Roger Freedman • Robert Geller • William Kaufmann III

Universe

Tenth Edition

Chapter 10

Our Barren Moon

By reading this chapter, you will learn

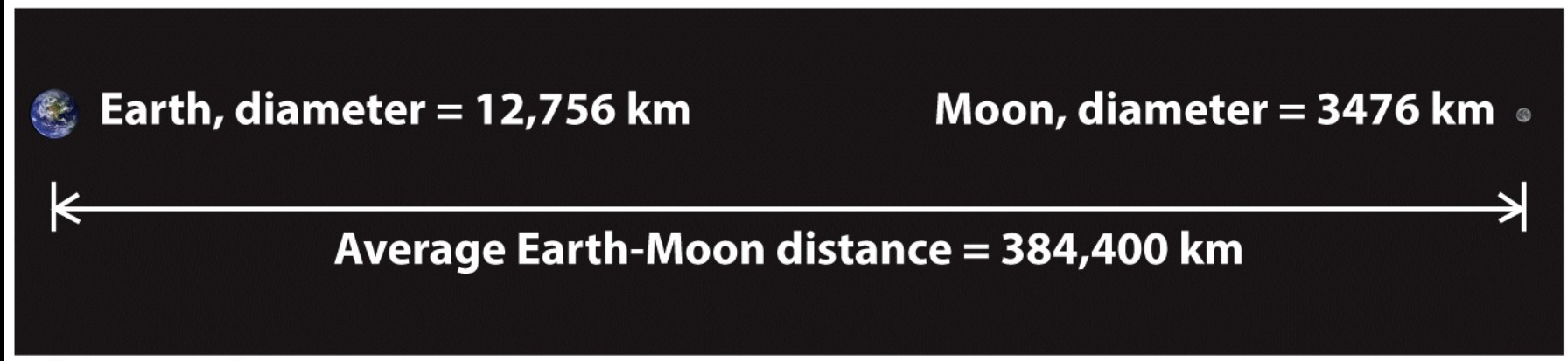
10-1 The nature of the Moon's surface

10-2 The story of human exploration of the Moon

10-3 How we have learned about the Moon's interior

10-4 How Moon rocks differ from rocks on Earth

10-5 Why scientists think the Moon formed as the result of a violent collision between worlds



The Earth-Moon system

Figure 10-1a
Universe, Tenth Edition
NASA

Earth and the Moon to scale, shown 10 times larger than in part (a)

Figure 10-1b
Universe, Tenth Edition
Earth: NASA Goddard Space Flight Center Image by Reto Stöckli; Moon: NASA/GSFC/Arizona State Univ./Lunar Reconnaissance Orbiter

Comparing Earth and the Moon

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

R I V U X G
(Larry Landolfi, Science Source)

Table 10-1
Universe, Tenth Edition

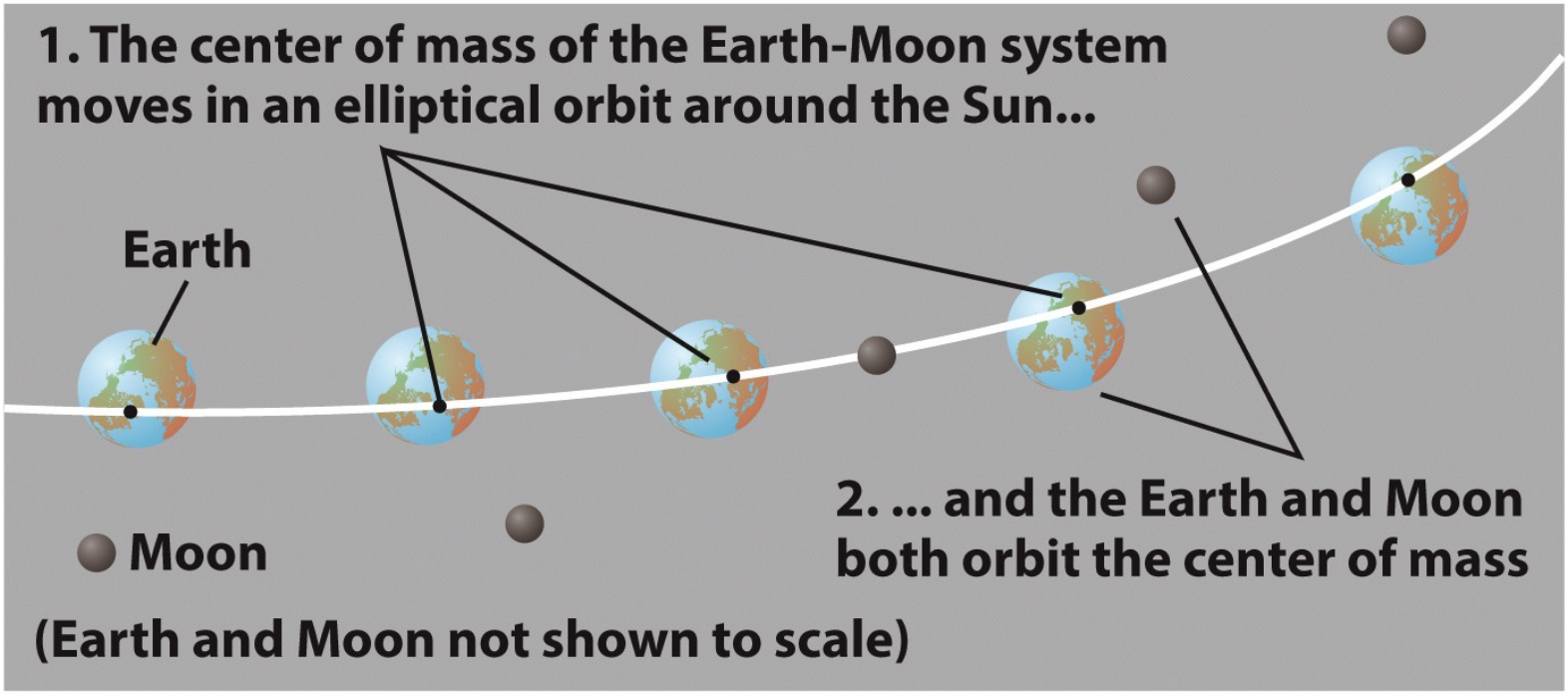


Figure 10-2a
Universe, Tenth Edition

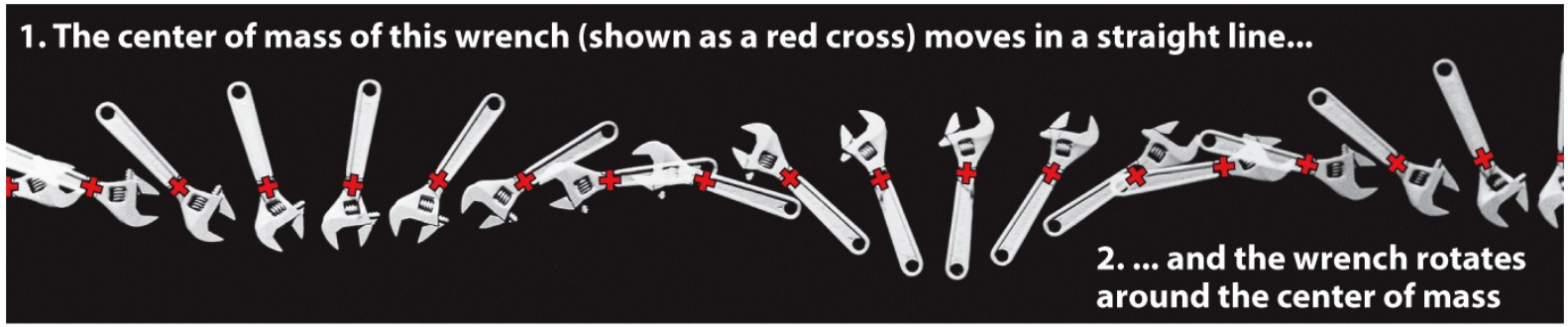


Figure 10-2b
Universe, Tenth Edition
Berenice Abbott/Photo Researchers

Motion of the Earth-Moon System

Moon’s Rotation and Libration

- Moon’s Rotation
  - Synchronous: keeps same face to Earth
  - Rotates once each month
- Moon's Libration
  - Speed and viewing angle change along orbit
  - Can see 59% of total surface

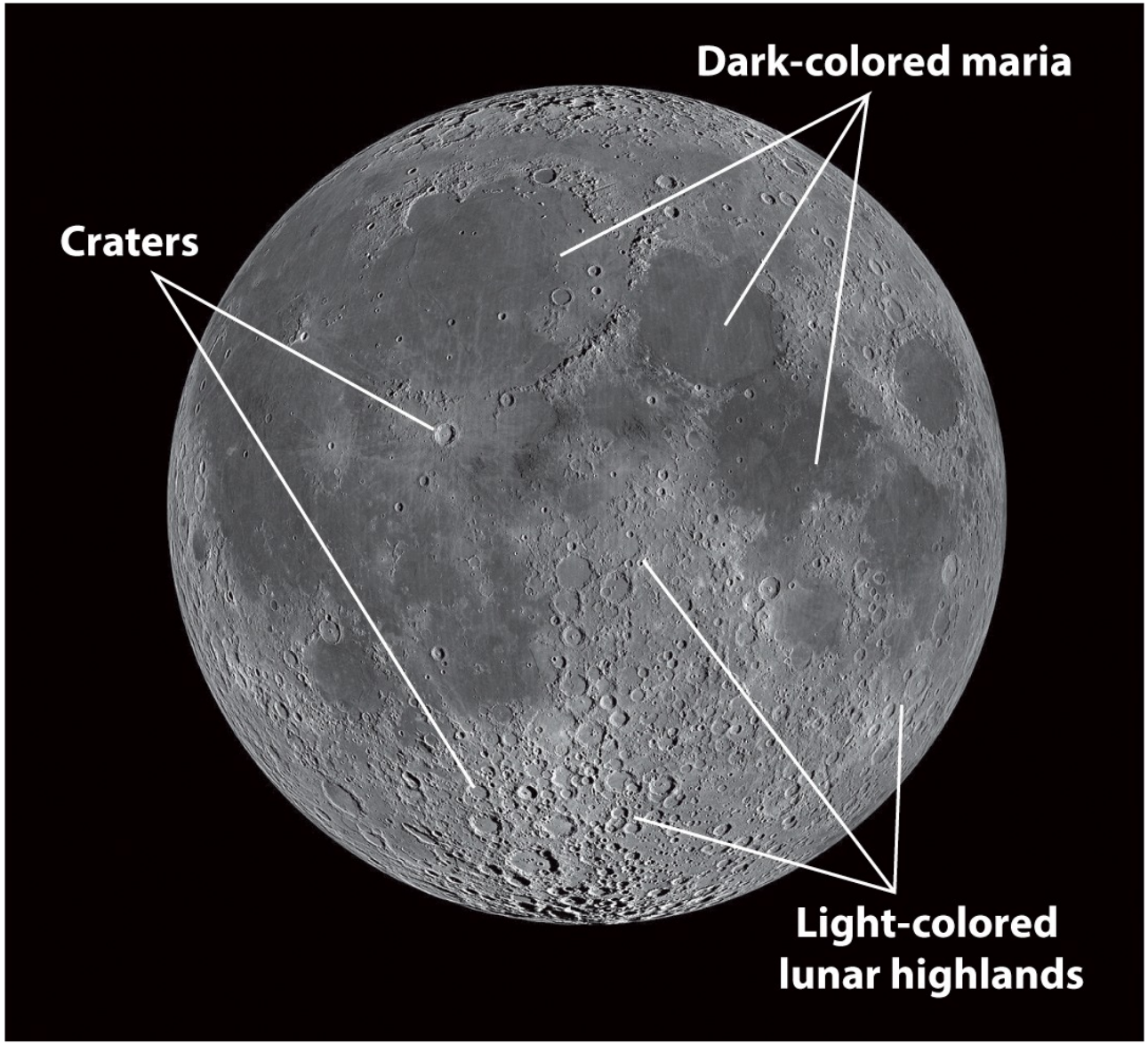


Figure 10-3
Universe, Tenth Edition
NASA/GSFC/Arizona State Univ./Lunar Reconnaissance Orbiter

The Near Side of the Moon

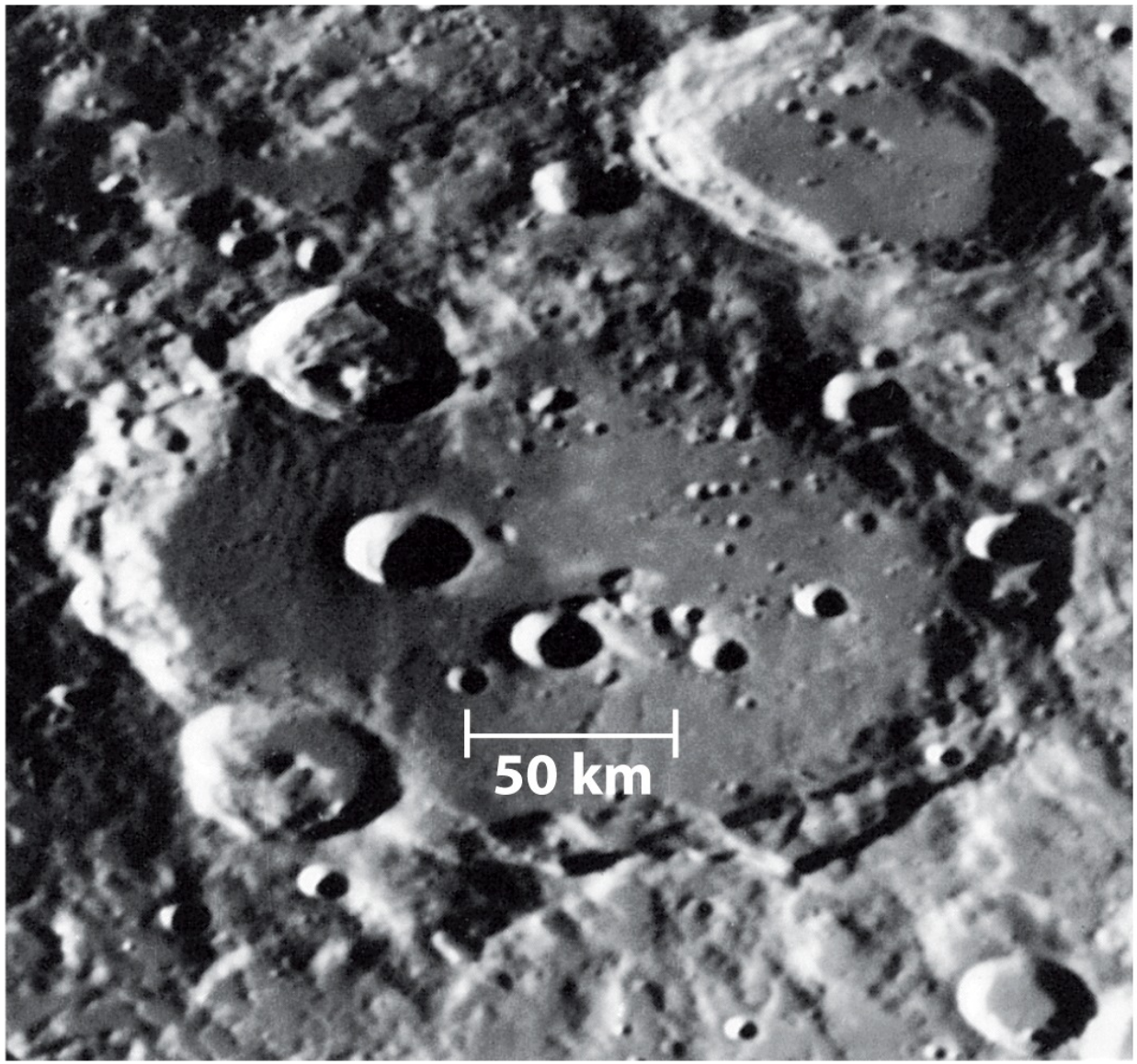


Figure 10-4
Universe, Tenth Edition
NASA

The Crater Clavius

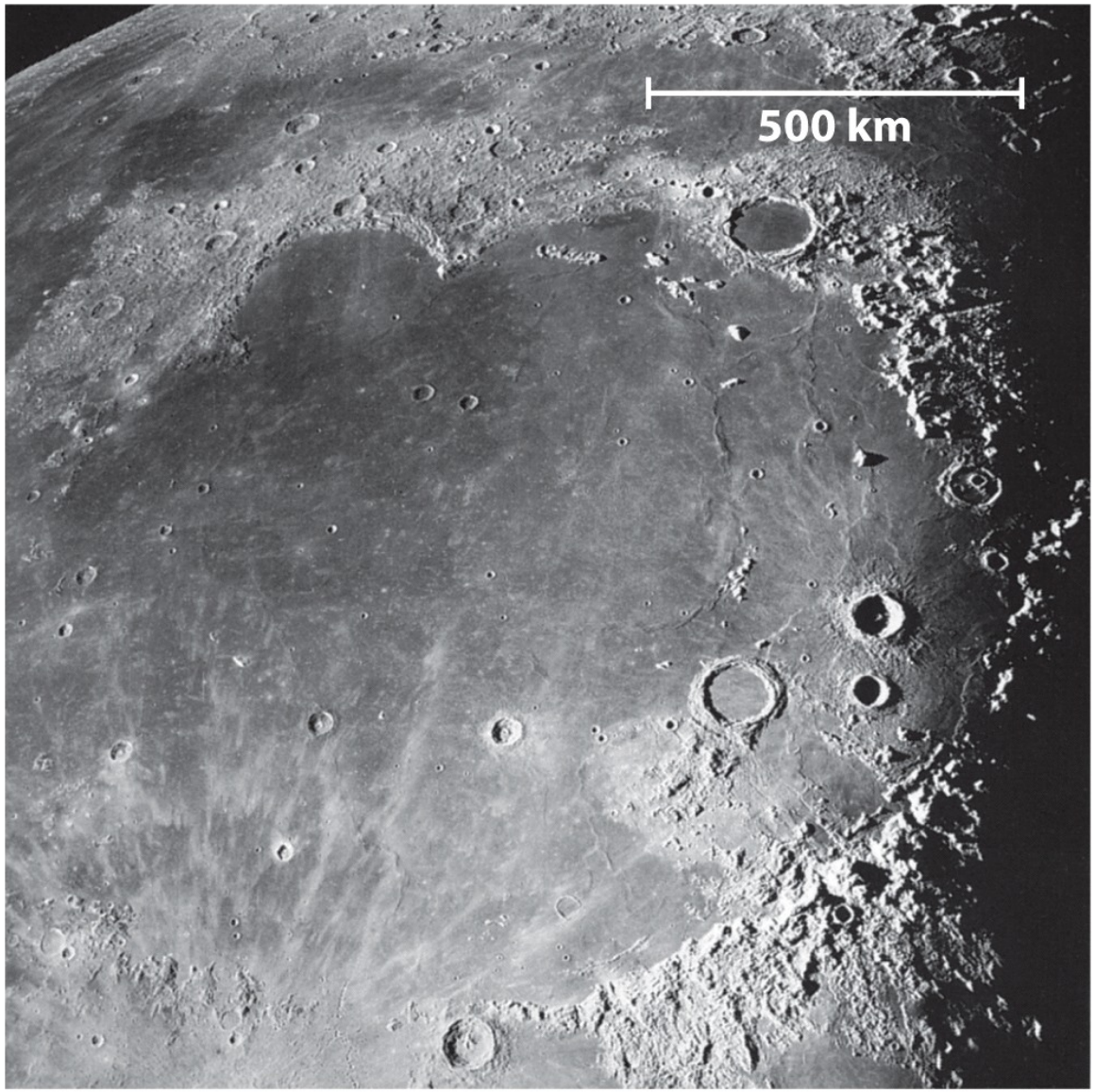


Figure 10-5
Universe, Tenth Edition
Carnegie Observatories

Mare Imbrium from Earth

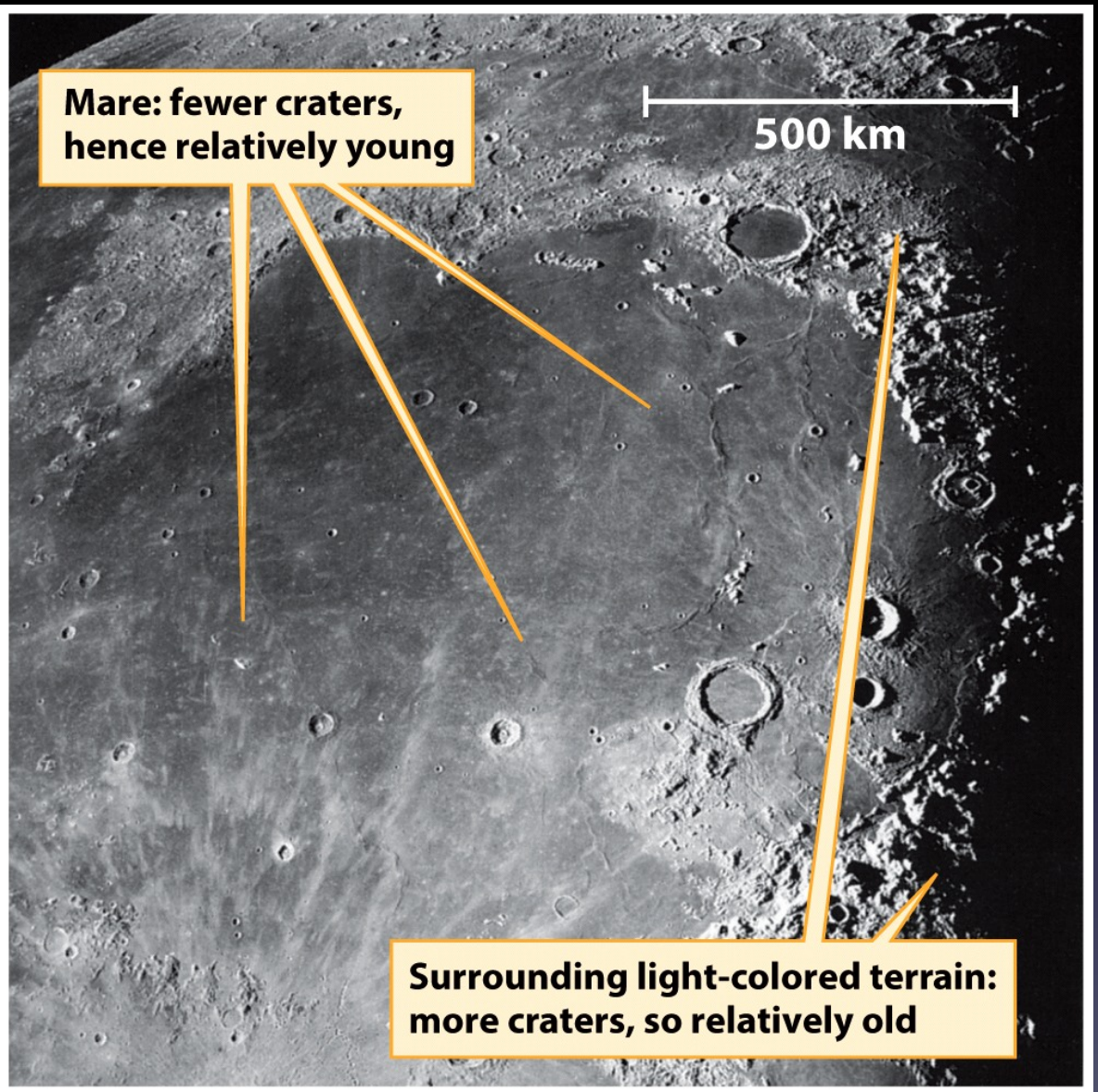
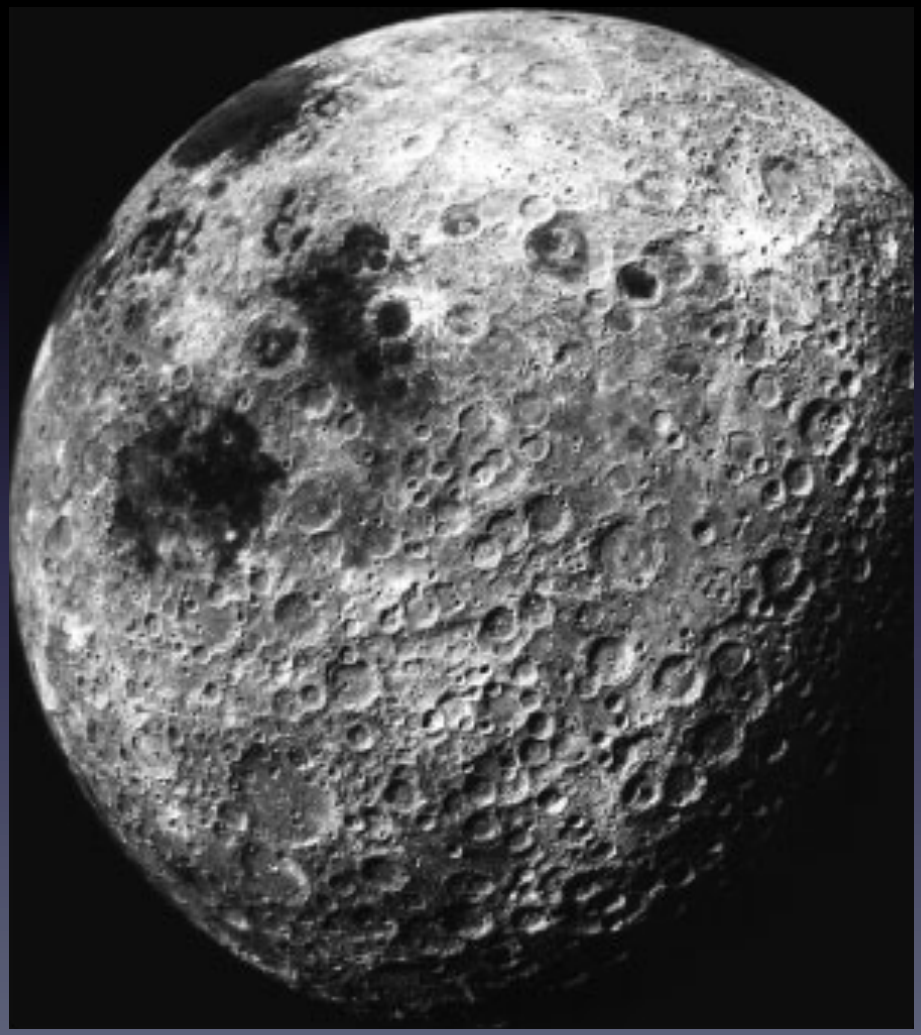


Figure 10-5
Universe, Tenth Edition
Carnegie Observatories

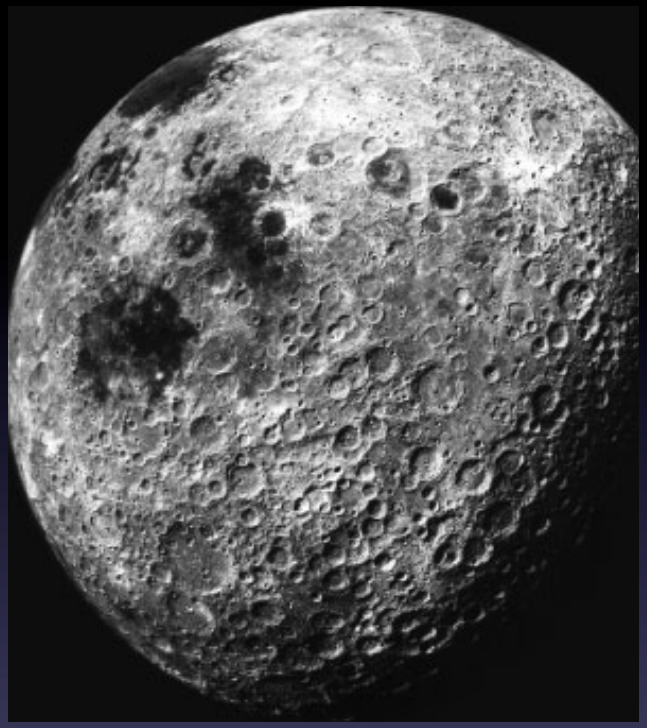
Mare Imbrium from Earth

History of Cratering

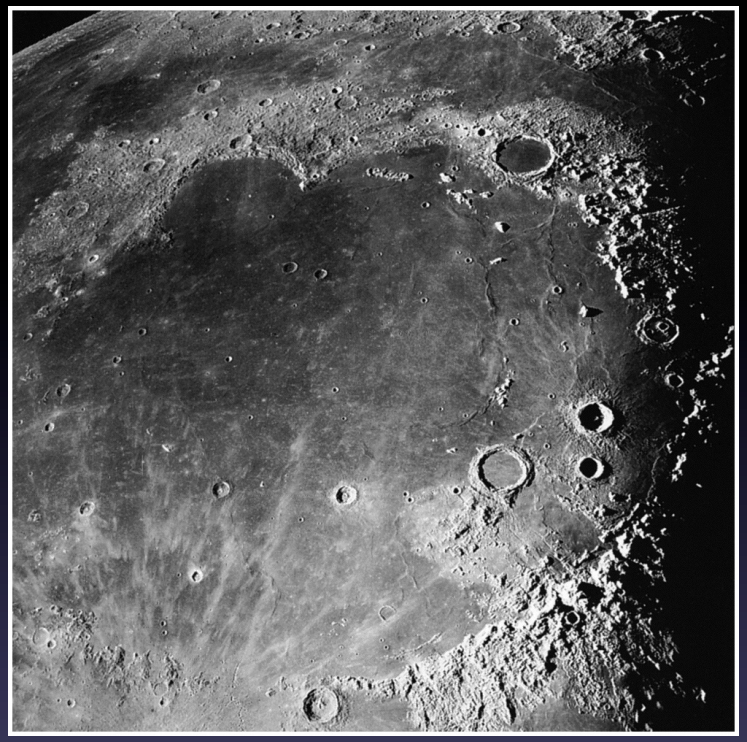


- Most cratering happened in first billion years
- A surface with many craters has not changed much in 3 billion years

Cratering



Some areas of Moon are more heavily cratered than others



Younger regions were flooded by lava after most cratering

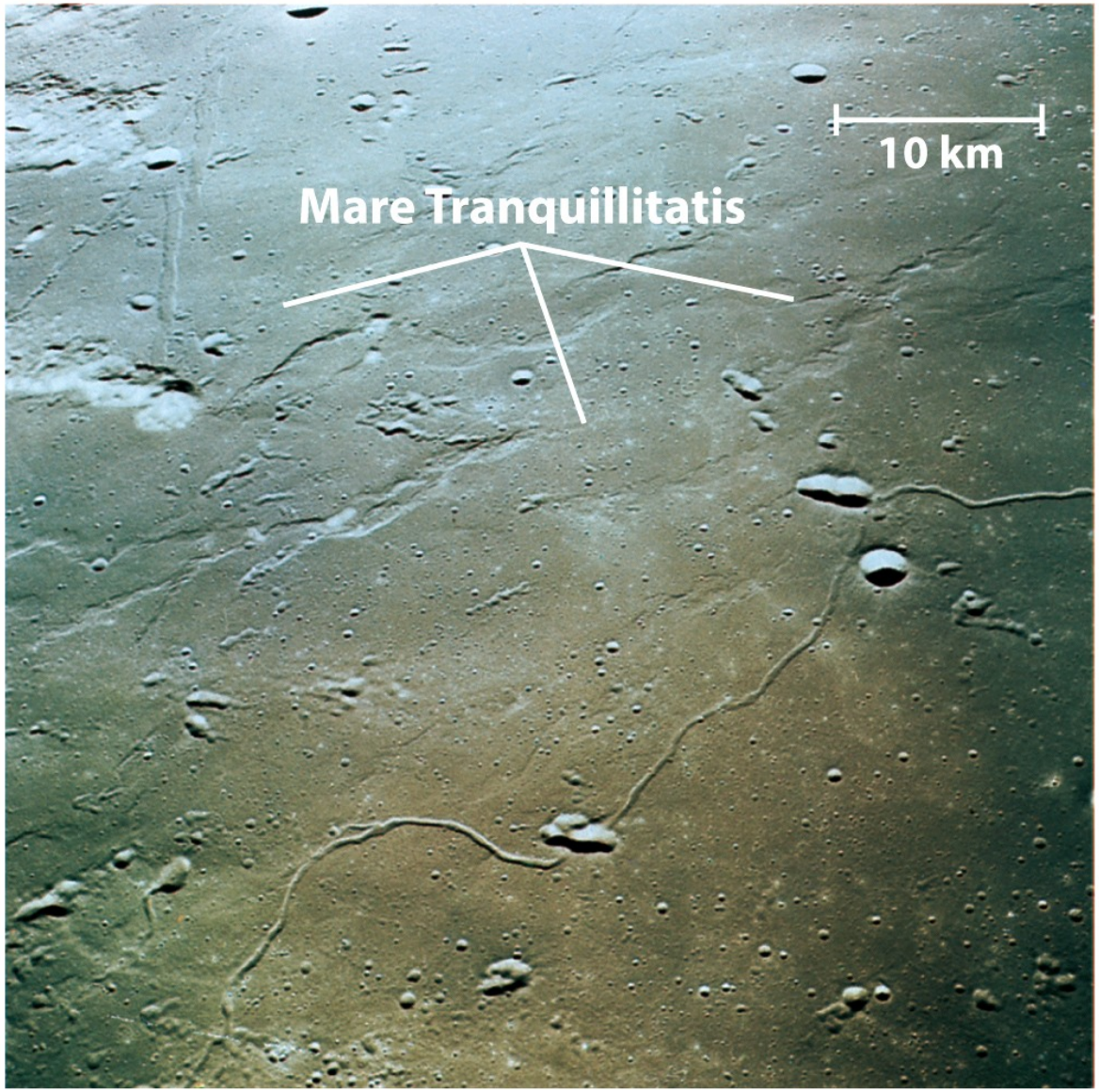


Figure 10-6
Universe, Tenth Edition
Apollo 10, NASA

Details of Mare Tranquillitatis

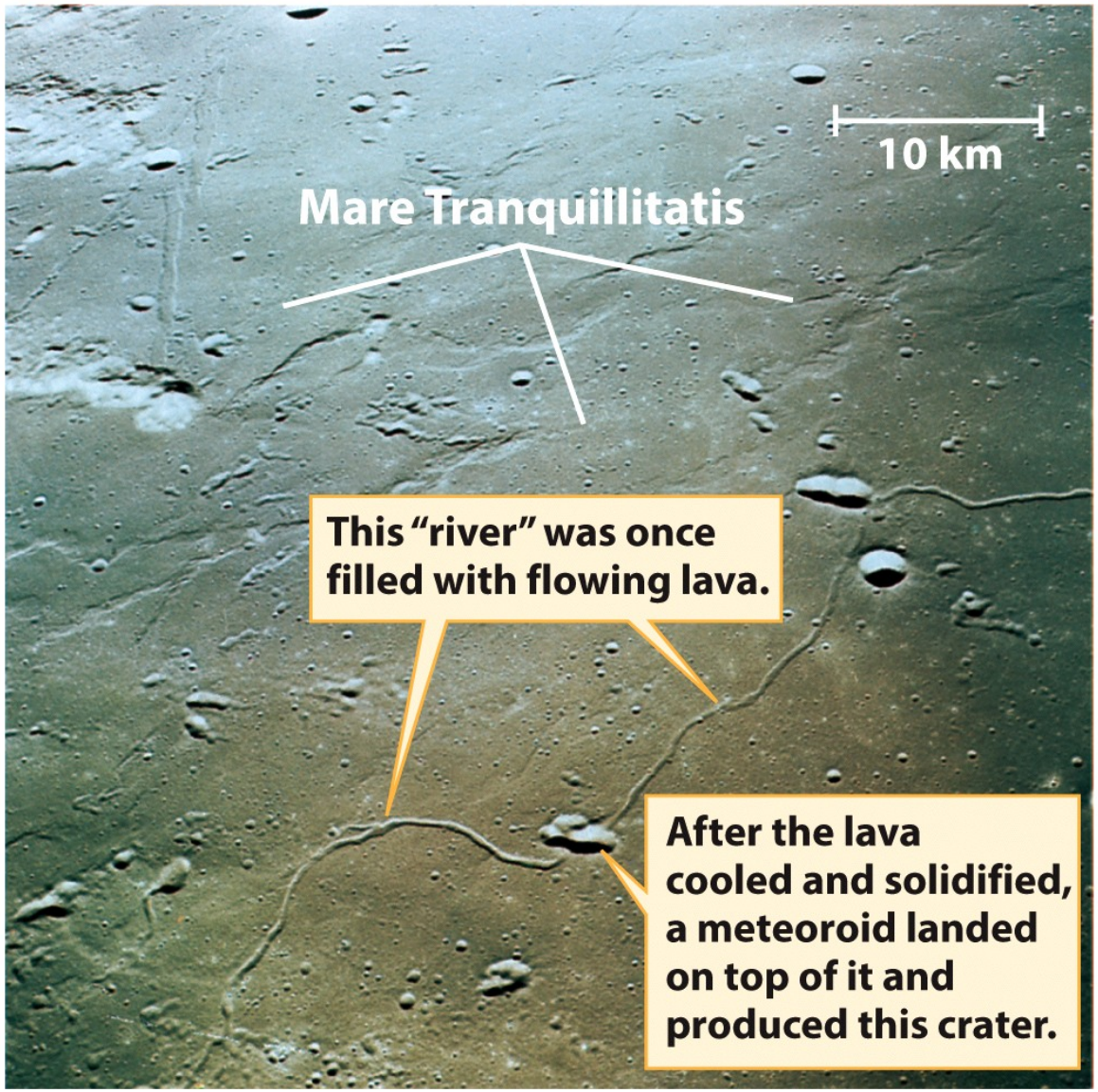
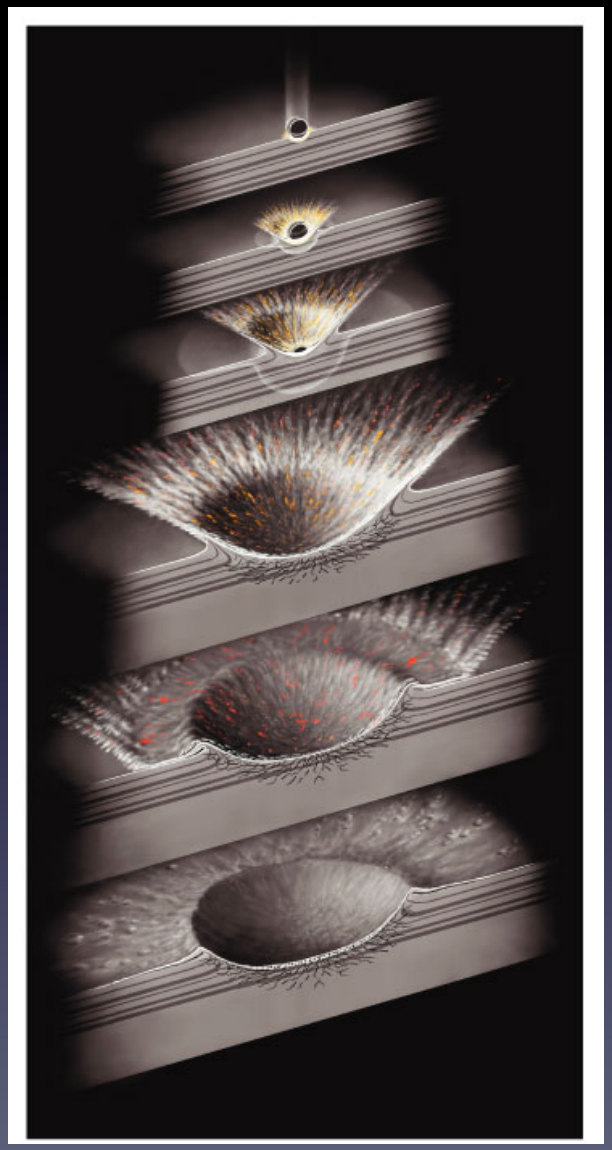


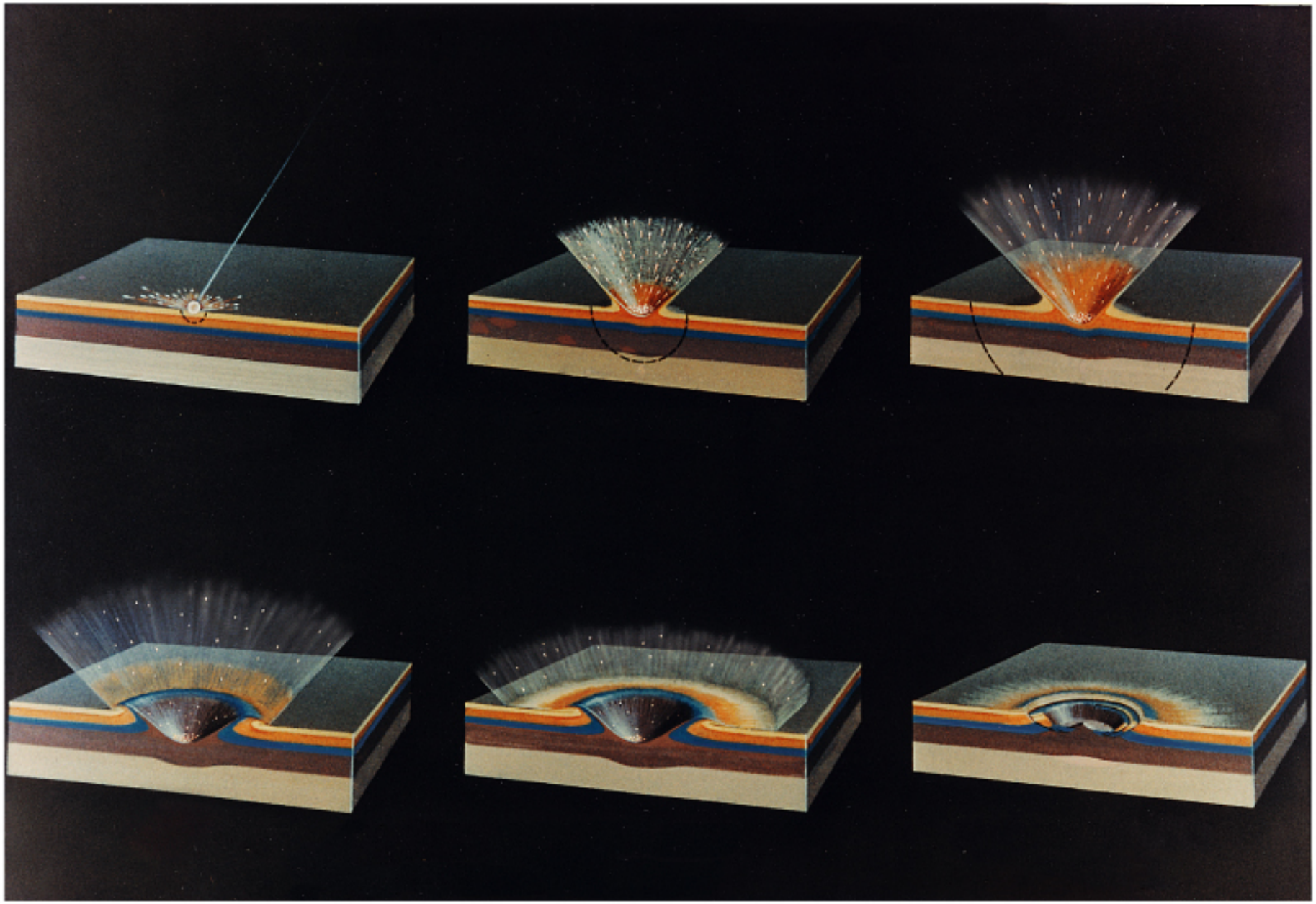
Figure 10-6
Universe, Tenth Edition
Apollo 10, NASA

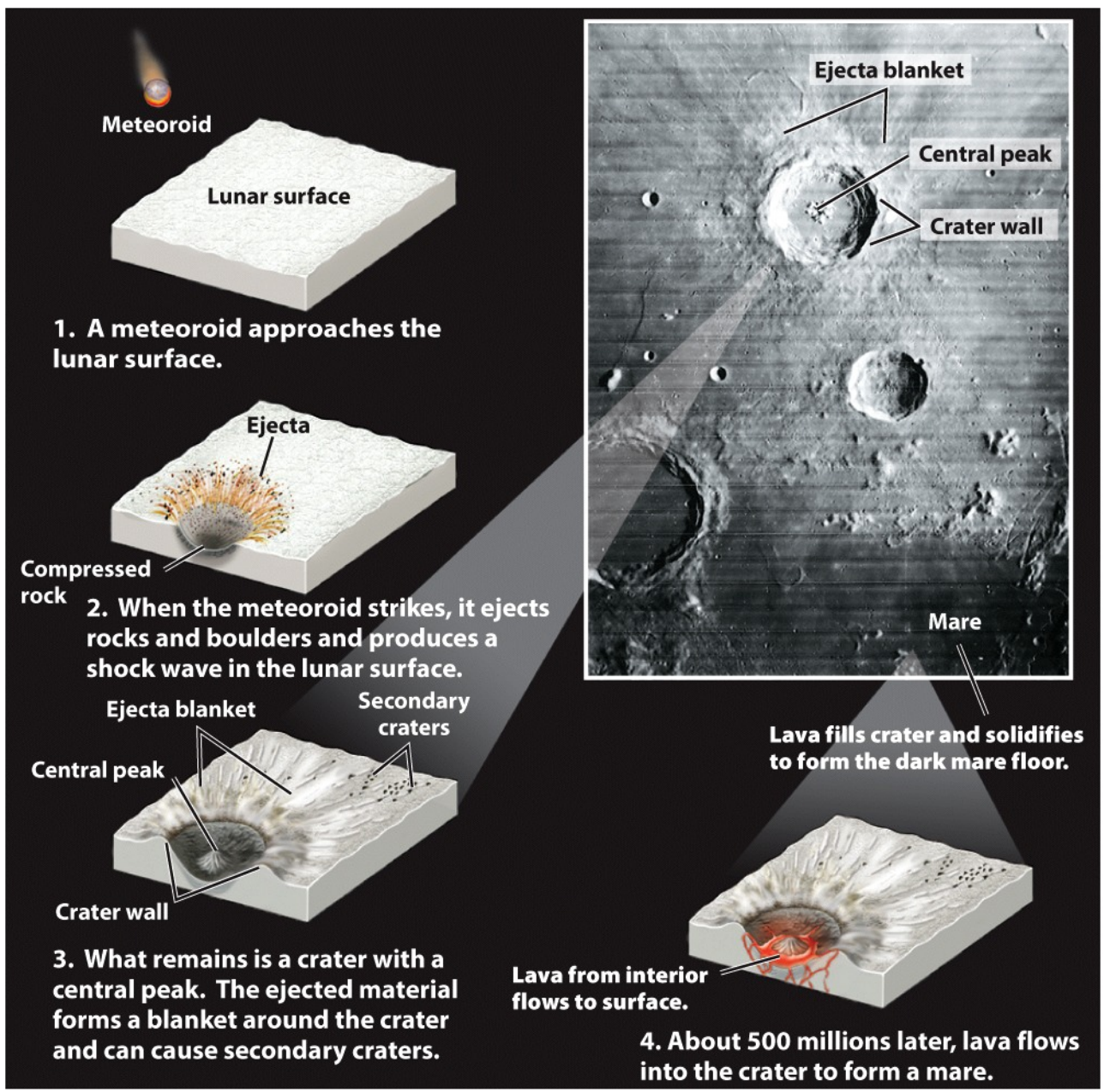
Details of Mare Tranquillitatis

1. Impact Cratering



- Most cratering happened soon after solar system formed
- Craters are about 10 times wider than object that made them
- Small craters greatly outnumber large ones



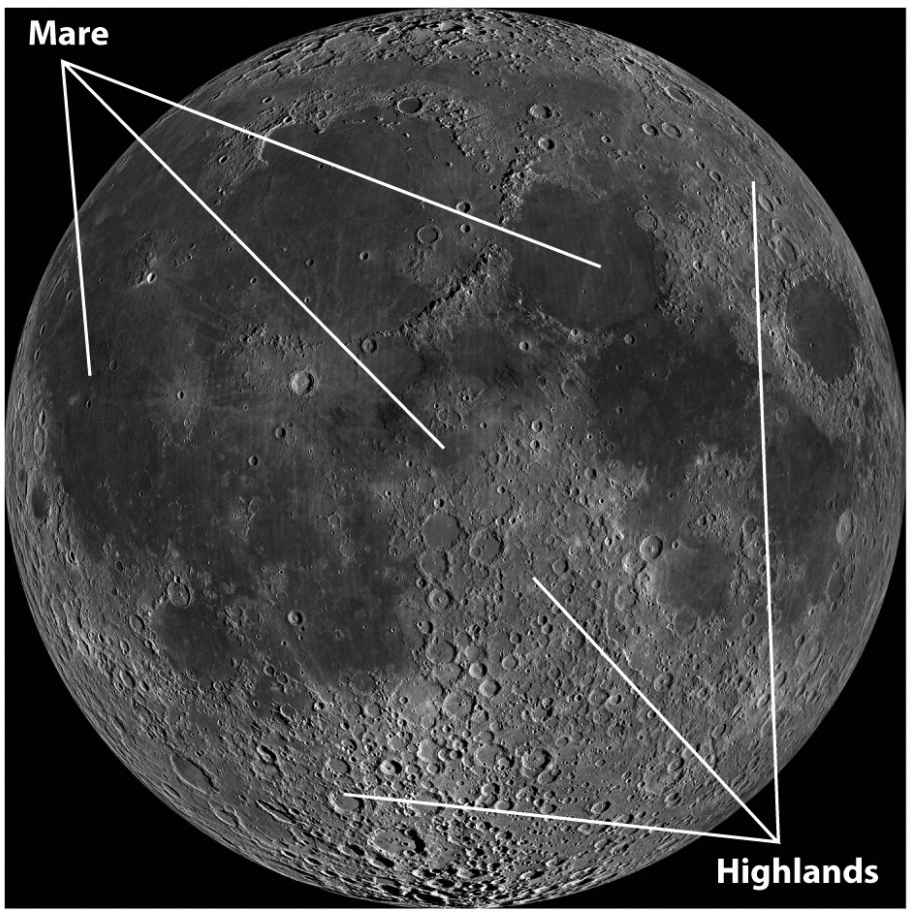


Cosmic Connections 10
Universe, Tenth Edition

The Formation of Craters and Maria on the Moon

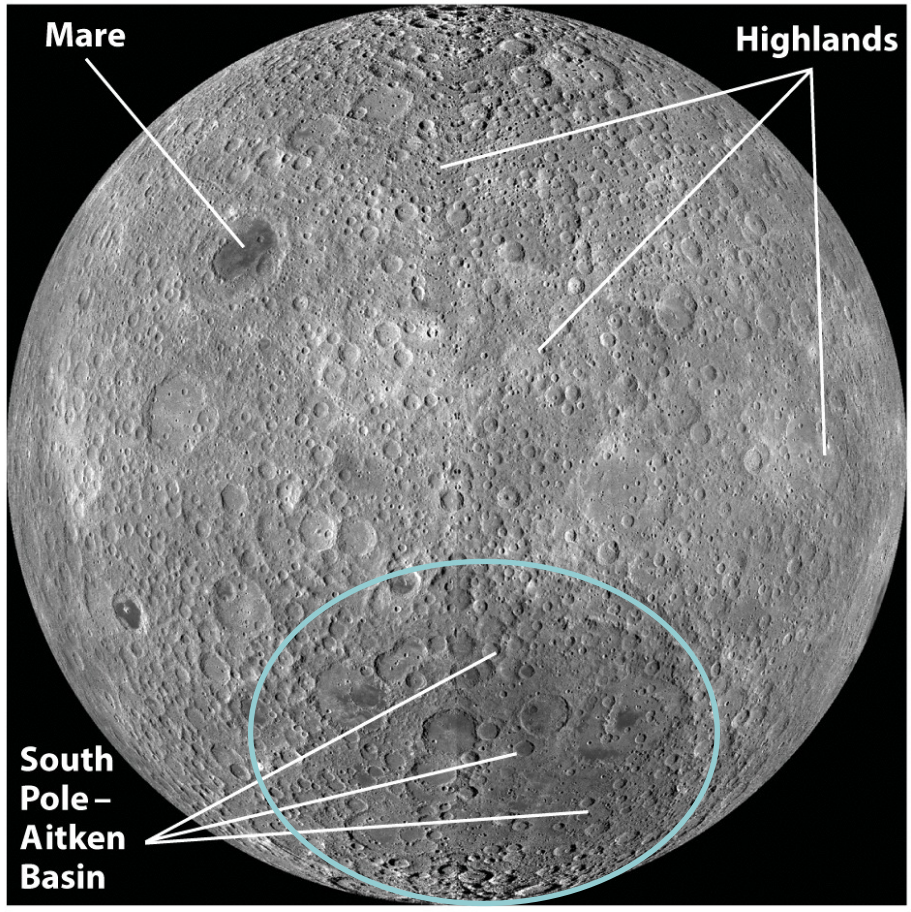

Near Side

Thicker crust on far side (?)



Near side: highlands and maria

Figure 10-7 part 1
Universe, Tenth Edition
NASA/GSFC/Arizona State Univ./Lunar Reconnaissance Orbiter



Far side: highlands but almost no maria

Figure 10-7 part 2
Universe, Tenth Edition
NASA

The Near and Far Sides of the Moon

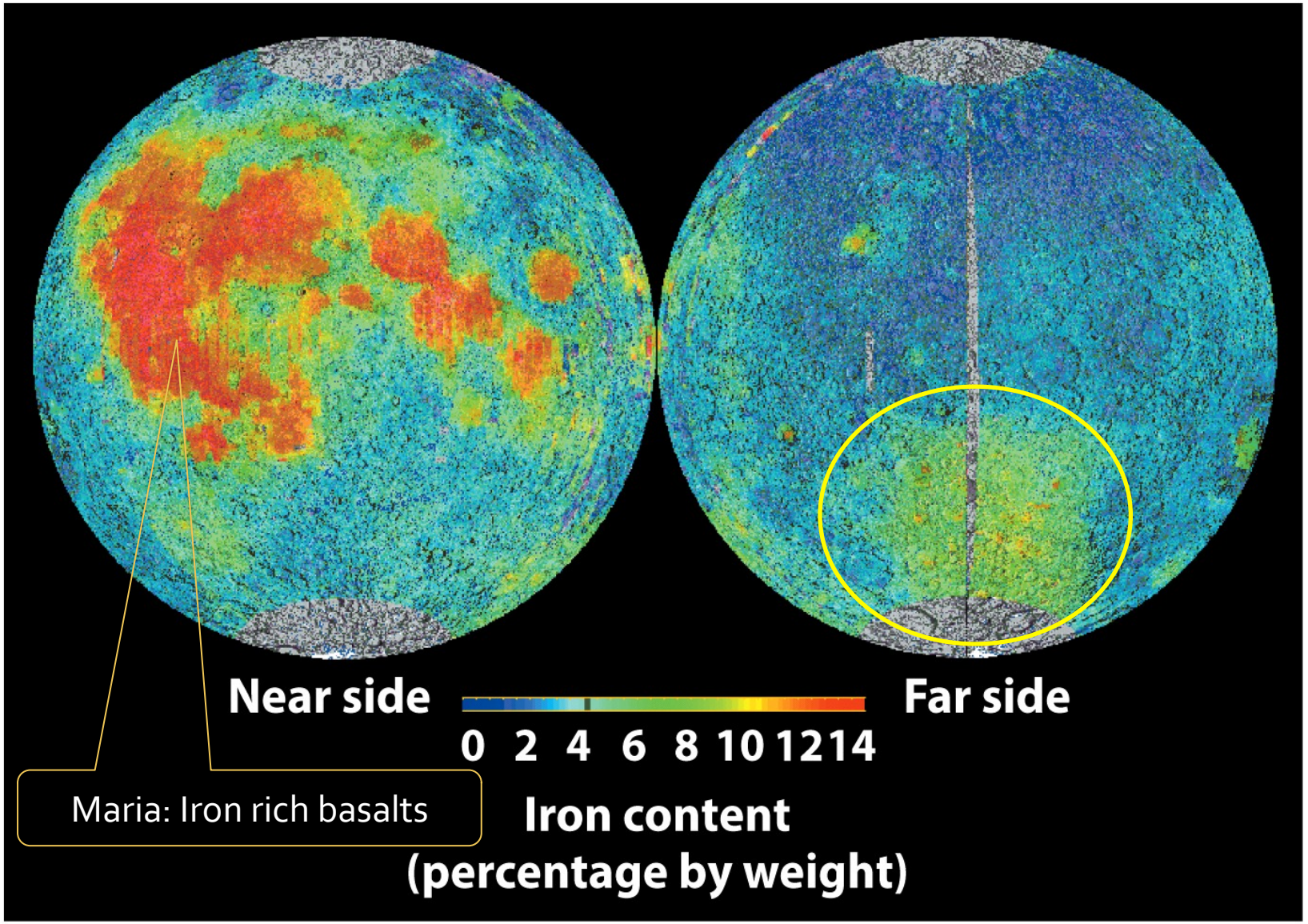
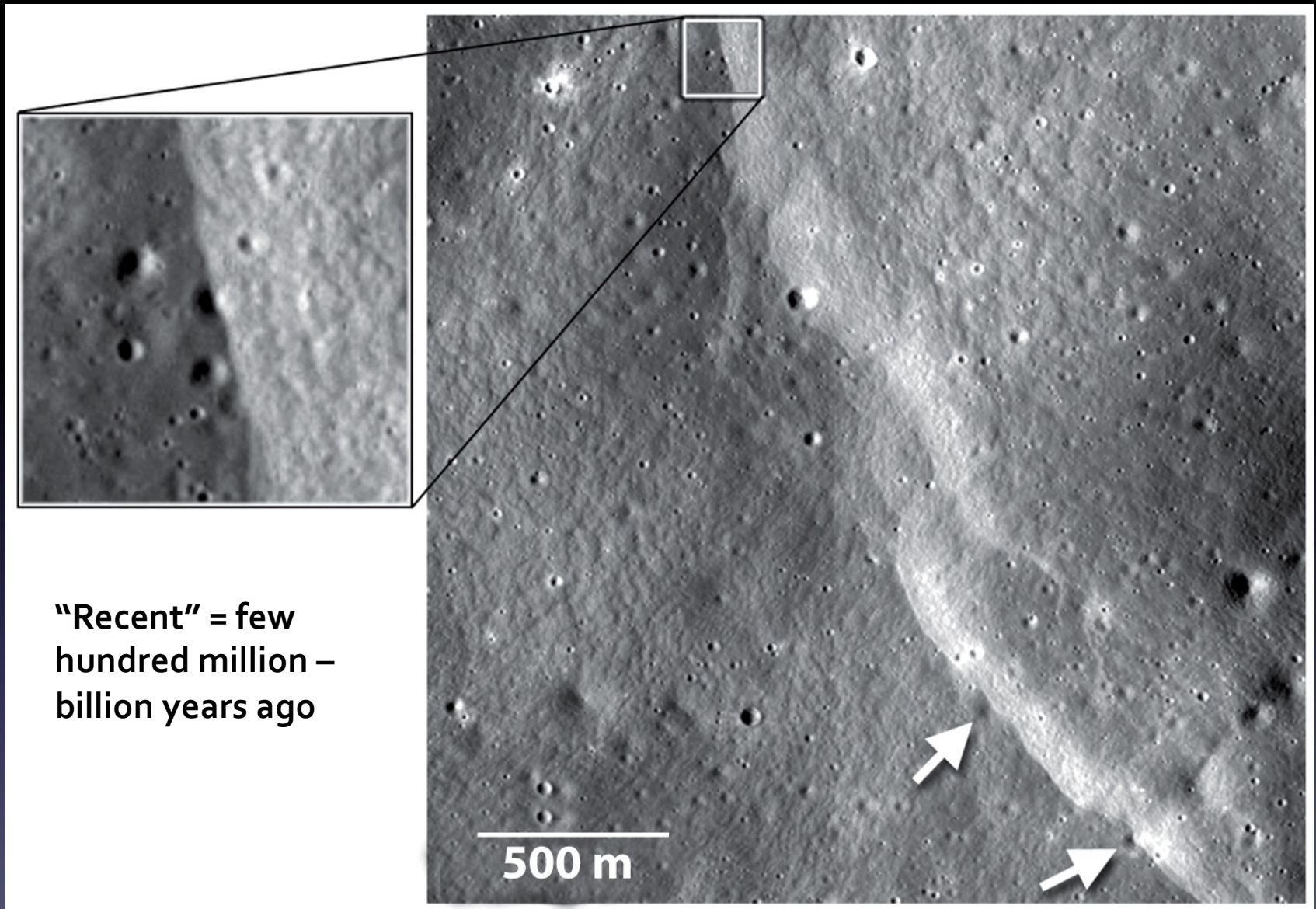


Figure 10-11
Universe, Tenth Edition
JSC/NASA

Iron on the Moon

Geologically Dead

- Moon is considered mostly geologically "dead" because geological processes have virtually stopped



"Recent" = few hundred million – billion years ago

Figure 10-8
Universe, Tenth Edition
NASA

Recent Geologic Activity of Scarps

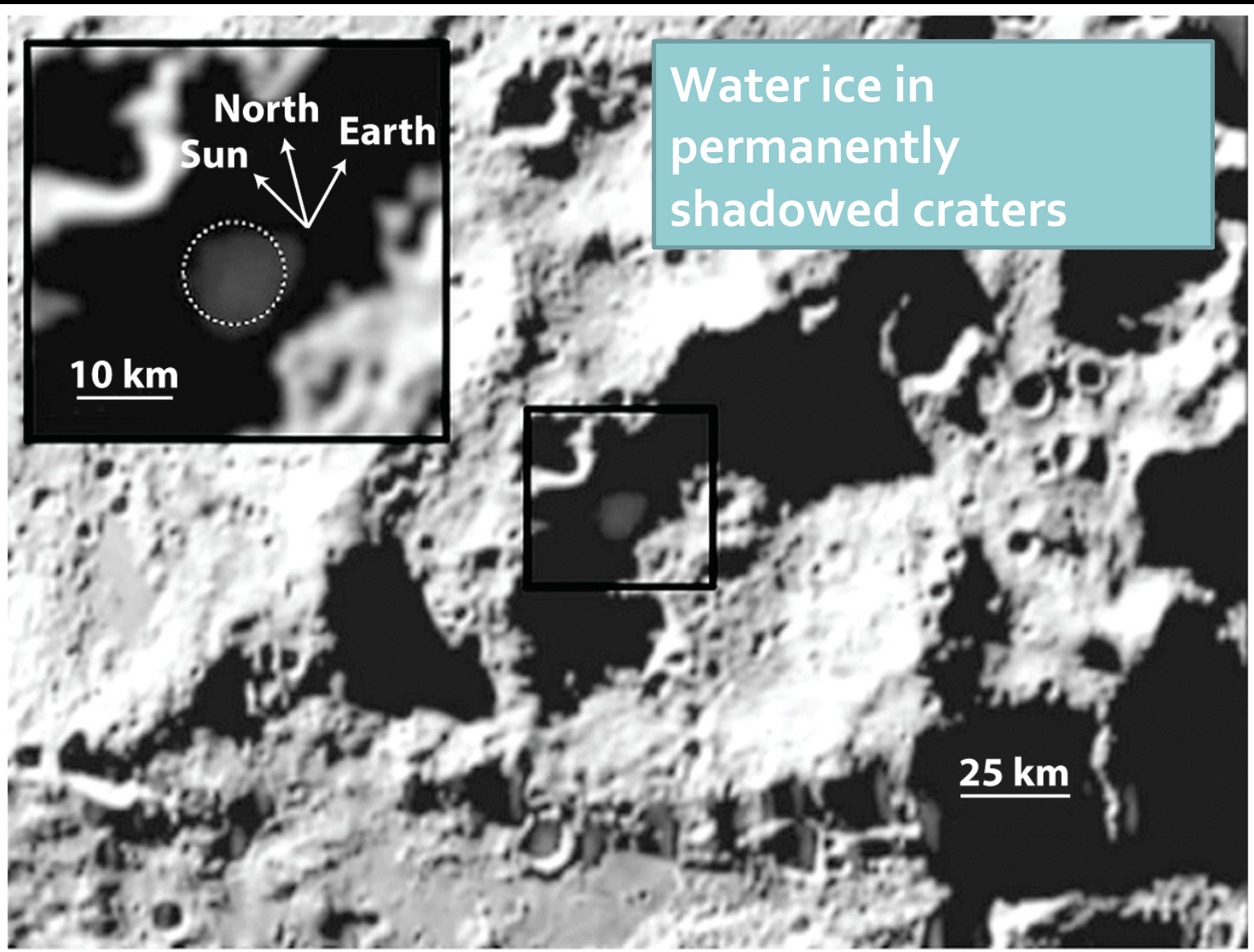


Figure 10-12
Universe, Tenth Edition
NASA

Water in the Plume Created by LCROSS

10-2: Human exploration of the Moon in the 1960s and 1970s has been continued by robotic spacecraft

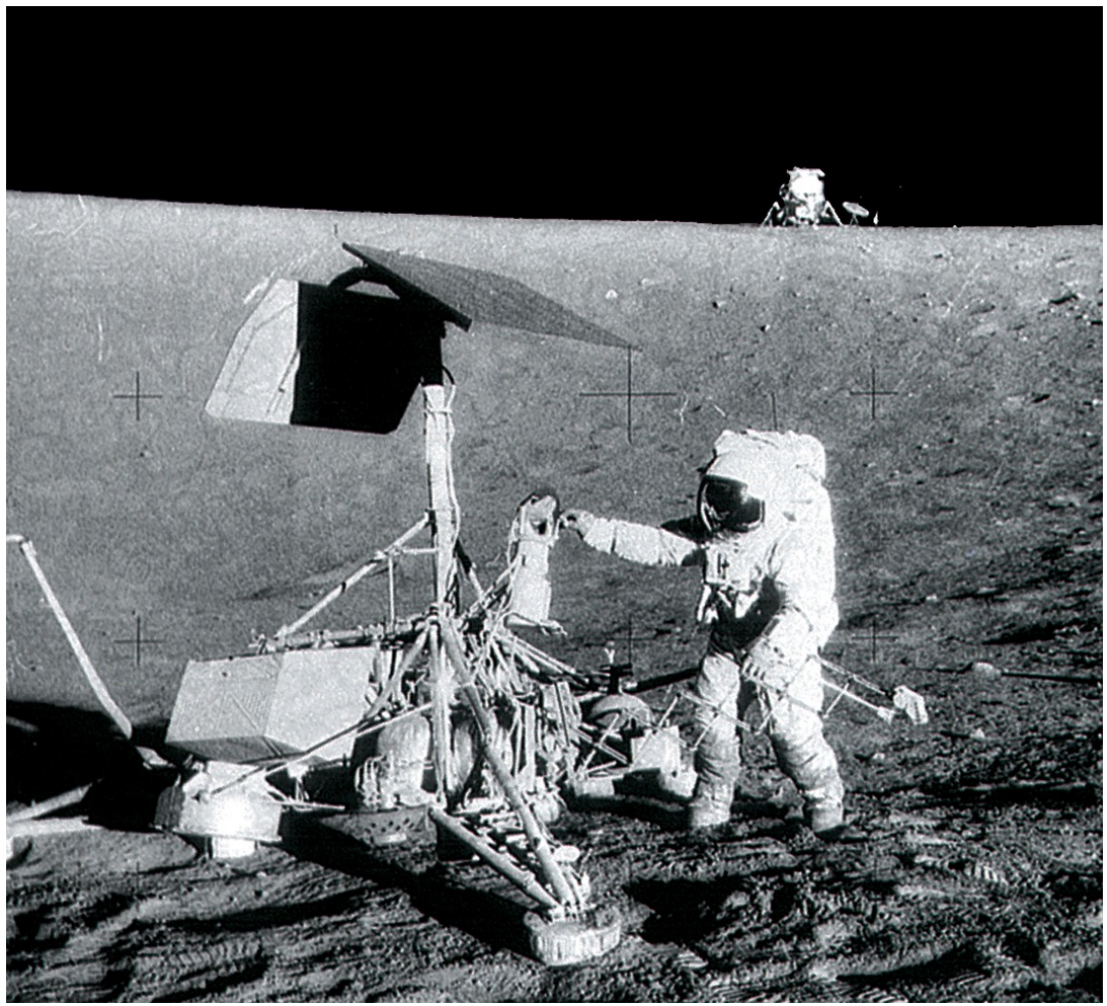


Figure 10-9
Universe, Tenth Edition
Pete Conrad, *Apollo 12*, NASA

Visiting an Unmanned Pioneer

Humans on the Moon: six landings between 1969 - 1972

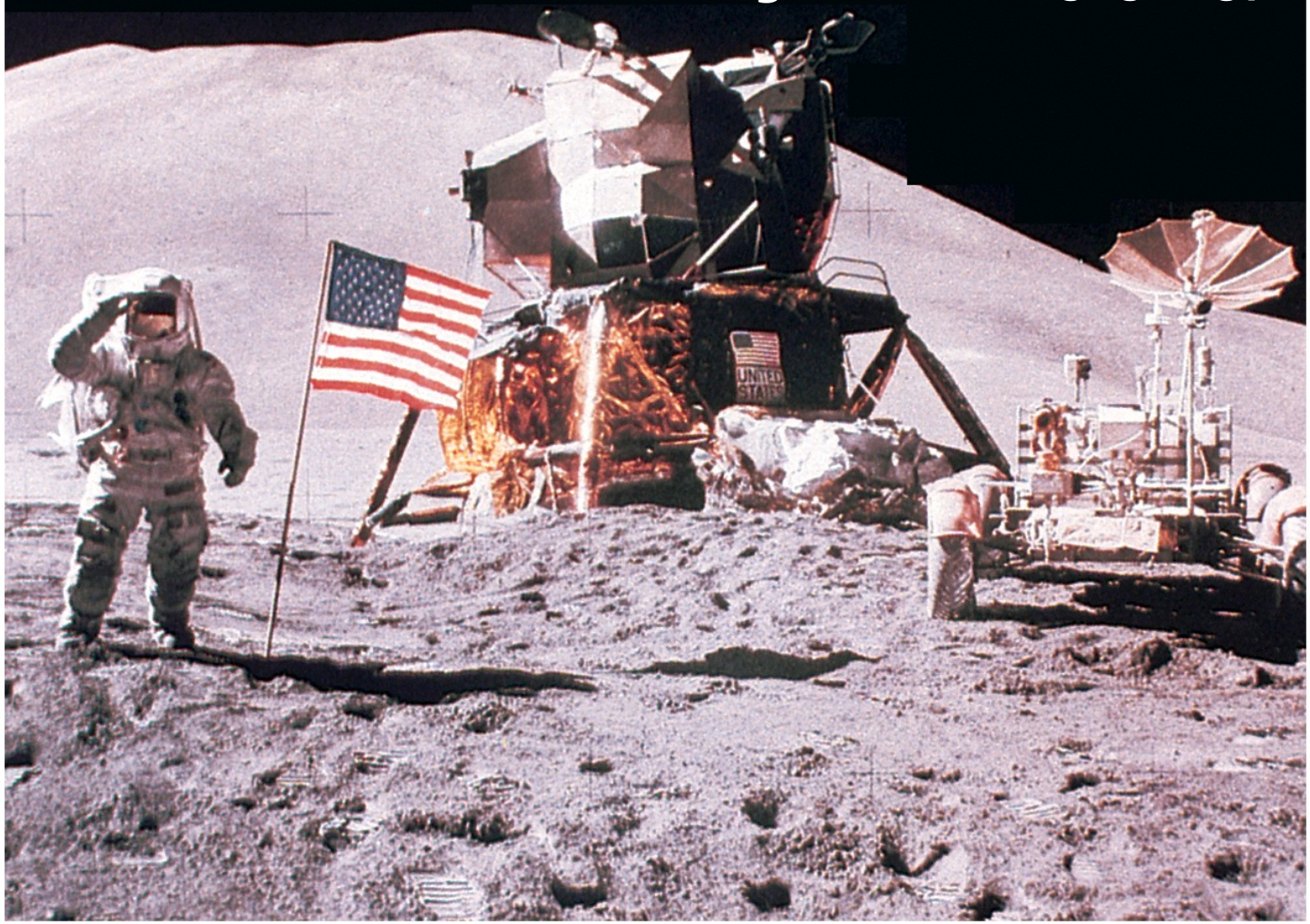


Figure 10-10
Universe, Tenth Edition
Dave Scott, *Apollo 15*, NASA

The *Apollo 15* Base

10-3: The Moon has no global magnetic field but has a small molten core

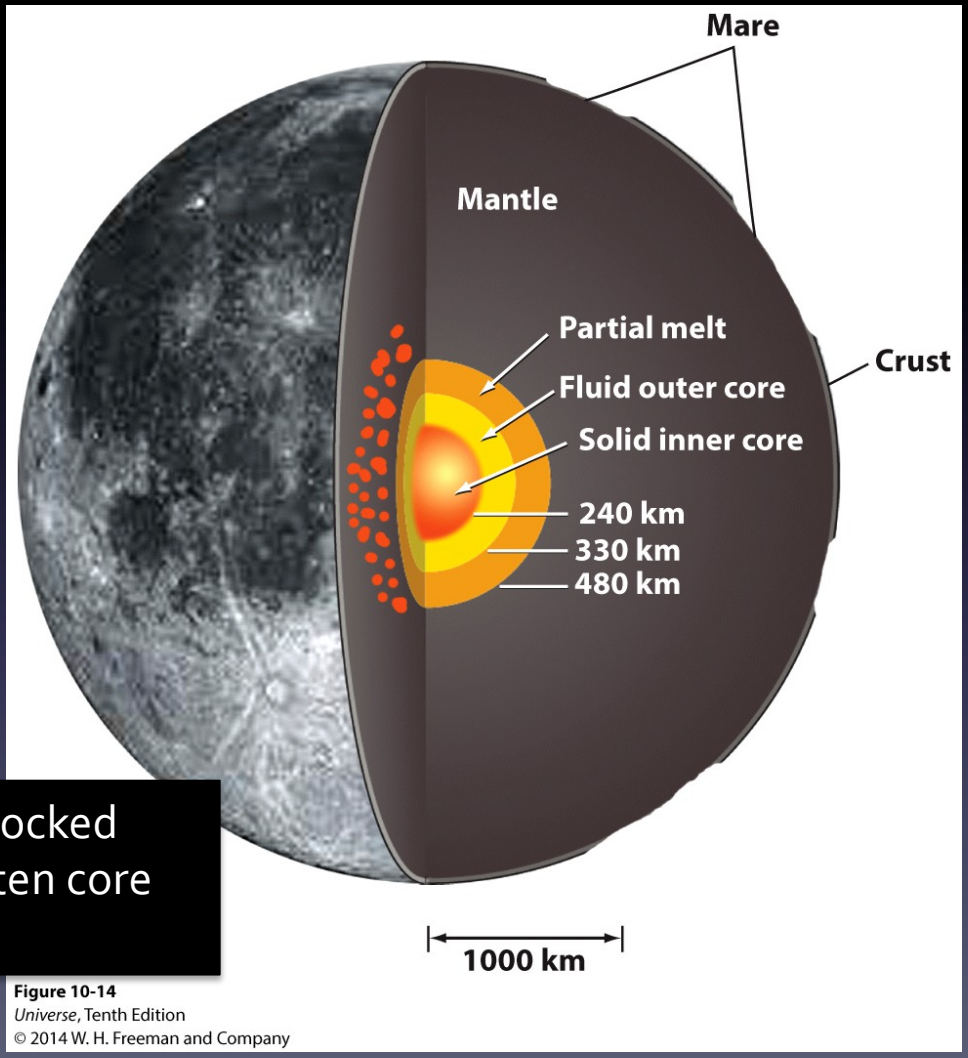


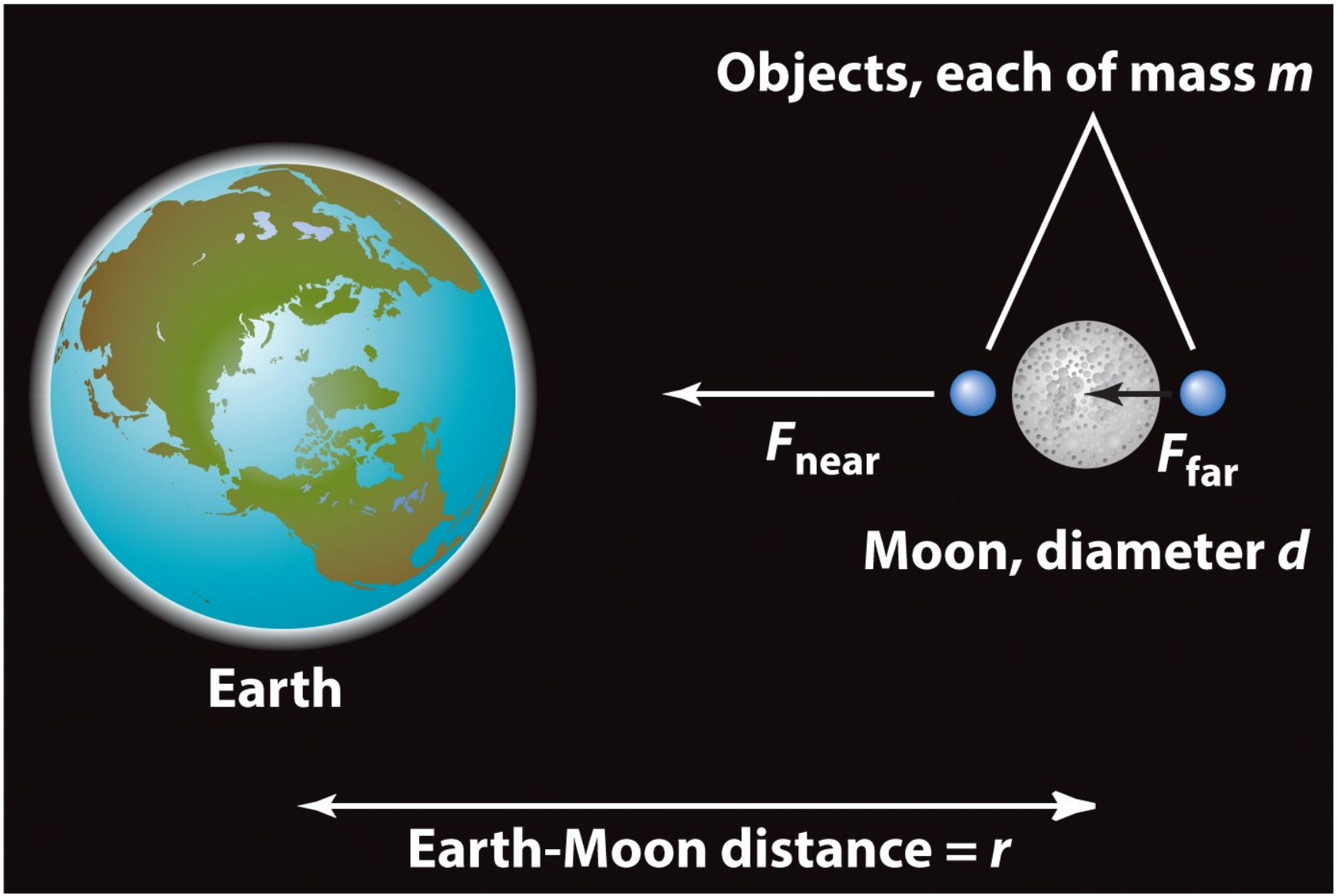
Figure 10-14
Universe, Tenth Edition

Weak remnant fields locked into rocks: larger molten core region in past

The Internal Structure of the Moon

Moonquakes

- Four seismometers set up on surface
- ~3000 moonquakes/year
- Very weak: 0.5 – 1.5 Richter scale
- Core offset slightly to one side; part is still molten
- Most occur when Moon is at perigee: From tidal stresses exerted by Earth
- Some from impacts



Box 10-1
Universe, Tenth Edition

Calculating Tidal Forces

10-4: Lunar rocks reveal a geologic history quite unlike that of Earth

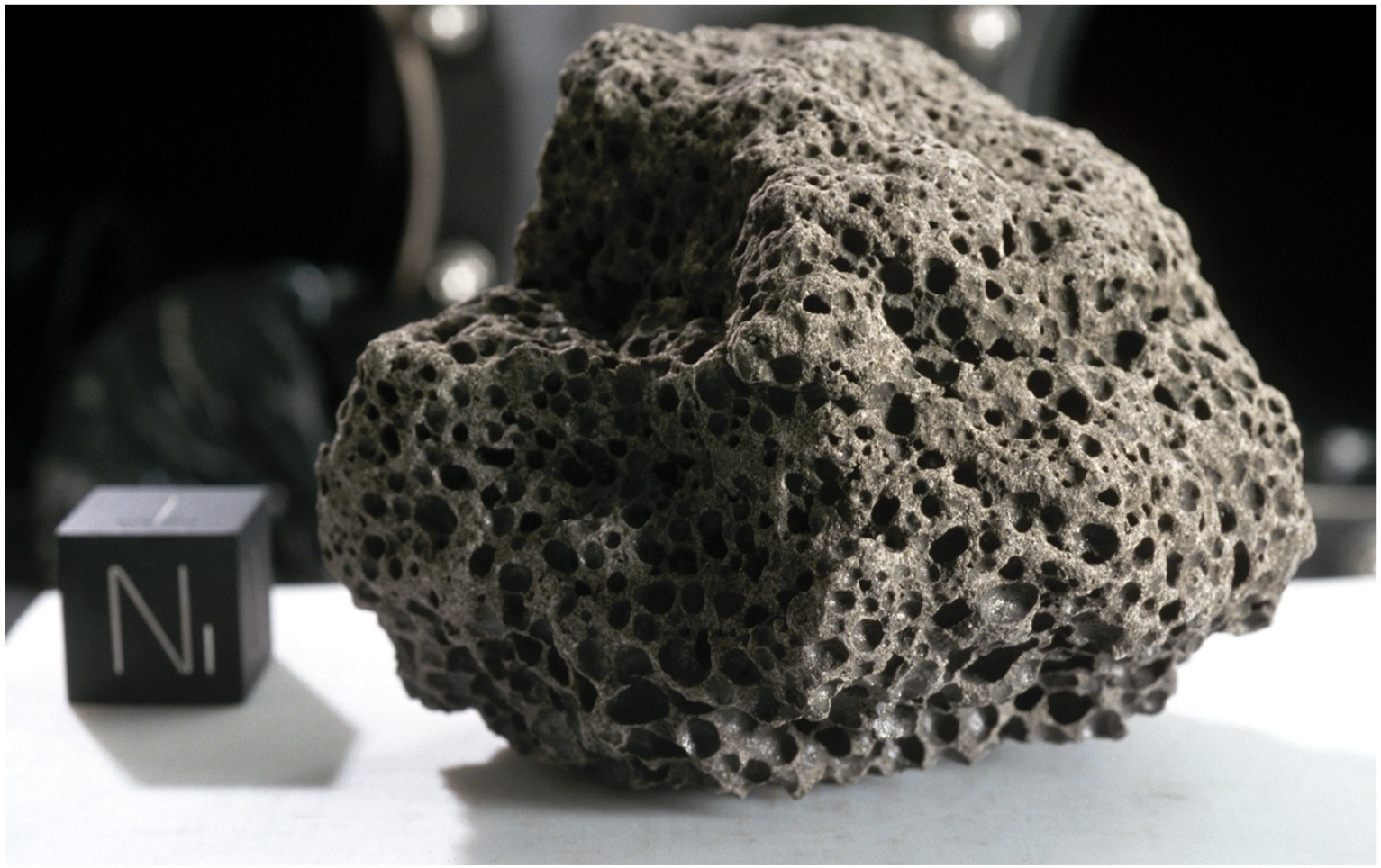


Figure 10-16
Universe, Tenth Edition
NASA

Mare Basalt

Lunar Surface: powdered rocks from micrometeorite impacts

Figure 10-15
Universe, Tenth Edition
Apollo 11, NASA

The Regolith

All lunar rocks are igneous

Figure 10-16
Universe, Tenth Edition
NASA

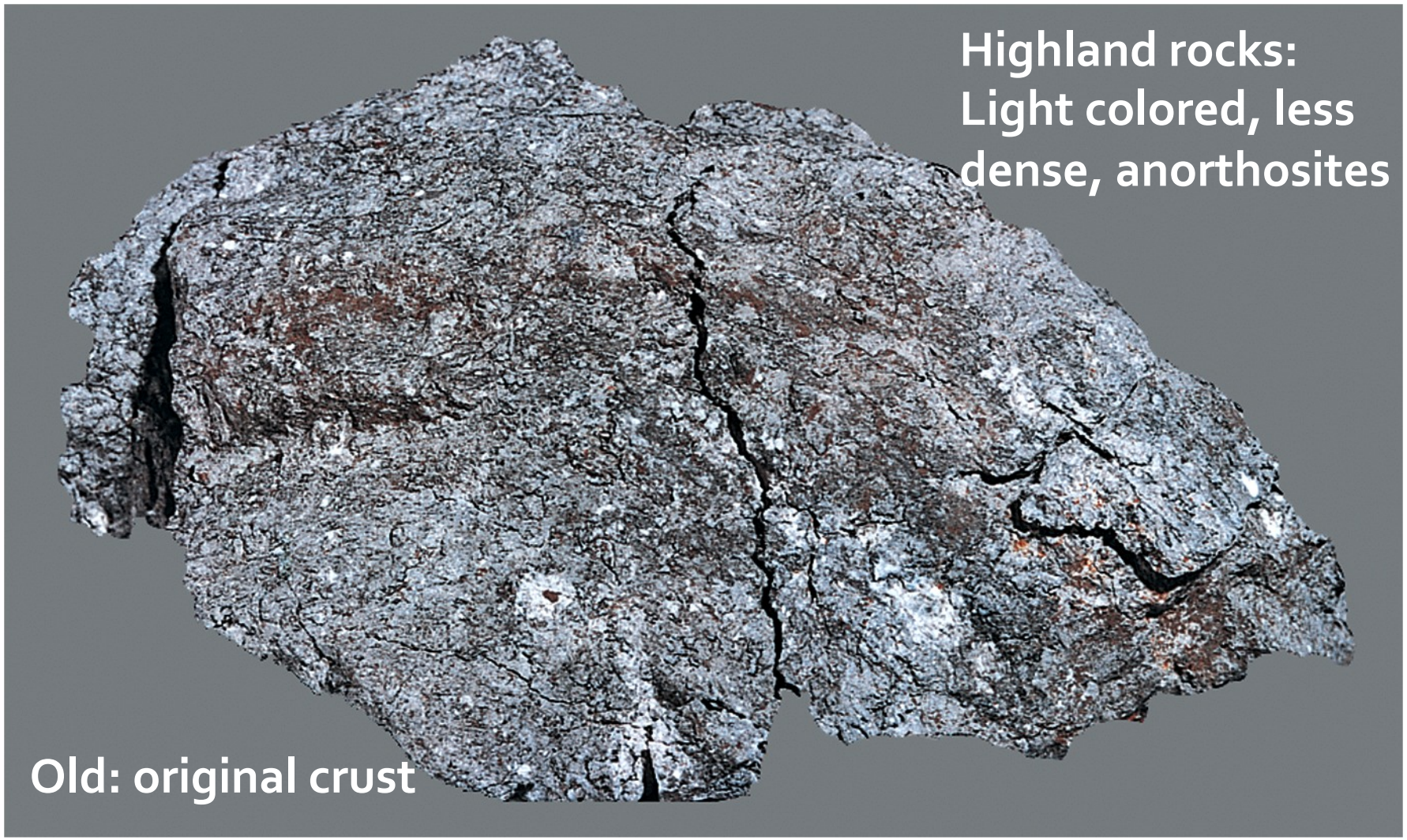


Figure 10-17
Universe, Tenth Edition
NASA

Anorthosite

Highland Impact Breccias: combination of fused rocks

Figure 10-18
Universe, Tenth Edition
NASA

Impact Breccias

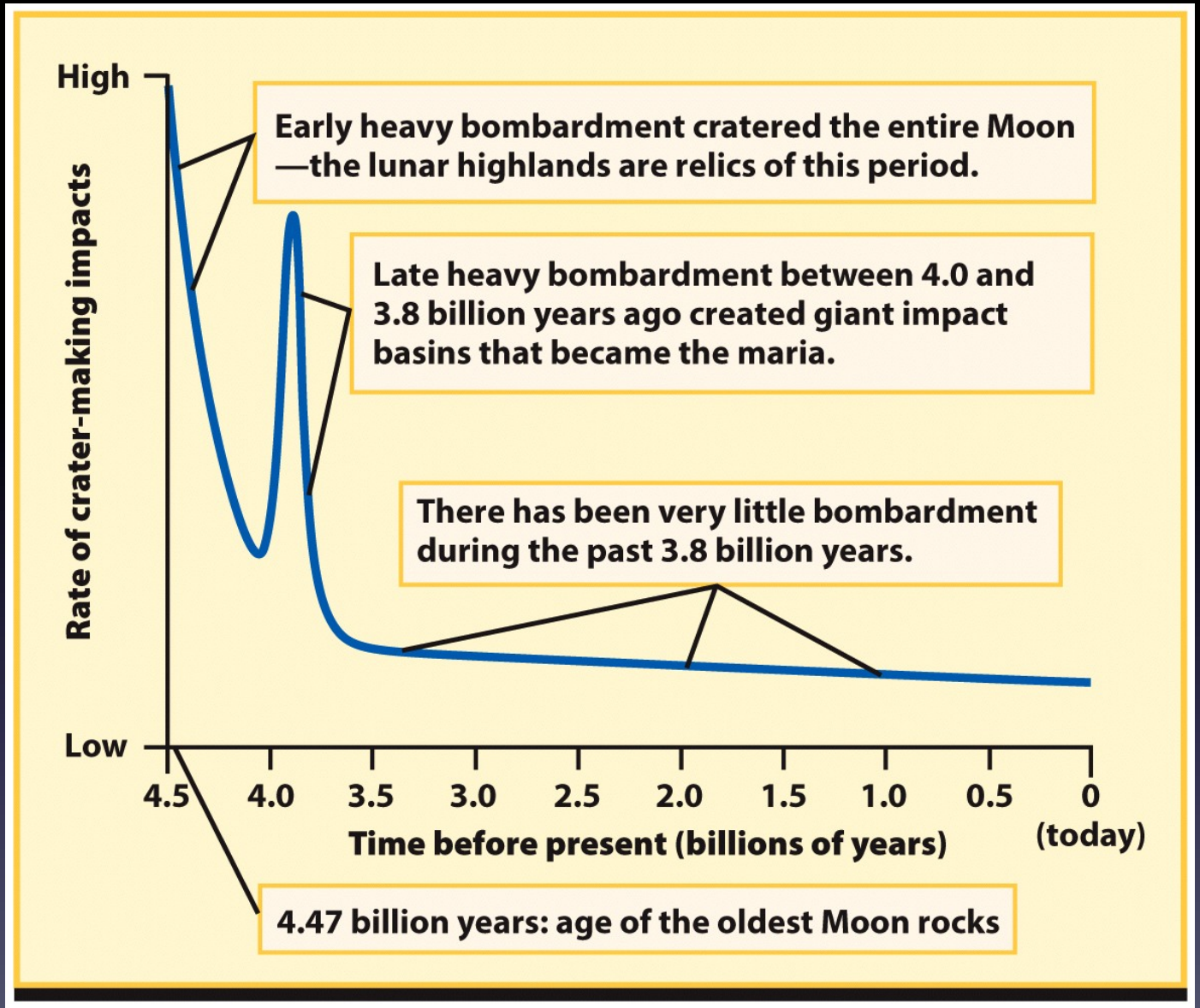


Figure 10-19
Universe, Tenth Edition
Adapted from T. Grotzinger, T. H. Jordan, F. Press, and R. Siever, *Understanding Earth*, 5th ed., W. H. Freeman, 2007

The Rate of Crater Formation on the Moon

10-5: The Moon probably formed from debris cast into space when a huge protoplanet struck the young Earth

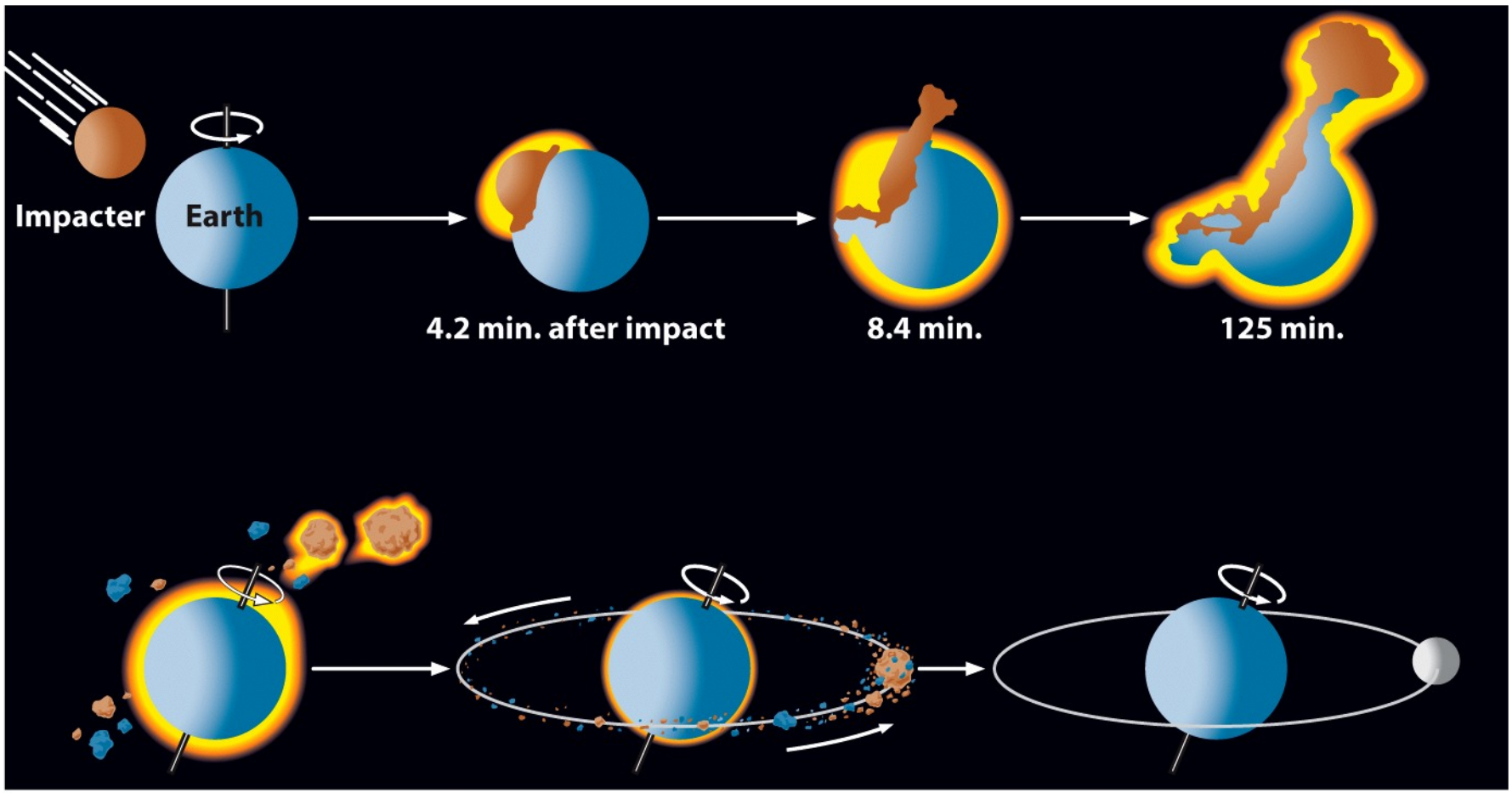


Figure 10-21
Universe, Tenth Edition
Adapted from T. Grotzinger, T. H. Jordan, F. Press, and R. Siever, *Understanding Earth*, 5th ed., W. H. Freeman, 2007

The Formation of the Moon

Lunar Formation

- Observations to be explained:
  - All rocks are igneous (once molten)
  - Lunar rocks are lacking volatile elements (easily vaporized)
  - Moon's density less than Earth's (3300 kg/m^3 vs. 5500 km/m^3)

Formation Theories

- Fission: spun off outer layers of faster-rotating Earth
  - Rocks should be like Earth rocks
- Captured into orbit
  - requires fine-tuning of motions
- Co-creation: formed from lots of smaller rocks
  - Why wouldn't they have accreted onto Earth?

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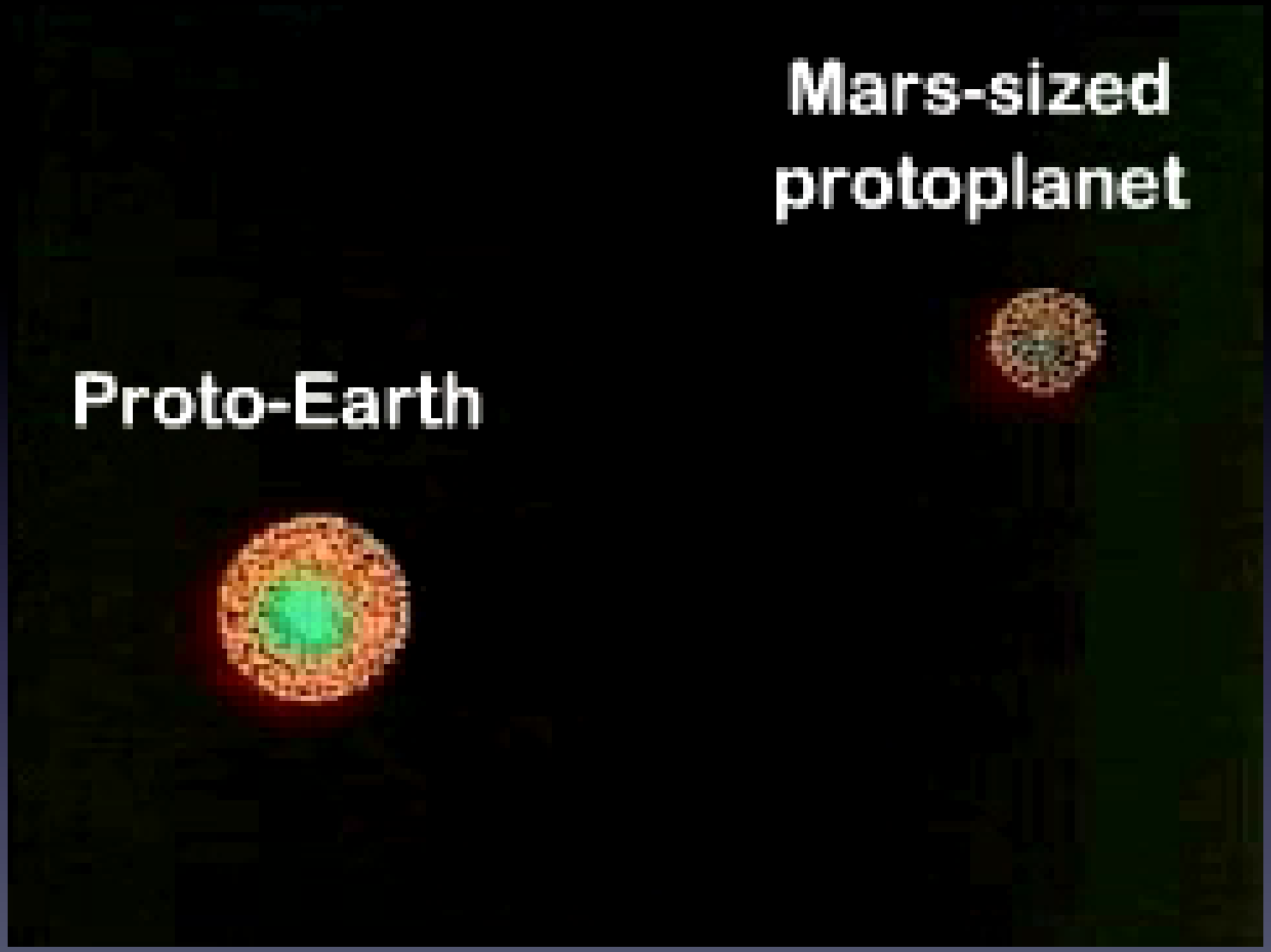
- ~~Captured into orbit~~
  - ~~requires fine-tuning of motions~~
- ~~Co-creation: formed from lots of smaller rocks~~
  - ~~Why wouldn't they have accreted onto Earth?~~

Formation Theories

- Collisional Ejection: Moon formed from debris ejected by large impactor
  - Great heating episode
  - Less dense outer layers ejected


Mars-sized
protoplanet
Proto-Earth

Key Ideas

- **Appearance of the Moon:** 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.
- Virtually all lunar craters were caused by space debris striking the surface. There is no evidence of plate tectonic activity on the Moon.

Key Ideas

- **Internal Structure of the Moon:** 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.
- Analysis of seismic waves and other data indicates that the Moon has a crust thicker than that of the Earth (and thickest on the far side of the Moon), a thick mantle, and a small iron core.
- The Moon has a solid inner core surrounded by a liquid outer core

Key Ideas

- The Moon has no global magnetic field today, although it had a weak magnetic field billions of years ago.
- **Geologic History of the Moon:** The anorthositic crust exposed in the highlands was formed between 4.3 and 4.0 billion years ago.
- The late heavy bombardment formed the maria basins between 4.1 and 3.8 billion years ago, and the mare basalts solidified between 3.8 and 3.1 billion years ago.
- The Moon's surface has undergone very little change over the past 3 billion years.

Key Ideas

- Meteoroid impacts have been the only significant "weathering" agent on the Moon. These weathering processes formed the Moon's regolith, or surface layer of powered and fractured rock
- All of the lunar rock samples are igneous rocks formed largely of the same minerals found in terrestrial rocks on Earth. However, material in lunar rocks appears to have been exposed to higher temperatures than terrestrial rocks.

Key Ideas

- **Origin of the Moon:** The collisional ejection theory of the Moon's origin 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.
- Tidal interactions between the Earth and Moon are slowing the Earth's rotation and pushing the Moon away from the Earth. This also causes the length of the Earth's day to slowly increase.