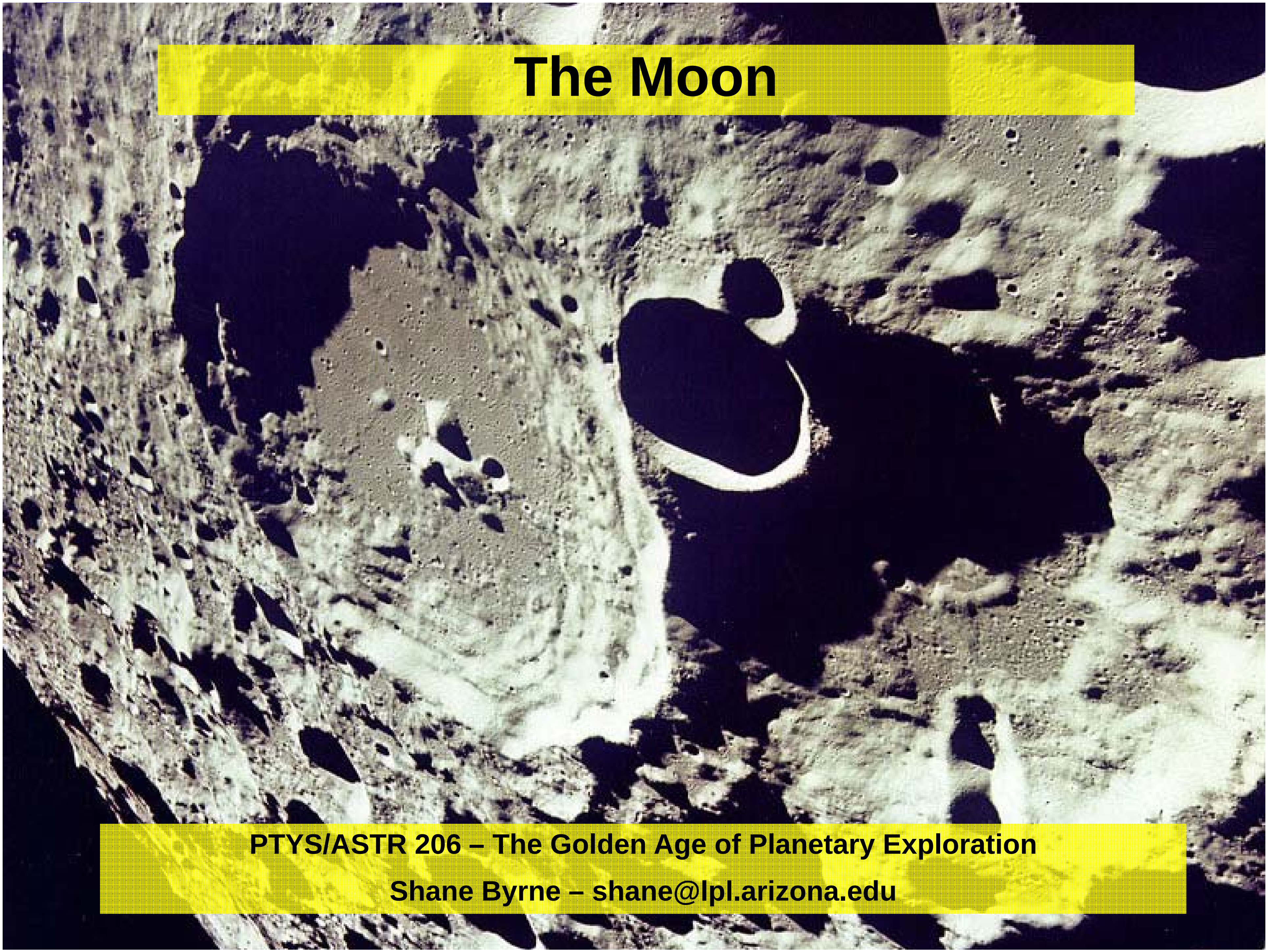
- **Announcements**
  - **Homework #2 due now**
    - **50% credit if handed in next Tuesday**
  - **Mid-term #1 in 1 week**
    - **Based on the first 10 lectures**
    - **Multiple choice - bring pencils**
    - **Lasts 1 hour and starts <u>on time</u>**

The Moon



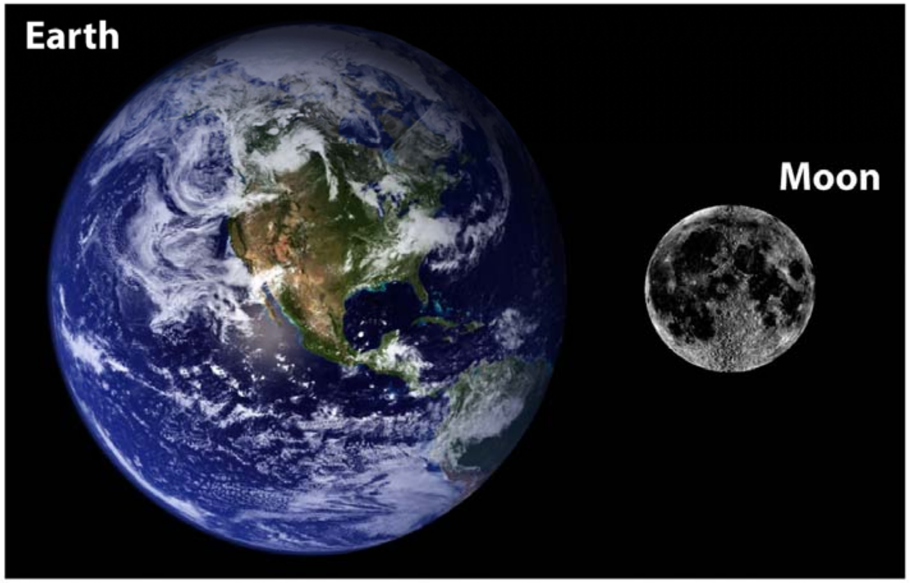
PTYS/ASTR 206 – The Golden Age of Planetary Exploration

Shane Byrne – shane@lpl.arizona.edu

In this lecture…

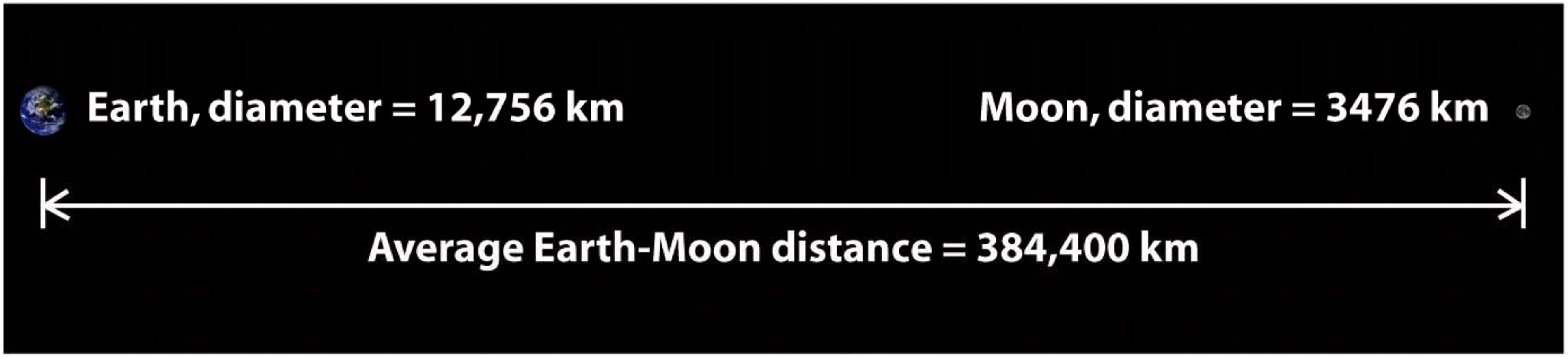
- **Two types of terrain**
  - **Highlands**
  - **Maria**
- **Geologic features on the Moon**
  - **Craters and Volcanoes**
- **Formation of the Moon**
  - **Giant impacts & Magma Oceans**
- **The late heavy bombardment**
- **Formation of the Maria**
- **The recent years**

- **The moon is very close in comparison to other solar system objects**
  - **It's 30 Earth diameters away**
  - **Mars (when closest) is ~6000 Earth diameters away**
  - **Other planets are even further**



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

Figure 10-1b
Universe, Eighth Edition



The Earth-Moon system

Figure 10-1a
Universe, Eighth Edition

- **5th largest satellite in the solar system**
- **Rock-like density**
- **No atmosphere**
  - **So no wind action e.g. sand dune**
  - **No river channels or rainfall etc…**
- **Critical body for planetary science**
  - **Much of what we do in studying solid planets started with work on the Moon**
  - **Simpler to understand than most planets**

The Earth and Moon to sca
than in part (a)

Figure 10-1b
Universe, Eighth Edition

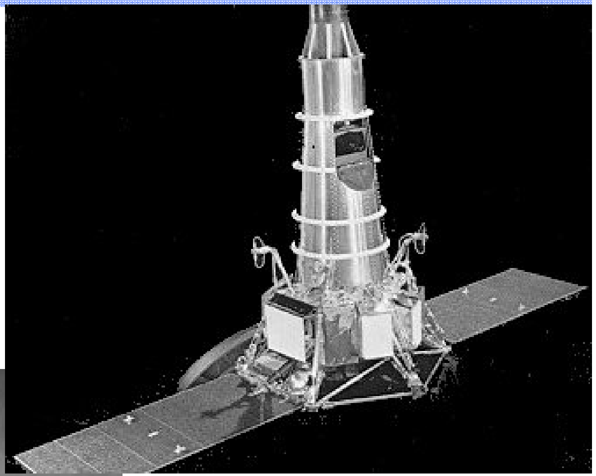
WEB LINK 7.3

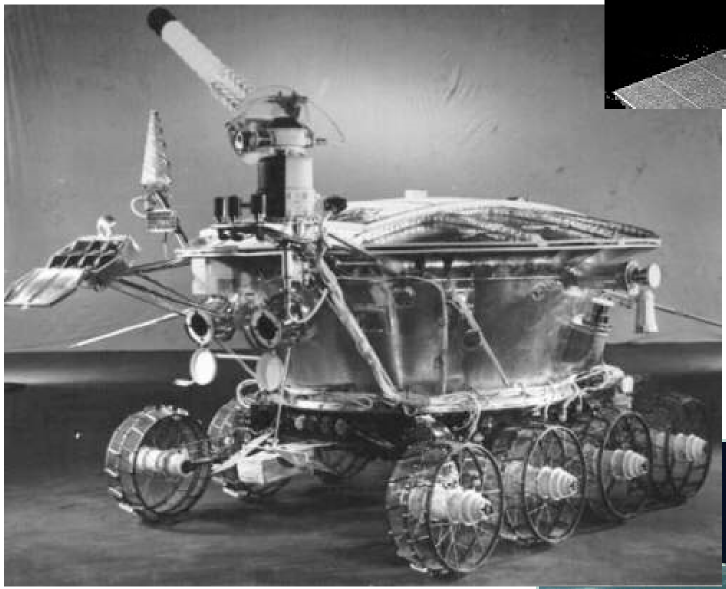
Table 7-2 The Seven Giant Satellites

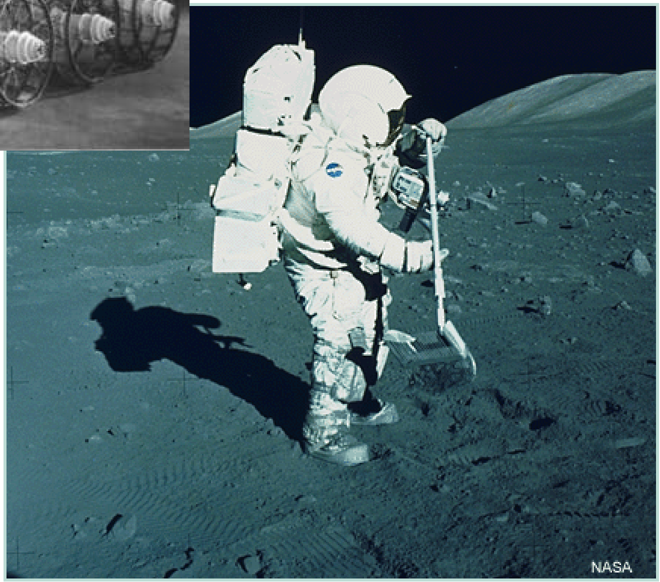
	Moon	Io	Europa	Ganymede	Callisto	Titan	Triton
Parent planet	Earth	Jupiter	Jupiter	Jupiter	Jupiter	Saturn	Neptune
Diameter (km)	3476	3642	3130	5268	4806	5150	2706
Mass (kg)	7.35×10^{22}	8.93×10^{22}	4.80×10^{22}	1.48×10^{23}	1.08×10^{23}	1.34×10^{23}	2.15×10^{22}
Average density (kg/m^3)	3340	3530	2970	1940	1850	1880	2050
Substantial atmosphere?	No	No	No	No	No	Yes	No

R I V U X G
(NASA/JPL/Space Science Institute)

- **Easy to get to – heavily visited by spacecraft**
- **Late 1950s to early 1970s**
  - **Robotic craft from the USA & USSR**
    - **Ranger**
    - **Lunar Orbiter**
    - **Surveyor**
    - **Luna**
  - **Robotic Rovers (USSR)**
    - **Lunokhod**
  - **Manned missions (USA)**
    - **Apollo**
- **1990s**
  - **Clementine**
  - **Lunar Prospector**



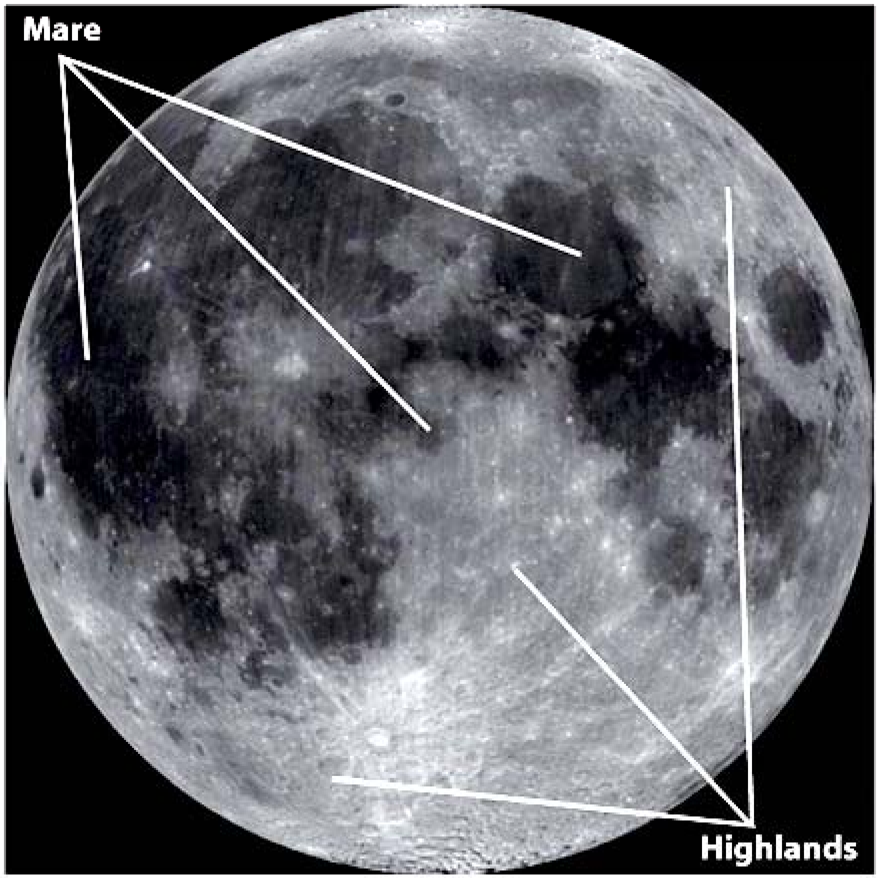


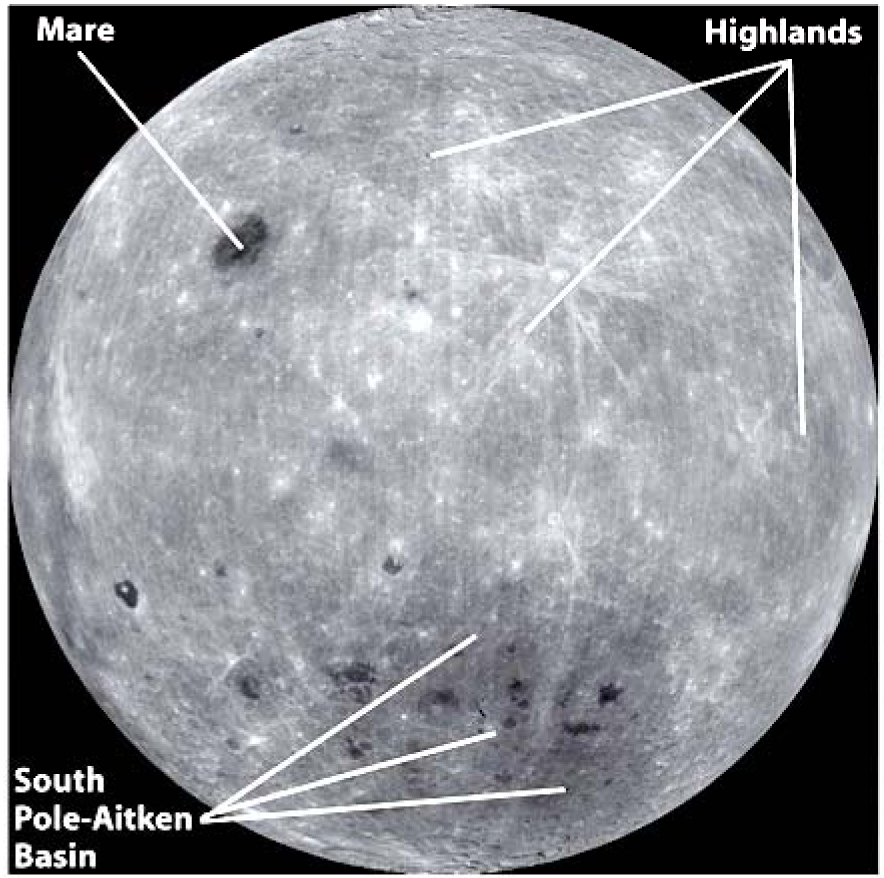


- **More missions**
  - **Chandrayaan (India)**
  - **Chang'E (China)**
  - **Kaguya (Japan)**
  - **Smart 1 (Europe)**
  - **LRO (USA) – launching soon**

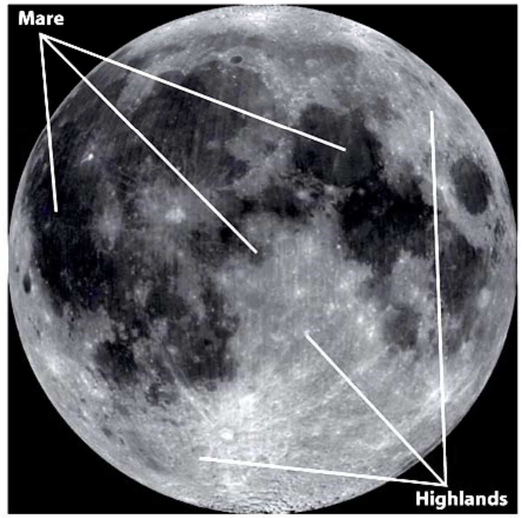
Two terrain types

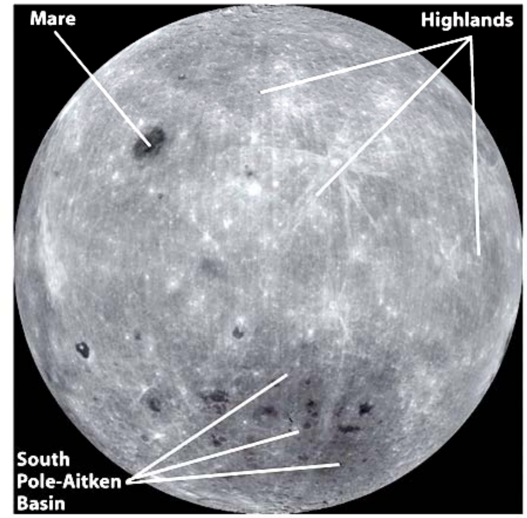
- Maria
  - Dark material – once thought to be seas
- Terrae
  - Highlands
  - Light material – once thought to be the dry land

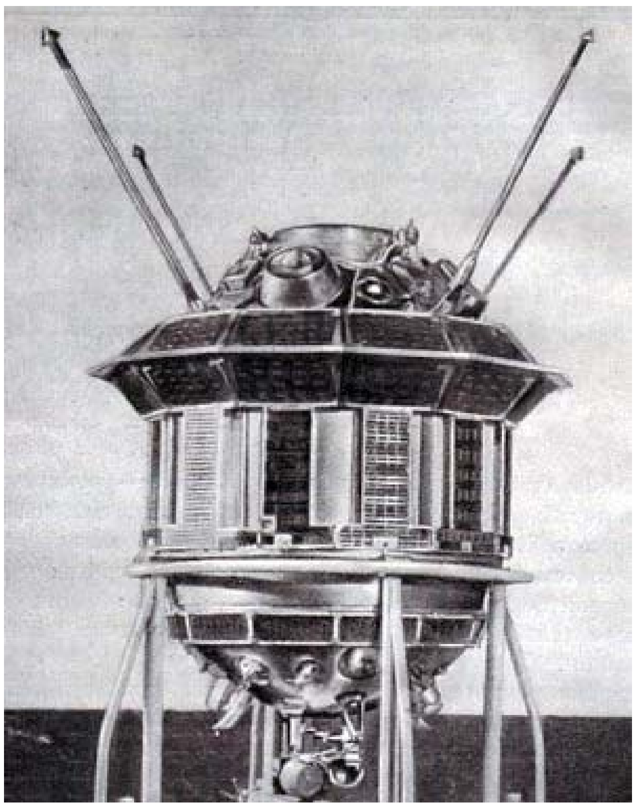




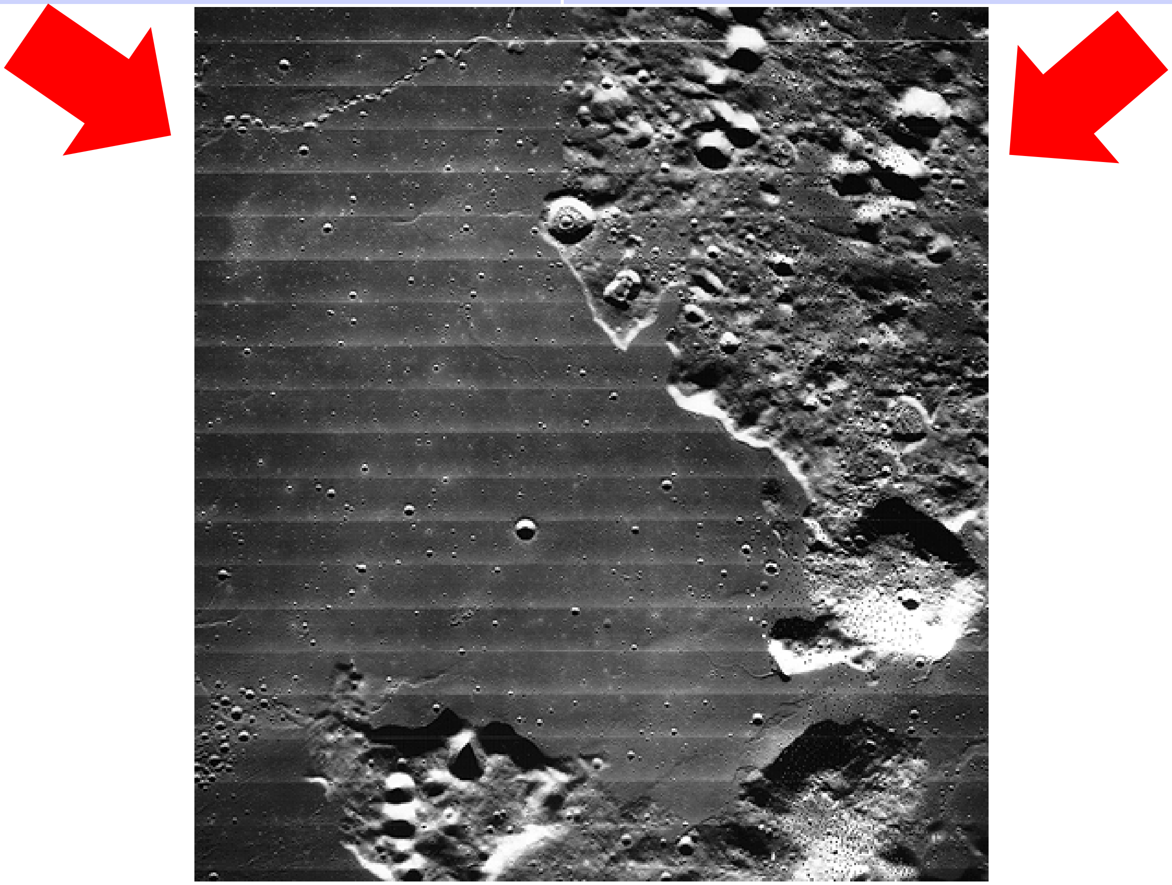
- No one knew what the far side of the Moon looked like until 1959
  - Soviet Union launched Luna 3
- Far-side looks nothing like the near side
  - No Maria





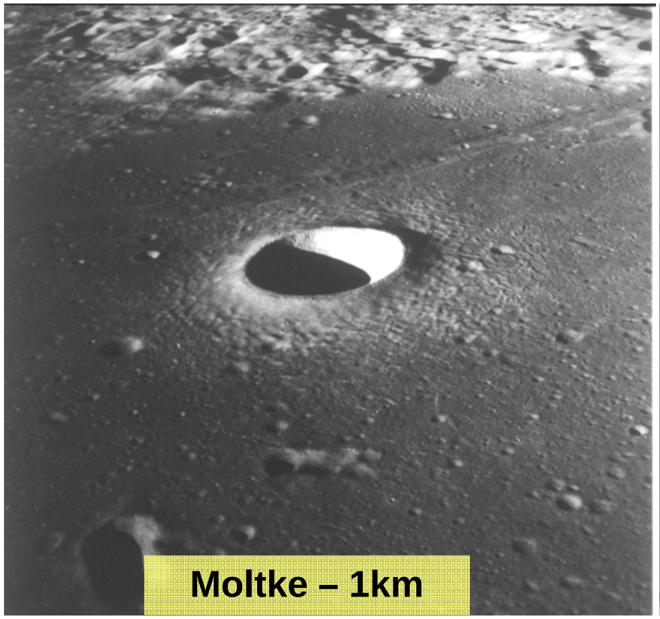


Maria	Highlands (Terrae)
Low elevations	High elevations
Darker	Brighter
Few craters	Many craters (saturated)
Smooth	Rough
Volcanic features	Few volcanic features

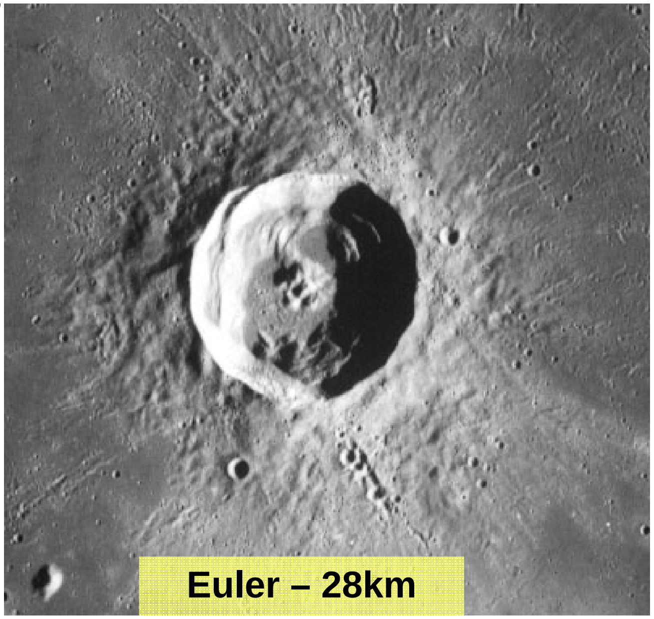


Geologic features on the Moon

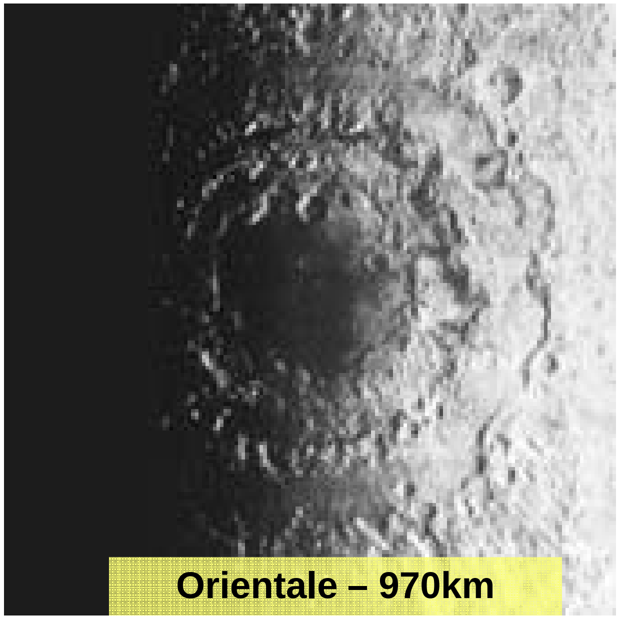
- The Moon is a really simple planet
- Craters
  - Simple craters <18km diameter
  - Complex craters >18km diameter
  - Multi-ring basins
- Pervasive ‘gardening’ from micrometeroites
  - Upper few km of the crust is fractured
  - Upper few meters has been turned into regolith



Moltke – 1km

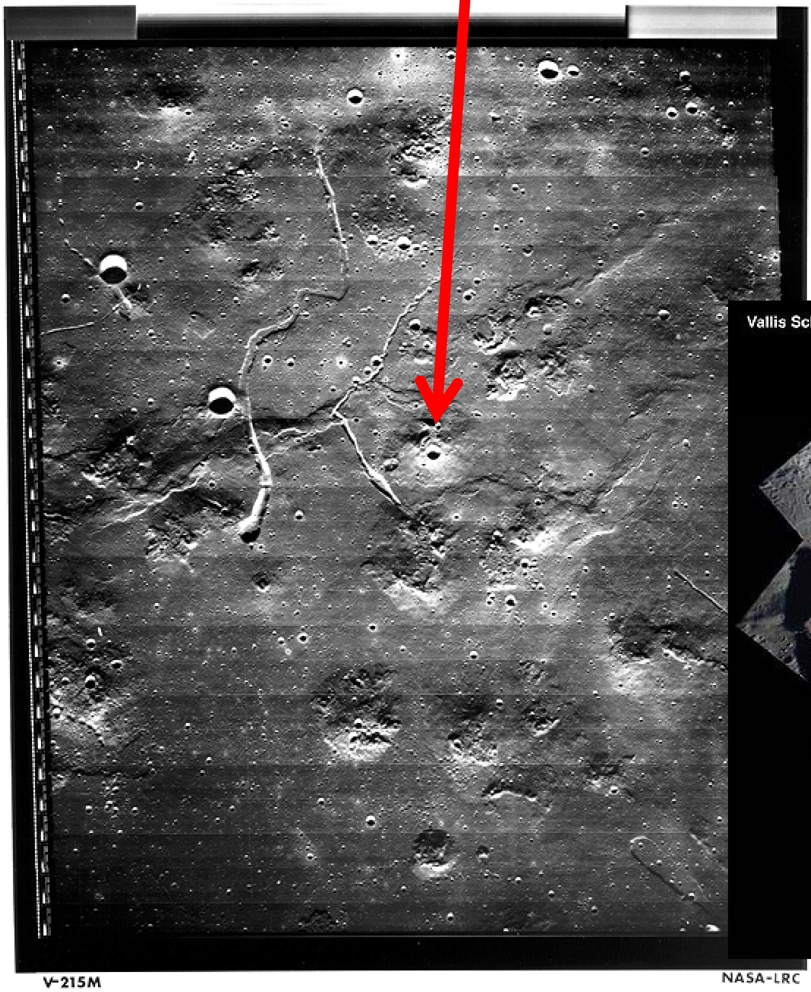


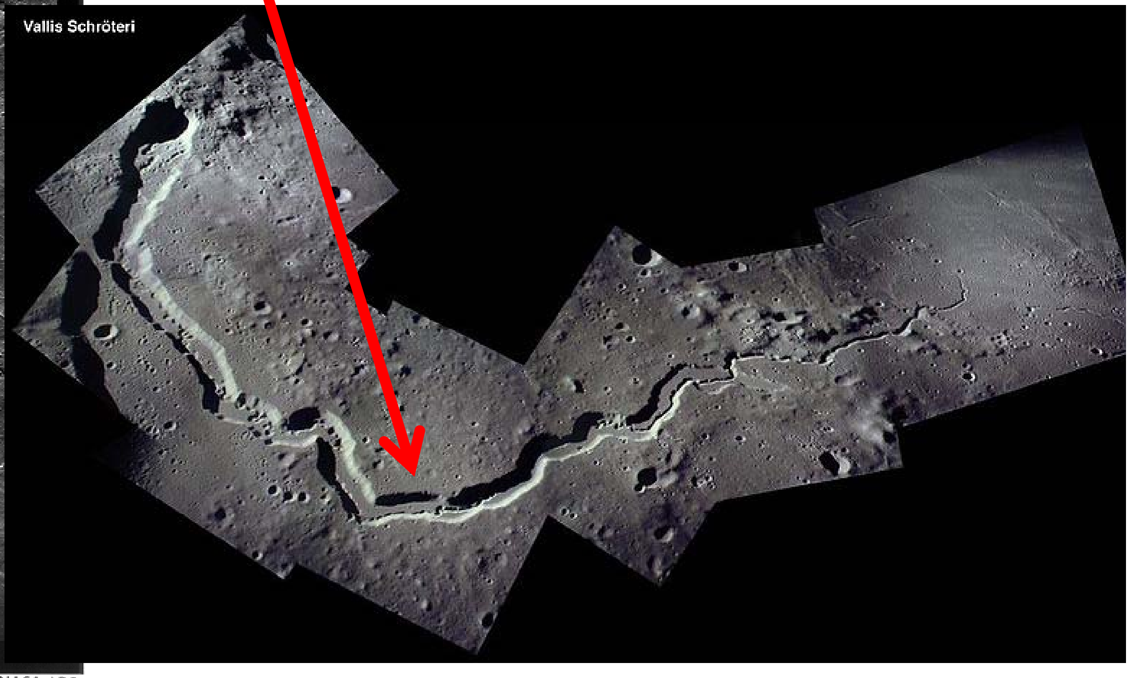
Euler – 28km



Orientale – 970km

- **Volcanic features on the Mare**
  - **Lava flow fronts**
  - **Sinuous rilles (Collapsed lave tubes)**
  - **Vents and domes**





- **Volcanic features on the Mare**
- **Apollo samples**
  - **Tell us that the mare are sheets of volcanic rock**

    - **Mare basalt**

Figure 10-13
Universe, Eighth Edition

- **Highland Anorthosite**

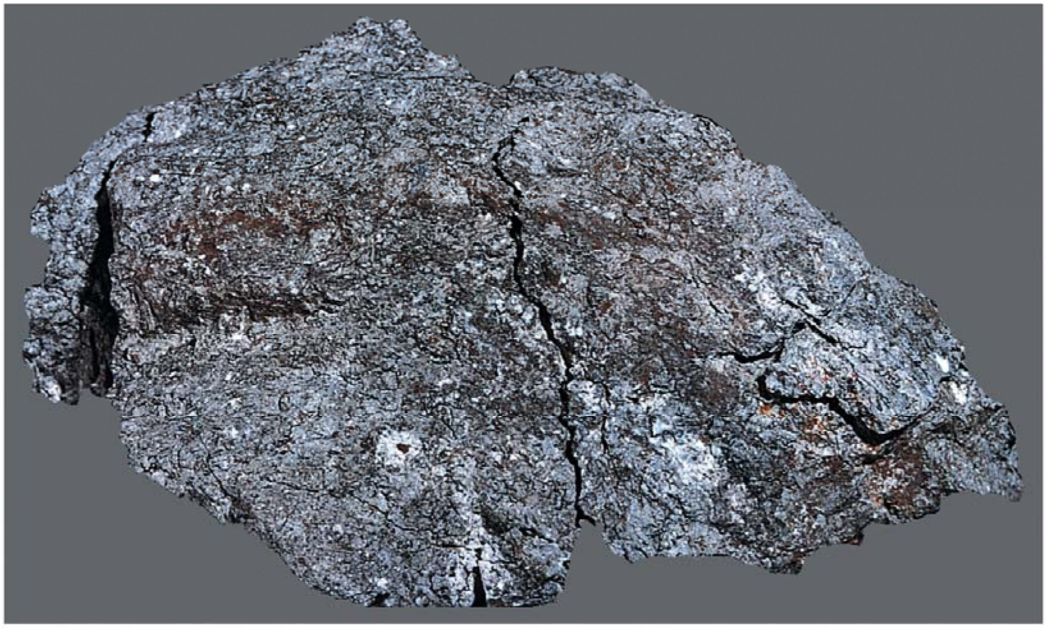


Figure 10-14
Universe, Eighth Edition

- **Most of the lunar rocks look like this**
  - **Breccia**
  - **Fragments of rock fused together**

Figure 10-15
Universe, Eighth Edition

- **Maria**
  - **Overlapping volcanic flows and impacts**
  - **Samples show a volcanic composition**
    - **Basalt**
- **Highlands**
  - **Just overlapping impacts**

- **How did the Moon get this way?**

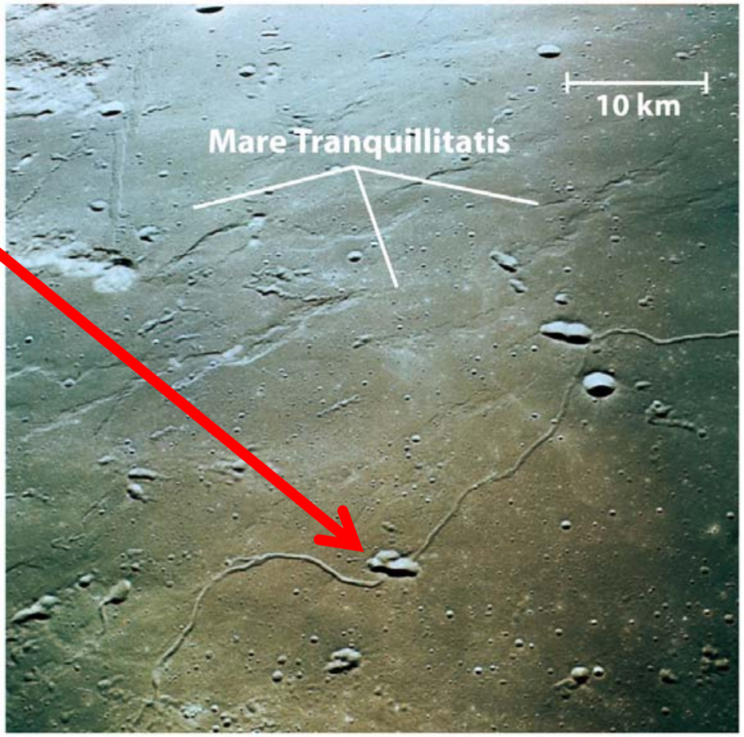
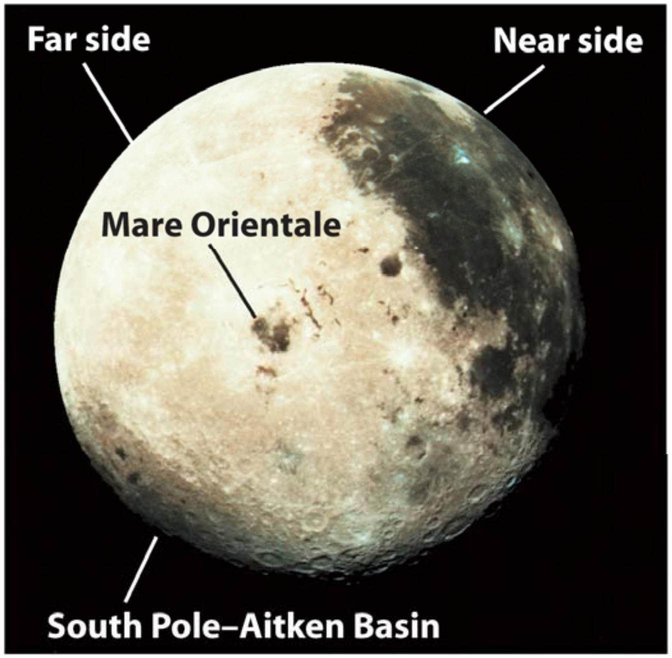
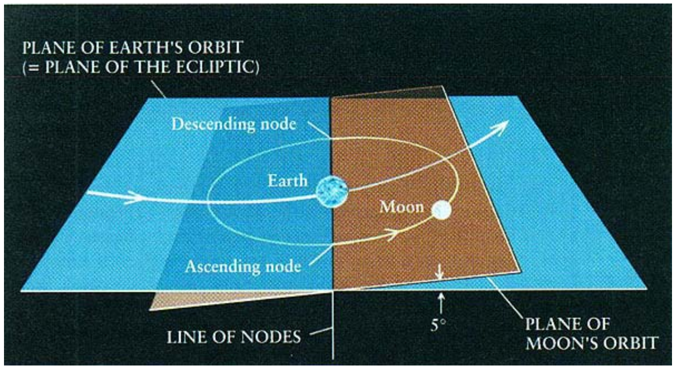


Figure 10-6
Universe, Eighth Edition



Formation of the Moon

- Facts to consider
  - Moon depleted in iron & volatile substances
    - Like light elements and water
  - Oxygen isotope ratios similar to Earth
  - Moon doesn't orbit in Earth's equatorial plane



- Possible theories (that didn't work)
  - Earth and Moon co-accreted
    - Explains oxygen isotopes
    - Doesn't explain iron and volatile depletion
  - Earth split into two pieces
    - Spinning so fast that it broke apart (fission)
    - …but the Moon doesn't orbit in Earth's equatorial plane
  - Capture of passing body
    - Earth captures an independently formed moon as it passes nearby
    - Pretty much a dynamical miracle
    - Doesn't explain oxygen isotope similarity to Earth

- **Current paradigm is Giant impact**
  - **Earth close to final size**
  - **Mars-sized impactor**
  - **Both bodies already differentiated**
  - **Both bodies formed at ~1 AU**

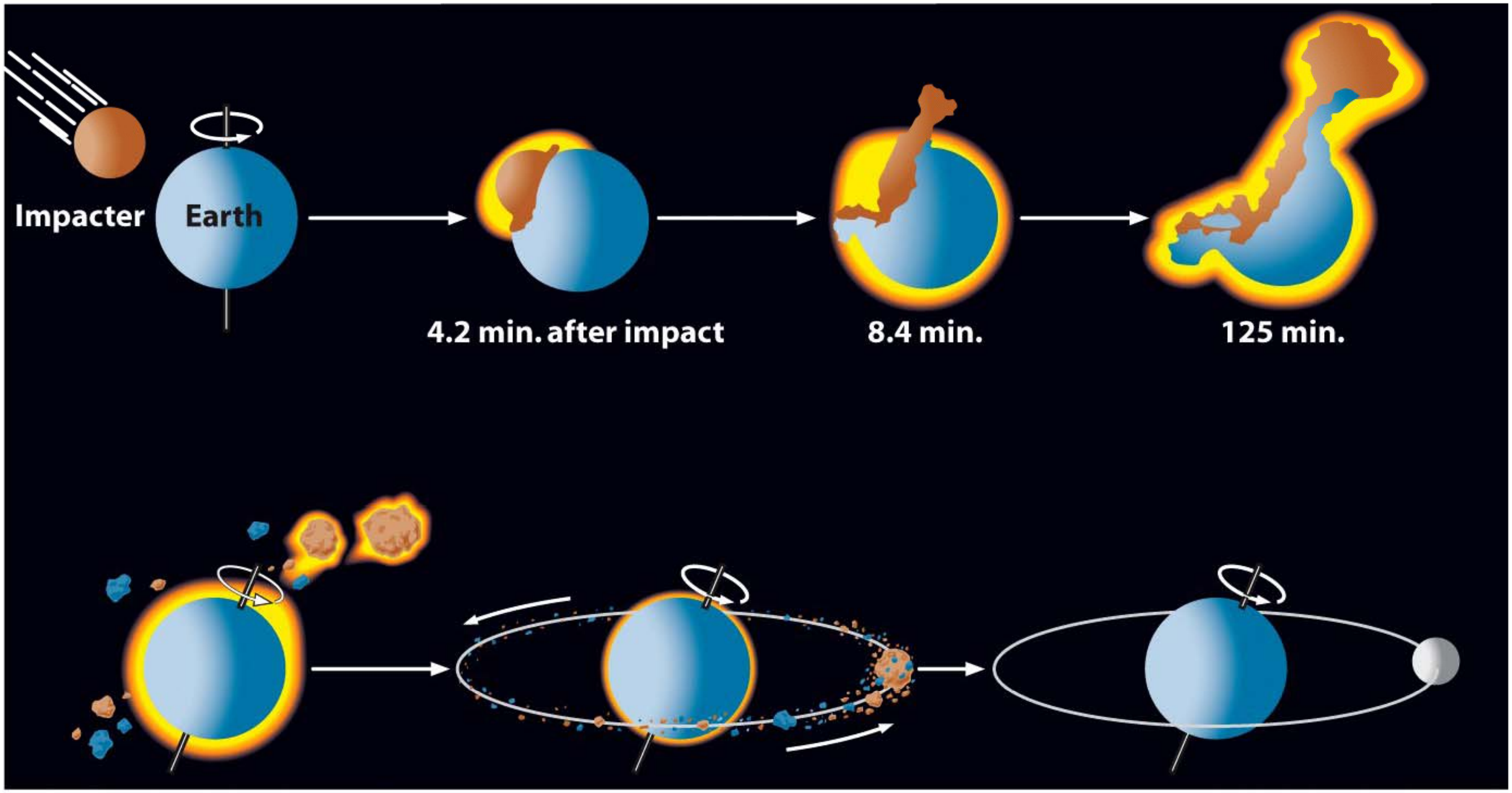
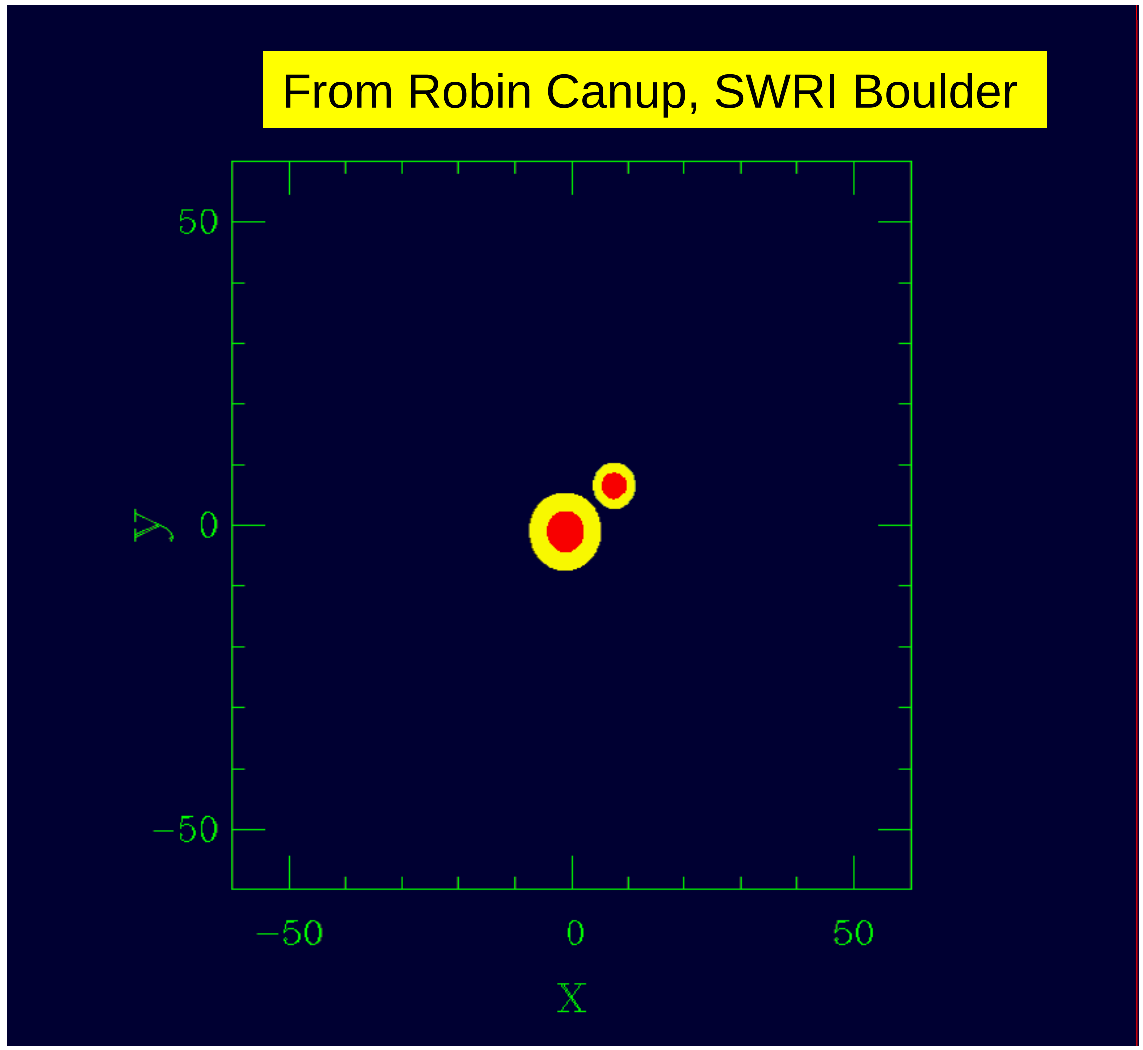
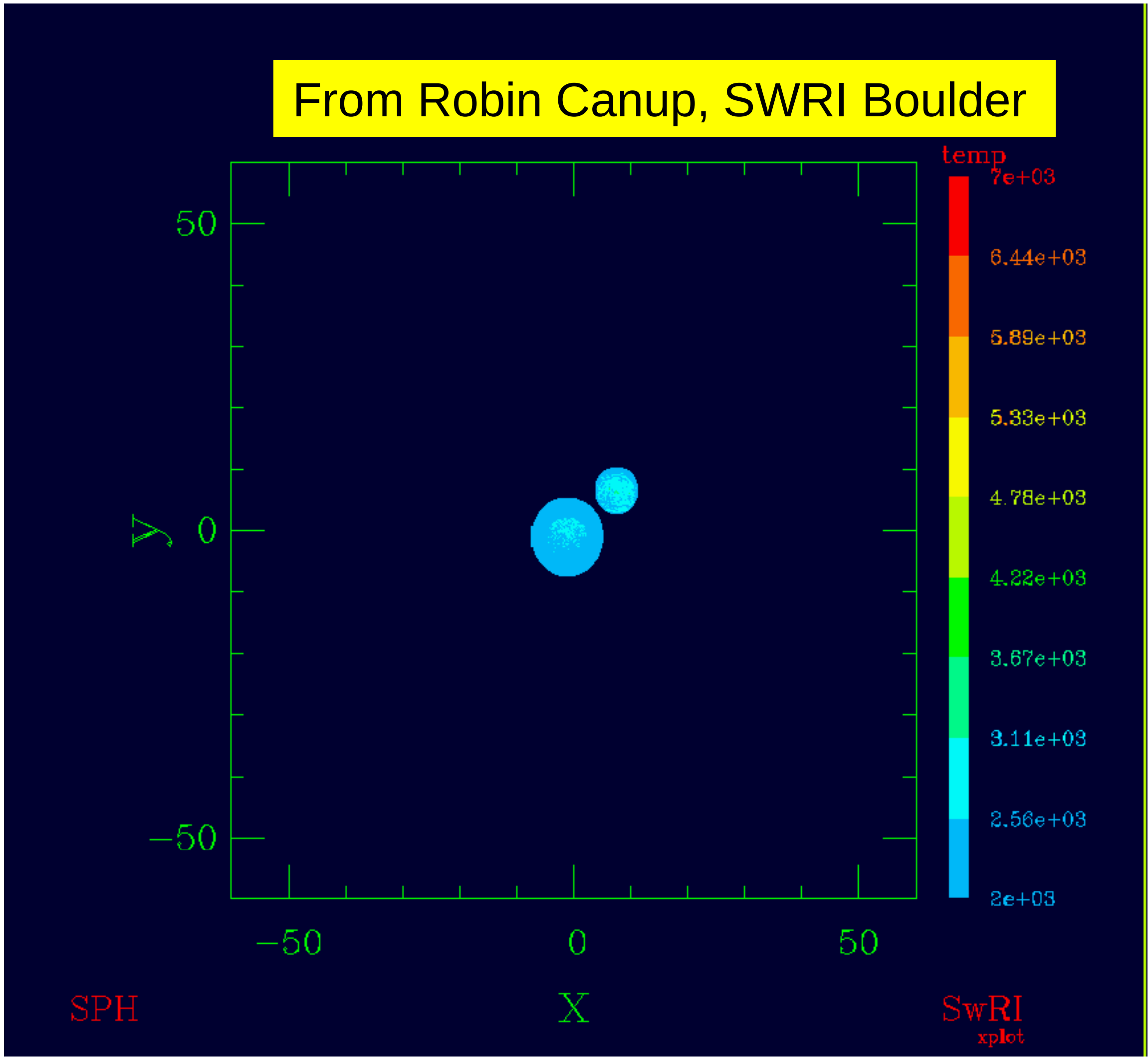


Figure 10-18
Universe, Eighth Edition

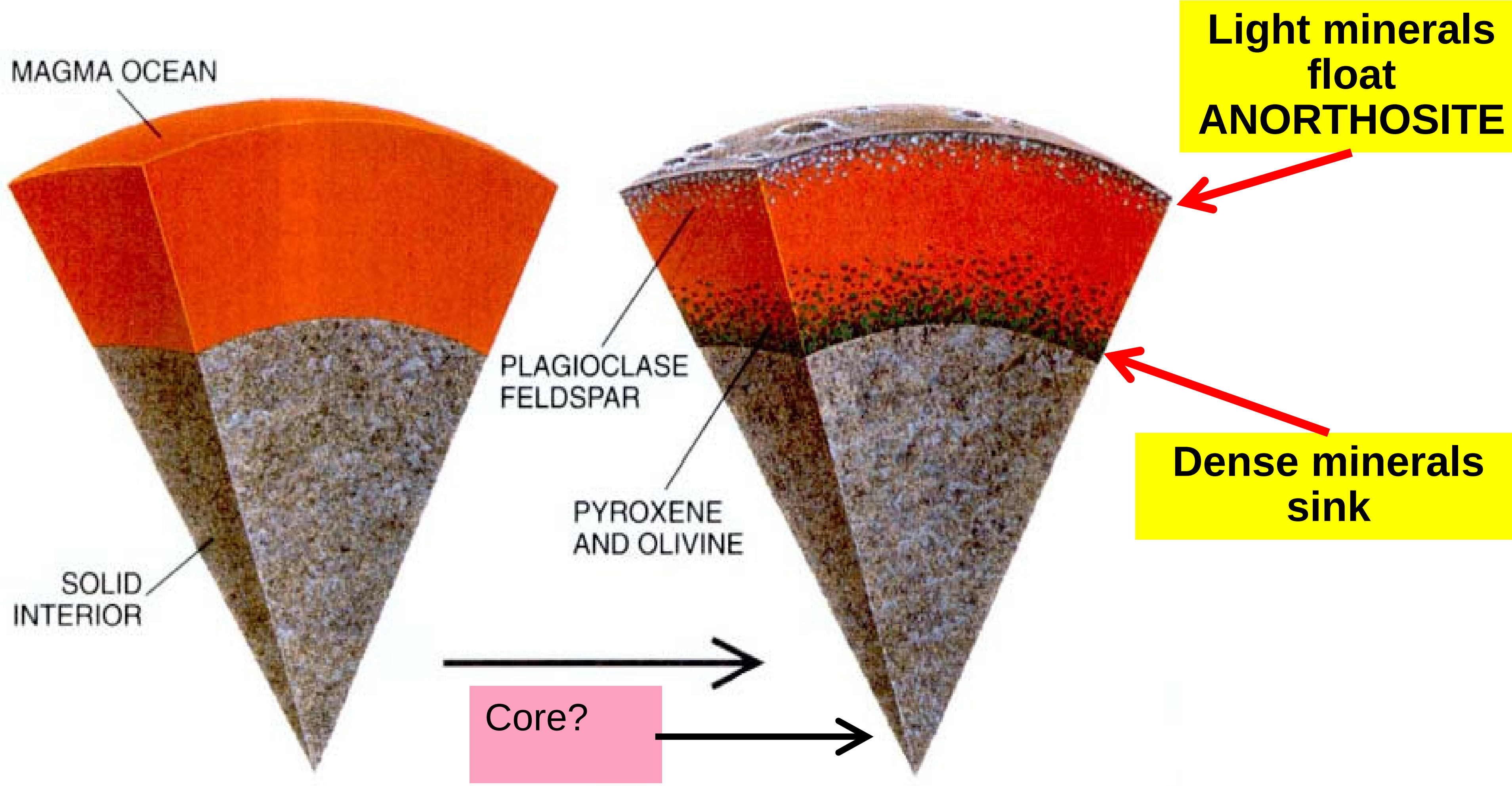
- **How does that explain the iron depletion**
  - **Bodies were already differentiated**
  - **All the iron sticks around in Earth's core**
  - **Moon rock comes from Earth's mantle – explains Oxygen isotope similarity**
  - **Red = iron**
  - **Yellow = rock**



- **What does that mean for the temperature of the two bodies?**
  - **Both very hot…**
  - **Magma oceans 100s of kilometers deep**
  - **Explains the Moon's lack of volatile elements**

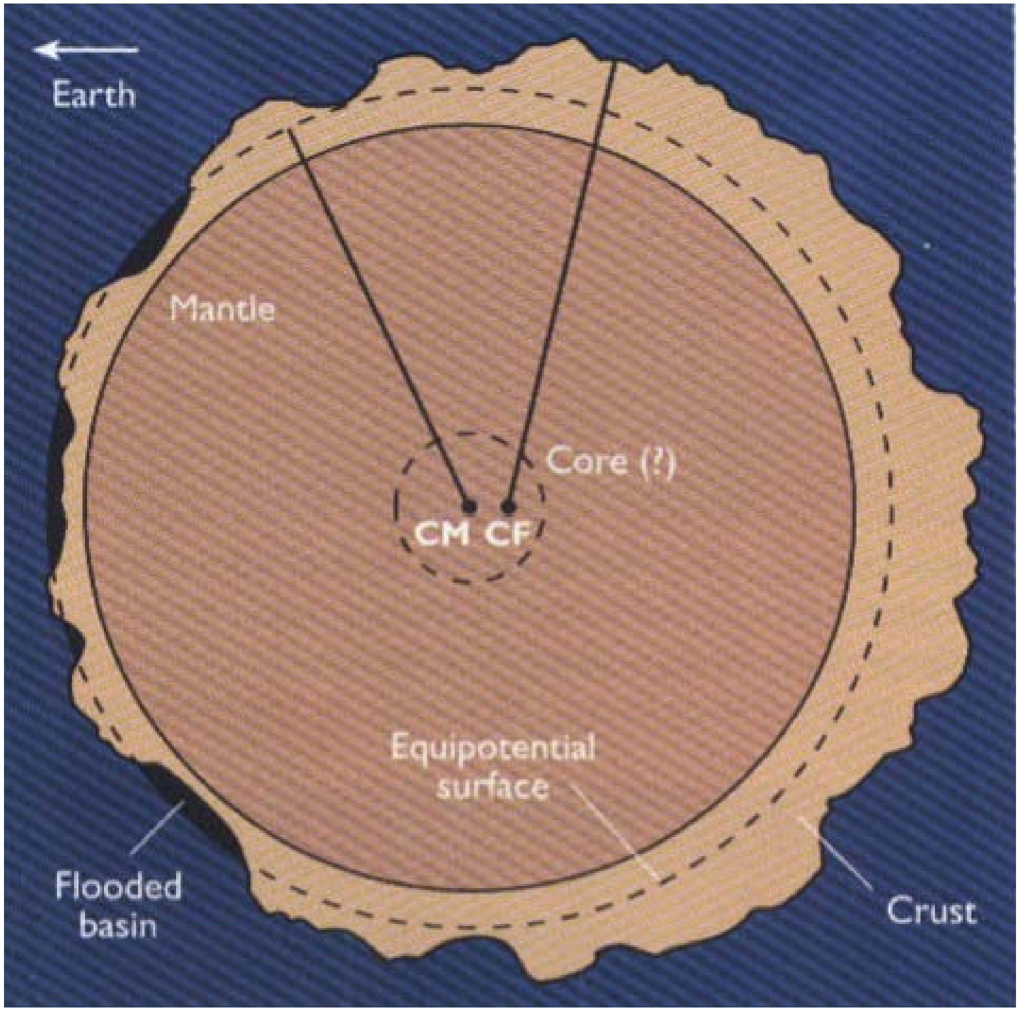


- **Accretion of lunar material into the Moon within a few years!**
- **High-accretion rates mean surface is molten**
  - Magma ocean probably a few hundred km thick
  - Apollo 11 returned highland fragments, first suggestion of Magma ocean
  - Idea since extended to other terrestrial planets

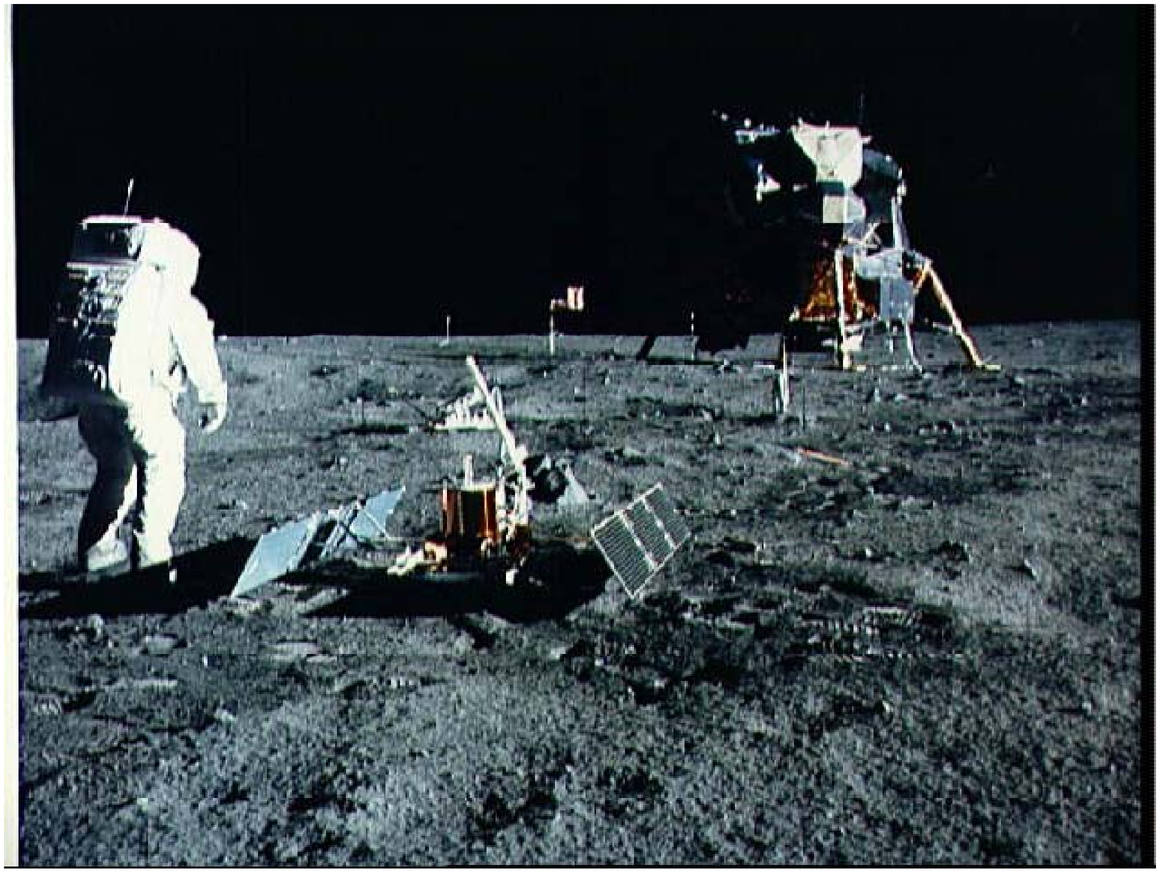


- **When the magma ocean freezes it seals in a lot of heat**
  - Will become important later…

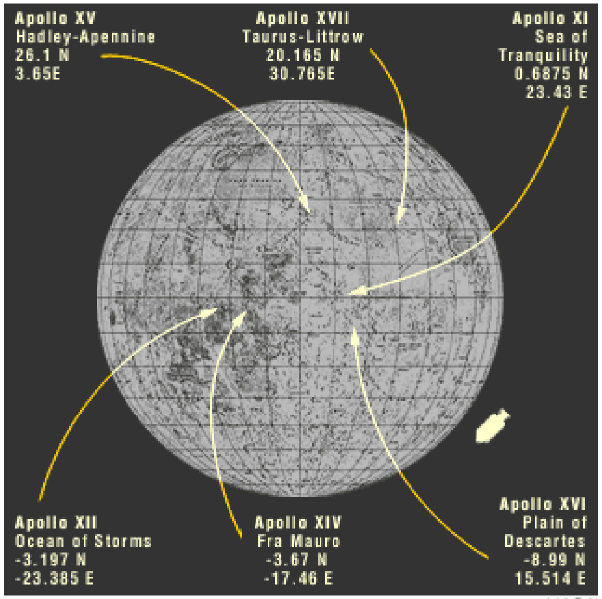
- **Crustal Thickness Asymmetry**
  - Average crust 54-62km thick (45km at Apollo sites)
  - Far-side crust is much (about 15km) thicker
  - Crustal asymmetry is one of the central unanswered questions in lunar science



- **Does the Moon have a core?**
  - Remnant magnetism shows there was once a liquid core
  - Seismic experiments from Apollo – inconclusive
  - Another major unanswered question



- **Better seismic experiments would answer this**
  - Apollo seismometers were all close together
  - Didn't probe very deeply
  - Switched off in the 1970s to save $$



NASA

Impact basins and the late heavy bombardment

- Once the crust is solid – craters start to form
- Some of these are still very large
  - 1000s of km across
- Oldest rock fragments
  - From highlands ~4.5 Gyr ago
- Spike in cratering rate
  - 4.0-3.8 Gyr ago
  - Late heavy bombardment
  - All the big basins we see today date from this period
- All the inner planets suffered this bombardment

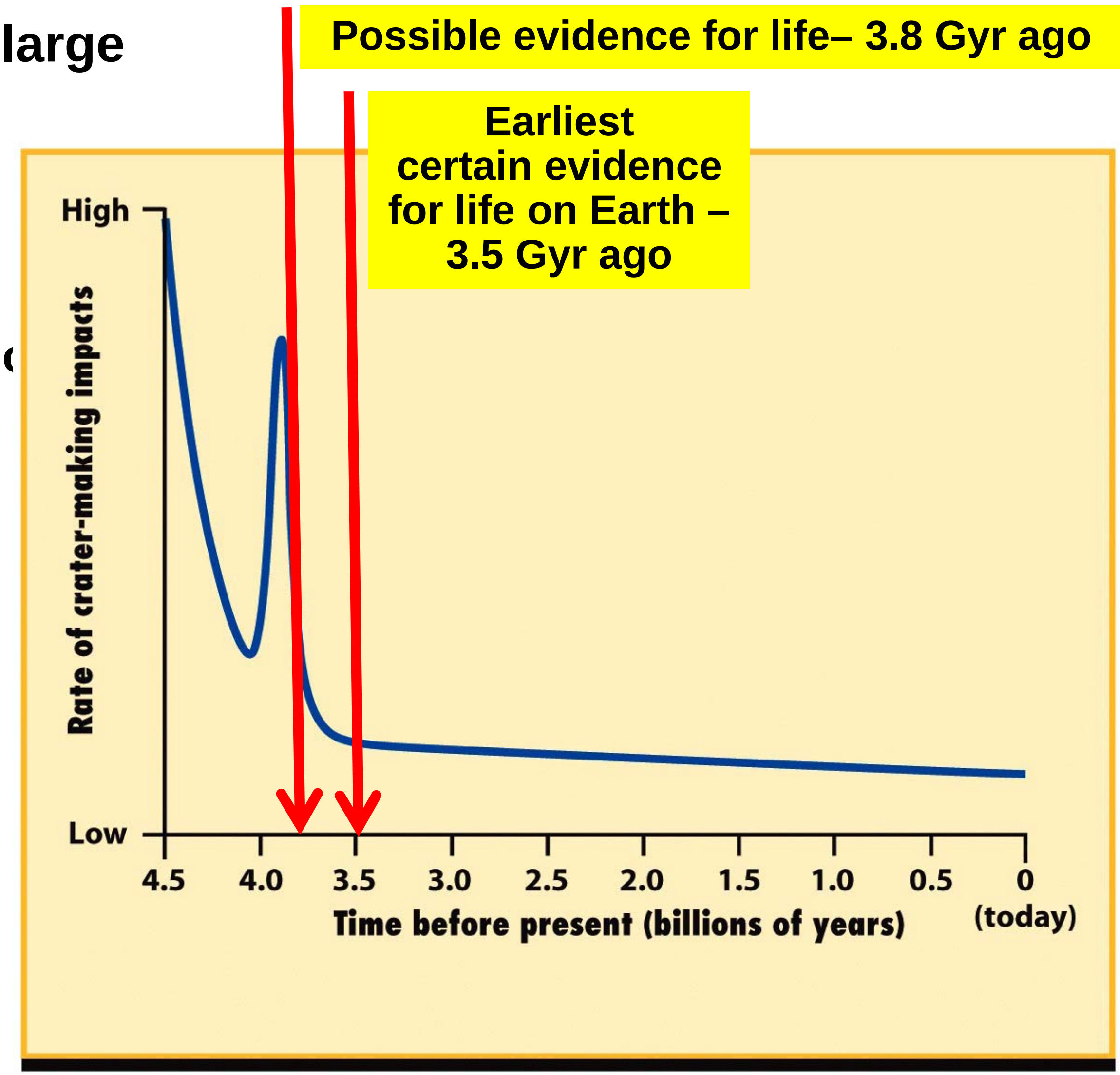
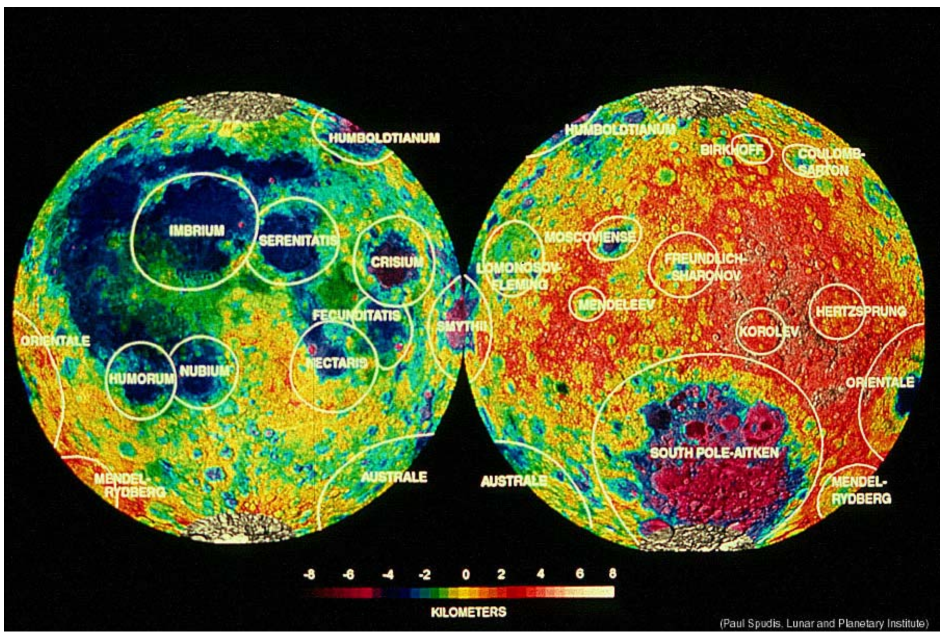


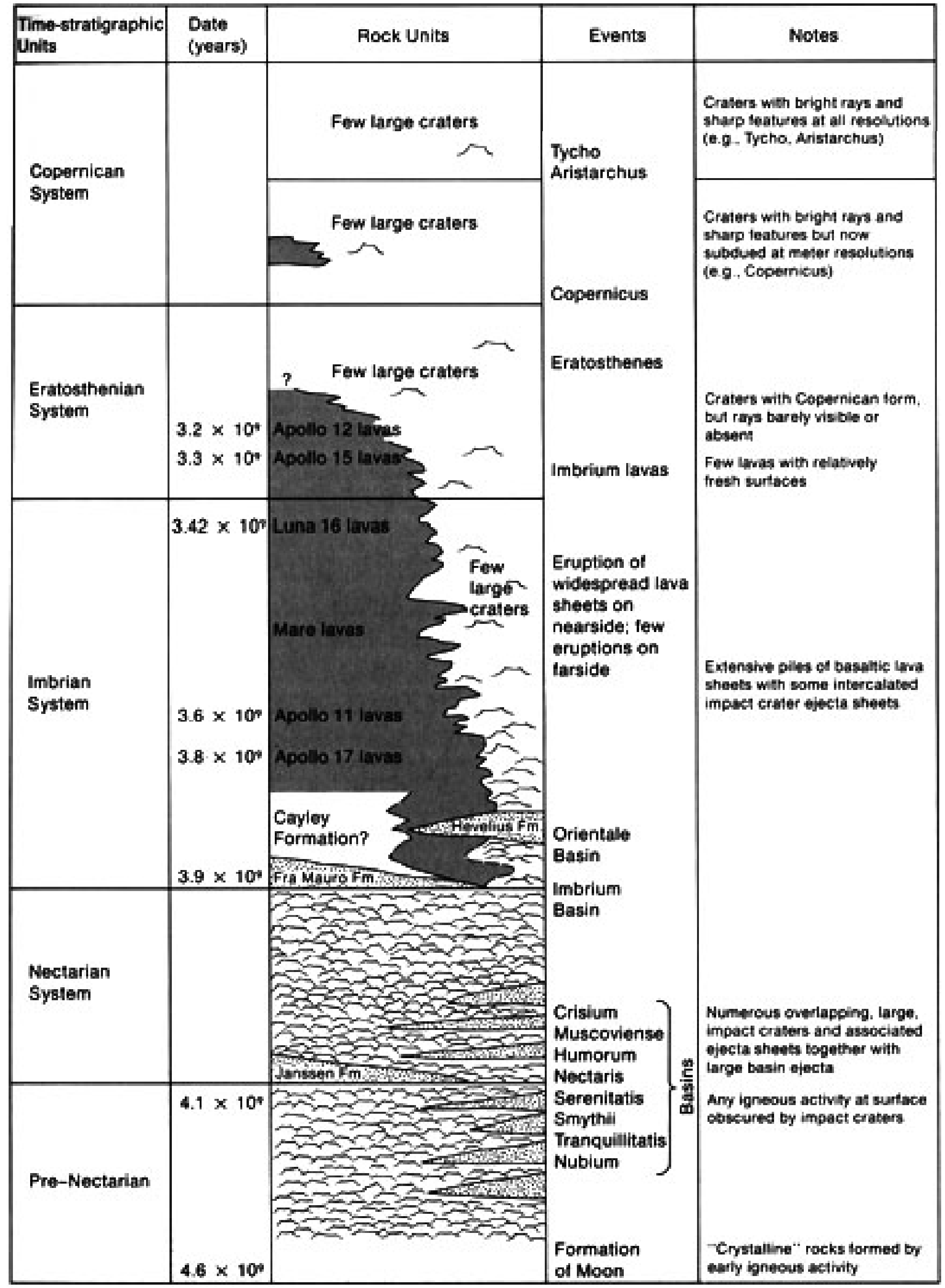
Figure 10-16
Universe, Eighth Edition

- **Bombardment movie played here**
  - **Research by LPL graduate student Dave Minton**

- Big basins used to divide up the lunar timeline
  - Nectaris
  - Serenitatis
  - Imbrium
  - Orientale
  - etc…



(Paul Spudis, Lunar and Planetary Institute)



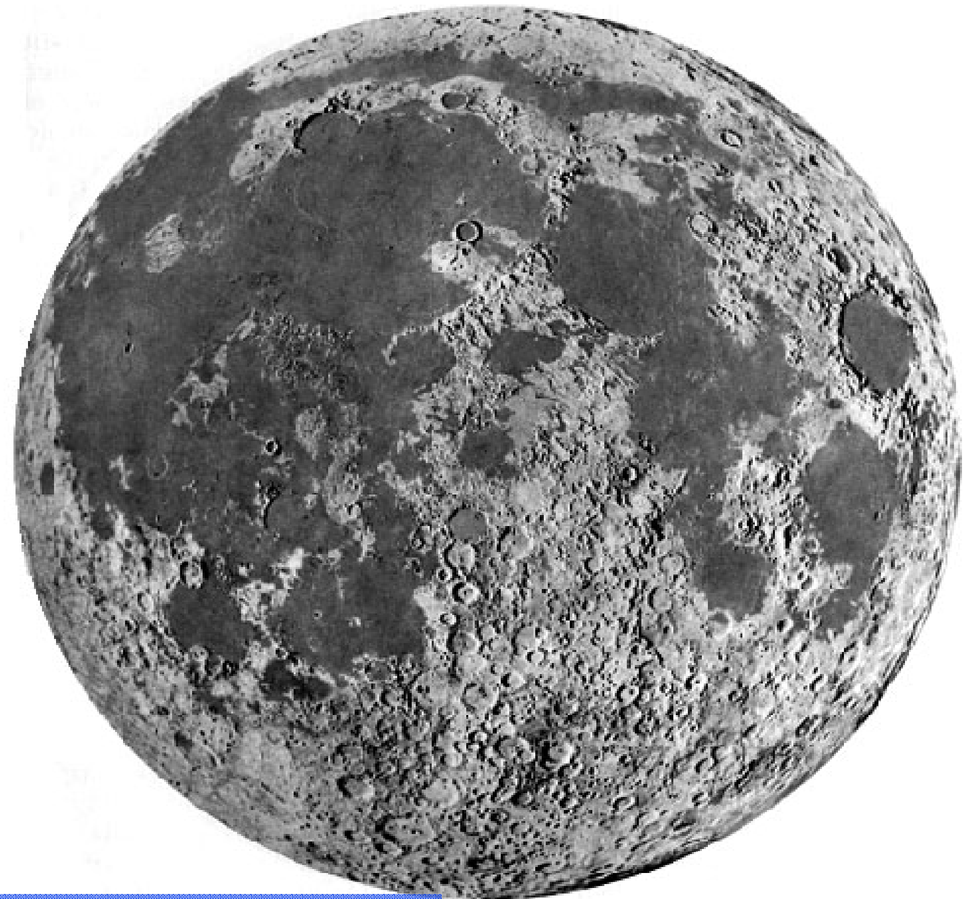
Time-stratigraphic Units	Date (years)	Rock Units	Events	Notes
Copernican System		Few large craters; Few large craters	Tycho, Aristarchus; Copernicus	Craters with bright rays and sharp features at all resolutions (e.g., Tycho, Aristarchus); Craters with bright rays and sharp features but now subdued at meter resolutions (e.g., Copernicus)
Eratosthenian System	3.2 × 10⁹; 3.3 × 10⁹	? Few large craters; Apollo 12 lavas; Apollo 15 lavas	Eratosthenes; Imbrium lavas	Craters with Copernican form, but rays barely visible or absent; Few lavas with relatively fresh surfaces
Imbrian System	3.42 × 10⁹; 3.6 × 10⁹; 3.8 × 10⁹; 3.9 × 10⁹	Luna 16 lavas; Few large craters; Mare lavas; Apollo 11 lavas; Apollo 17 lavas; Cayley Formation?; Hevelius Fm; Fra Mauro Fm	Eruption of widespread lava sheets on nearside; few eruptions on farside; Orientale Basin; Imbrium Basin	Extensive piles of basaltic lava sheets with some intercalated impact crater ejecta sheets
Nectarian System		Janssen Fm	Basins: Crisium, Muscoviense, Humorum, Nectaris	Numerous overlapping, large, impact craters and associated ejecta sheets together with large basin ejecta
Pre-Nectarian	4.1 × 10⁹; 4.6 × 10⁹		Basins: Serenitatis, Smythii, Tranquillitatis, Nubium; Formation of Moon	Any igneous activity at surface obscured by impact craters; "Crystalline" rocks formed by early igneous activity

- **What does the Moon look like at that point?**
  - **Heavily cratered**
  - **All bright material**
  - **Orbits close to the Earth**
  - **Dotted with huge basins**
- **The cratering rate dies off rapidly**
- **Meanwhile….**
  - **Things have been heating up in the subsurface**

3.8 Gyr ago

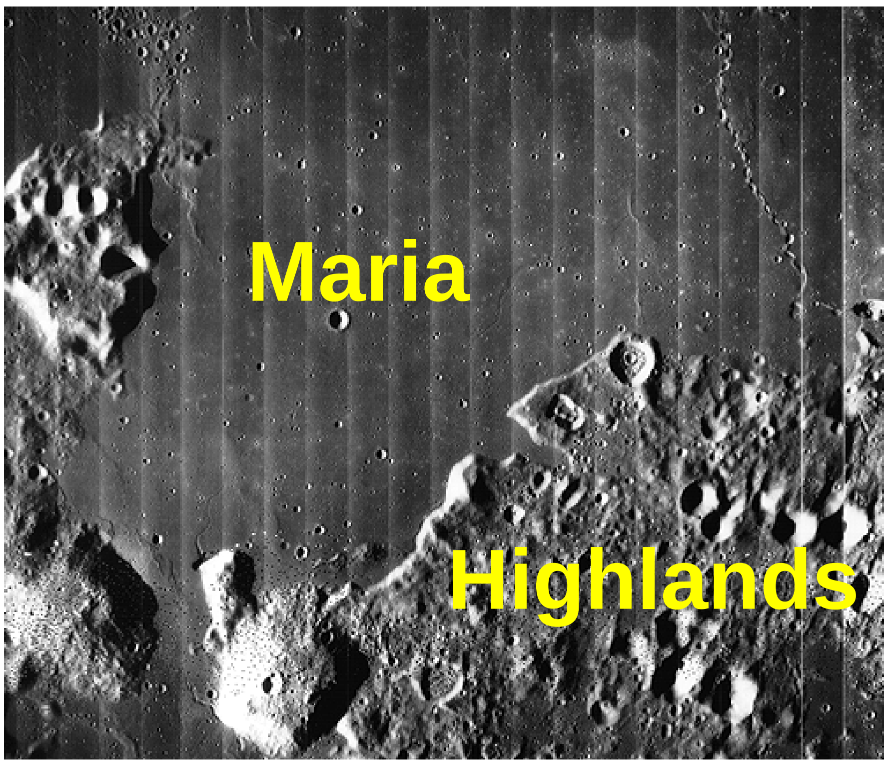
Formation of the Maria

- Still need to add the dark patches
  - Huge amounts of volcanic material erupted onto the surface
  - Fills the existing big basins

3.8 Gyr ago 3.1 Gyr ago

- **Maria start forming as the heavy bombardment era ends.**
  - **Maria crater density is much lower than the highlands**
  - **Regolith is shallower than highlands probably a few meters deep**
- **Craters continue to accrue at a relatively slow rate until present day**



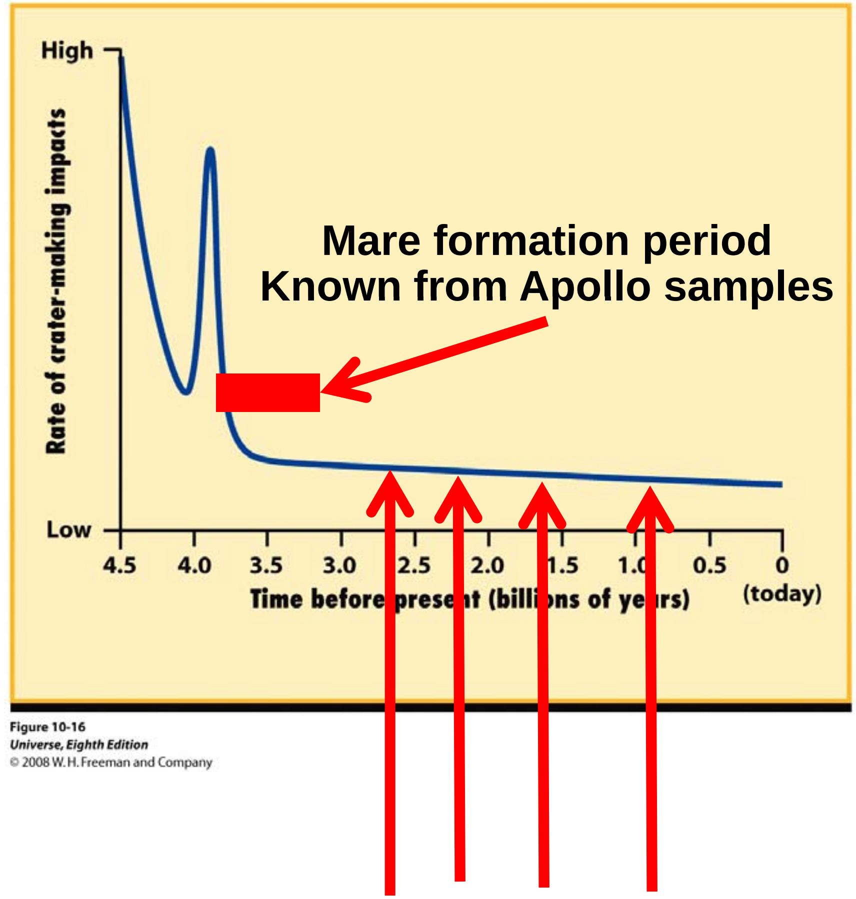


Figure 10-16
Universe, Eighth Edition
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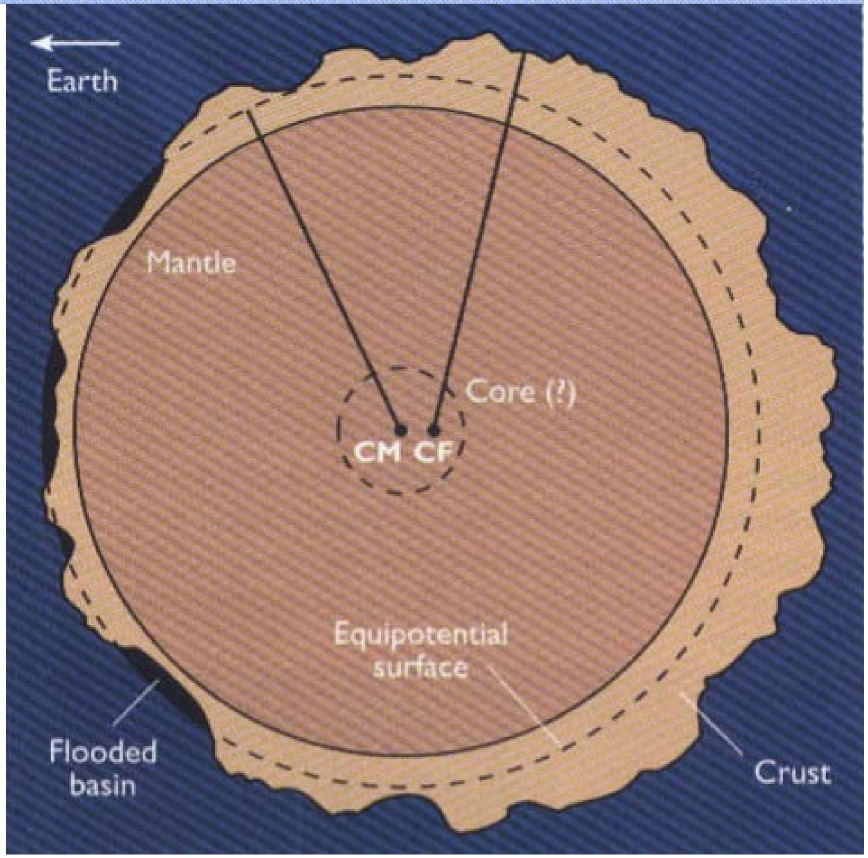
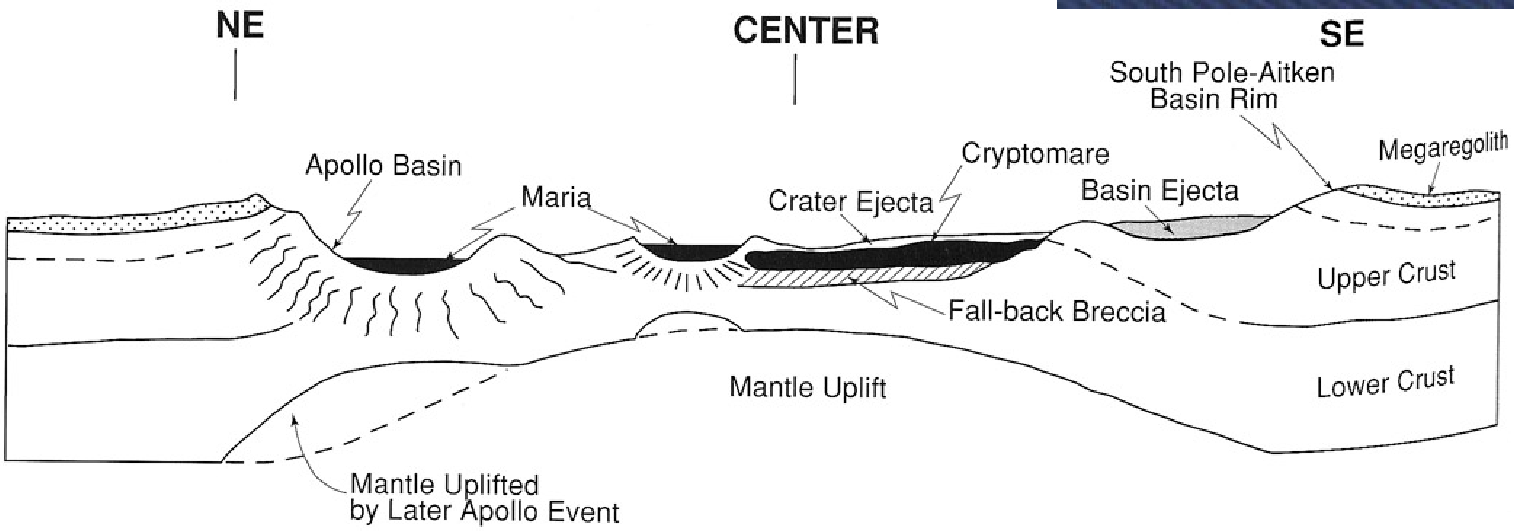
Cratering rate low after these lava flows form

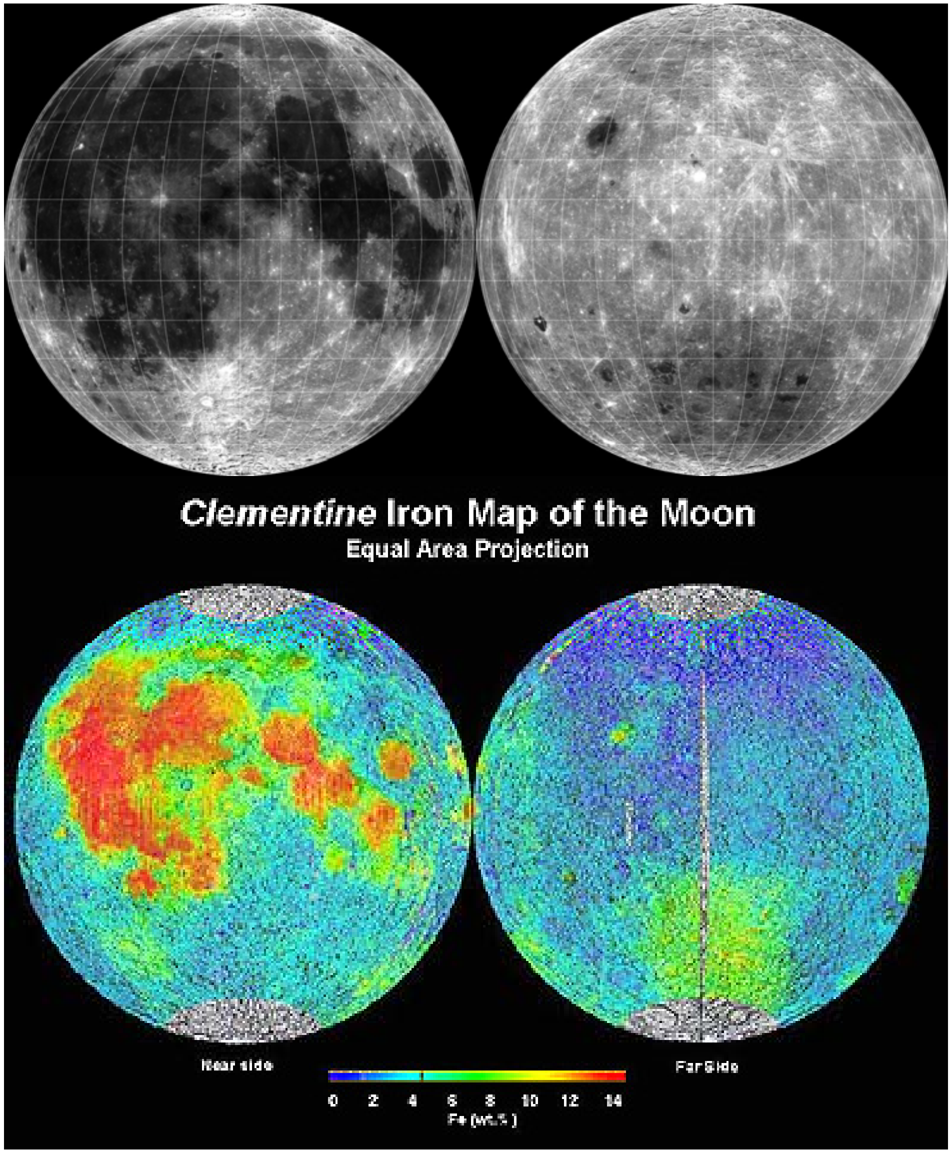
- **No volcanism on the far side**
  - **Thicker crust**
  - **Lava floods the pre-existing basins**



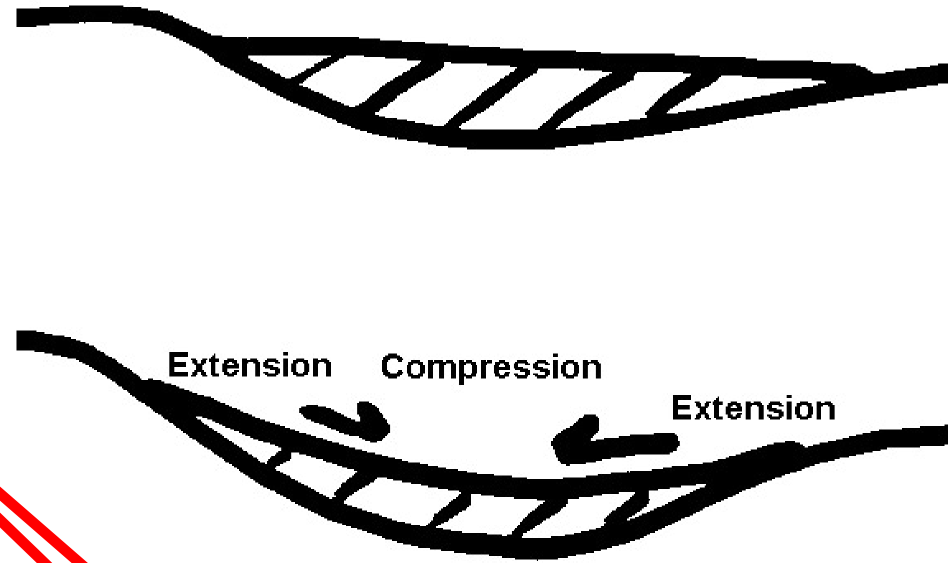


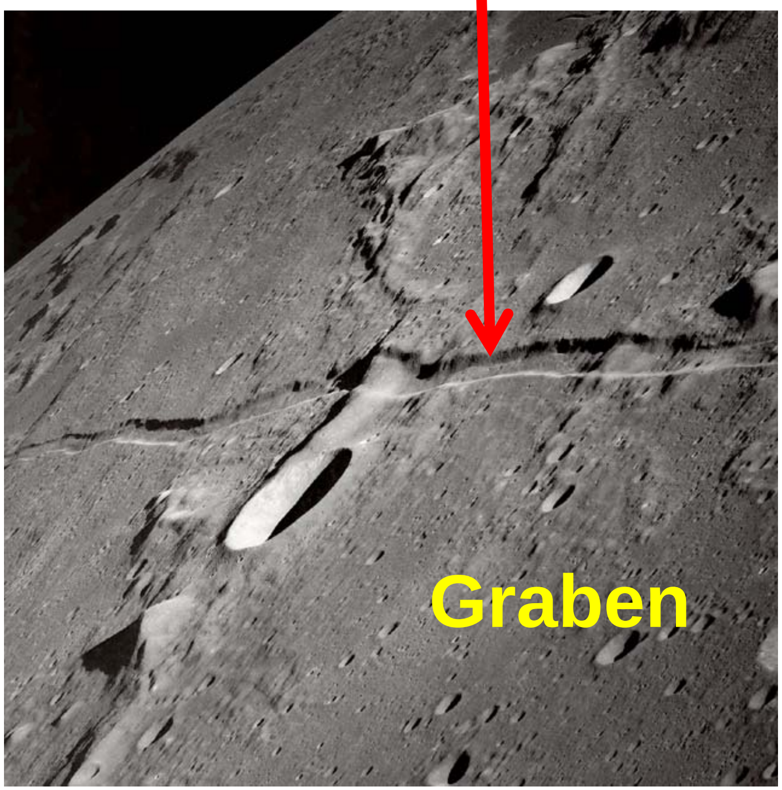
- **Mare material originates deep in the crust**
  - **Maria lava fill pre-existing depressions (impact basins)**
  - **Very similar to terrestrial basalt**
    - **Except that it is completely devolatilized**
  - **Darker color due to higher Fe content**

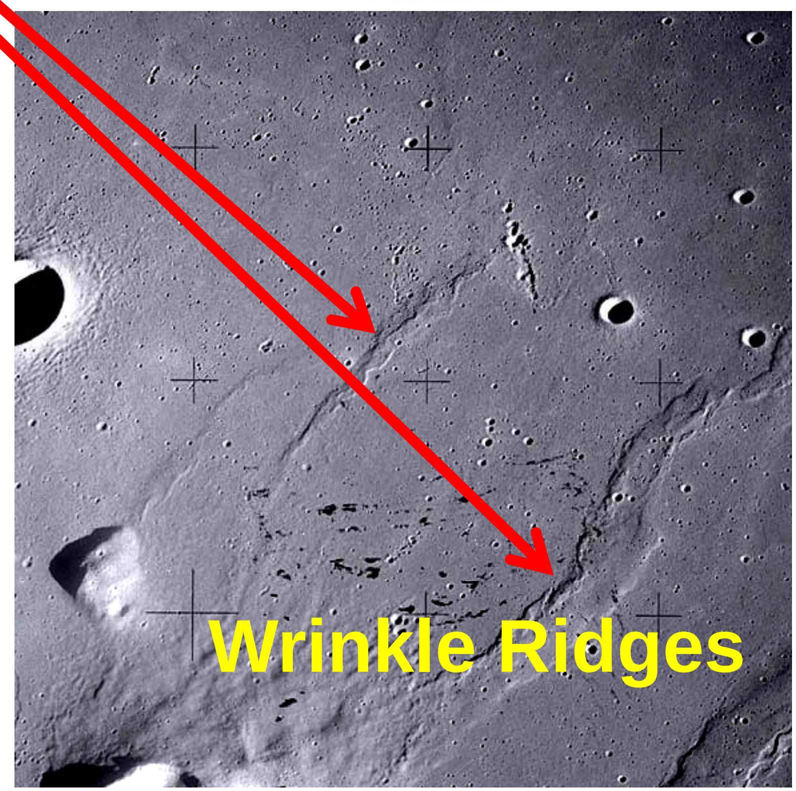
- **Amounts are small…**
  - **Most Maria 1-2km thick**
  - **5km in Imbrium, 0.6km in Orientale**
  - **Individual flows ~10-40m thick**
  - **VERY low viscosity**
    - **Flood basalts**



- **A few kilometers of volcanic rock is heavy… even on the Moon.**
  - **Subsidence of crust under basin**
  - **Compression in the center**
  - **Extension at edges**

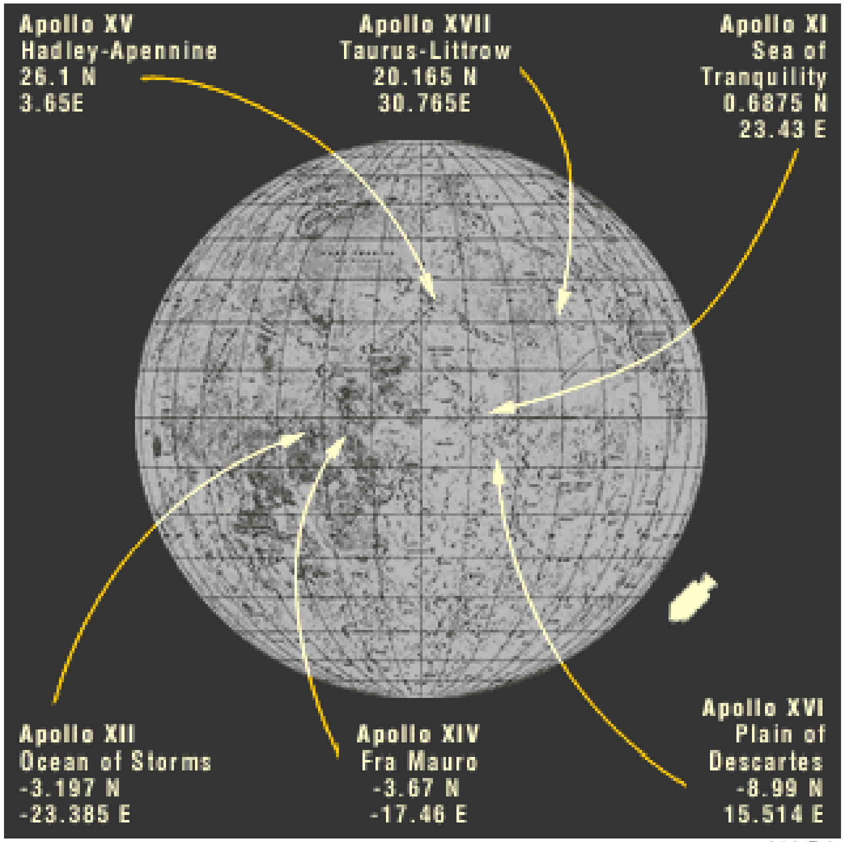






- So how reliable is this?
  - Everything is based on Apollo samples
  - Some of these sites were later found to be geochemically ‘unusual’

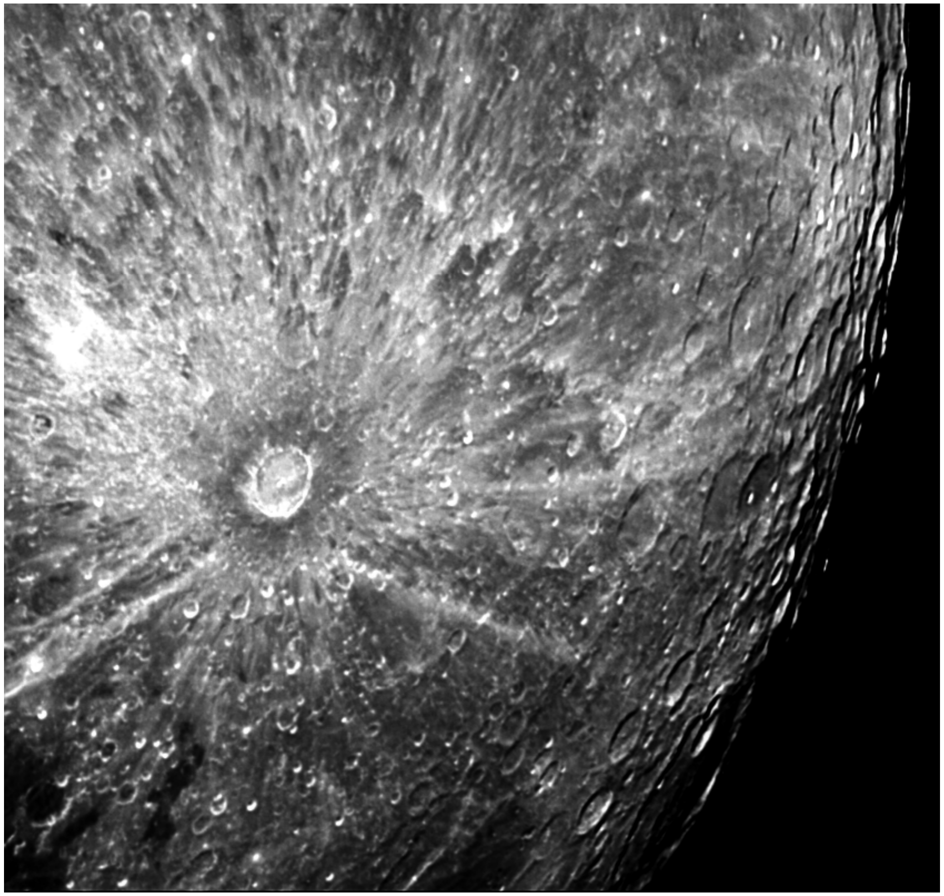
- Lunar meteorites back up the Apollo results
  - Ejected from the Moon by impacts
  - Random sampling from around the Moon



NASA

- **What happens after that?**
  - **Not much….**
  - **More craters form over the last 3.1 Gyr, but a much lower rate.**
  - **The Moon has been pretty much dead for three billion years**

  - **Craters form bright rays that get darkened over time by micrometeorites**
    - **E.g. Tycho**



Lunar Timeline

- Giant impact between Earth and Mars sized body forms Moon
- Magma ocean
  - Olivine rich rocks crystallize (rocks that sink)
  - Anorthosite highland formation (rocks that float)
- Late Heavy bombardment
  - Homogenizes regolith up to 20 km
  - Large basins form

Pre-Nectarian
4.5 – 3.92 Ga

Nectarian
3.92 – 3.85 Ga

- Impact rate declines significantly
  - Life forms on the Earth ?
- Maria erupt onto surface
  - Mare material fills in preexisting basins

Imbrian
3.85 – 3.15 Ga

- Lighter cratering continues
- Recent craters still have bright rays

Eratosthenian
3.15 – 1.0 Ga

Copernican
1.0 – 0 Ga

In this lecture…

- Two types of terrain
  - Highlands
  - Maria
- Geologic features on the Moon
  - Craters and Volcanoes
- Formation of the Moon
  - Giant impacts & Magma Oceans
- The late heavy bombardment
- Formation of the Maria
- The recent years

Next: Craters

- Reading
  - Chapter 10 to revise this lecture
  - Chapter 11-1,11-2 & 11-3 for next lecture