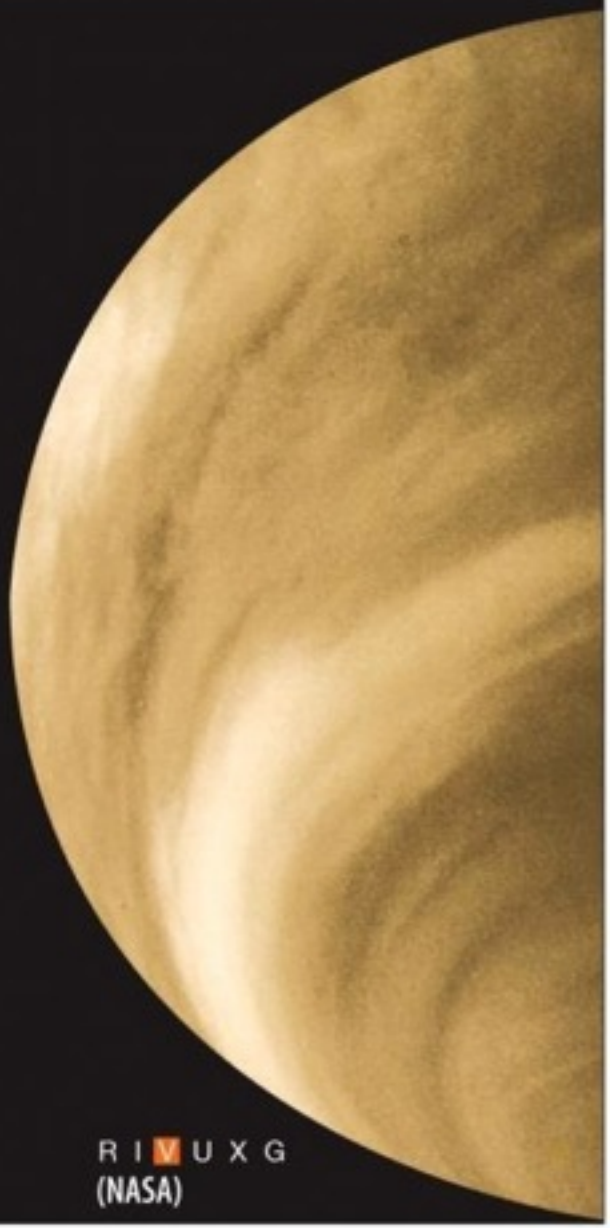


Table 11-2
Universe, Tenth Edition

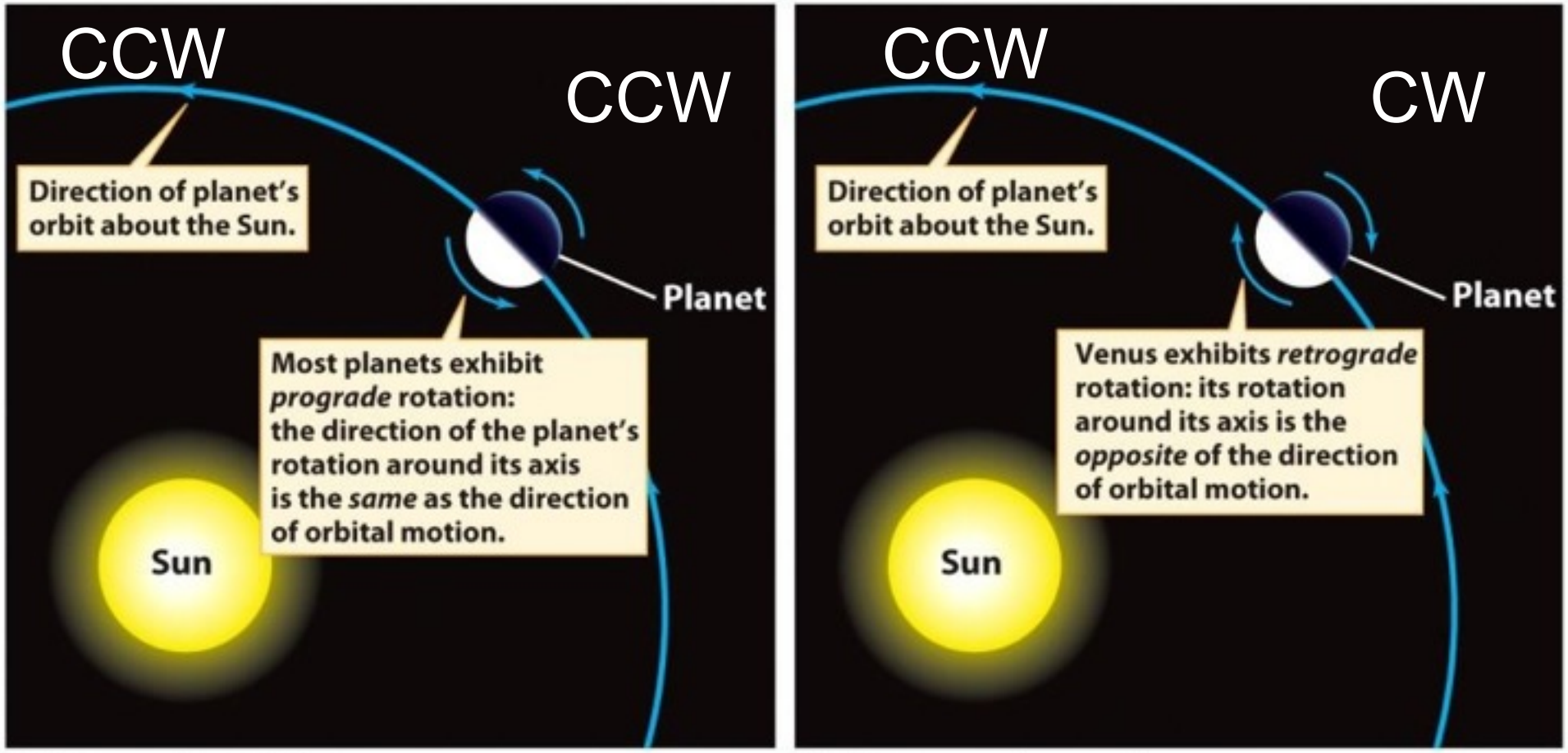


Figure 11-4
Universe, Tenth Edition

Prograde and Retrograde Rotation

11-3: Mercury is cratered like the Moon but has a surprising magnetic field.

Figure 11-5
Universe, Tenth Edition
NASA

Messenger Image of Mercury

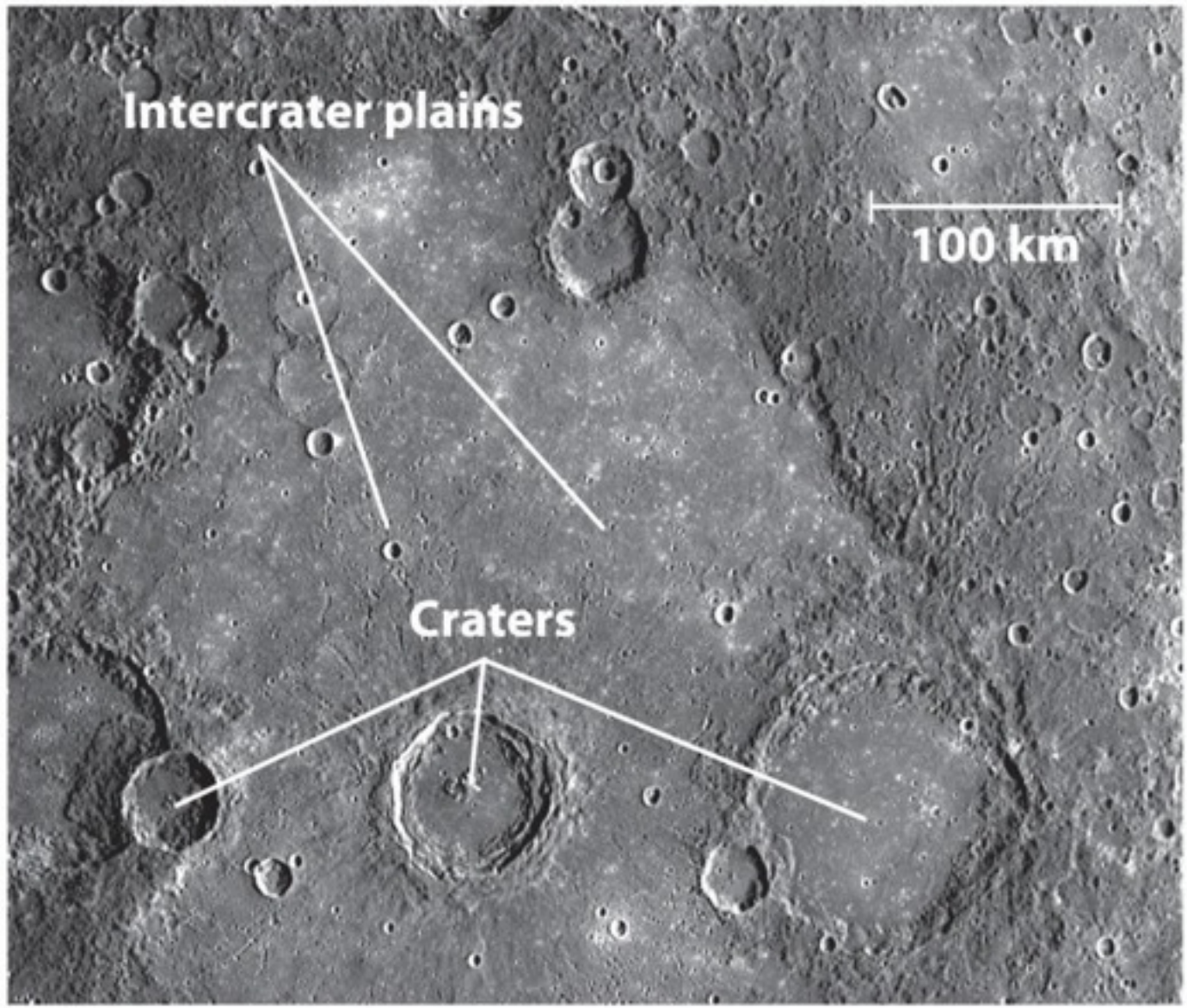


Figure 11-6
Universe, Tenth Edition
NASA/Johns Hopkins U. Applied Physics Laboratory/Carnegie Institution of Washington

Mercurian Craters and Plains

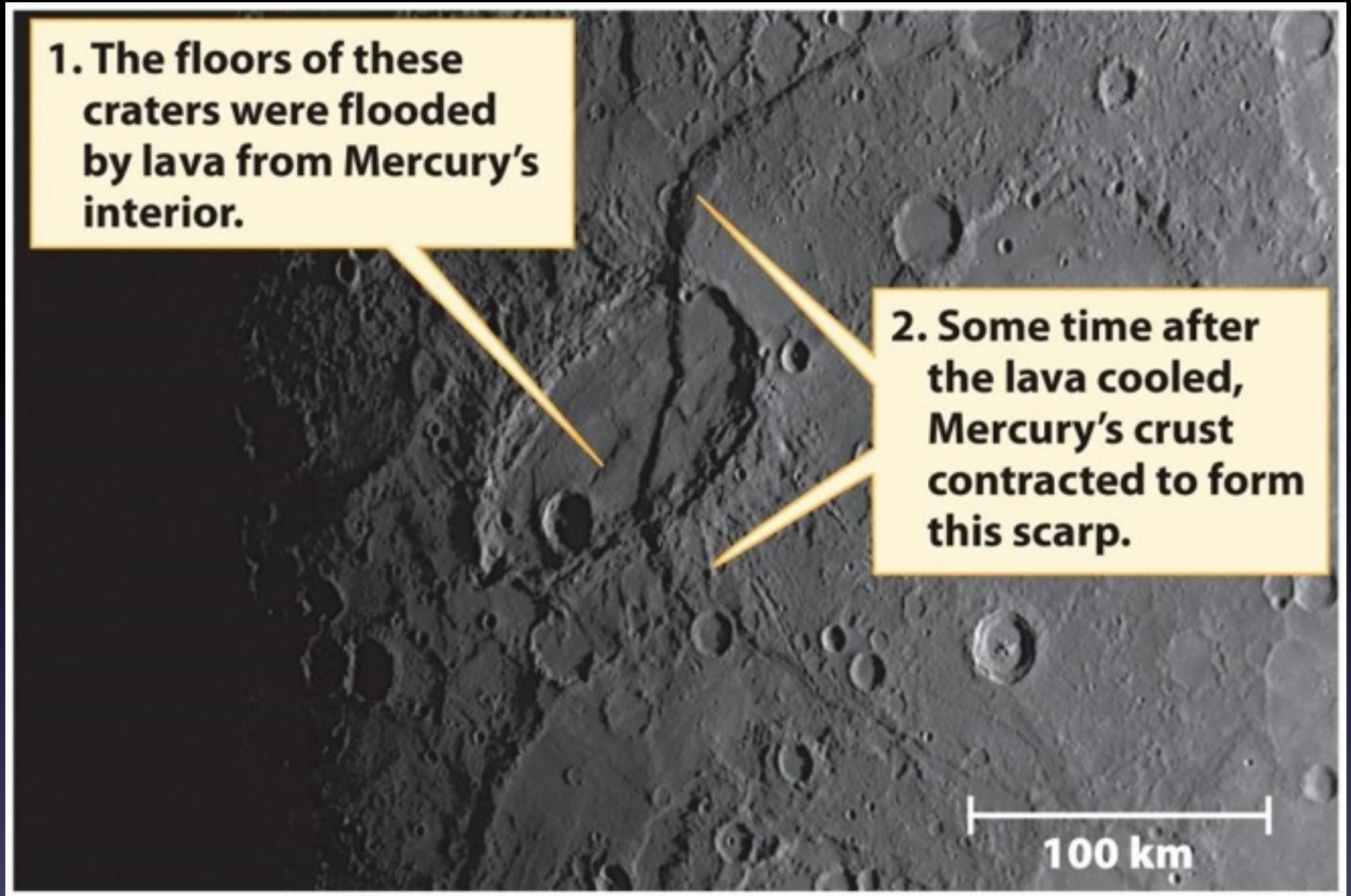


Figure 11-7
Universe, Tenth Edition
NASA/Johns Hopkins U. Applied Physics Laboratory/Carnegie Institution of Washington

A Scarp

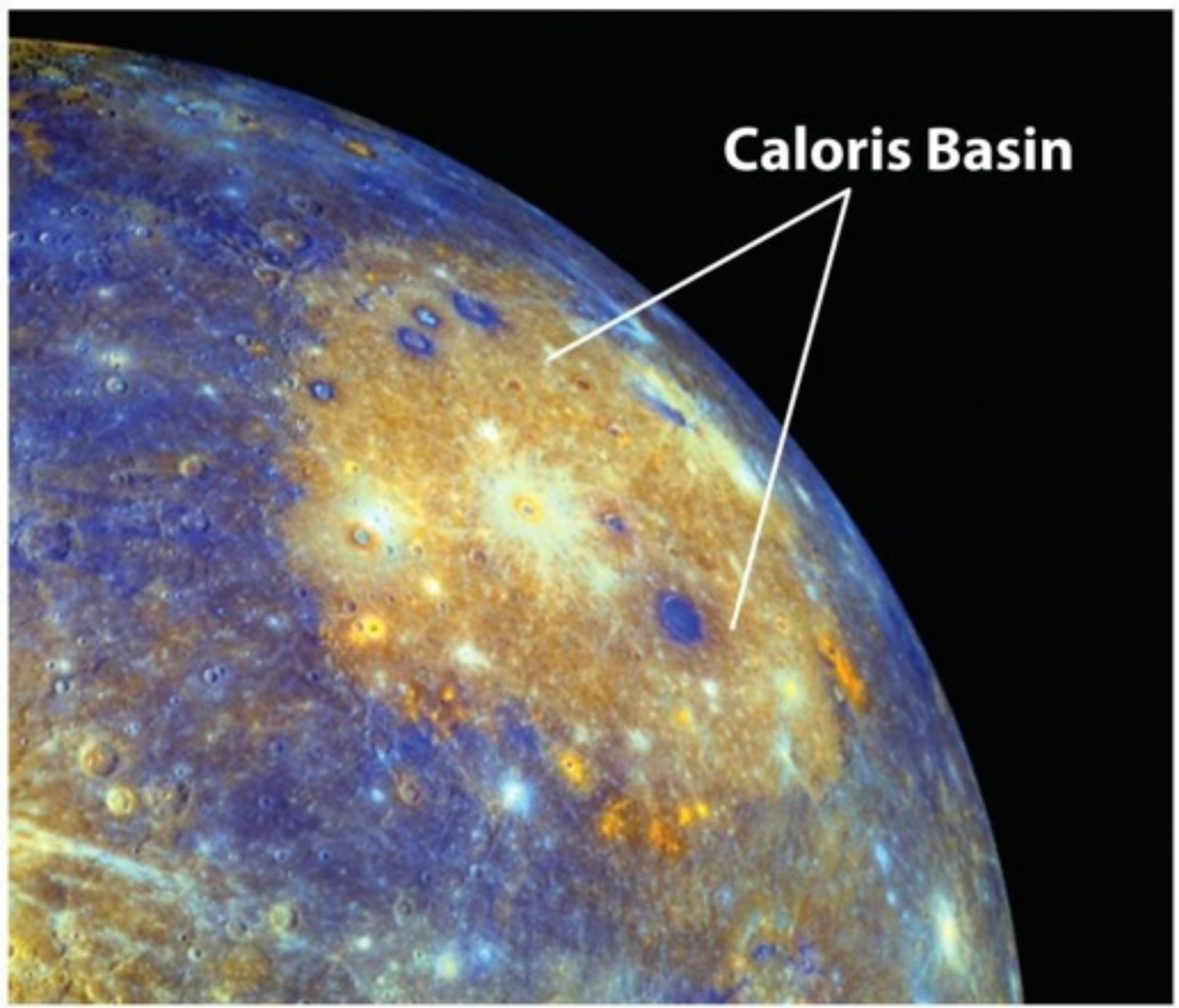


Figure 11-8
Universe, Tenth Edition
NASA/Johns Hopkins U. Applied Physics Laboratory/Arizona State U./Carnegie Institution of Washington

The Caloris Basin

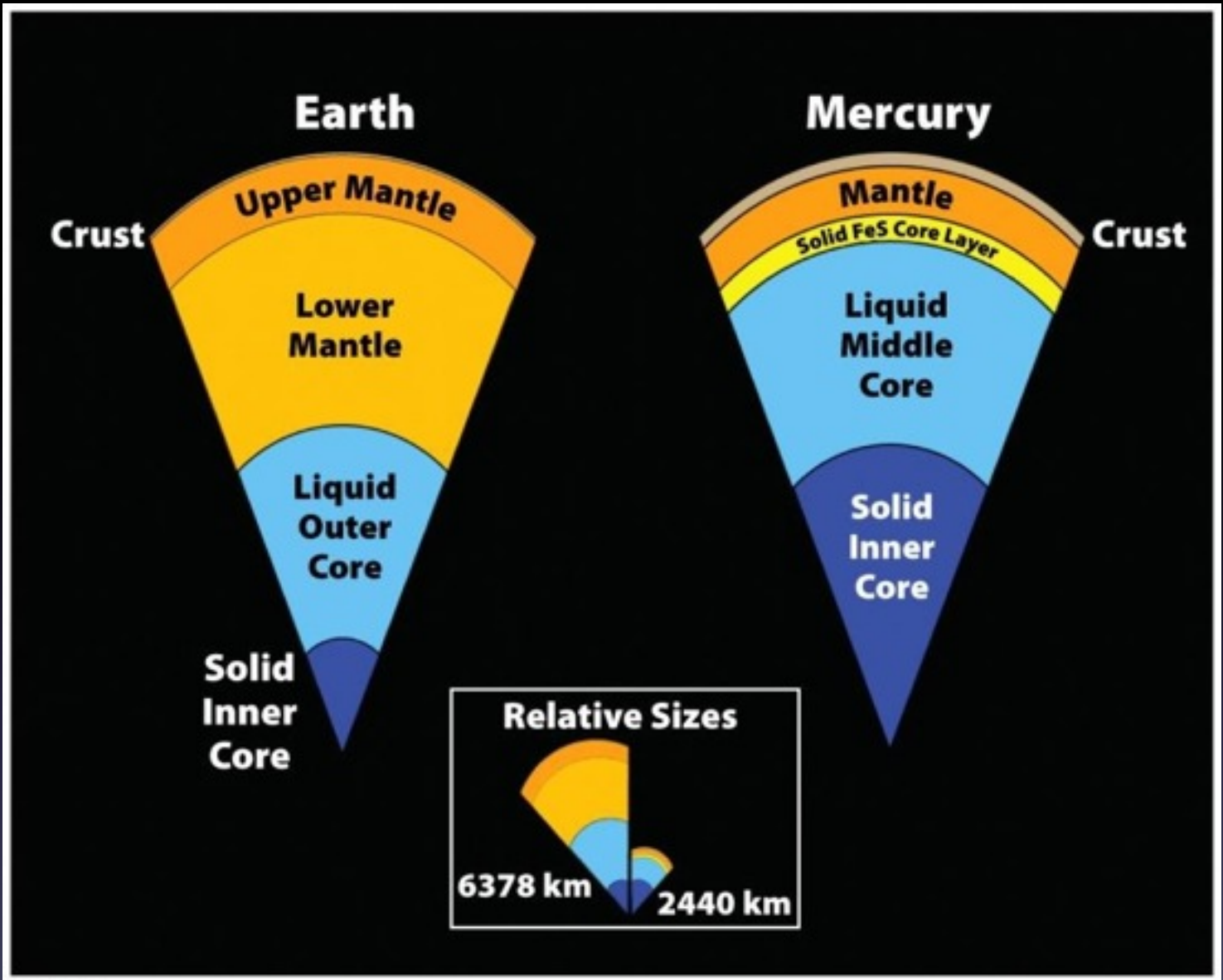
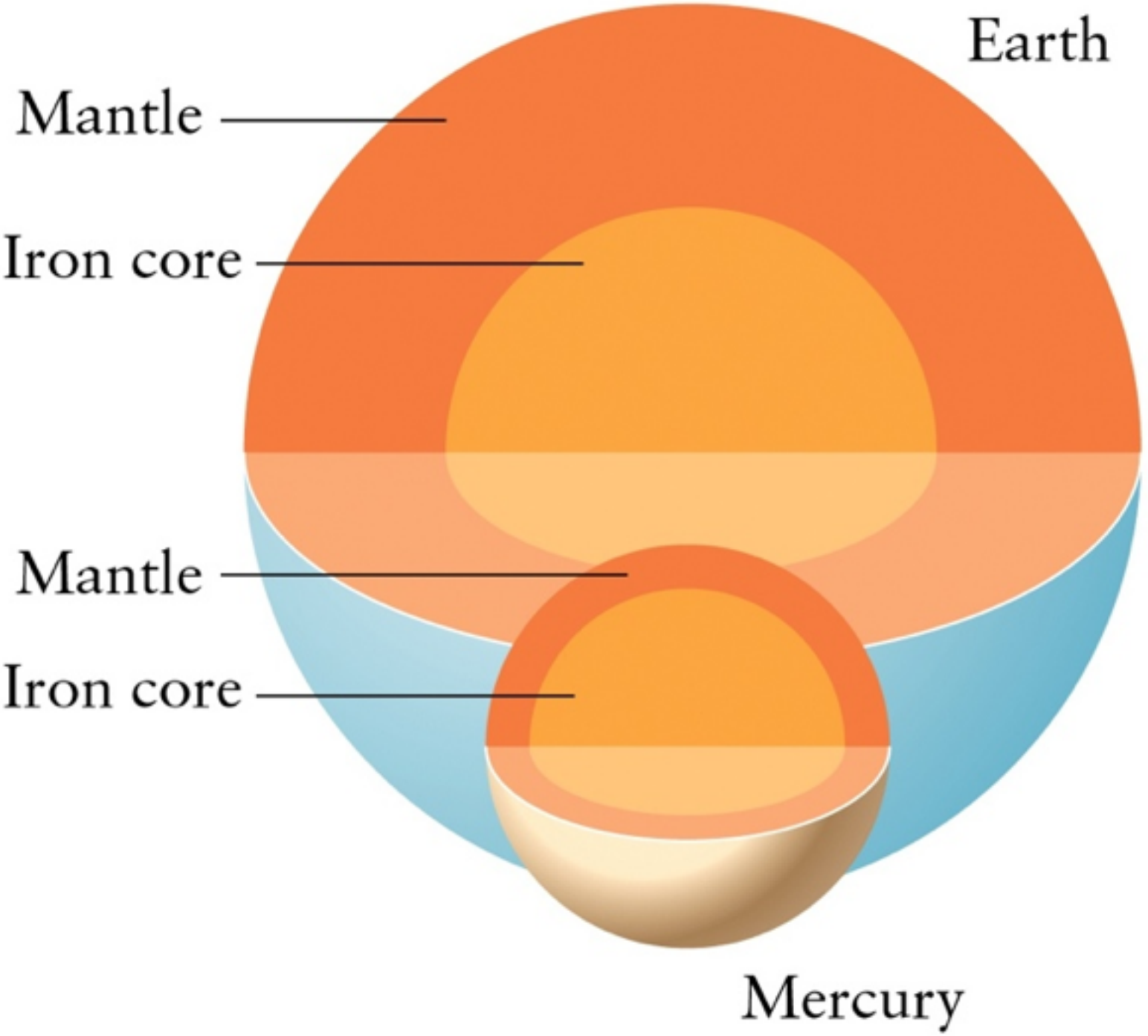


Figure 11-9
Universe, Tenth Edition
NASA

The Internal Structures of Mercury and Earth


Earth
Mantle
Iron core
Mantle
Iron core
Mercury

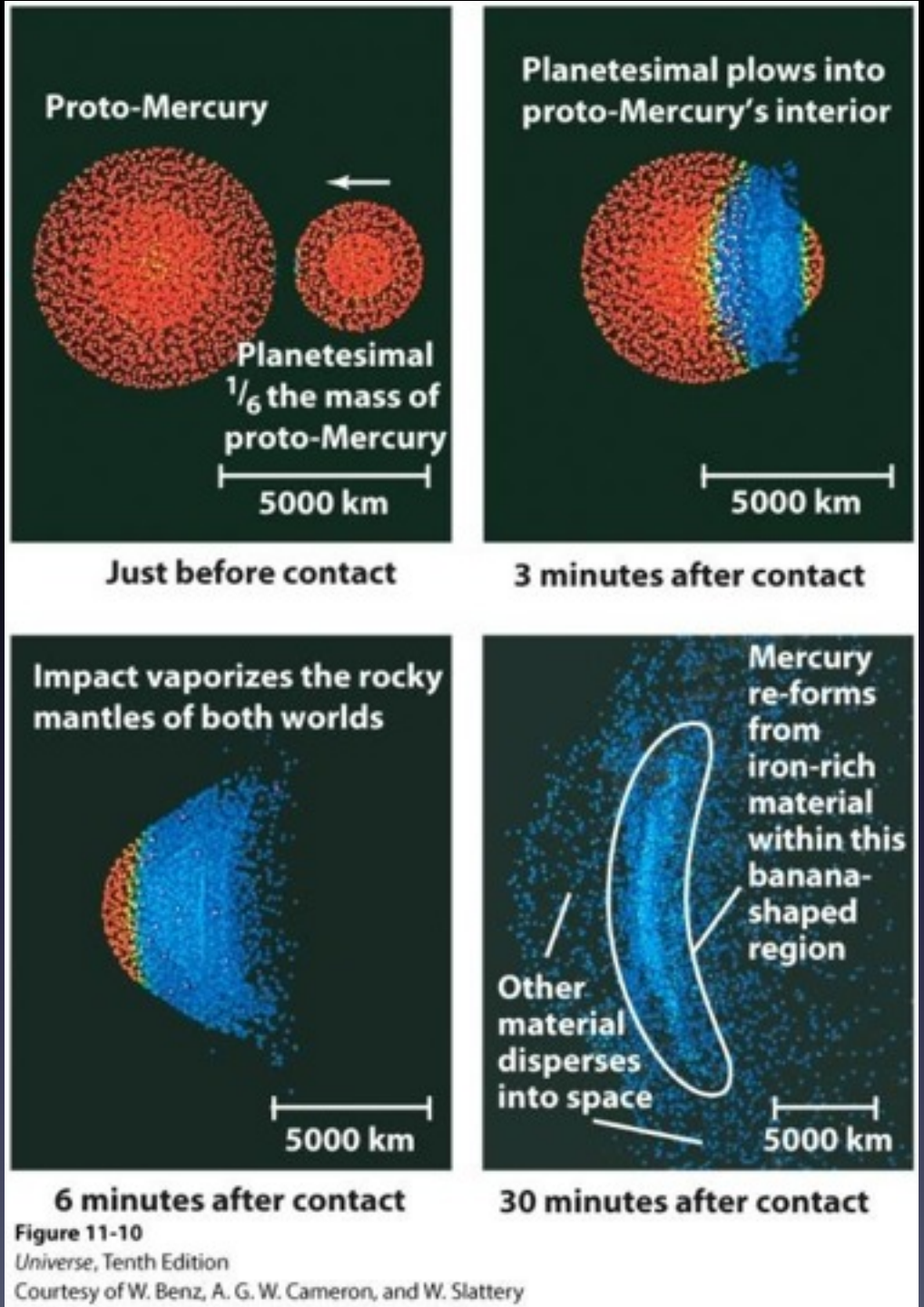
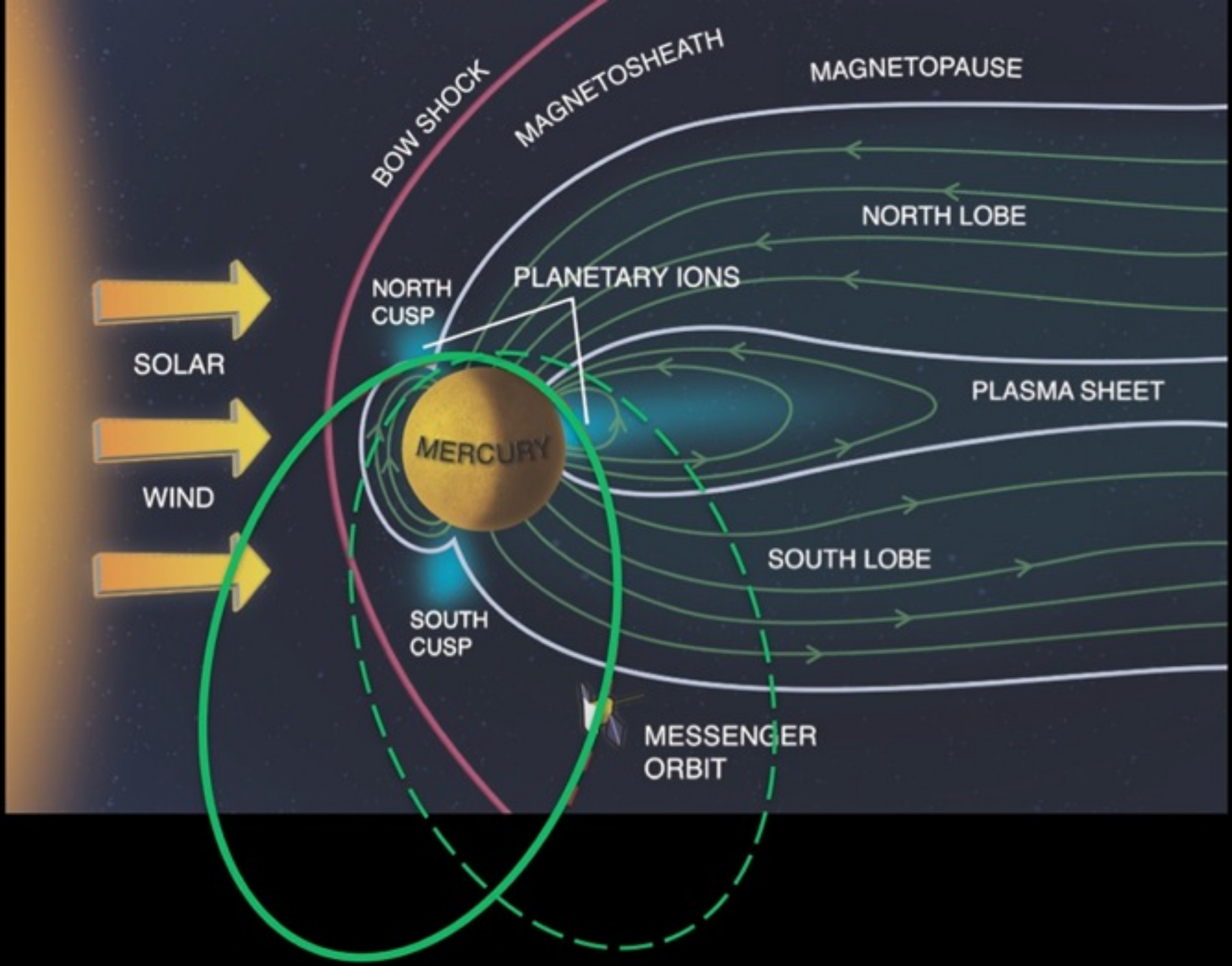


Figure 11-10
Universe, Tenth Edition
Courtesy of W. Benz, A. G. W. Cameron, and W. Slattery

Stripping Mercury's Mantle by a Collision

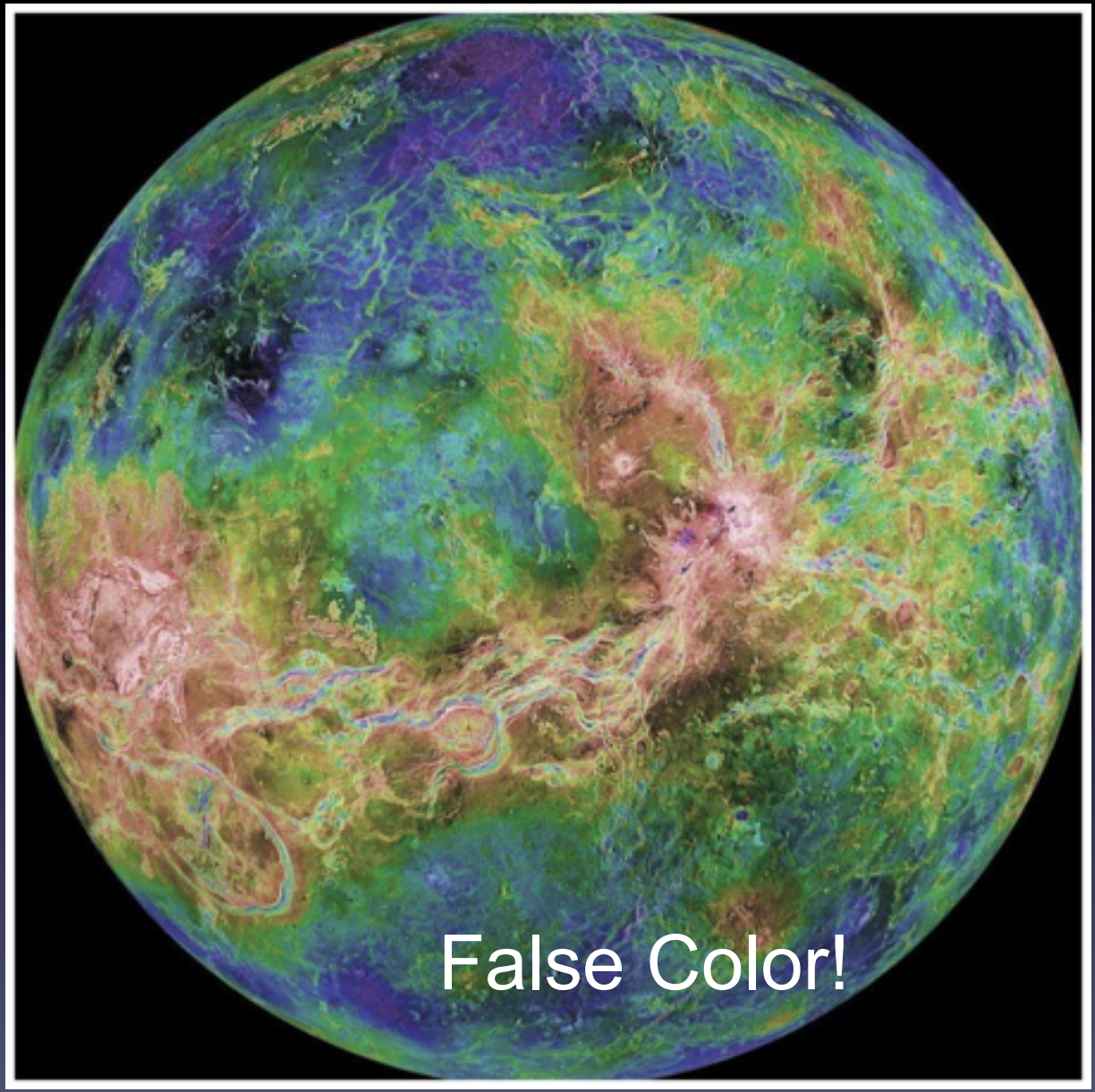

BOW SHOCK
MAGNETOSHEATH
MAGNETOPAUSE
NORTH LOBE
PLANETARY IONS
NORTH CUSP
SOLAR
WIND
MERCURY
PLASMA SHEET
SOUTH LOBE
SOUTH CUSP
MESSENGER ORBIT

11-4: The first missions to Venus and Mars demolished decades of speculations about these planets.

Figure 11-11
Universe, Tenth Edition
GSFC/NASA

The Mariner 2 Spacecraft

Venus: Tropical? (No!)



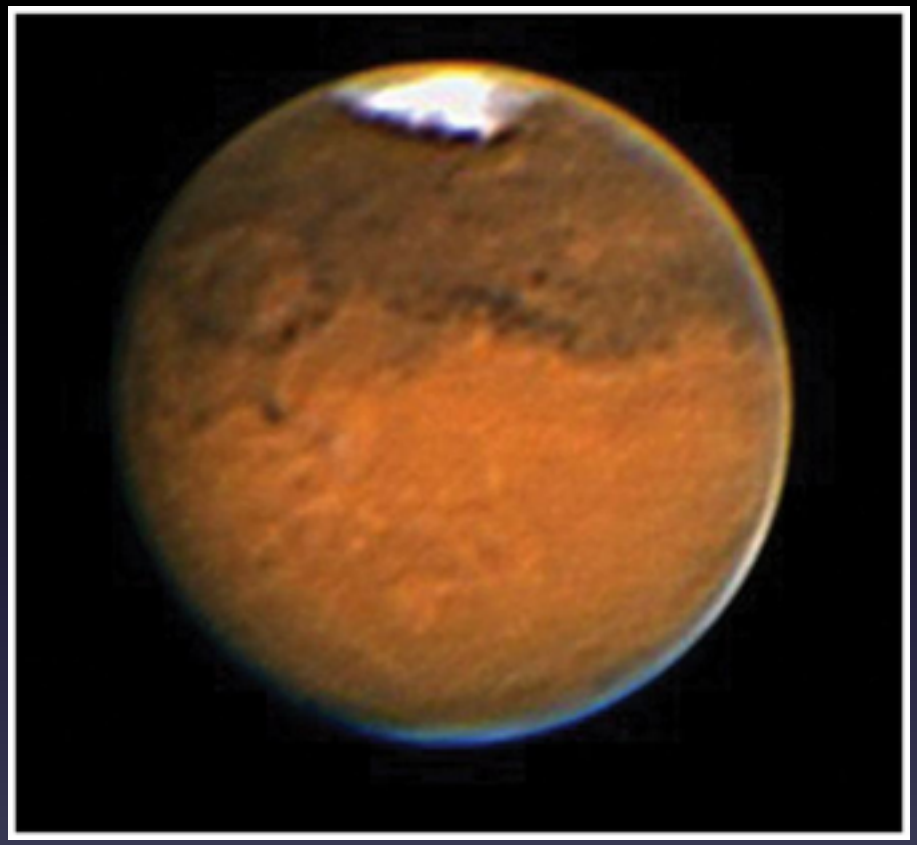


Figure 11-12
Universe, Tenth Edition
©G.V. Schiaparelli

The Mirage of the Martian Canals

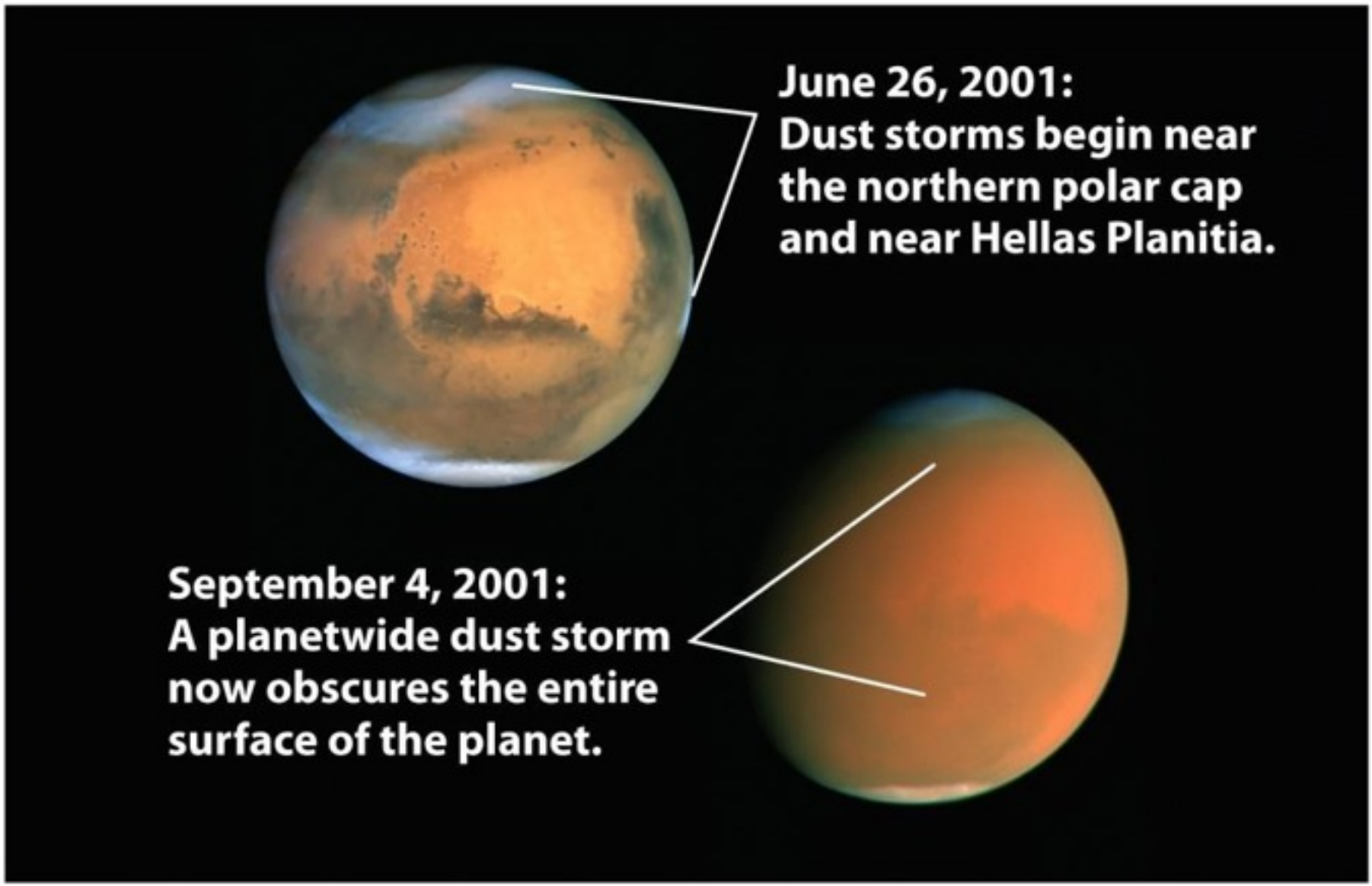
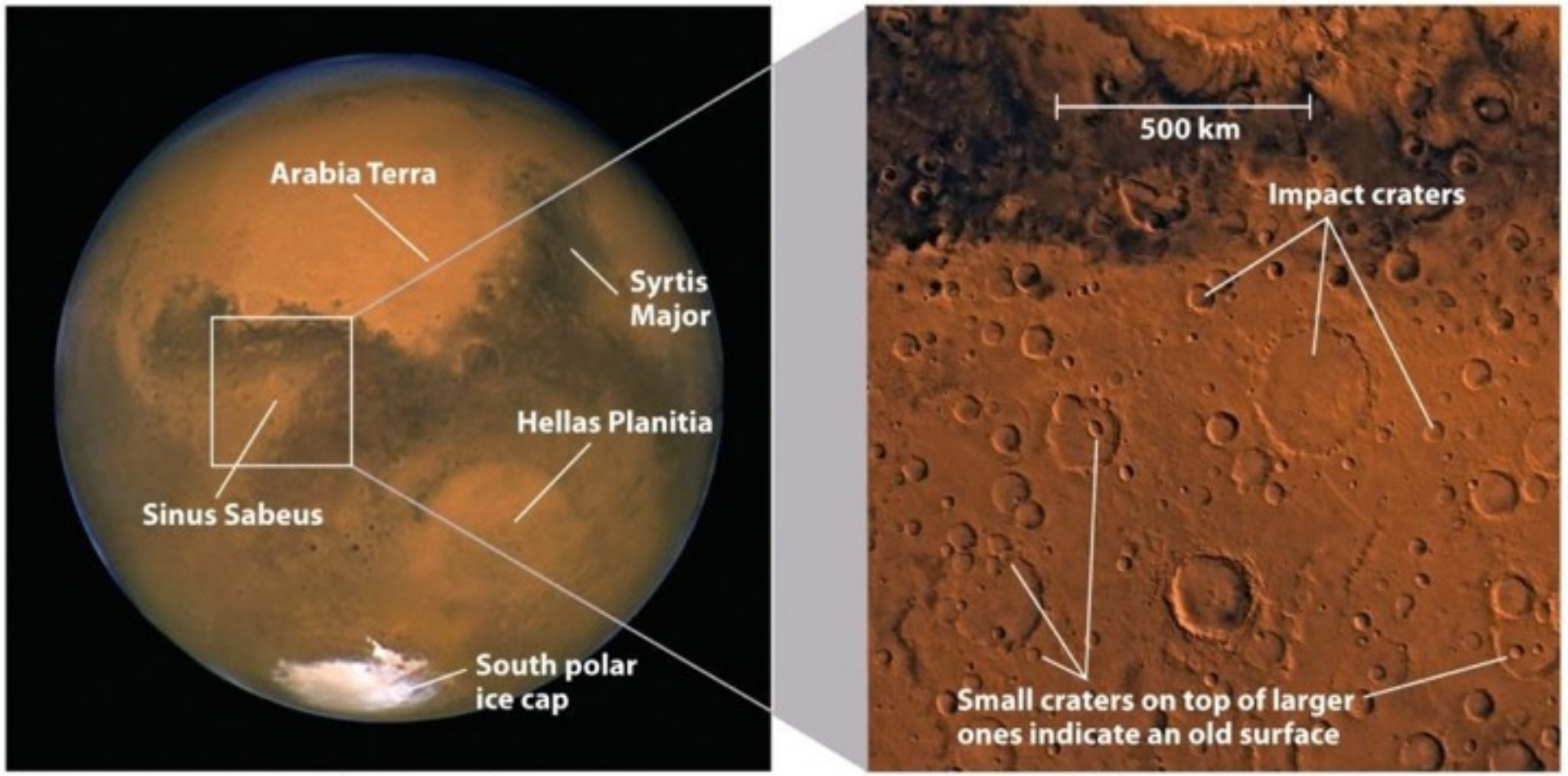


Figure 11-14
Universe, Tenth Edition
NASA; J. Bell, Cornell University; M. Wolff, SSI; and the Hubble Heritage Team, STScI/AURA

A Martian Dust Storm



(a) Mars from the Hubble Space Telescope

(b) Closeup of Sinus Sabeus region

Figure 11-13

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a: NASA; J. Bell, Cornell University; and M. Wolff, SSI; b: USGS

Martian Craters

11-5: Both Venus and Mars have volcanoes – and Mars has signs of ancient plate tectonics.

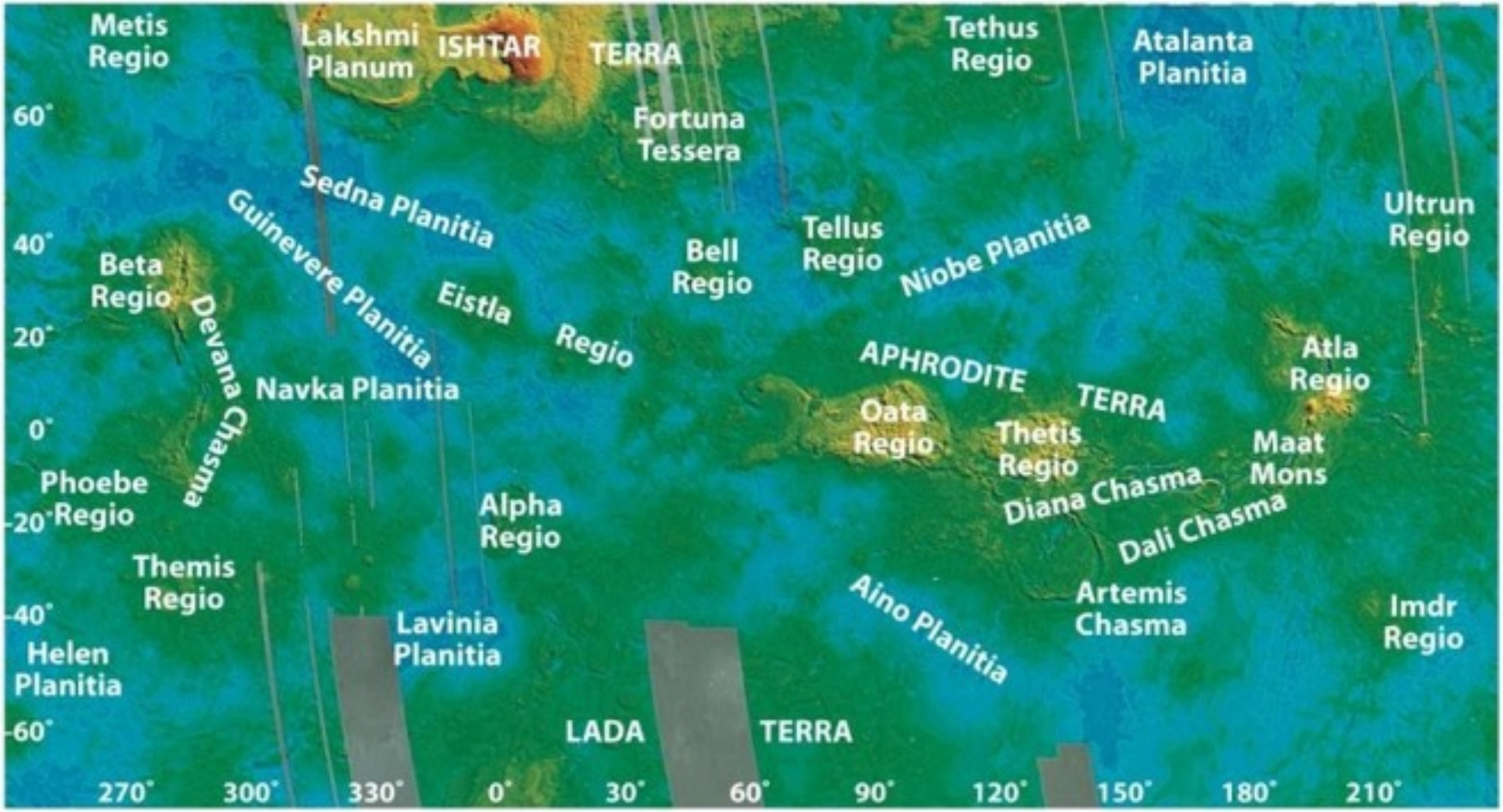


Figure 11-16
Universe, Tenth Edition
Peter Ford, MIT; NASA/JPL

A Topographic Map of Venus

Mars

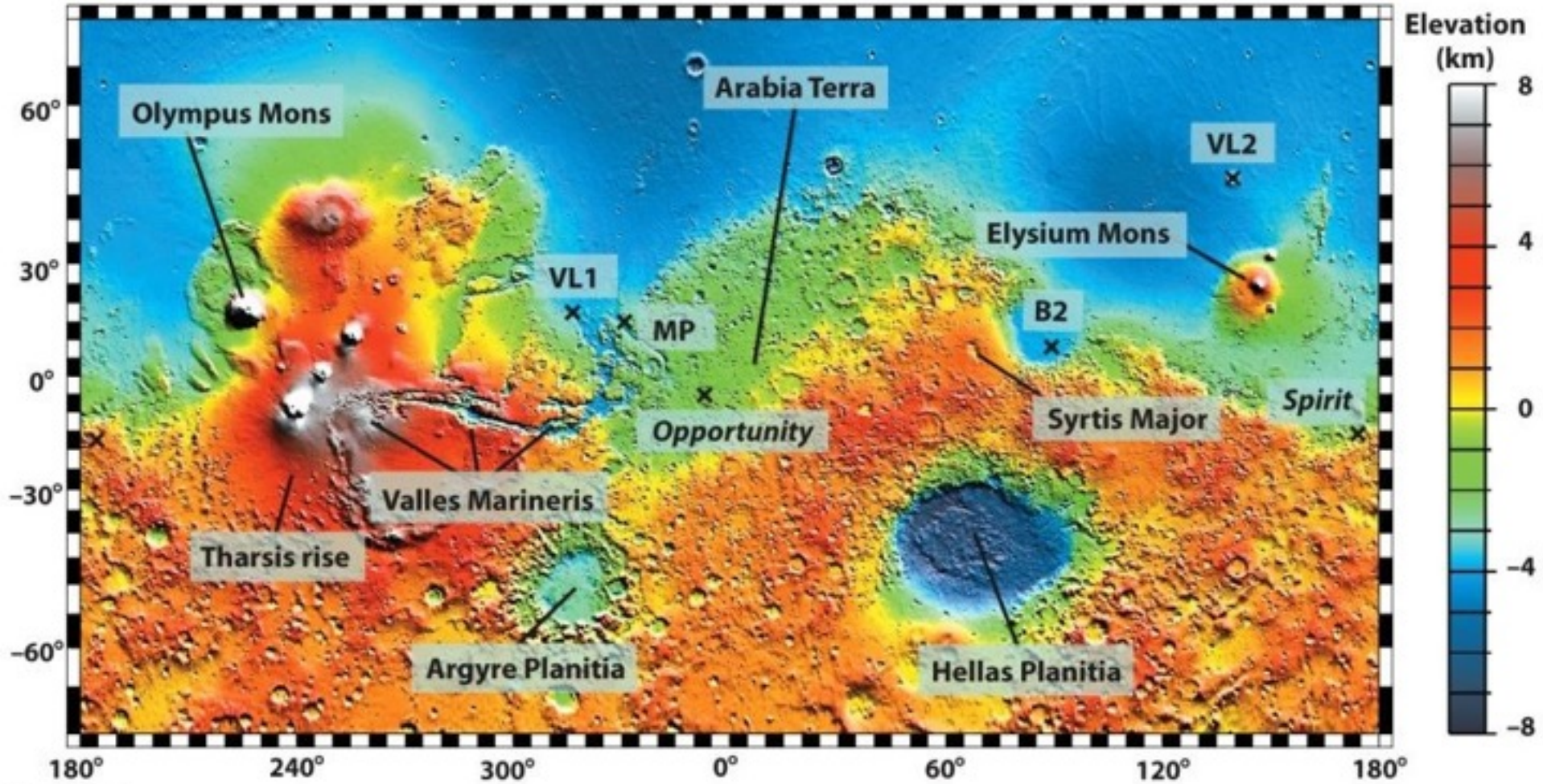


Figure 11-17
Universe, Tenth Edition
MOLA Science Team, NASA/GSFC

A Topographic Map of Mars

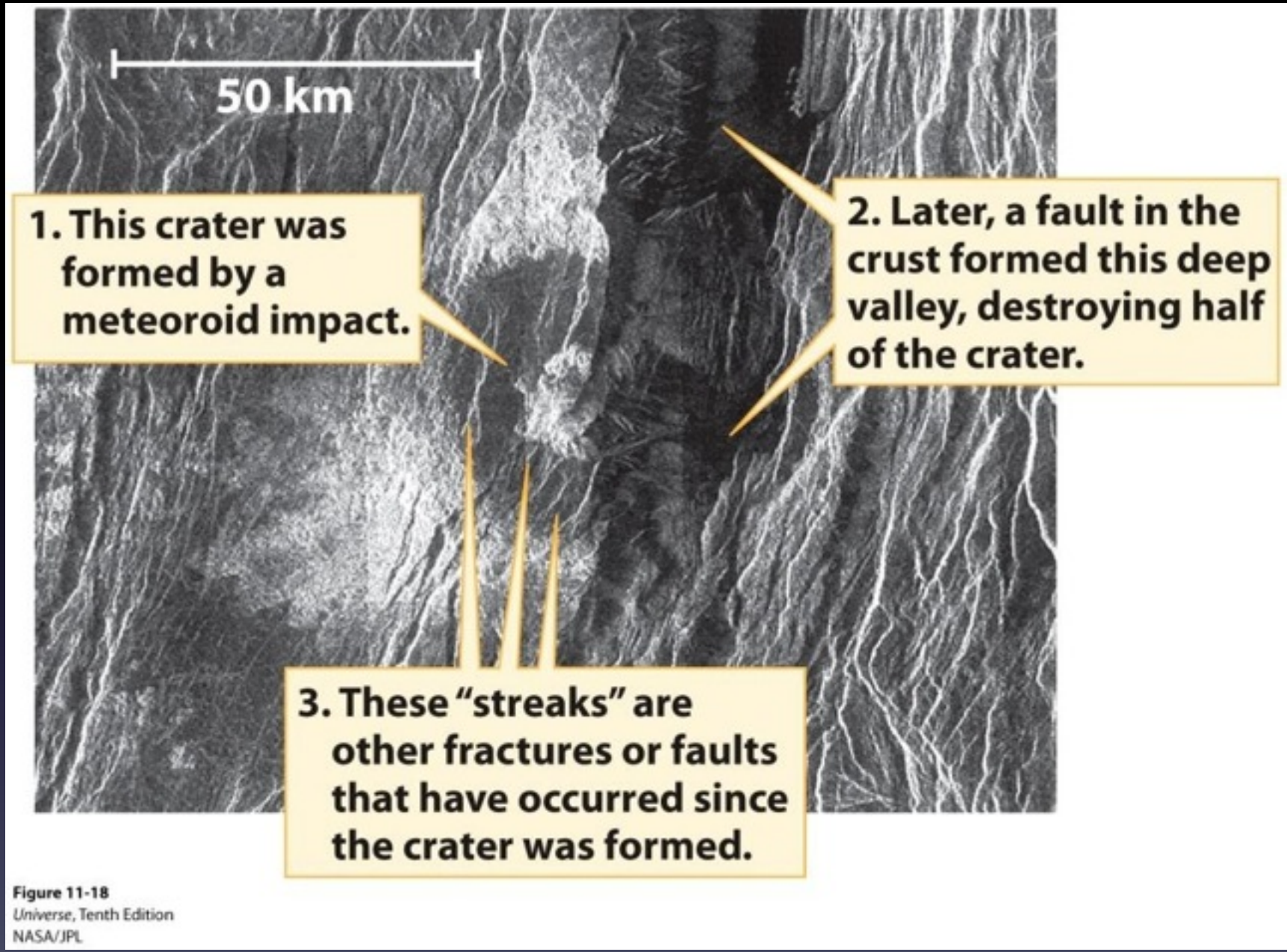


Figure 11-18
Universe, Tenth Edition
NASA/JPL

A Partially Obliterated Crater on Venus

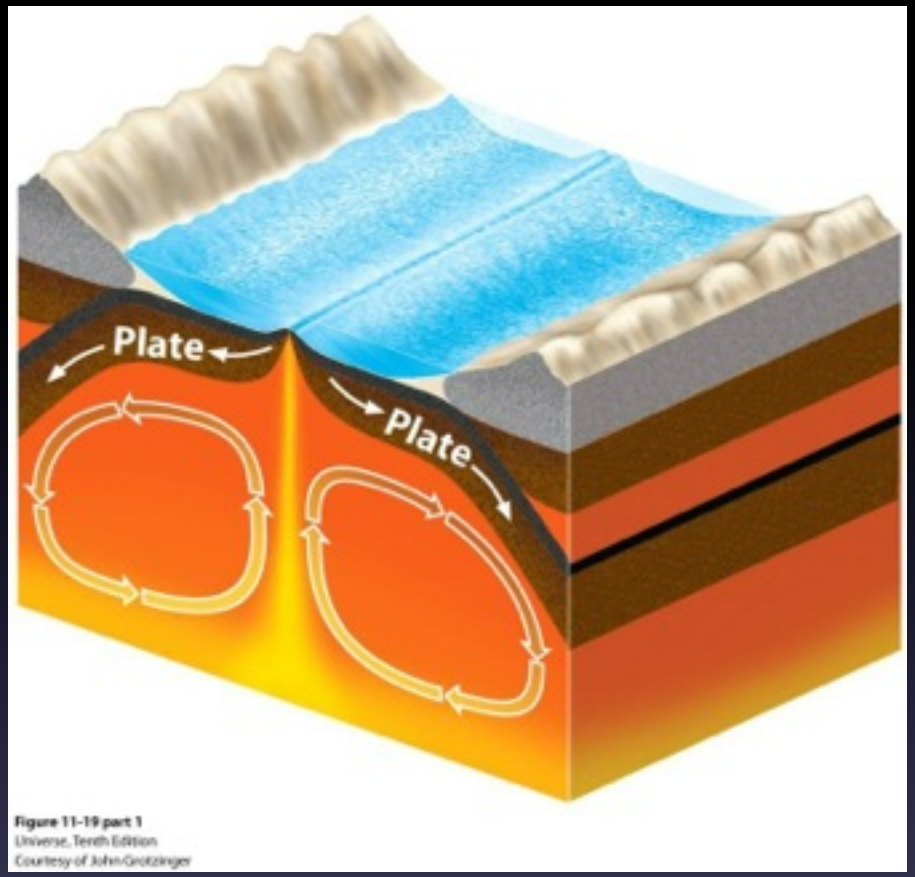


Figure 11-19 part 1
Universe, Tenth Edition
Courtesy of John Grotzinger

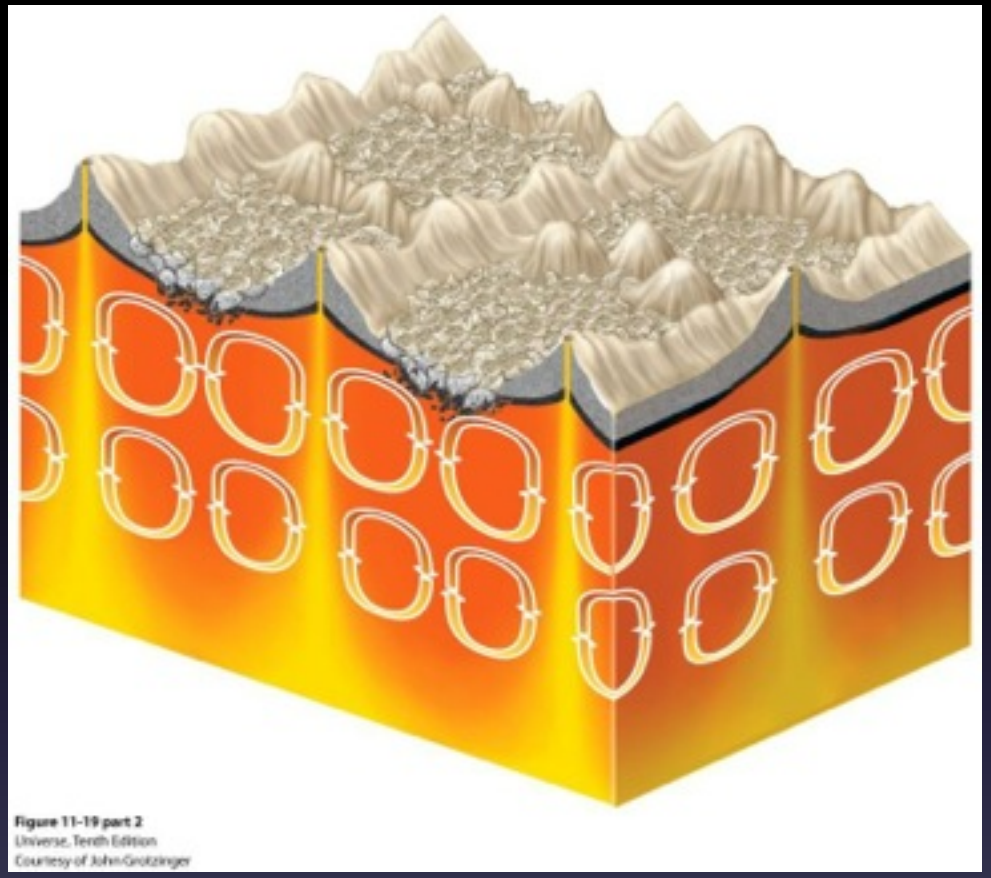


Figure 11-19 part 2
Universe, Tenth Edition
Courtesy of John Grotzinger

Plate Tectonics Versus Flake Tectonics

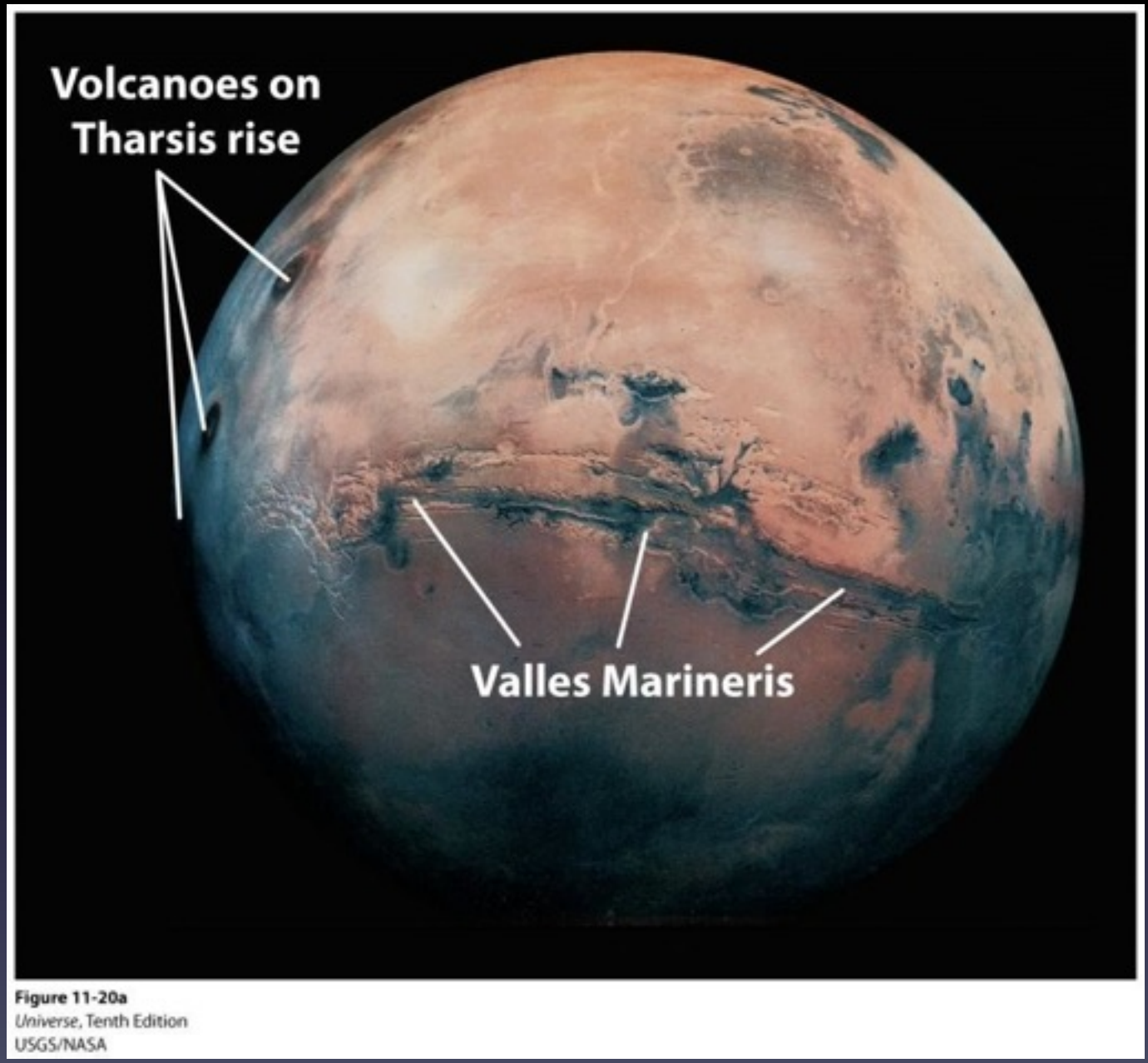
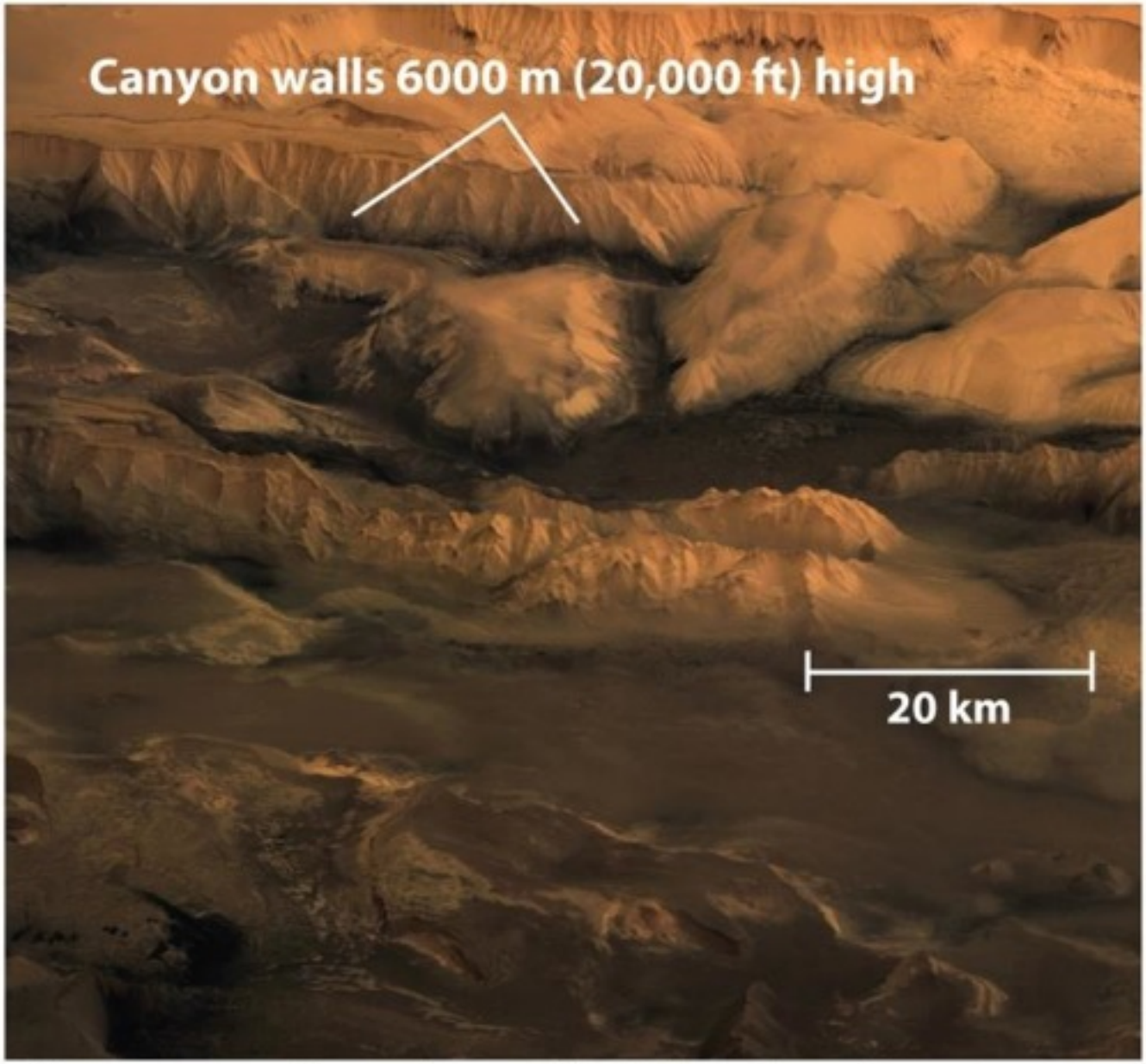


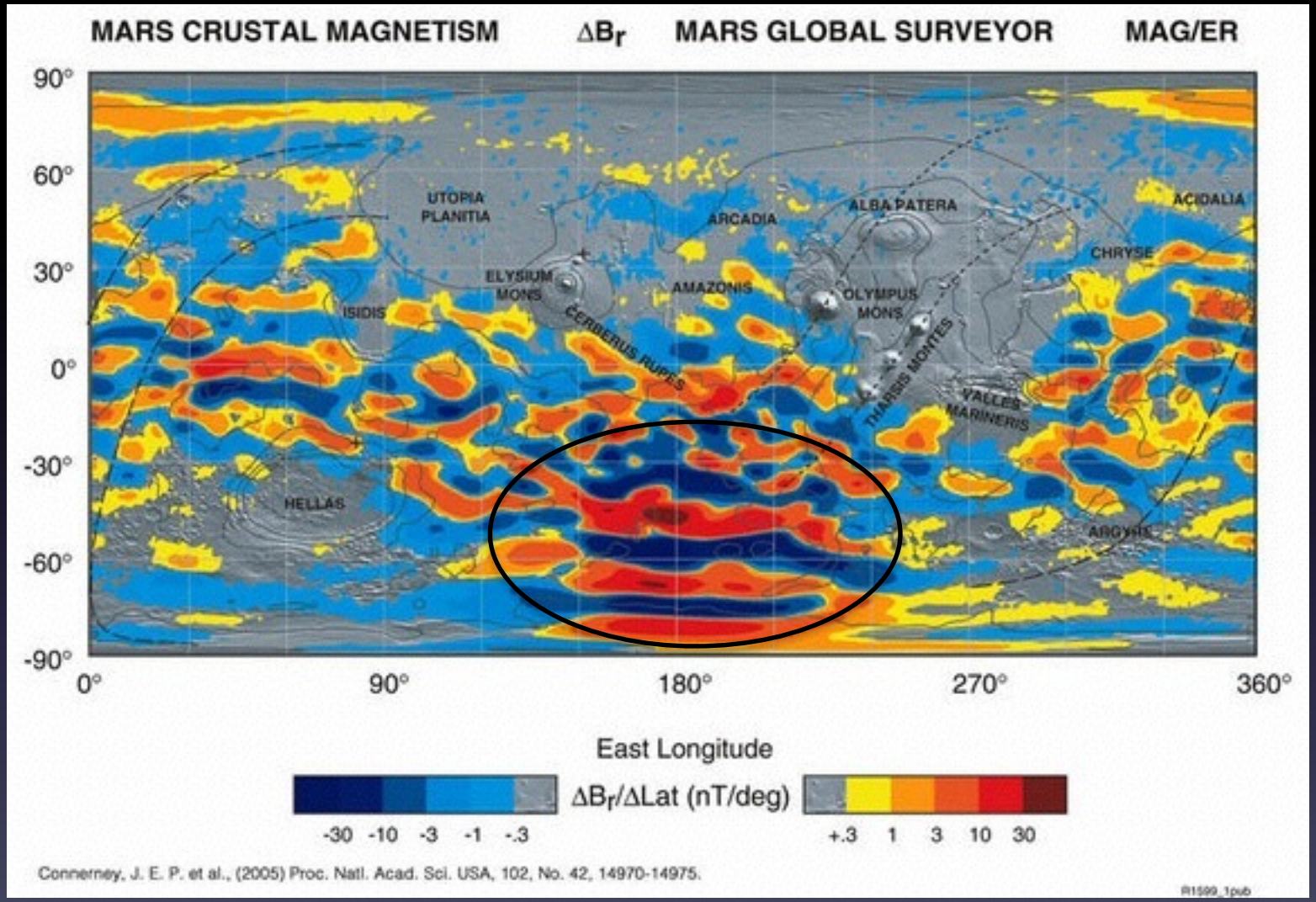
Figure 11-20a
Universe, Tenth Edition
USGS/NASA

Mars and Valles Marineris



The central region of Valles Marineris

Figure 11-20b
Universe, Tenth Edition
ESA/DLR/FU Berlin, G. Neukum


MARS CRUSTAL MAGNETISM
ΔBr
MARS GLOBAL SURVEYOR
MAG/ER
90°
60°
30°
0°
-30°
-60°
-90°
0°
90°
180°
270°
360°
UTOPIA PLANITIA
ARCADIA
ALBA PATERA
ACIDALIA
CHRYSE
ELYSIUM MONS
AMAZONIS
OLYMPUS MONS
ISIDIS
CERBERUS RUPES
THARSIS MONTES
VALLES MARINERIS
HELLAS
ARGYRE
East Longitude
ΔBr/ΔLat (nT/deg)
-30 -10 -3 -1 -.3
+.3 1 3 10 30
Connerney, J. E. P. et al., (2005) Proc. Natl. Acad. Sci. USA, 102, No. 42, 14970-14975.

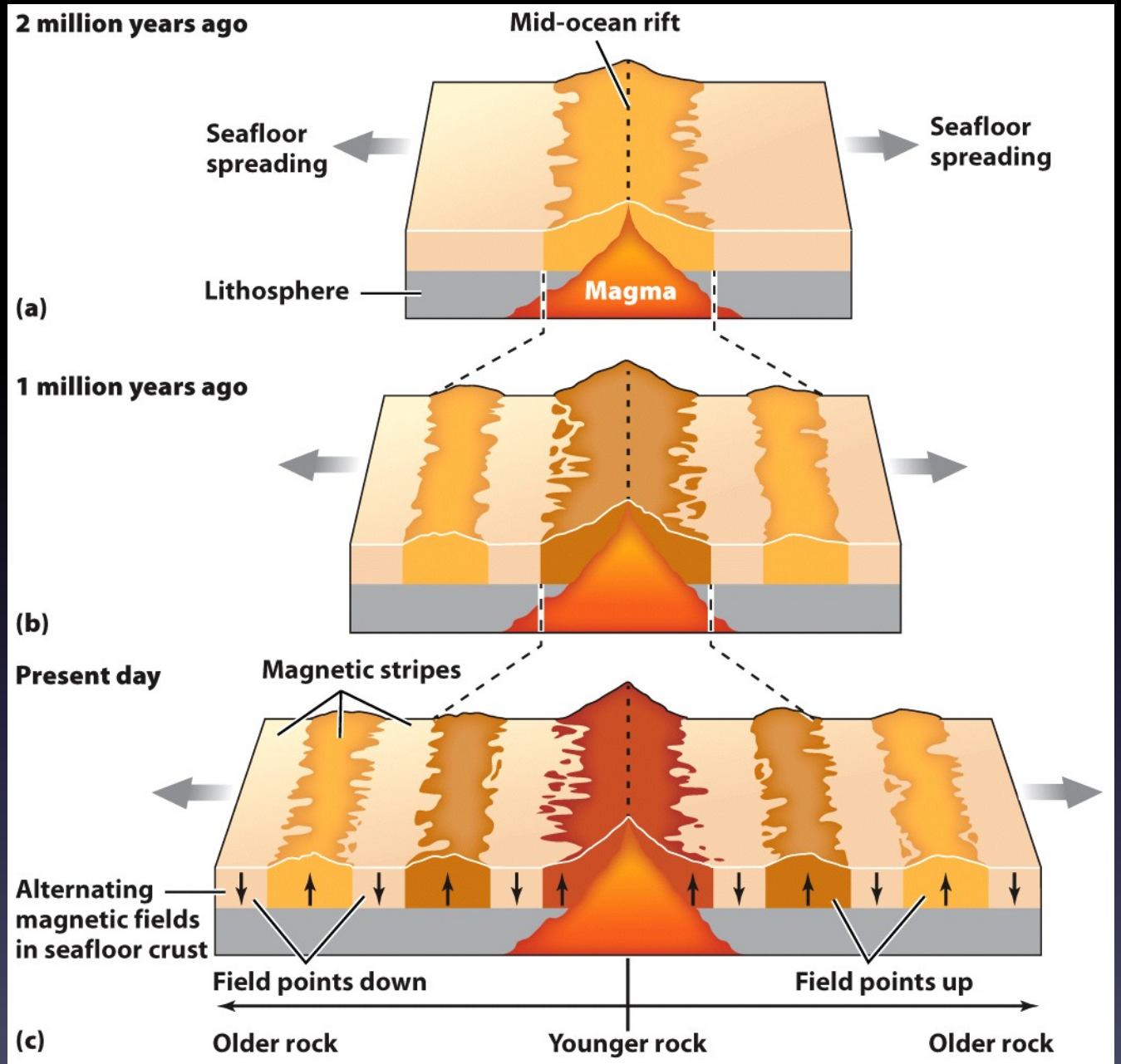


Figure 9-22
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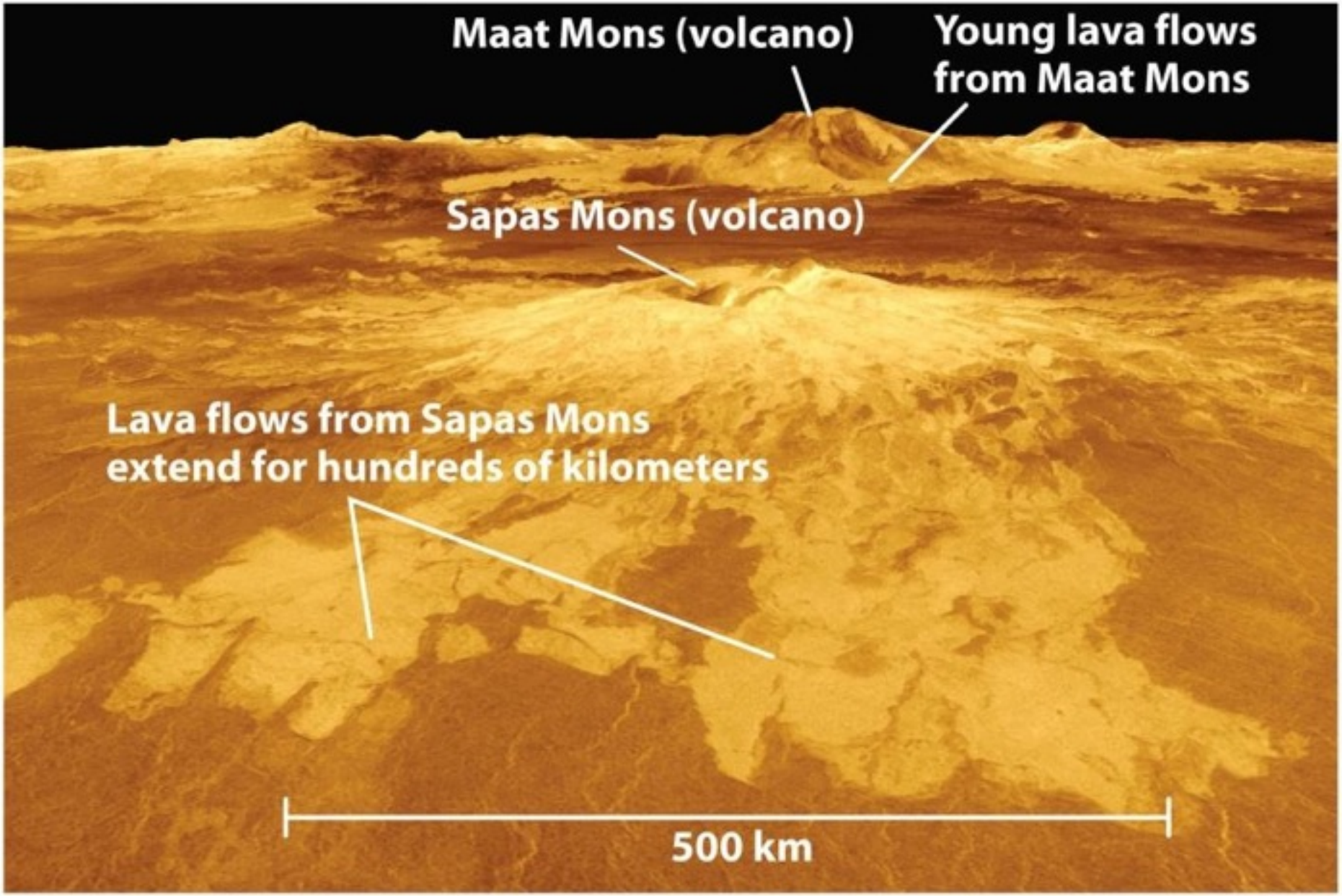
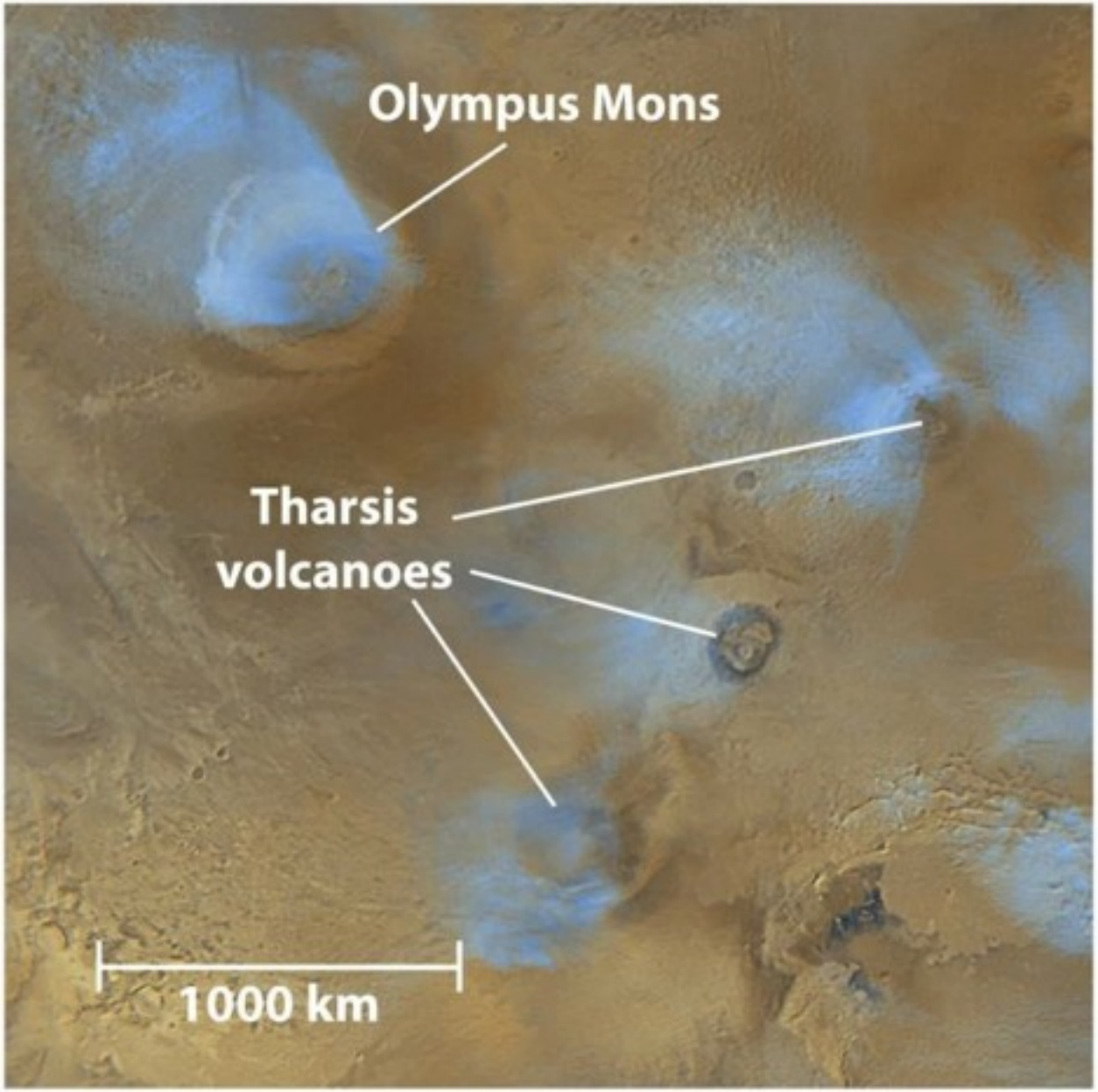


Volcanoes and lava flows on Venus

Figure 11-21a
Universe, Tenth Edition
NASA, JPL Multimission Image Processing Laboratory

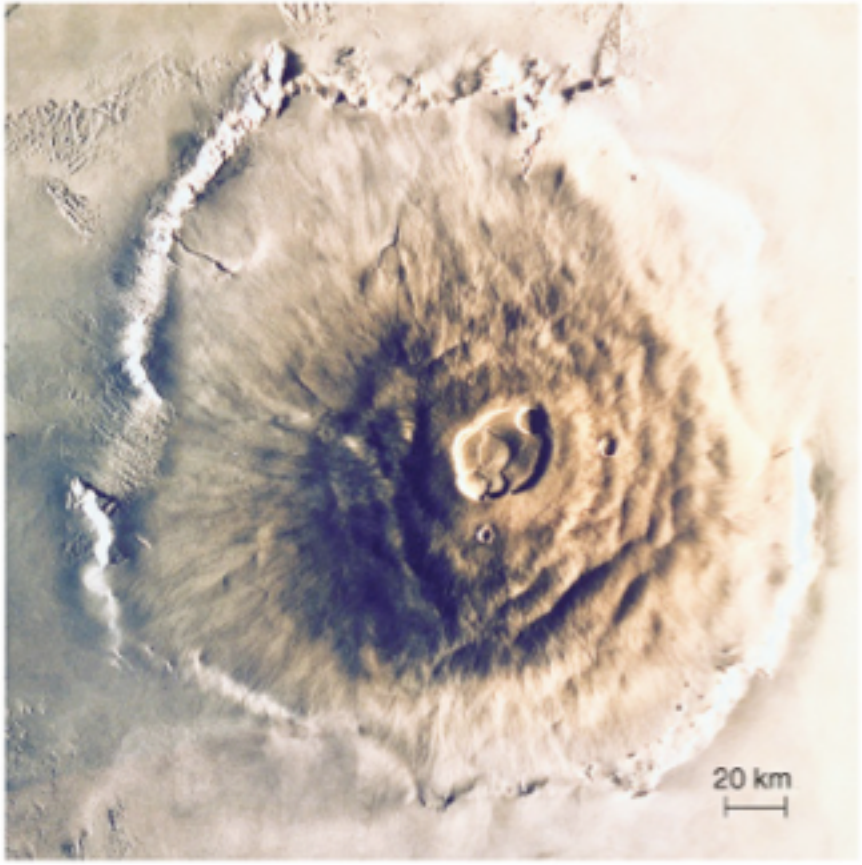


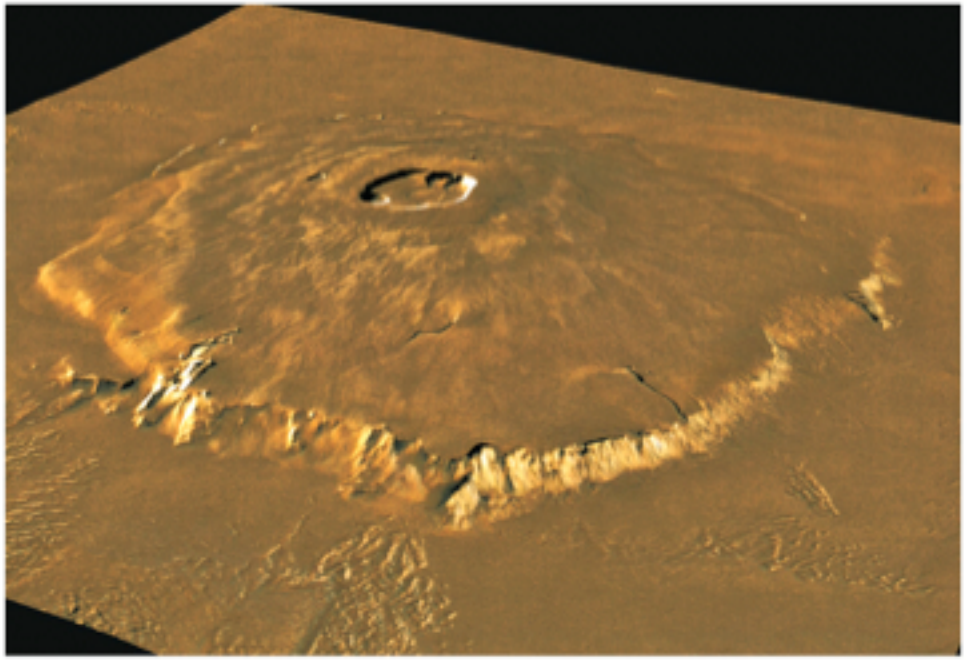
Cloud-topped volcanoes on Mars

Figure 11-21b
Universe, Tenth Edition
NASA/JPL/Malin Space Science Systems

Volcanism on Mars

- Mars has many large shield volcanoes
- Olympus Mons is largest volcano in solar system





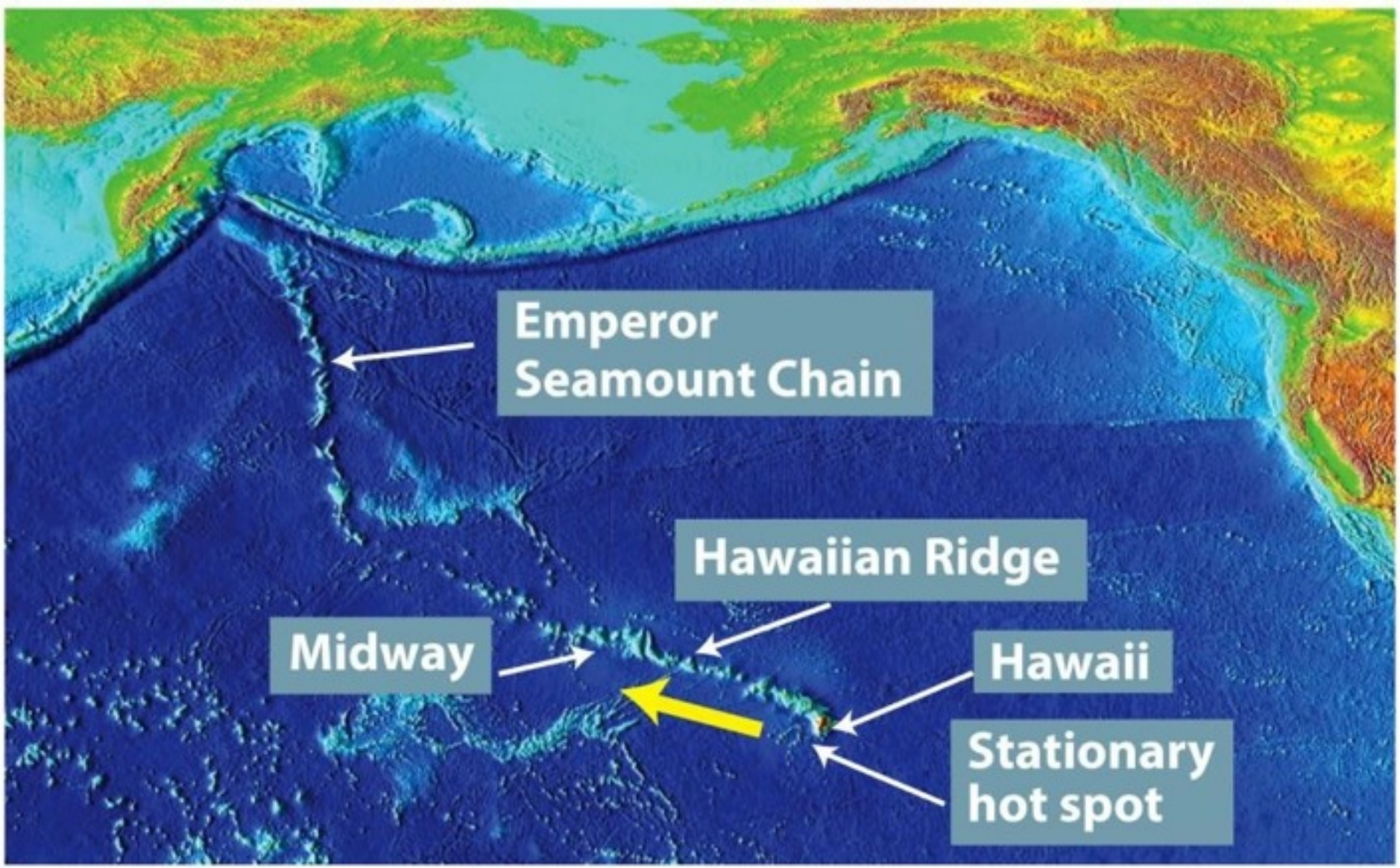
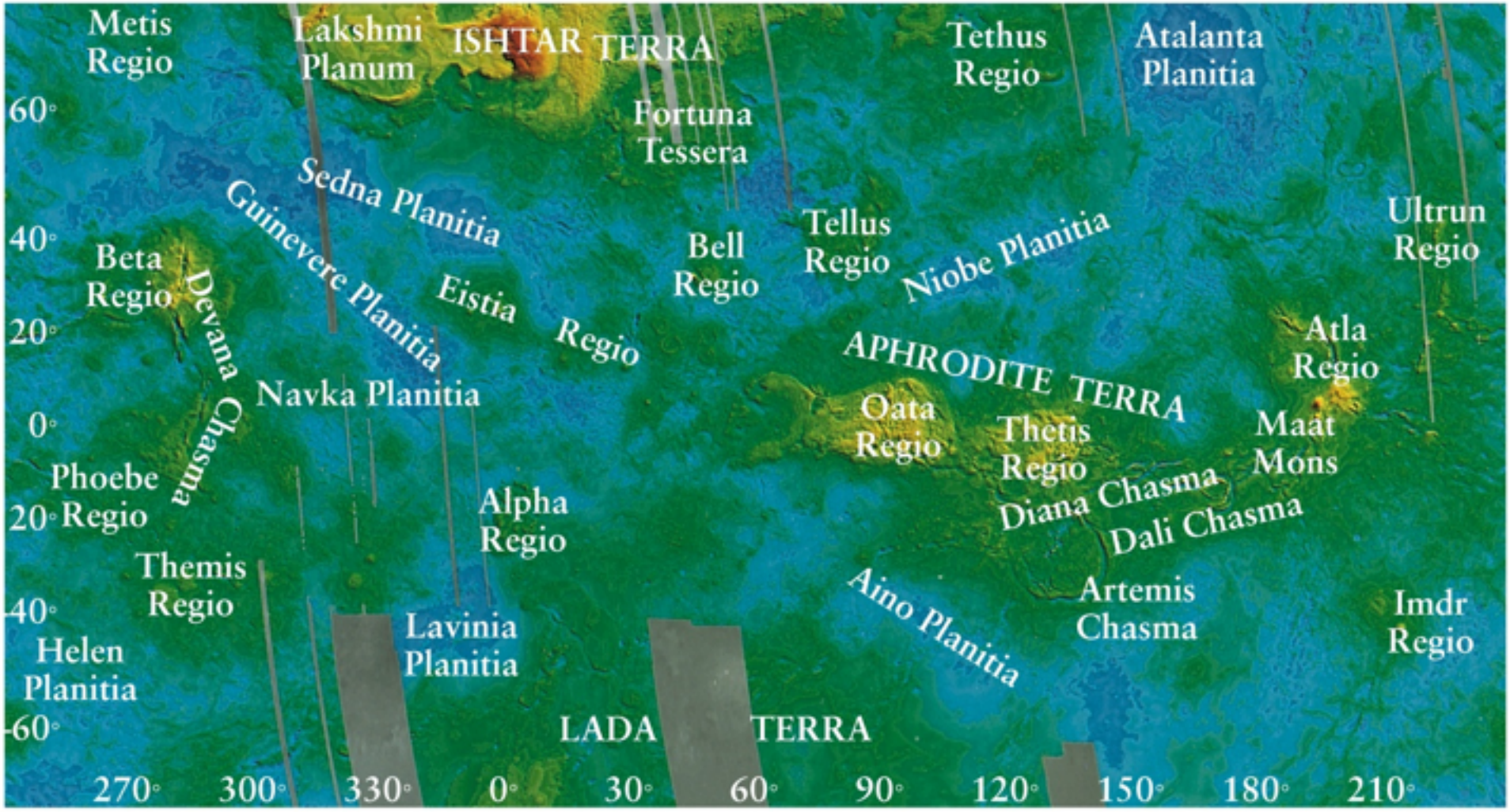


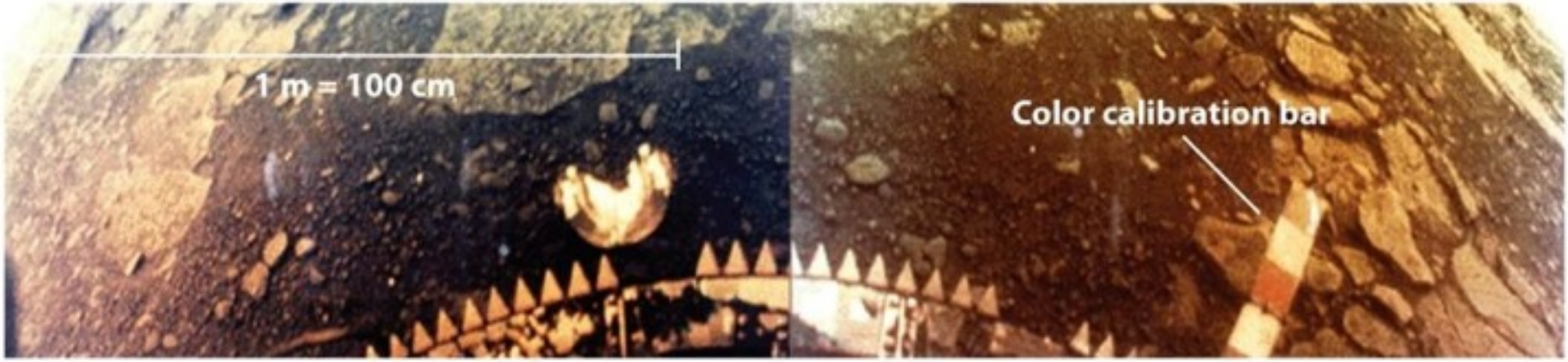
Figure 11-22
Universe, Tenth Edition
World Ocean Floor, based on bathymetric studies by Bruce C. Heezen and Marie Tharp. Painting by Heinrich C. Berann. Copyright Marie Tharp, 1977

Hot-Spot Volcanoes on Earth

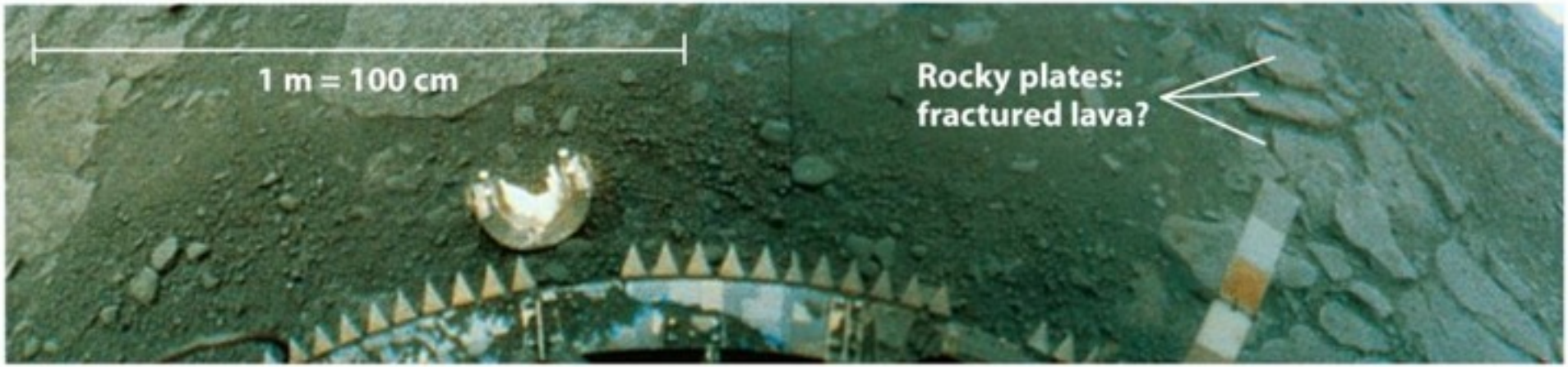
Venus is mostly flat plains



Volcanic lava surface



(a) Image from *Venera 13*

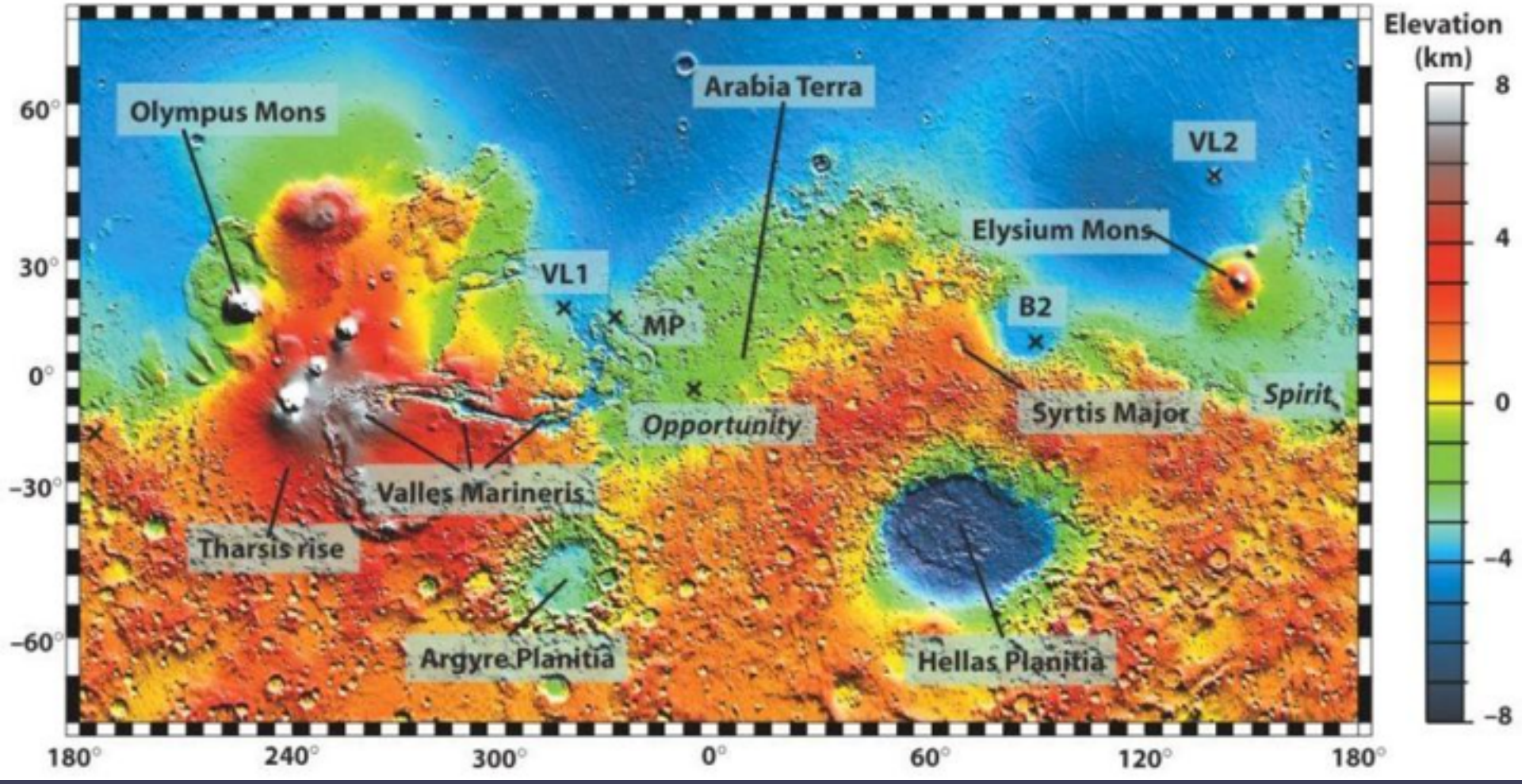


(b) Color-corrected image

Figure 11-23
Universe, Tenth Edition
a: NSSDC/NASA; b: GSFC/NASA

A Venusian Landscape

Mars


Olympus Mons
Arabia Terra
VL2
Elysium Mons
VL1
MP
B2
Opportunity
Syrtis Major
Spirit
Valles Marineris
Tharsis rise
Argyre Planitia
Hellas Planitia
60°
30°
0°
-30°
-60°
180°
240°
300°
0°
60°
120°
180°
Elevation (km)
8
4
0
-4
-8

11-6: The dense atmosphere of Venus and the thin Martian atmosphere are dramatically different but have similar chemical compositions.

Table 8-3 Chemical Compositions of Three Planetary Atmospheres

	Venus	Earth	Mars
Nitrogen (N_2)	3.5%	78.08%	2.7%
Oxygen (O_2)	almost zero	20.95%	almost zero
Carbon dioxide (CO_2)	96.5%	0.035%	95.3%
Water vapor (H_2O)	0.003%	about 1%	0.03%
Other gases	almost zero	almost zero	2%

Atmospheres of the Terrestrial Planets

Venus has a strong greenhouse effect

Table 8-3 Chemical Compositions of Three Planetary Atmospheres

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Other gases	almost zero	almost zero	2%

Earth **Venus** Mars

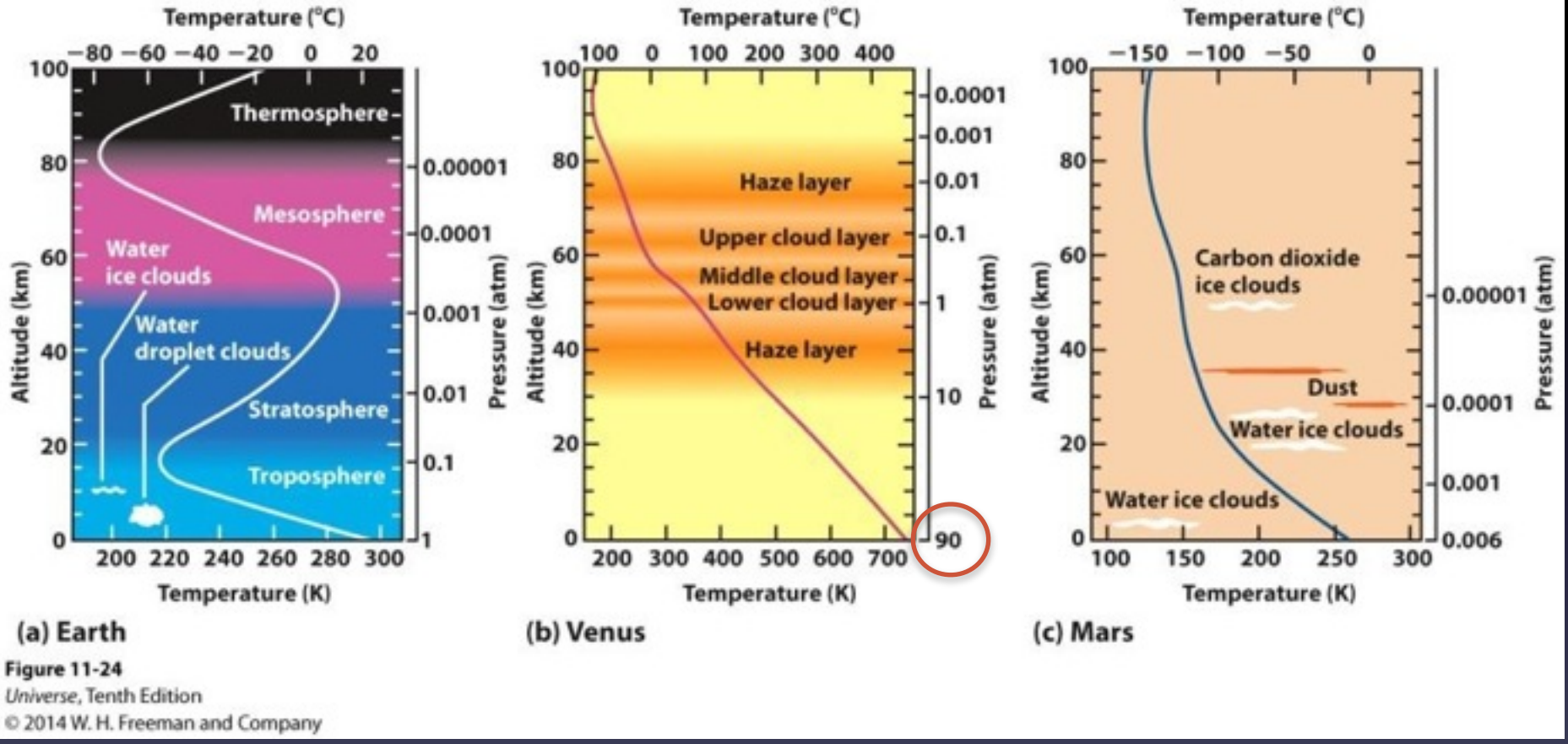
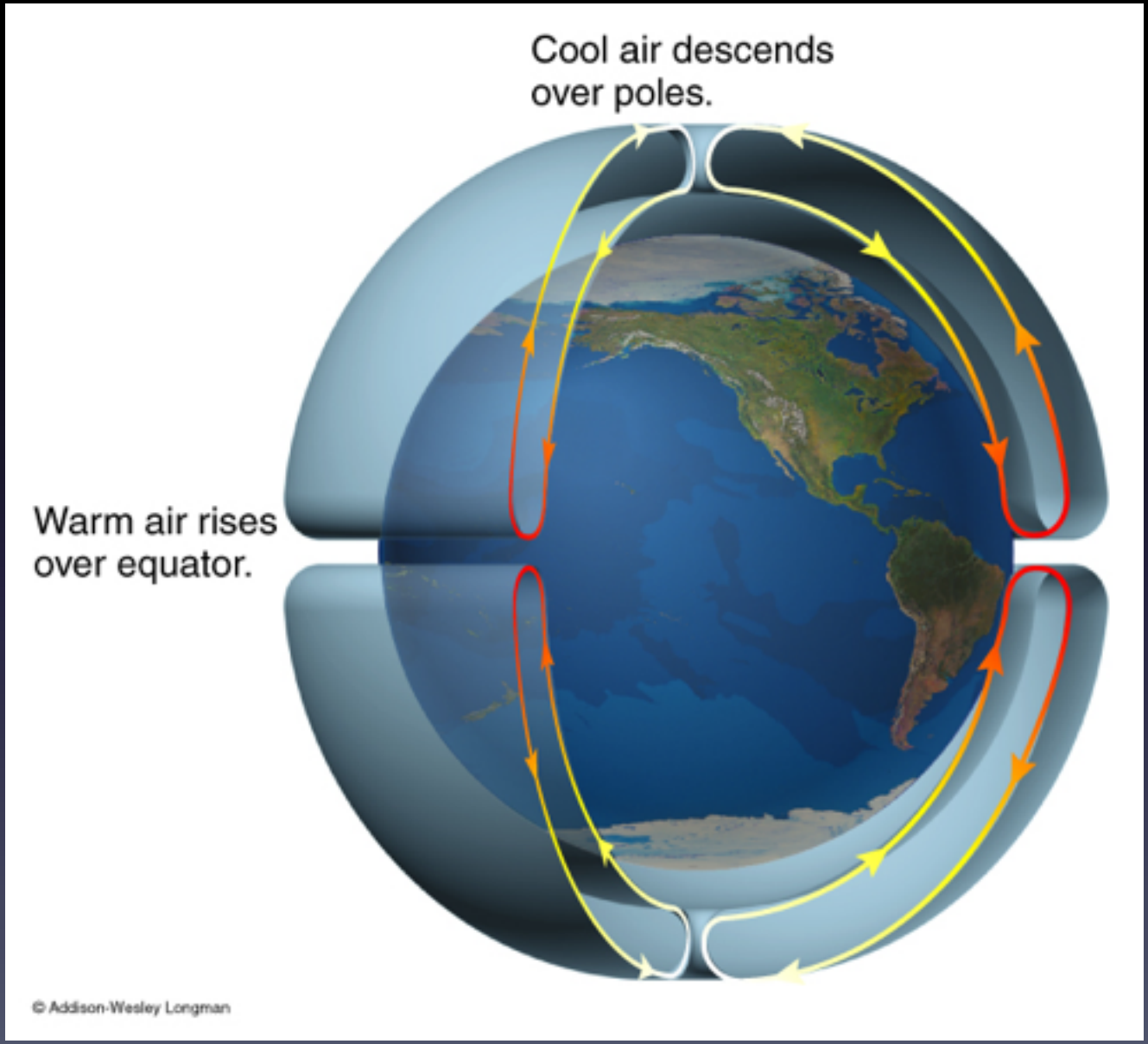
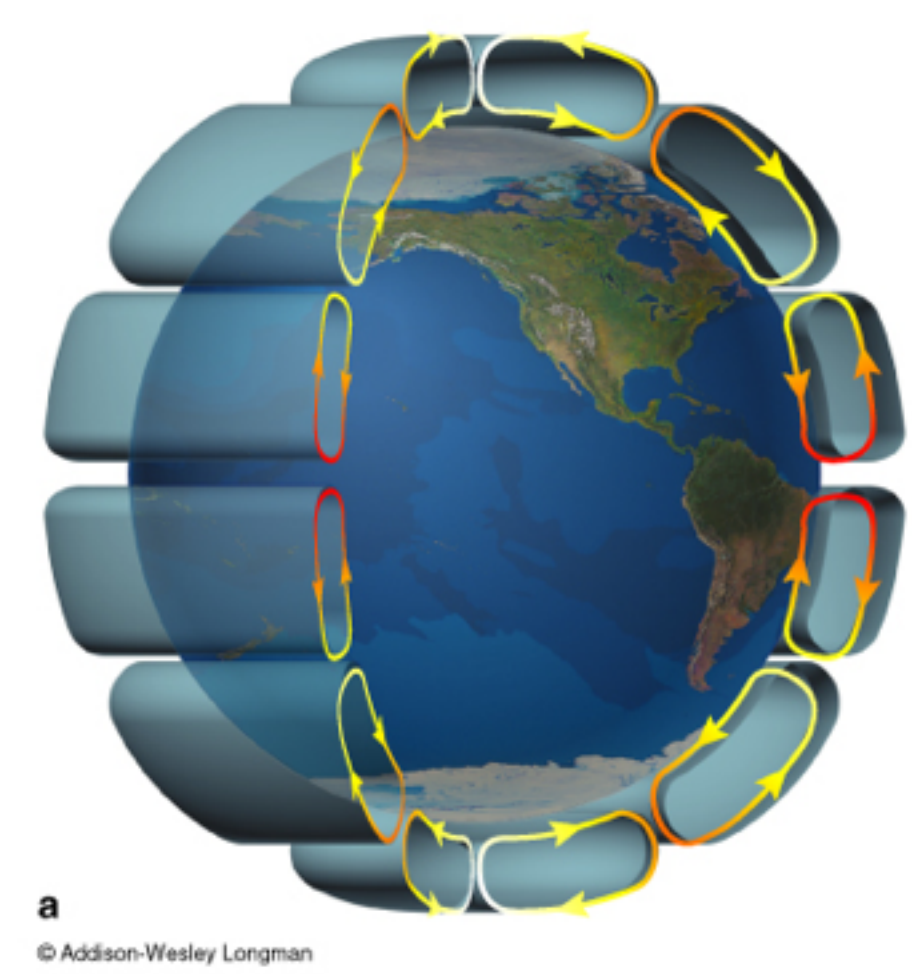


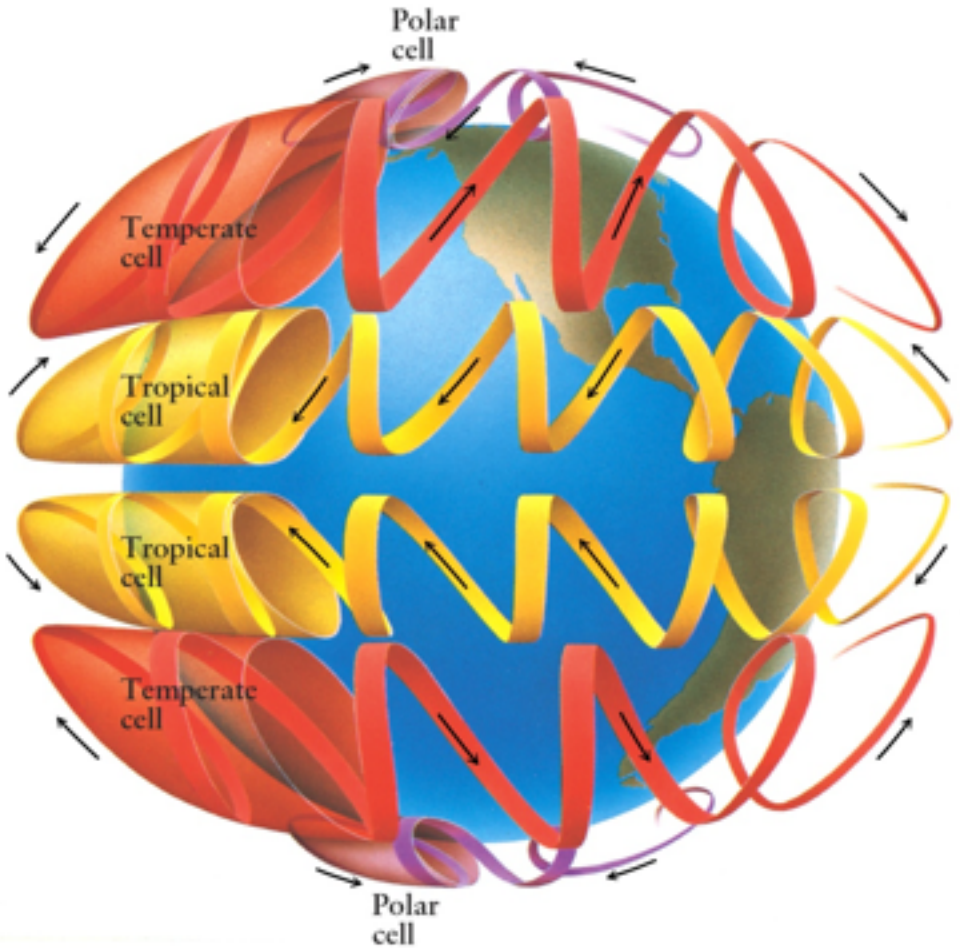
Figure 11-24
Universe, Tenth Edition

Convection on Venus



Convection on Earth





Fast winds on Venus: Atmosphere rotates around planet in 4 days

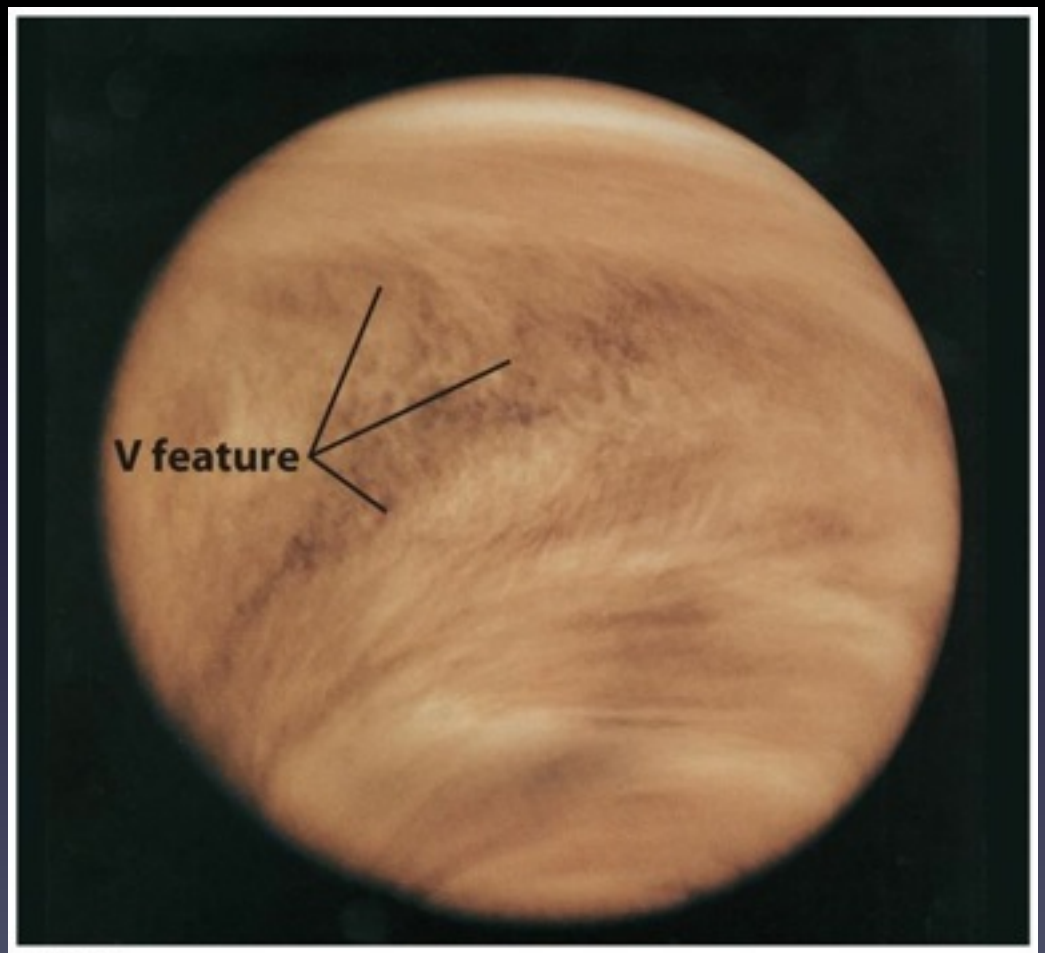


Figure 11-26
Universe, Tenth Edition
GSFC/NASA

Earth Venus **Mars**

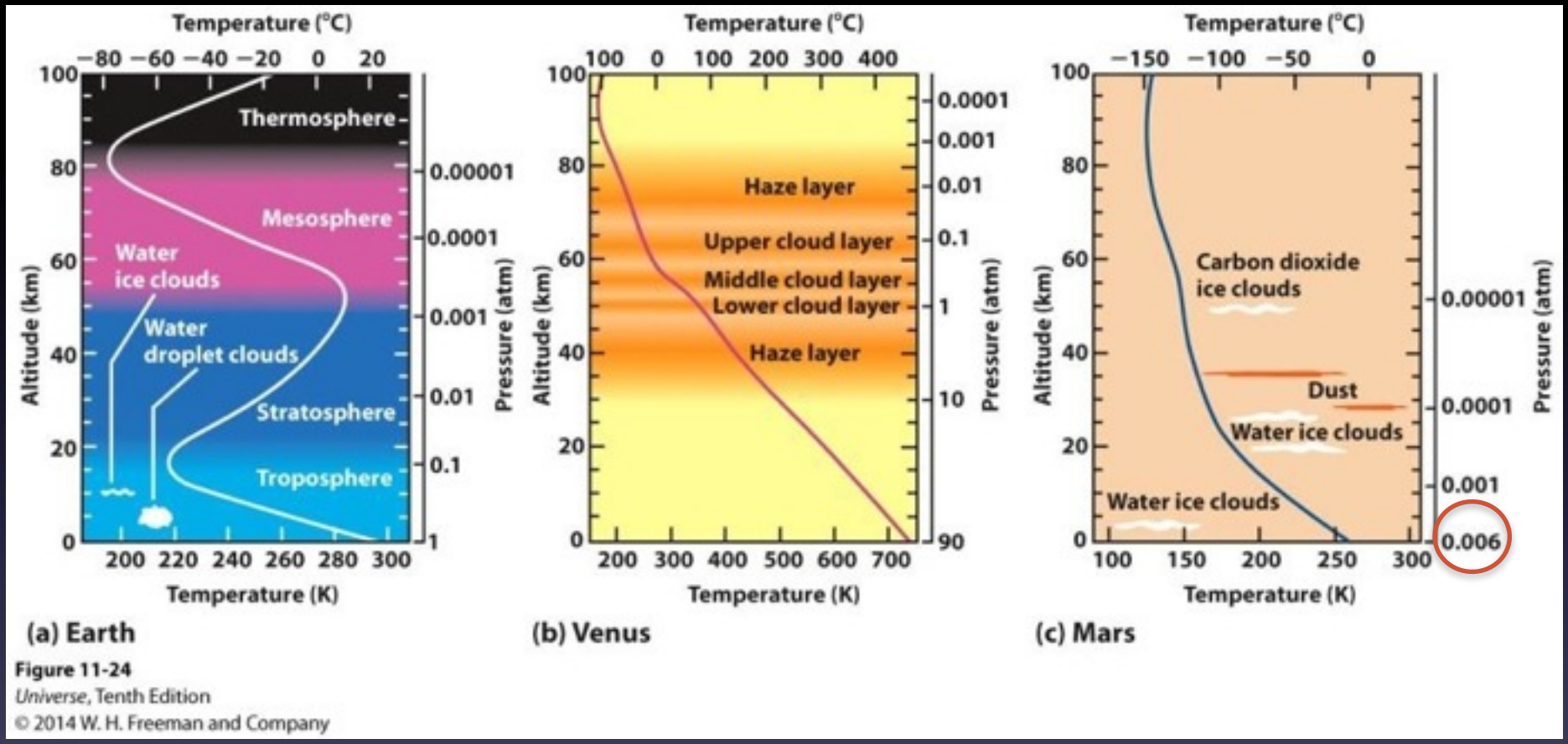


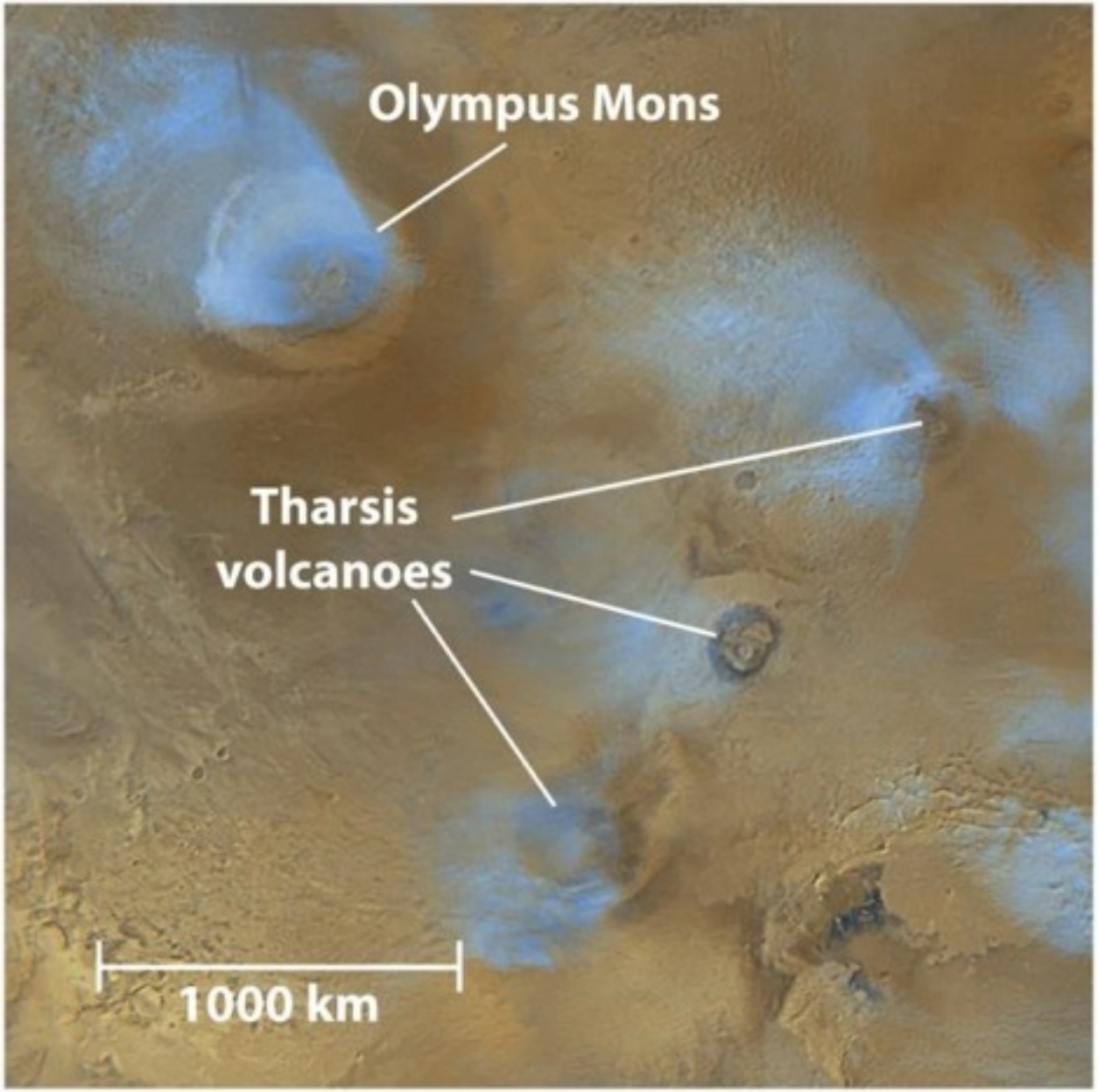
Figure 11-24
Universe, Tenth Edition

Mars' Atmosphere

Table 8-3 Chemical Compositions of Three Planetary Atmospheres

	Venus	Earth	Mars
Nitrogen (N_2)	3.5%	78.08%	2.7%
Oxygen (O_2)	almost zero	20.95%	almost zero
Carbon dioxide (CO_2)	96.5%	0.035%	95.3%
Water vapor (H_2O)	0.003%	about 1%	0.03%
Other gases	almost zero	almost zero	2%

Composition like Venus, but very thin; so almost no greenhouse effect



Cloud-topped volcanoes on Mars

Figure 11-21b
Universe, Tenth Edition
NASA/JPL/Malin Space Science Systems

Methane in Mars' Atmosphere

Discovered 2003; variable with location, season.

Unusual… what is source?

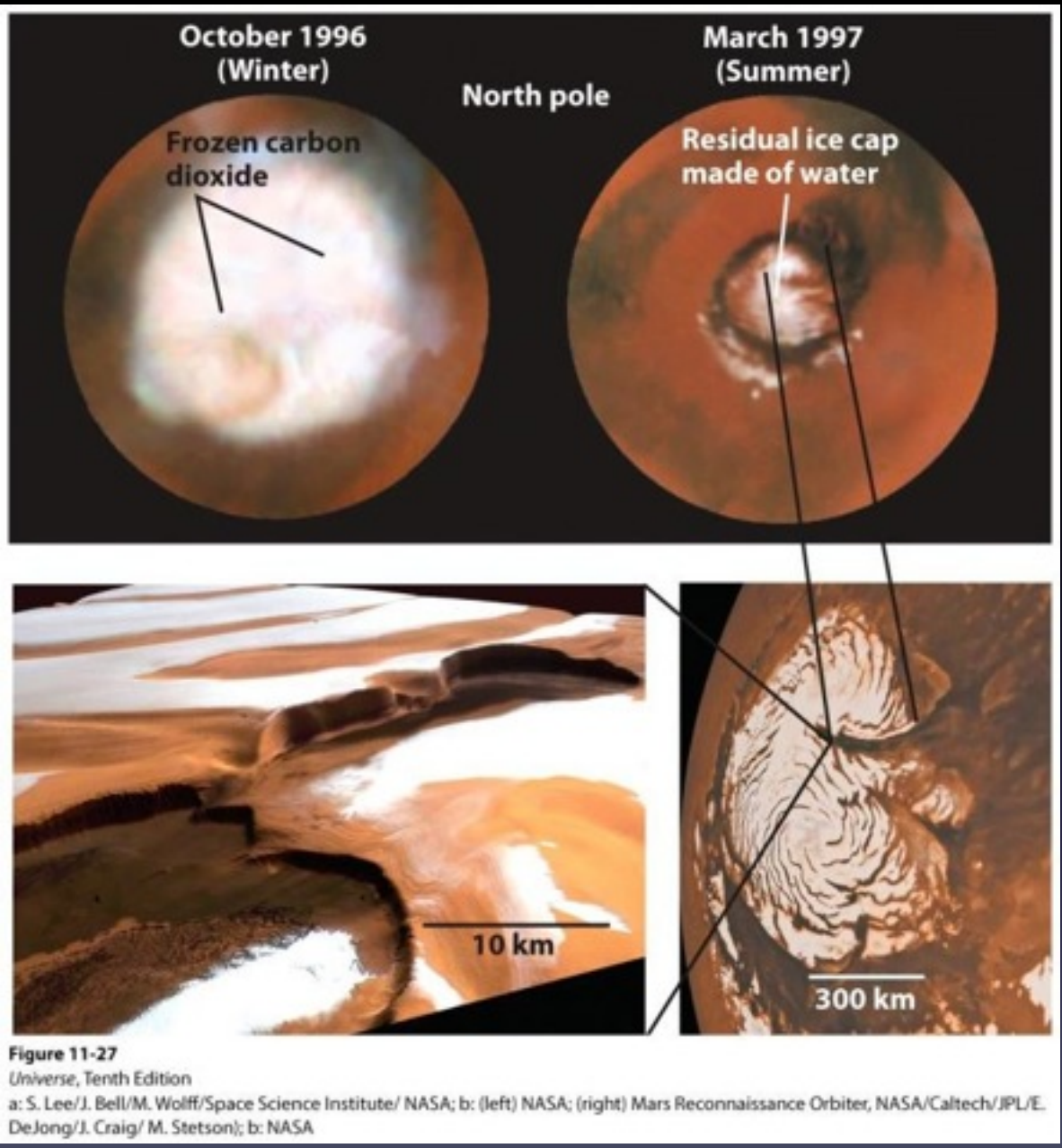
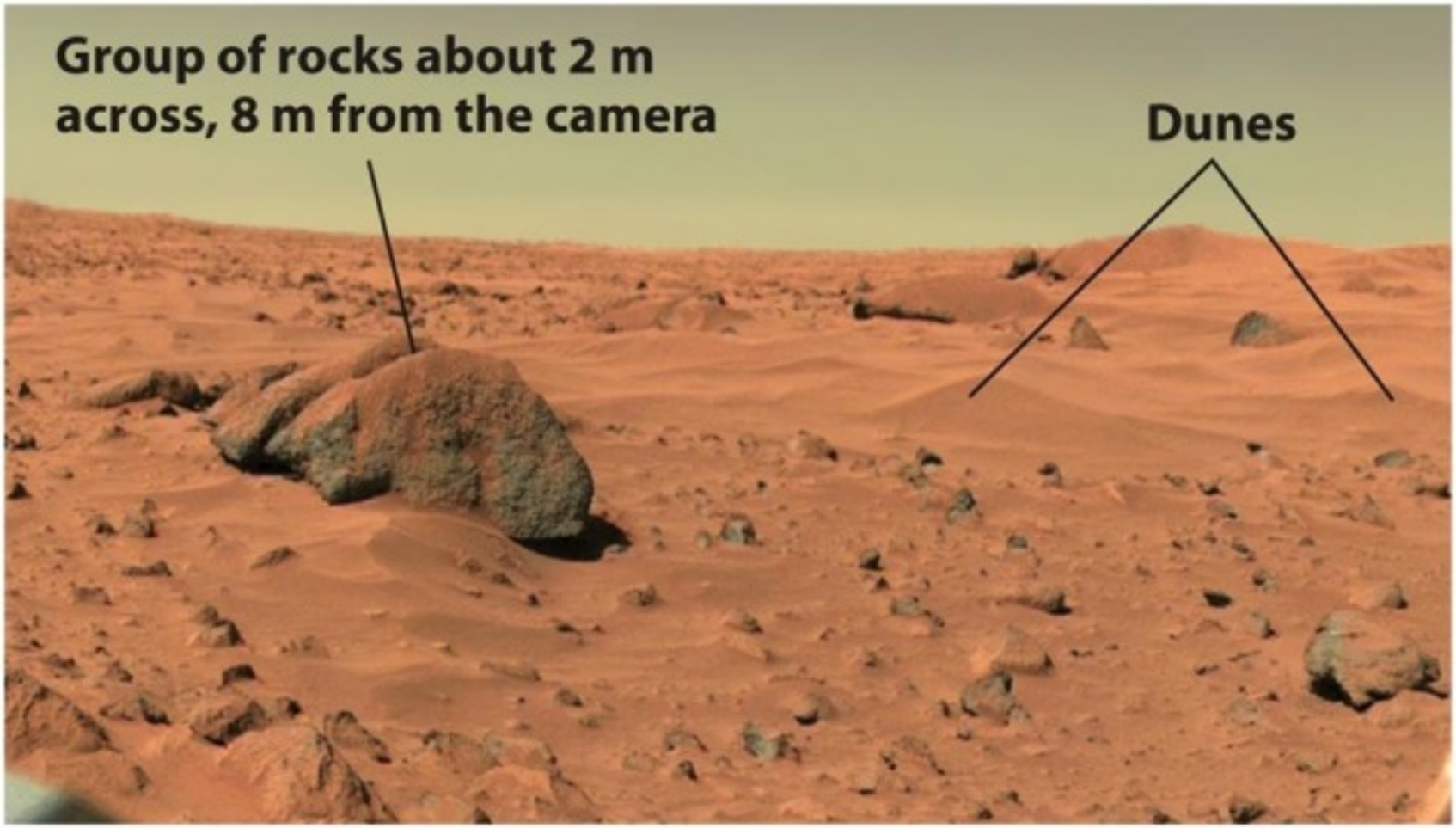


Figure 11-27
Universe, Tenth Edition
a: S. Lee/J. Bell/M. Wolff/Space Science Institute/ NASA; b: (left) NASA; (right) Mars Reconnaissance Orbiter, NASA/Caltech/JPL/E. DeJong/J. Craig/ M. Stetson); b: NASA

Changing Seasons Reveal Water-Ice at the Martian North Pole

Summer on Mars



A view from *Viking Lander 1*

Figure 11-28a
Universe, Tenth Edition
Dr. Edwin Bell II/NSSDC/GSFC/NASA

Winter on Mars

A wintertime view from *Viking Lander 2*

Figure 11-28b
Universe, Tenth Edition
NASA

Dark dust patches and slides at summer pole

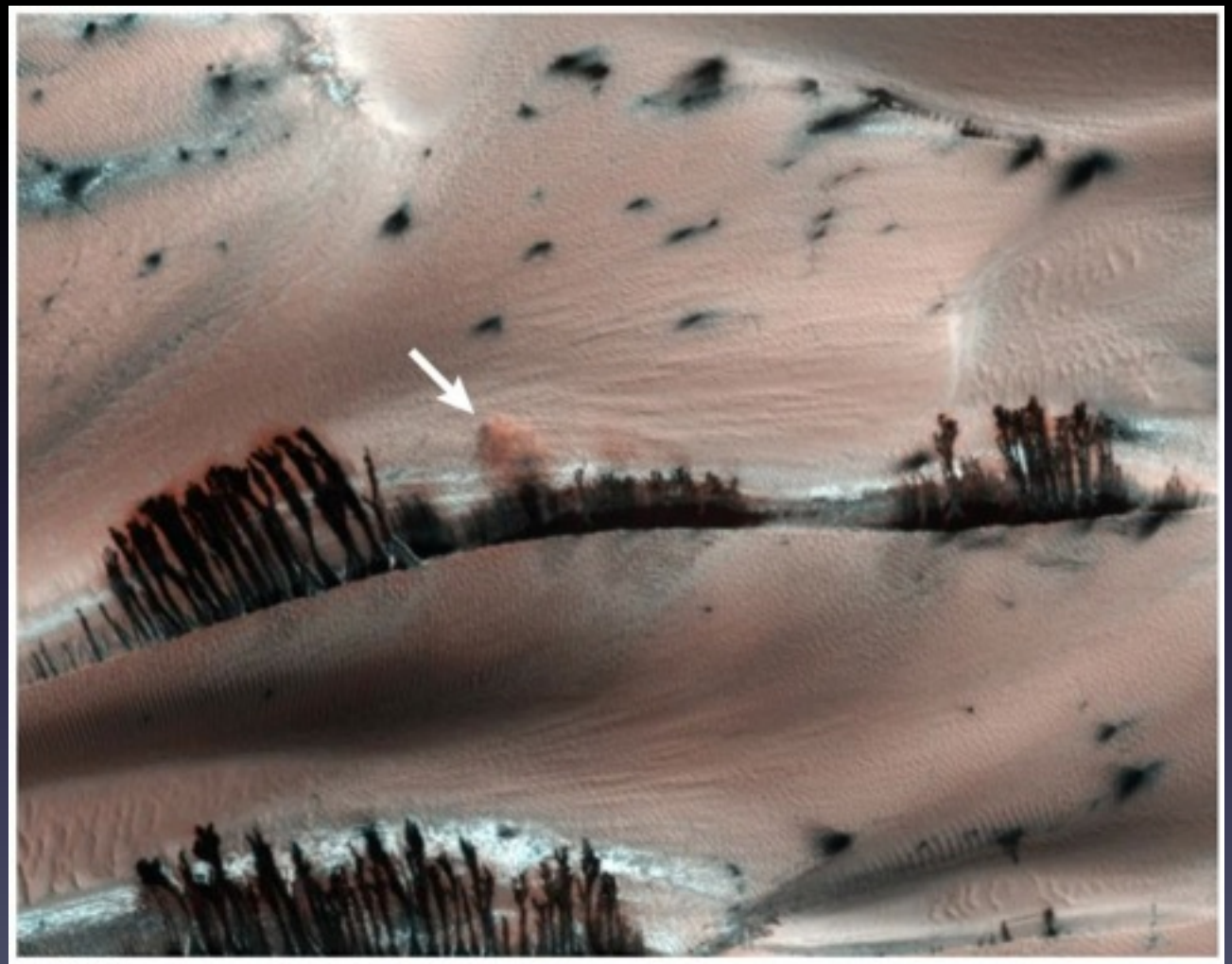
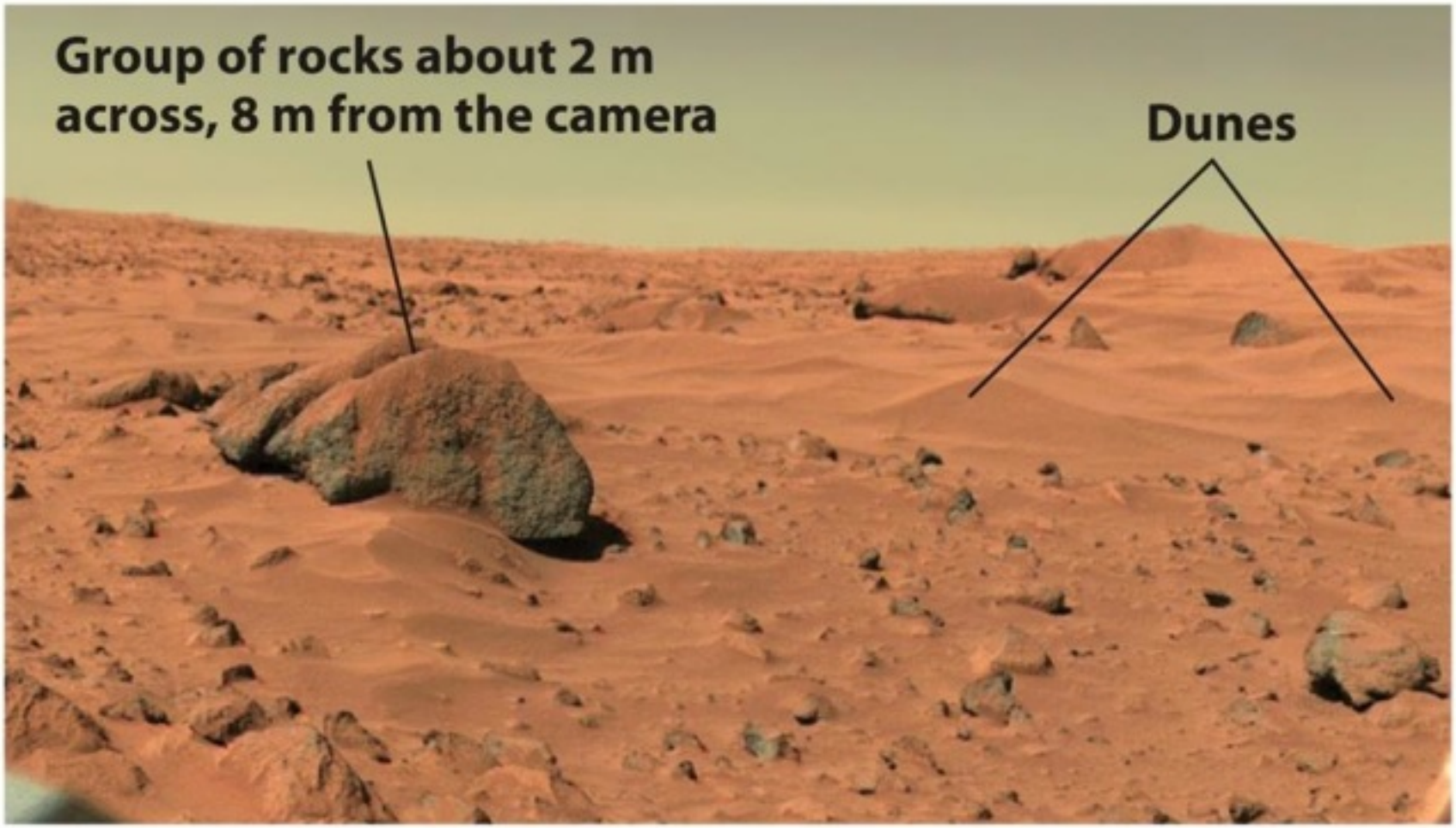


Figure 11-29
Universe, Tenth Edition
NASA/JPL/University of Arizona

Dunes on Mars



A view from *Viking Lander 1*

Figure 11-28a
Universe, Tenth Edition
Dr. Edwin Bell II/NSSDC/GSFC/NASA

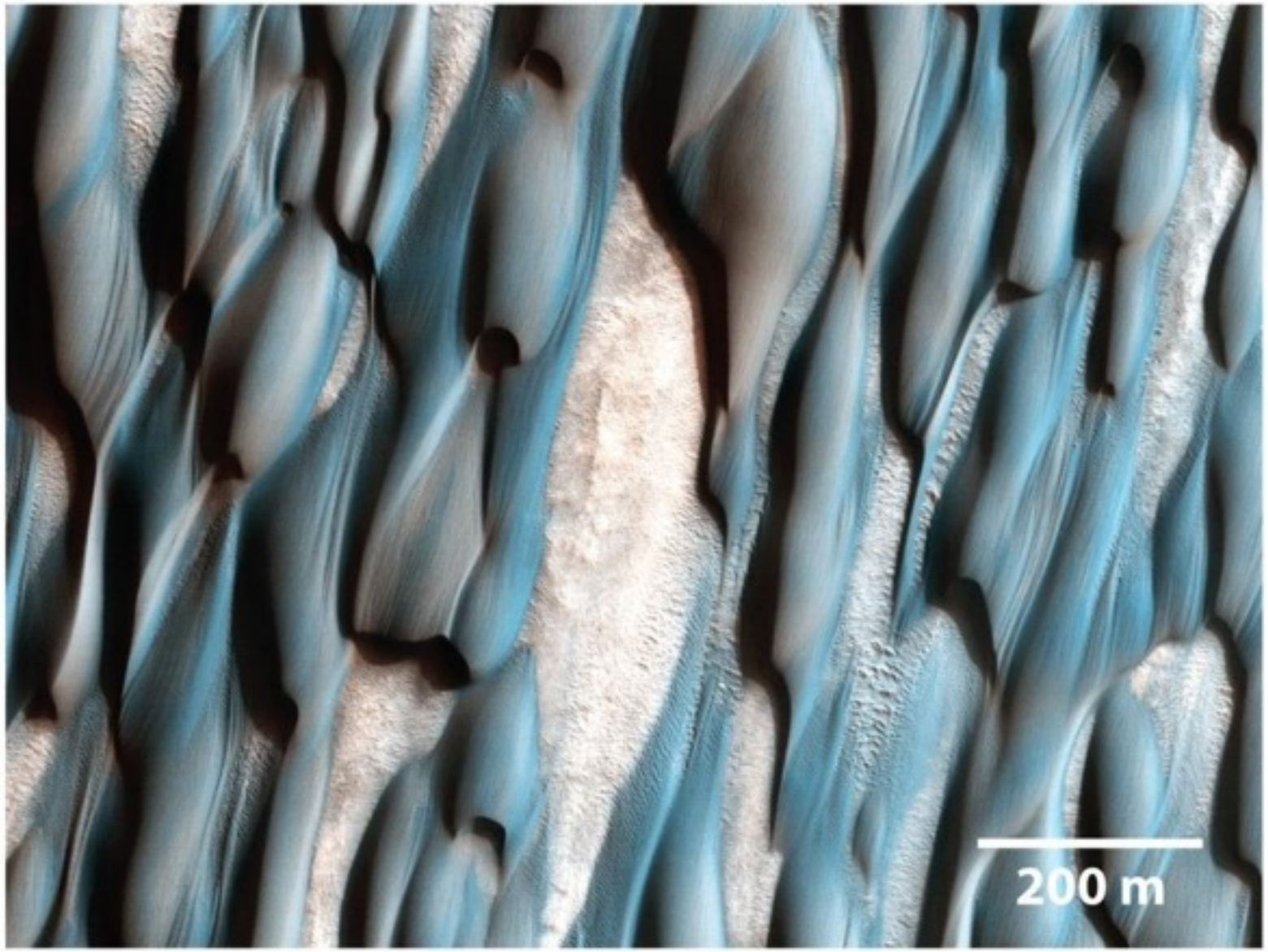


Figure 11-30a
Universe, Tenth Edition
NASA/JPL/University of Arizona

Martian Sand Dunes

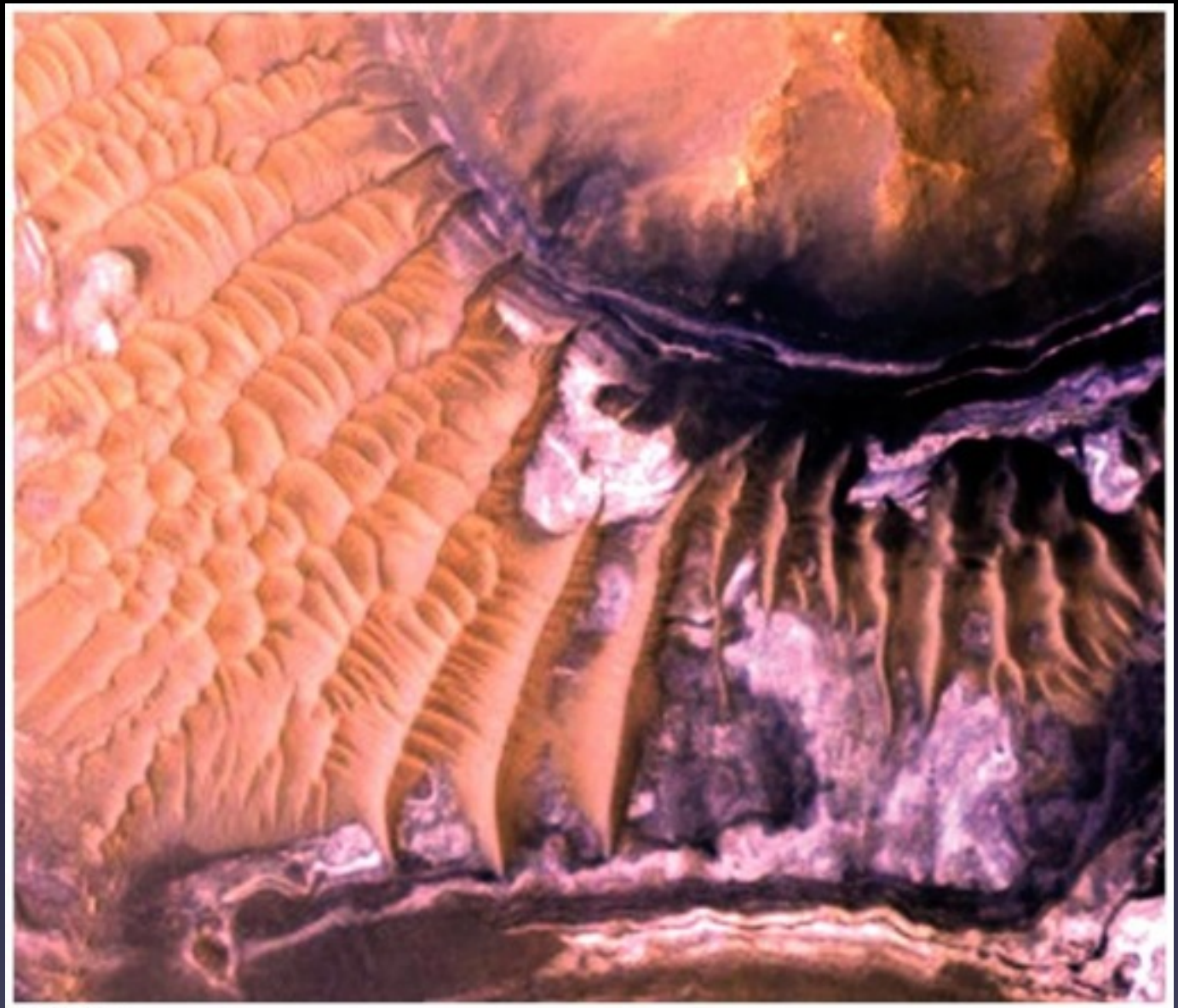


Figure 11-30b
Universe, Tenth Edition
NASA/JPL/University of Arizona

Martian Sand Dunes

Figure 11-31
Universe, Tenth Edition
NASA/JPL-MRO/Caltech/University of Arizona

A Martian Dust Devil

Martian Dust Devils

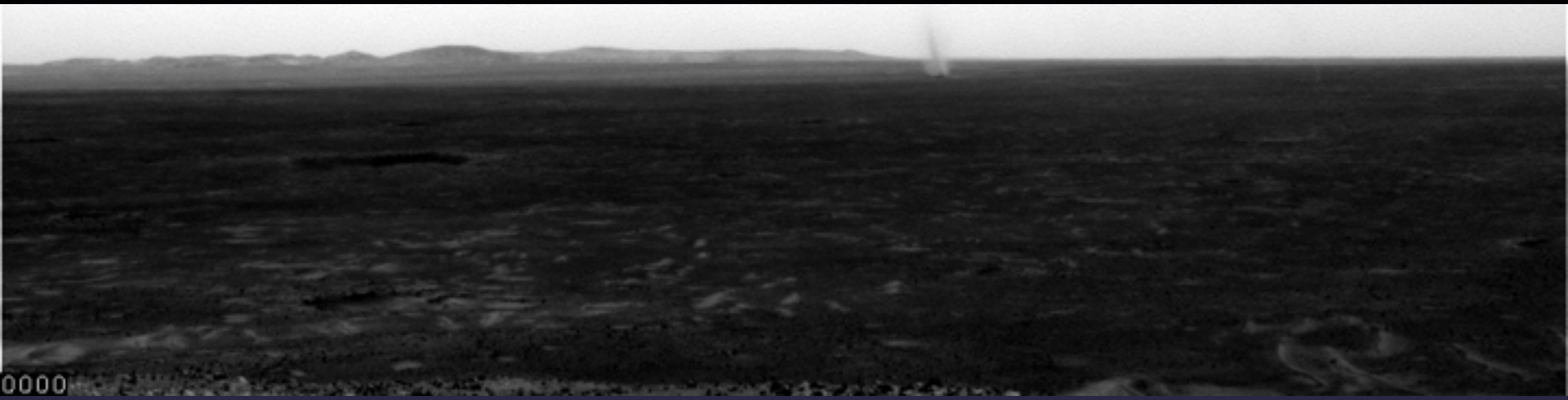
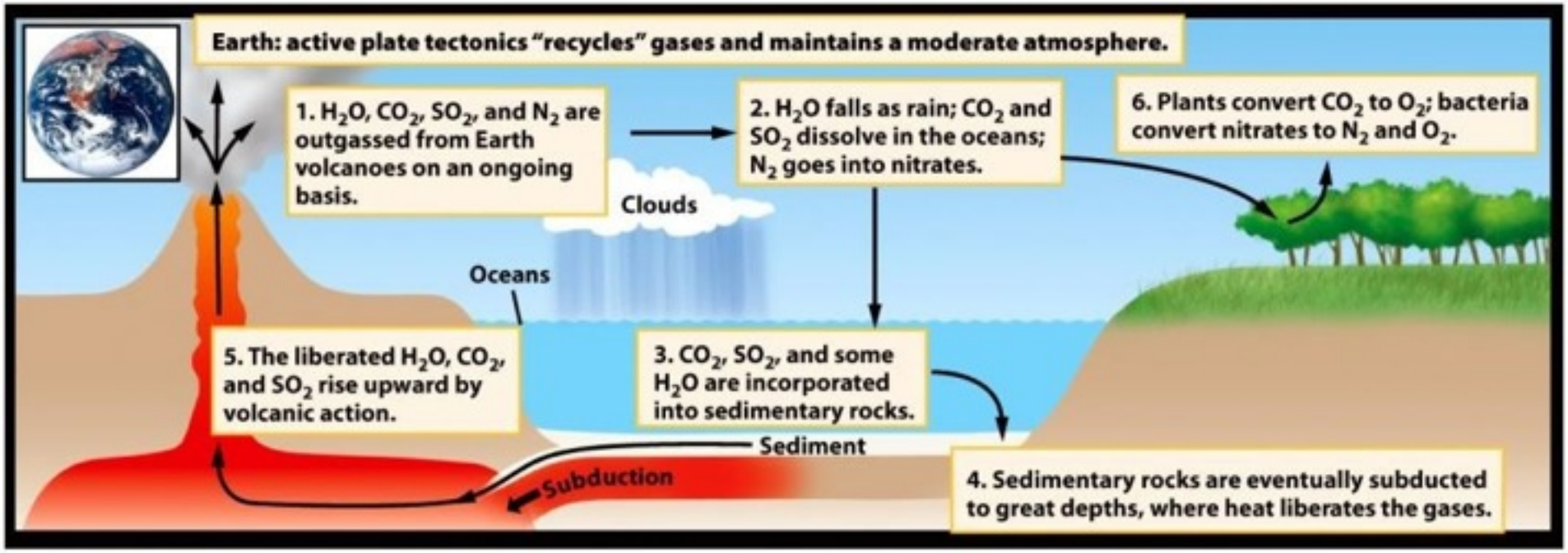


Figure 11-32
Universe, Tenth Edition
USGS

A Volcanic Eruption on Earth

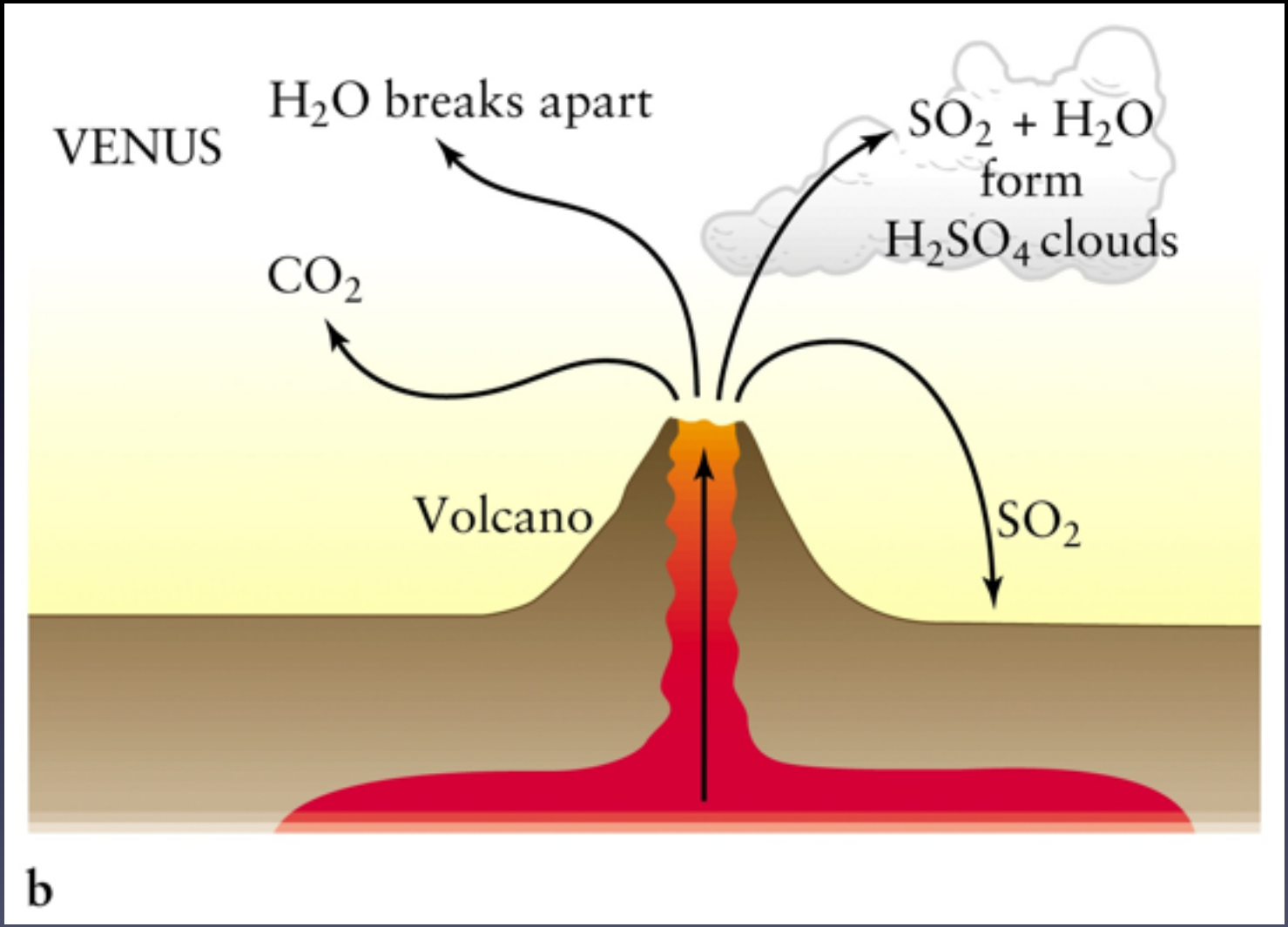

USGS
Oct 12, 2008 07:28 explosive eruption
x3 speed

Evolution of Earth's Atmosphere

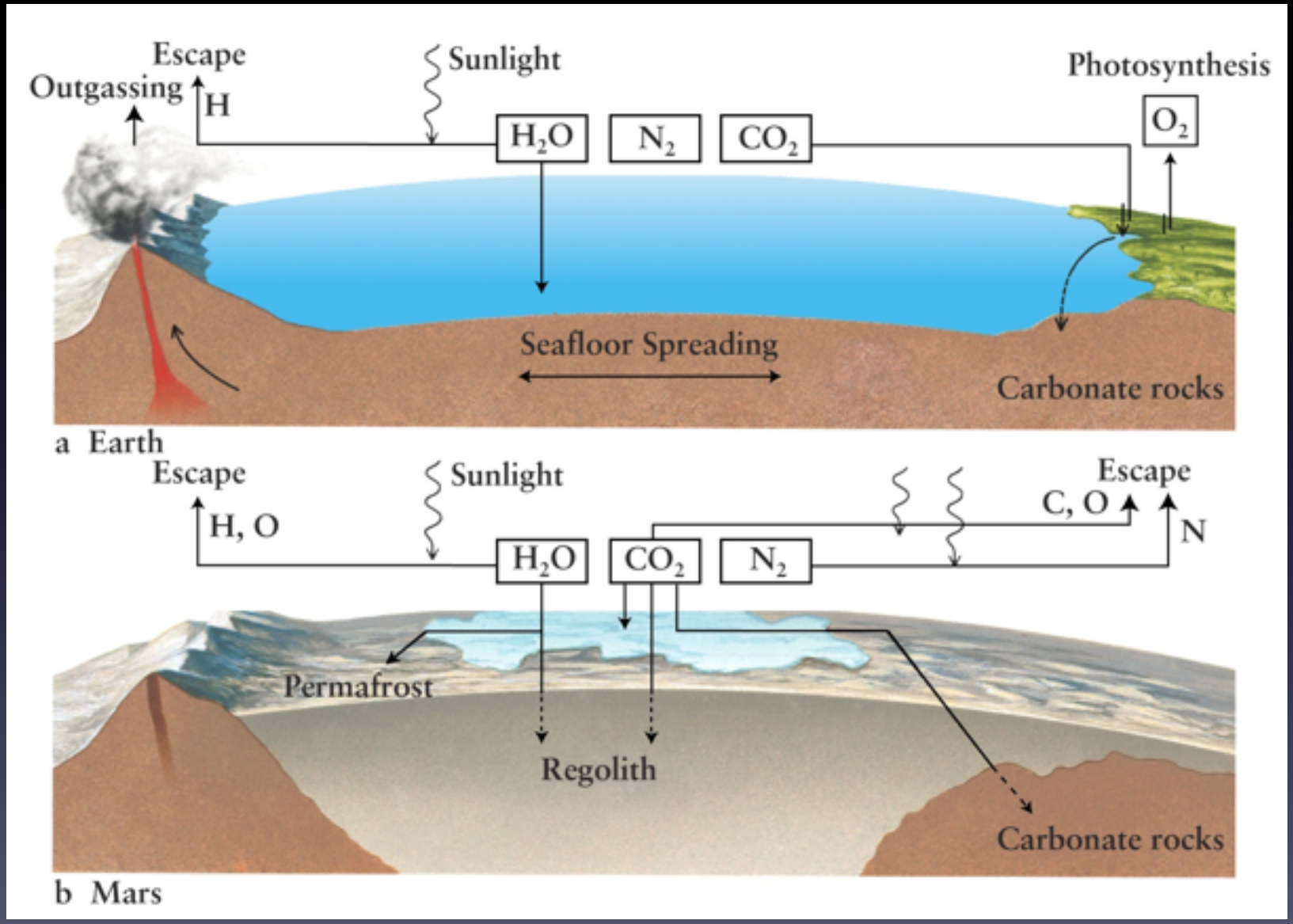


Cosmic Connections 11a
Universe, Tenth Edition

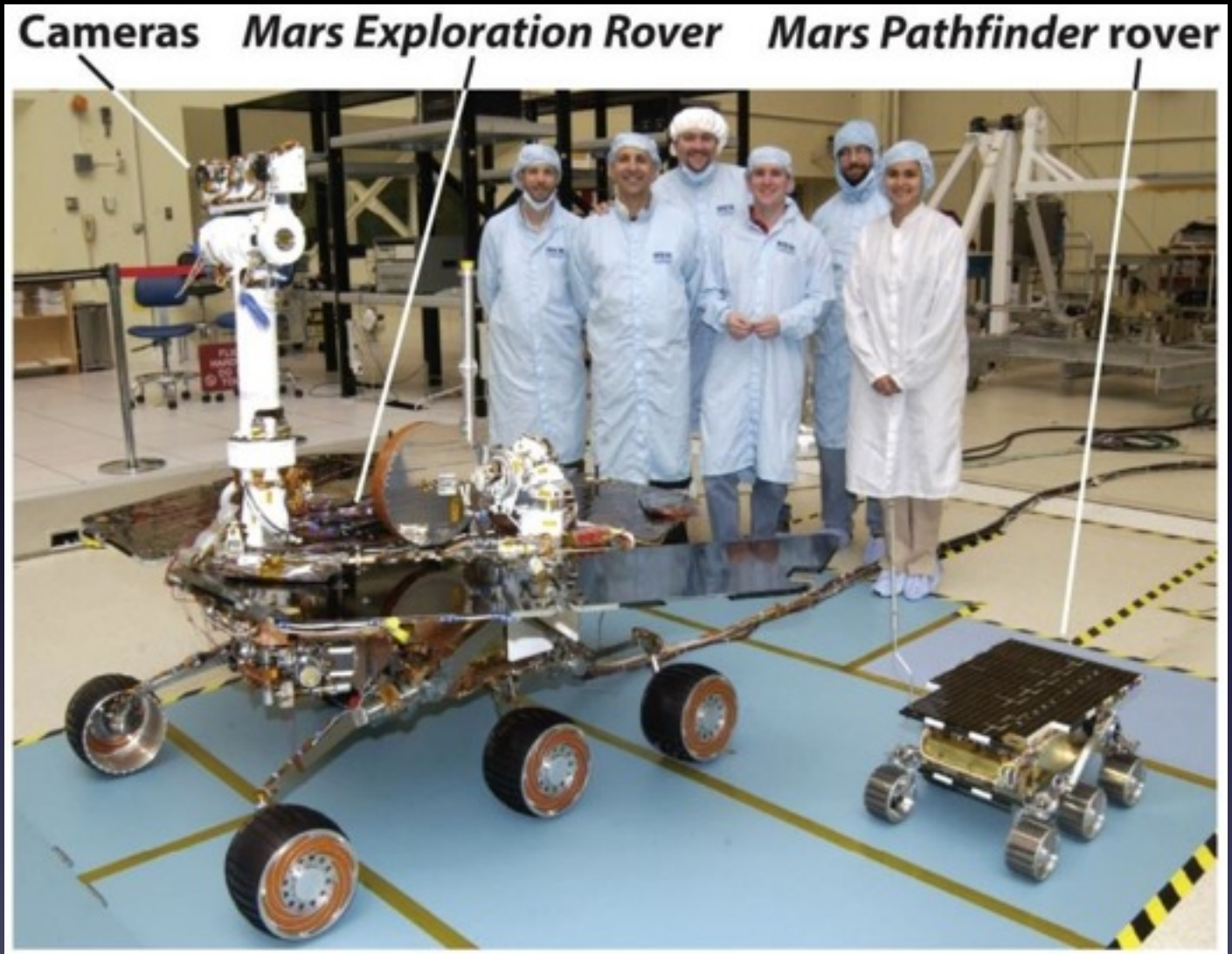
Venus Now


VENUS
H_2O breaks apart
$SO_2 + H_2O$ form H_2SO_4 clouds
CO_2
Volcano
SO_2
b

Mars lost most of its atmosphere

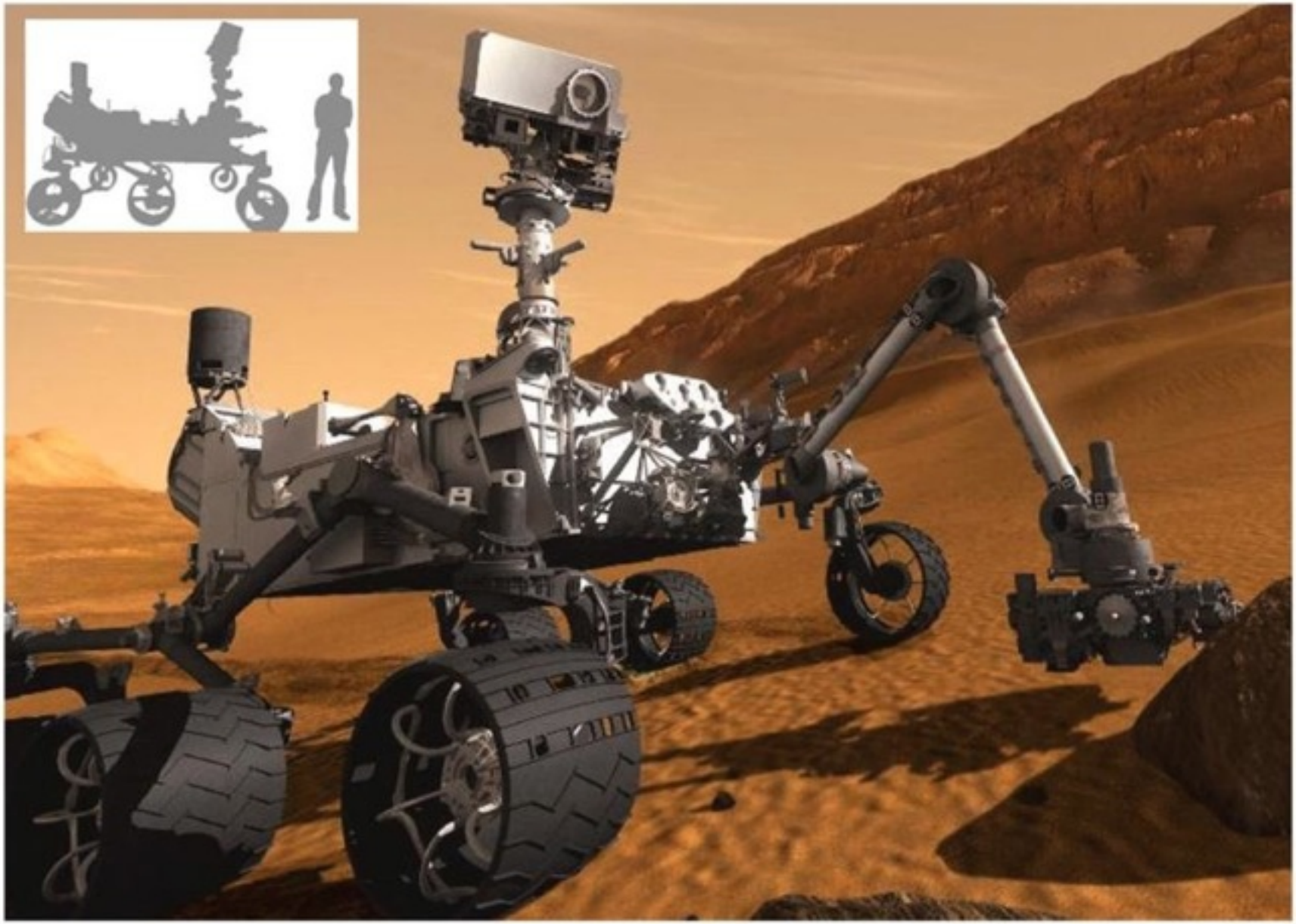


11-8: Rovers have found evidence of ancient Martian water.



Two generations of rovers

Figure 11-33a
Universe, Tenth Edition
JPL/NASA



Curiosity rover

Figure 11-33b
Universe, Tenth Edition
NASA/USGS

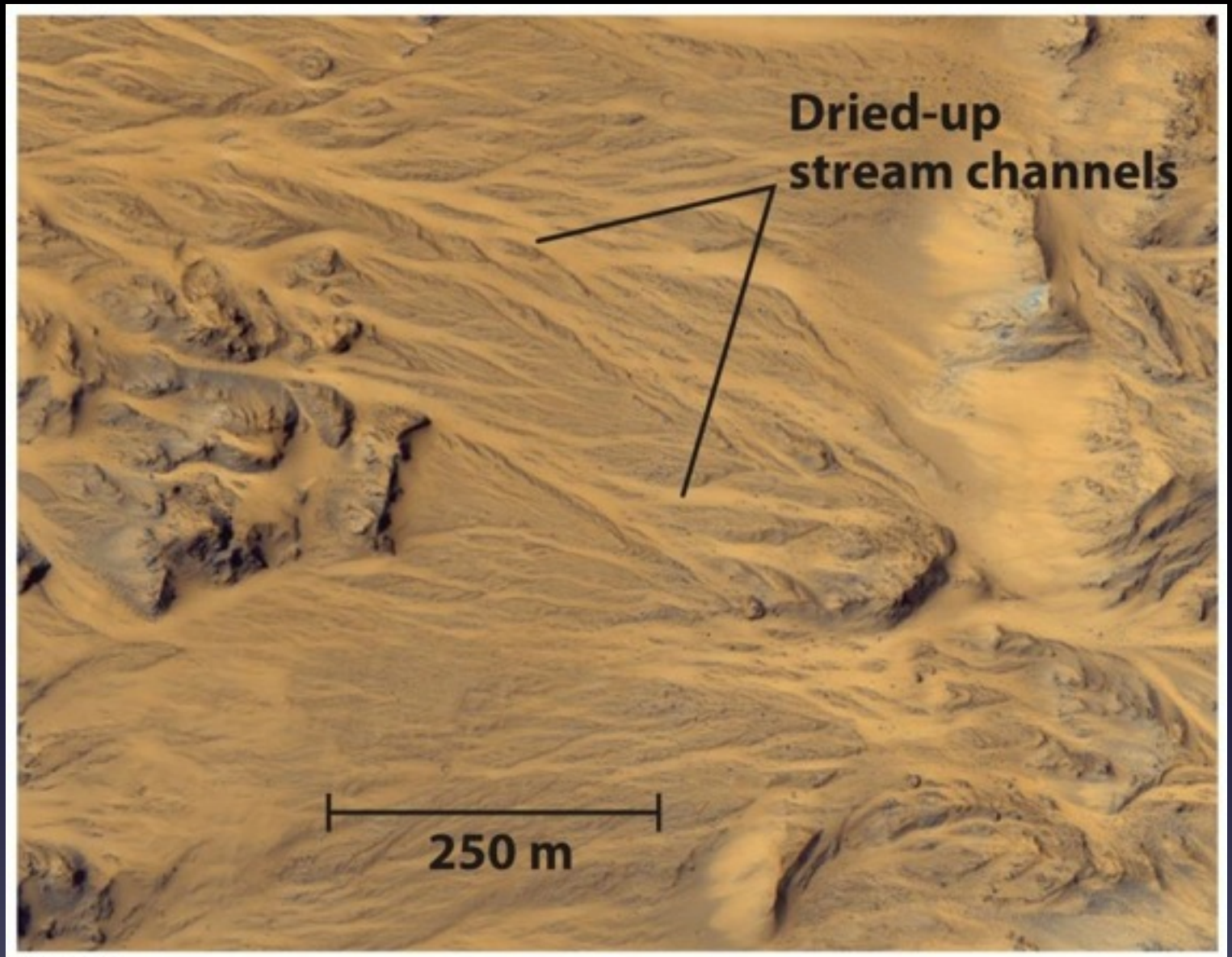


Figure 11-34a
Universe, Tenth Edition
NASA/JPL/U. of Arizona

Sign of Ancient Martian Water

Figure 11-34b
Universe, Tenth Edition
NASA/USGS

Sign of Ancient Martian Water

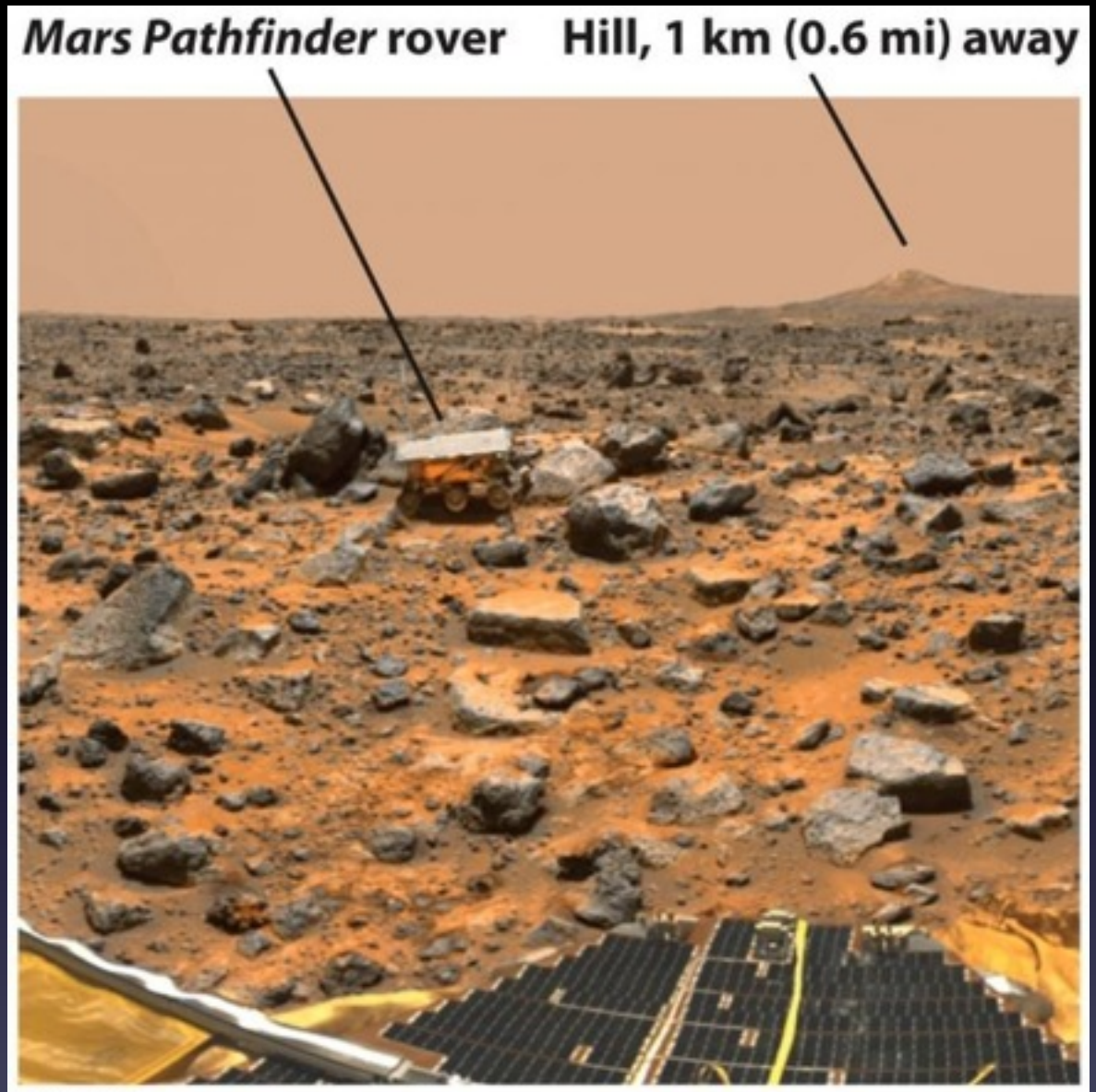


Figure 11-35
Universe, Tenth Edition
NASA/JPL

Roving the Martian Surface

Figure 11-37
Universe, Tenth Edition
NASA/JPL/Cornell

Wet Mars

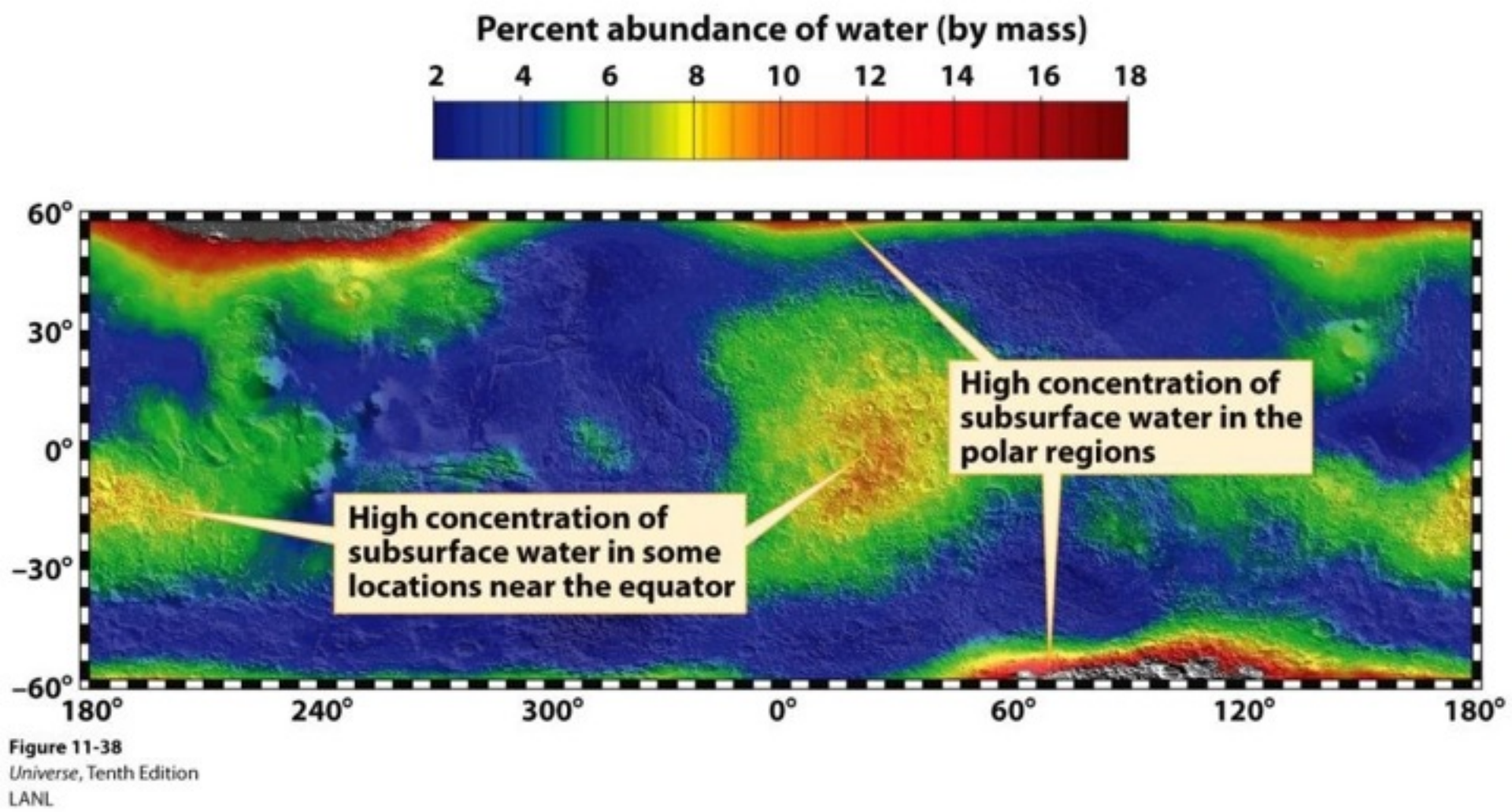
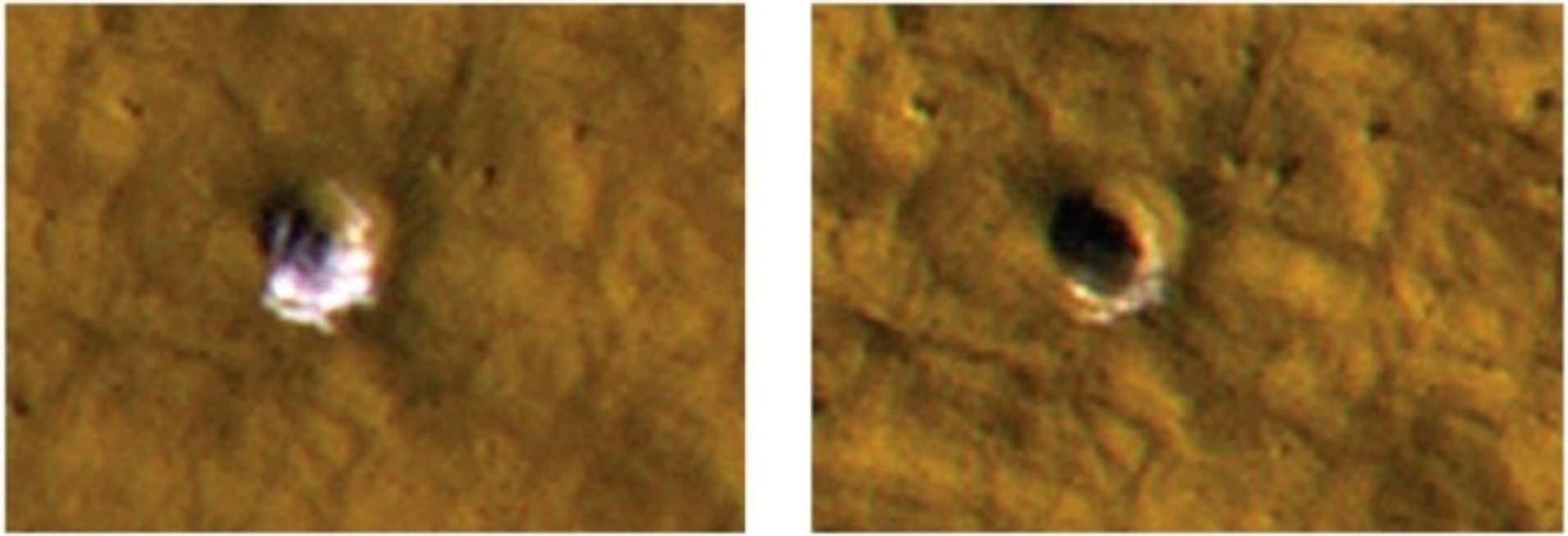


Figure 11-38
Universe, Tenth Edition
LANL

Water Beneath the Martian Surface



October 2008

January 2009

Figure 11-39
Universe, Tenth Edition
NASA/JPL-Caltech/University of Arizona

Water Revealed by Recent Impacts

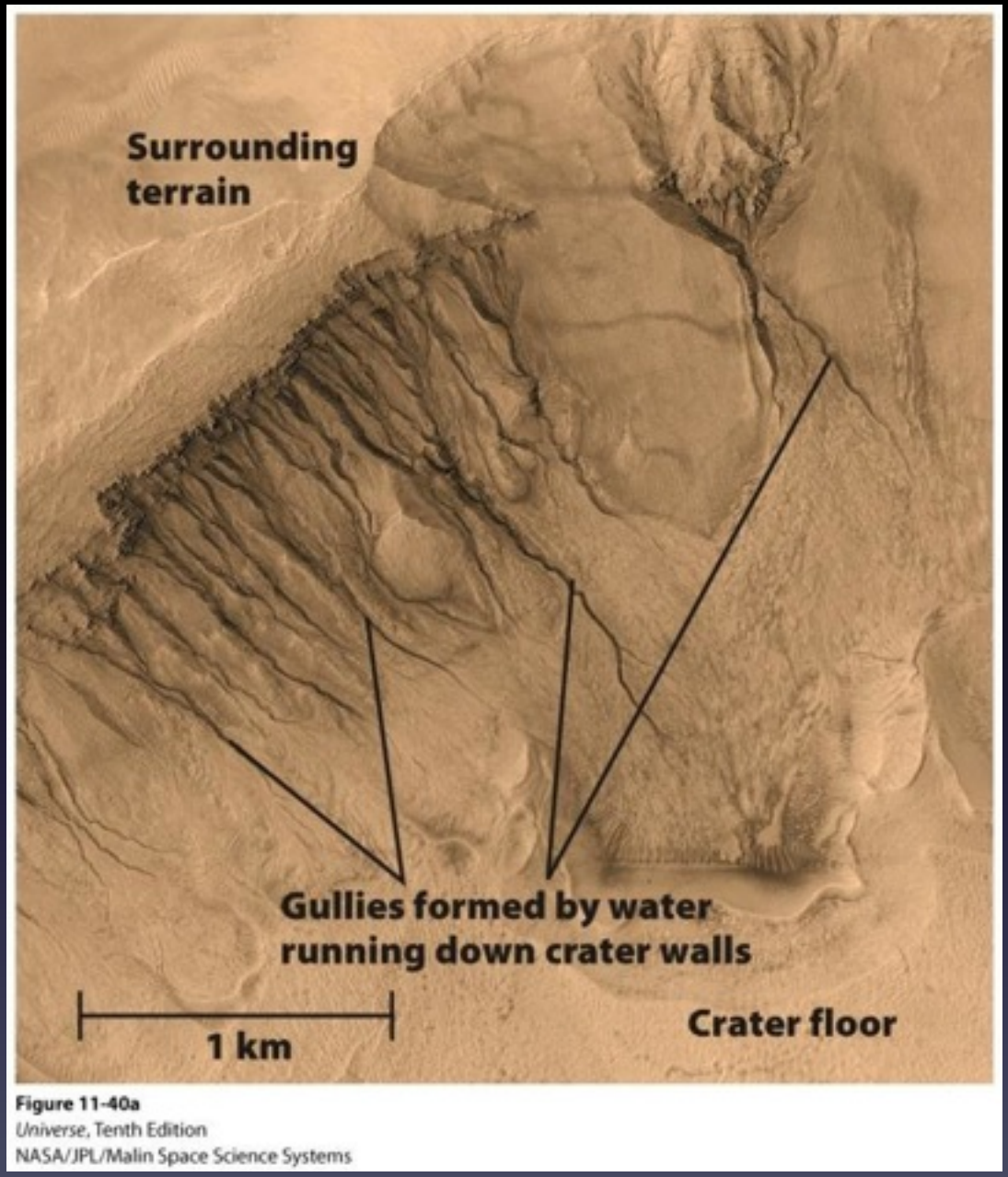


Figure 11-40a
Universe, Tenth Edition
NASA/JPL/Malin Space Science Systems

Martian Gullies

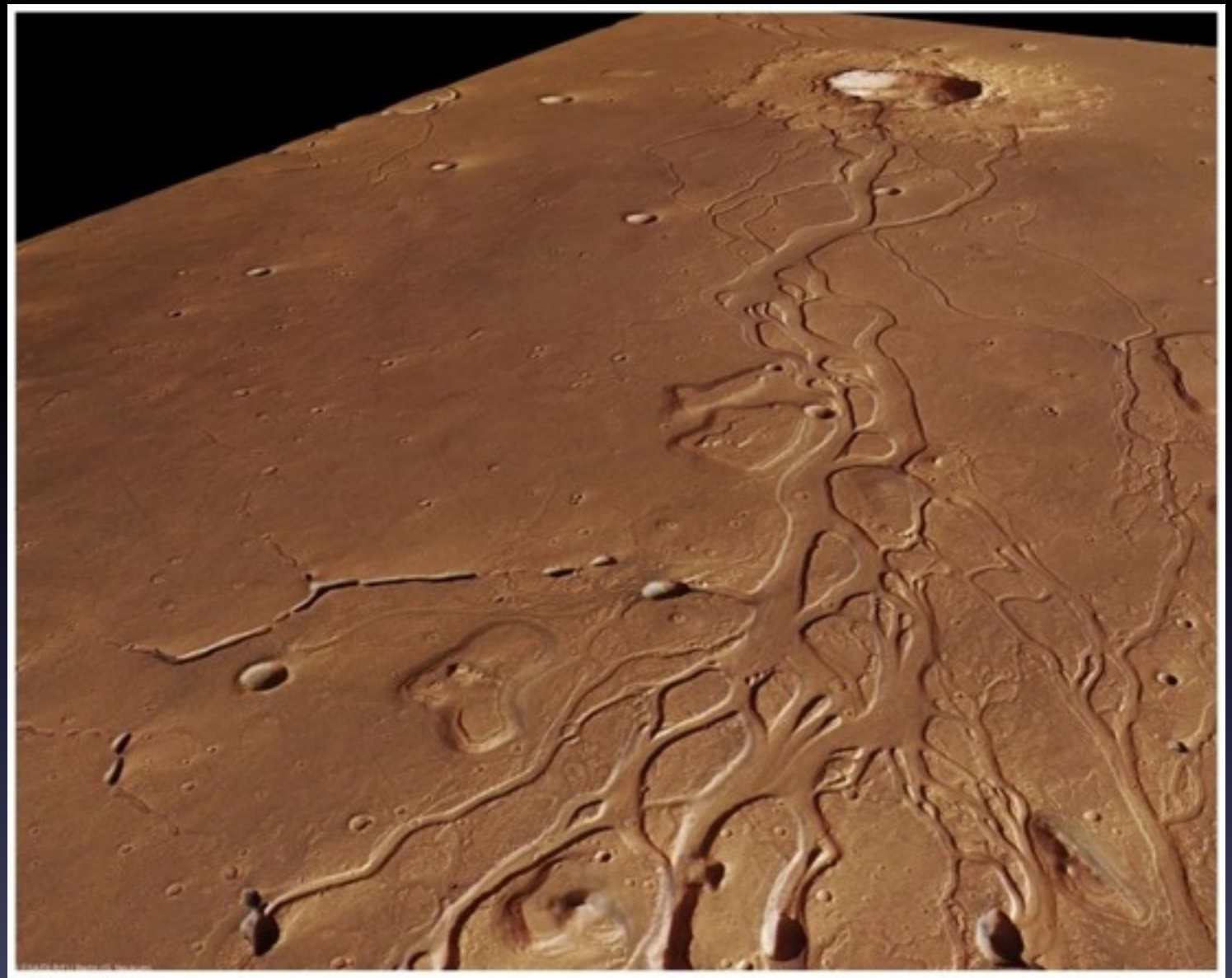
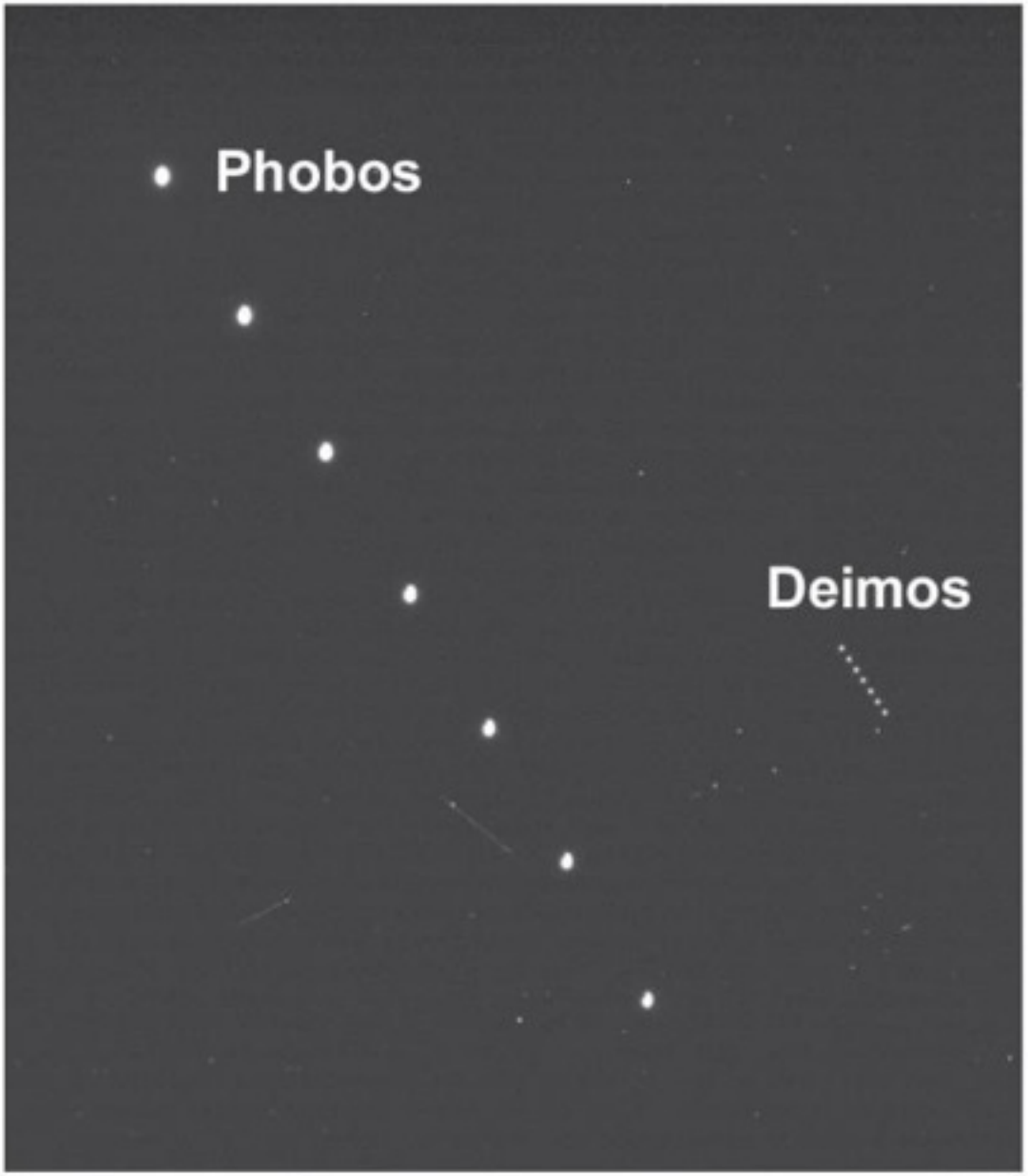


Figure 11-41
Universe, Tenth Edition
NASA/DLR/FU Berlin [G. Neukum]

Impact Melts Subsurface Ice

Figure 11-42
Universe, Tenth Edition
NASA

Dry Streambed



As seen from Mars

Figure 11-43a
Universe, Tenth Edition
NASA/JPL/Cornell/Texas A&M

The Moons of Mars

11-9: The two Martian moons resemble asteroids

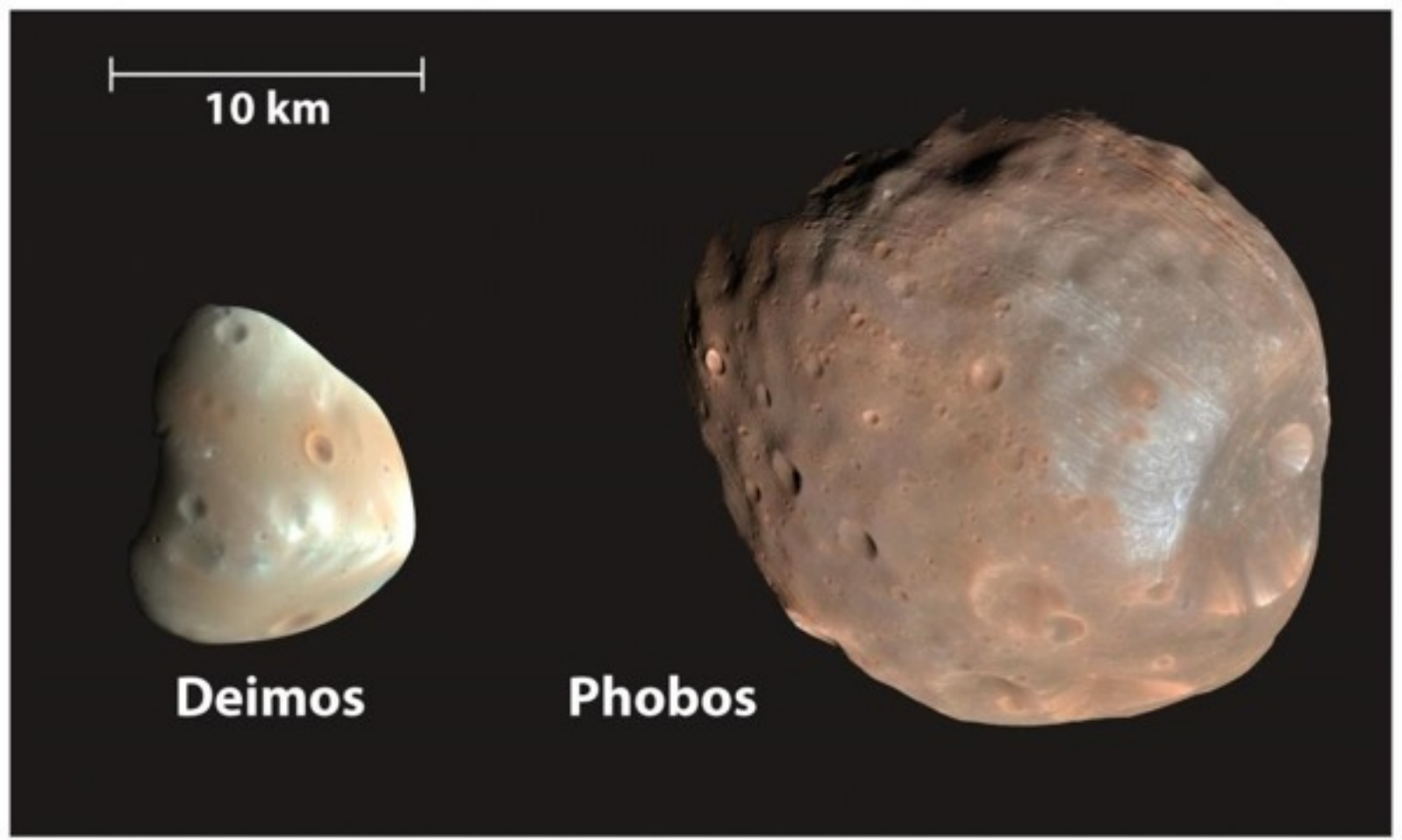
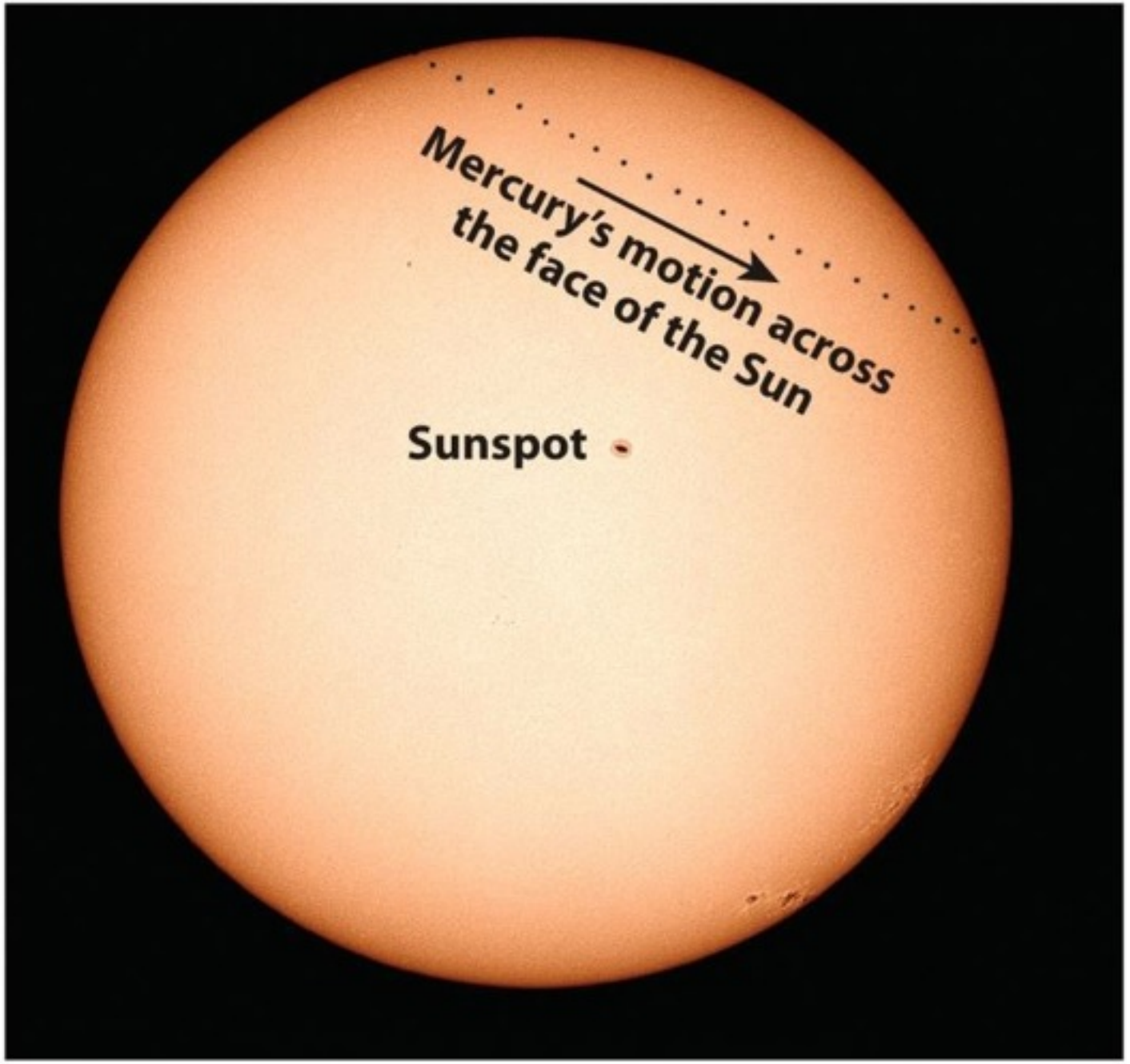


Figure 11-43b
Universe, Tenth Edition
NASA/JPL Caltech/University of Arizona

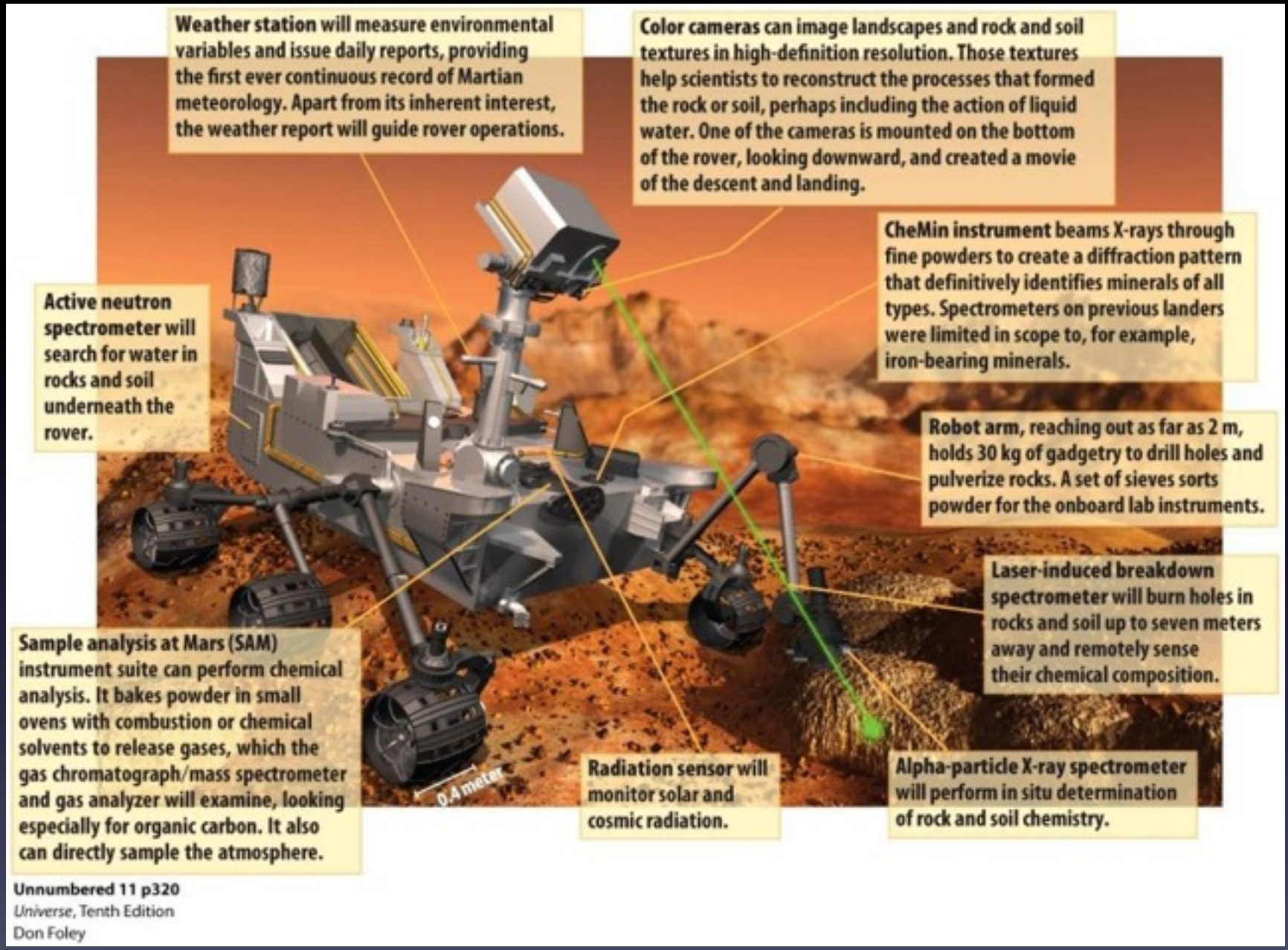
The Moons of Mars



Problem 11-43
Universe, Tenth Edition
Dominique Dierick

Unnumbered 11 p320
Universe, Tenth Edition
Don Foley

Reading the Red Planet



Unnumbered 11 p320
Universe, Tenth Edition
Don Foley

Reading the Red Planet

Key Ideas

- **Motions of Mercury, Venus, and Mars in the Earth's Sky:** Mercury and Venus can be seen in the morning or evening sky only, while it is possible to see Mars at any time of night depending on its position in its orbit.
- At their greatest eastern and western elongations, Mercury is only 28° from the Sun and Venus is only 47° from the Sun.

Key Ideas

- **Rotation of Mercury, Venus, and Mars:** Poor telescopic views of Mercury's surface led to the mistaken impression that the planet always keeps the same face toward the Sun (1-to-1 spin-orbit coupling).
- Radio and radar observations revealed that Mercury in fact has 3-to-2 spin-orbit coupling: The planet rotates on its axis three times every two orbits.
- Venus rotates slowly in a retrograde direction. Its rotation period is longer than its orbital period.
- Mars rotates at almost the same rate as the Earth, and its rotation axis is tilted by almost the same angle as the Earth's axis.

Key Ideas

- **Mercury's Surface, Interior, and Magnetic Field:** Mercury's surface is pocked with craters, but there are extensive smooth plains between these craters.
- Long cliffs called scarps meander across the surface of Mercury. These probably formed as the planet's crust cooled, solidified, and shrank.
- Mercury has an iron core with a diameter equal to about 83% of the planet's diameter. By contrast, the diameter of the Earth's core is only slightly more than 1/2 of Earth's diameter.
- Mercury has a weak magnetic field, which indicates that at least part of the iron core is liquid. However, the field is off-center by 20%, which remains unexplained
- The high abundance of volatile elements that should have "boiled off" from Mercury's material during formation presents a mystery considering the planet's close proximity to the Sun.

Key Ideas

- **Comparing Venus and Mars:** Most of the surface of Venus is at about the same elevation, with just a few elevated regions. On Mars, the southern highlands rise several kilometers above the northern lowlands.
- Venus has a thick atmosphere and a volcanically active surface. Mars has a very thin atmosphere and little or no current volcanism.
- There is no evidence of plate tectonics on Venus, but Valles Marineris shows there are at least two plates on Mars. On Venus, there is vigorous convection in the planet's interior, but the crust is too thin to move around in plates; instead, it wrinkles and flakes. On Mars, the planet's smaller size means the crust cooled long ago and became too thick to allow widespread plate tectonic activity.

Key Ideas

- Volcanoes on both Venus and Mars were produced by hot spots in the planet's interior.
- The entire Venusian surface is about 500 million years old and has relatively few craters. By contrast, most of the Martian surface is cratered and is probably billions of years old. The southern highlands on Mars are the most heavily cratered and hence the oldest part of the planet's surface.

Key Ideas

- **The Atmospheres of Venus and Mars:** Both planetary atmospheres are over 95% carbon dioxide, with a small percentage of nitrogen.
- The pressure at the surface of Venus is about 90 atmospheres. The greenhouse effect is very strong, which raises the surface temperature to 460°C. The pressure at the surface of Mars is only 0.006 atmosphere, and the greenhouse effect is very weak.
- The permanent high-altitude clouds on Venus are made primarily of sulfuric acid. By contrast, the few clouds in the Martian atmosphere are composed of water ice and carbon dioxide ice.

Key Ideas

- The circulation of the Venusian atmosphere is dominated by two huge convection currents in the cloud layers, one in the northern hemisphere and one in the southern hemisphere. The upper cloud layers of the Venusian atmosphere move rapidly around the planet in a retrograde direction, with a period of only about 4 Earth days.
- Weather on Mars is dominated by the north and south flow of carbon dioxide from pole to pole with the changing seasons. This can trigger planetwide dust storms.

Key Ideas

- **Evolution of Atmospheres:** Earth, Venus, and Mars all began with relatively thick atmospheres of carbon dioxide, water vapor, and sulfur dioxide.
- On Earth, most of the carbon dioxide went into carbonate rocks and most of the water into the oceans. Ongoing plate tectonics recycles atmospheric gases through the crust.
- On Venus, more intense sunlight and the absence of plate tectonics led to a thick carbon dioxide atmosphere and a runaway greenhouse effect.
- On Mars, a runaway icehouse effect resulted from weaker sunlight and a lack of strong plate tectonic activity.

Key Ideas

- **Water on Mars:** Liquid water cannot exist on present-day Mars because the atmosphere is too thin and cold. But there is evidence for frozen water at the polar ice caps and beneath the surface of the regolith.
- Geological evidence from unmanned rovers shows that much of the Martian surface has been dry for billions of years, but some regions had substantial amounts of liquid water in the past.
- **The Moons of Mars:** 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.