Lecture 20: The Moon & Mercury

The Moon and Mercury are similar in some ways:
- They both have:
  - Heavily cratered
  - Dark colored surfaces
  - No atmosphere
  - No water
- They also have some interesting differences:
  - The Moon is somewhat smaller than Mercury
  - Mercury has a much larger core
  - They have different formation histories

The Moon & Mercury

- The albedo of an object is the fraction of the incident light that is reflected:
  - Albedo = 0.1 for Mercury
  - Albedo = 0.1 for Moon
  - Albedo = 0.4 for Earth
  - Albedo = 0.7 for Venus

- Even though Mercury's albedo is so low, it appears very bright because it is so close to the Sun.
The Moon & Mercury

Gravity on the Moon and Mercury

- Using the lunar values for the mass and radius, we obtain for the surface acceleration

\[ A_{\text{moon}} = \frac{-GM_{\text{moon}}}{R_{\text{moon}}^2} = 1.7 \text{ m/s}^2 \]

- For the Earth the surface acceleration obtained is

\[ A_{\text{earth}} = \frac{-GM_{\text{earth}}}{R_{\text{earth}}^2} = 9.8 \text{ m/s}^2 \]

- For Mercury the surface acceleration obtained is

\[ A_{\text{merc}} = \frac{-GM_{\text{merc}}}{R_{\text{merc}}^2} = 3.7 \text{ m/s}^2 \]

Gravity on the Moon

- The ratio of the lunar and Mercury surface accelerations compared with Earth’s is

\[ \frac{A_{\text{moon}}}{A_{\text{earth}}} = \frac{1}{6} \quad \frac{A_{\text{merc}}}{A_{\text{earth}}} = \frac{1}{3} \]

- Hence objects on the Moon weigh about 1/6 of their weight on Earth

- Objects on Mercury weigh about 1/3 of their weight on Earth
We can compare the bulk properties of the Moon and Mercury.

We have for the radius and mass of the Moon:

- \( R_{\text{moon}} = 1,700 \text{ km} = 0.25 R_{\text{earth}} \)
- \( M_{\text{moon}} = 7.4 \times 10^{25} \text{ g} = 0.0125 M_{\text{earth}} \)

The volume is therefore given by

\[
V_{\text{moon}} = \frac{4}{3} \pi R_{\text{moon}}^3
\]

Hence \( V_{\text{moon}} = 2 \times 10^{25} \text{ cm}^3 \)

We can use these results to compute the average density of the Moon.
bulk properties of the moon
•the average density of the moon is therefore
\[ \rho_{\text{moon}} = \frac{M_{\text{moon}}}{V_{\text{moon}}} = \frac{7.4 \times 10^{25} \text{ g}}{2 \times 10^{25} \text{ cm}^3} \]
•we obtain
\[ \rho_{\text{moon}} = 3.5 \text{ g cm}^{-3} \]
•this is similar to the density of the surface rocks in the earth’s crust
•the moon does not contain much iron, or a large, dense core

bulk properties of mercury
•we have for the radius and mass of mercury
  \( R_{\text{mercury}} = 2,439 \text{ km} = 0.38 R_{\text{earth}} \)
  \( M_{\text{mercury}} = 3.3 \times 10^{26} \text{ g} = 0.05 M_{\text{earth}} \)
•the volume is therefore given by
\[ V_{\text{mercury}} = \frac{4}{3} \pi R_{\text{mercury}}^3 \]
•hence \( V_{\text{mercury}} = 6.1 \times 10^{25} \text{ cm}^3 \)
•we can use these results to compute the average density of mercury
•the average density of mercury is therefore
\[ \rho_{\text{mercury}} = \frac{M_{\text{mercury}}}{V_{\text{mercury}}} = \frac{3.3 \times 10^{26} \text{ g}}{6.1 \times 10^{25} \text{ cm}^3} \]
•we obtain
\[ \rho_{\text{mercury}} = 5.4 \text{ g cm}^{-3} \]
•this is similar to the average density of the earth
•hence mercury probably contains a lot of iron, and a large, dense core
The Moon & Mercury

- Comparison of bulk properties:
  - $M_{\text{moon}} = 0.0125 \, M_{\text{earth}}$
  - $M_{\text{mercury}} = 0.05 \, M_{\text{earth}}$
  - $R_{\text{moon}} = 0.25 \, R_{\text{earth}}$
  - $R_{\text{mercury}} = 0.4 \, R_{\text{earth}}$
  - $\rho_{\text{moon}} = 0.6 \, \rho_{\text{earth}}$
  - $\rho_{\text{mercury}} = 0.98 \, \rho_{\text{earth}}$

- Although Mercury looks a lot like the Moon, its interior must be more like that of the Earth.
- Mercury and the Earth contain large iron cores.

Types of Lunar Terrain

- The near side of the Moon includes heavily cratered highlands and less cratered lowlands, or “maria.”
- The maria (seas) are dark colored, flat regions created by ancient lava flows.
- The highlands (terrae) are bright areas elevated several kilometers above the maria.
Observations show that the dark maria contain far fewer craters than the bright highlands.

This led people to think that the maria are only about $10^8$ years old, while the highlands are about $4 \times 10^9$ years old.

The Apollo missions to the Moon brought back samples of lunar rocks from the maria and the highlands.

Dating Lunar Terrain

Radioactive dating of the samples shows that

- The maria are about $3.5 \times 10^9$ years old
- The highlands are about $4 \times 10^9$ years old

These results indicate that the period of volcanic activity that flooded the maria must have ended about $3 \times 10^9$ years ago.

Also, the cratering rate must have declined sharply about $4 \times 10^9$ years ago, just after the maria solidified.
Lunar Interior

- The average density of the Moon is comparable to the density of surface rocks on Earth, about 3 grams / cm³.
- Hence, there is no large nickel-iron core at the center of the Moon.

- The Moon's interior is divided into layers:
  - Core (molten?): Central layer
  - Lithosphere: Layer between core and crust
  - Asthenosphere: Magma beneath the lithosphere
  - Crust: Outermost layer

- The Moon's surface features:
  - More permanent highlands:
    - Mare鲷 fields:
  - Less broken:
    - 100 km thick on far side
There are four major theories to explain the formation of the Moon:

- Coformation – not likely, since Earth and Moon have different compositions
- Capture – it’s difficult for the Earth to capture so massive an object
- Fission – Moon is “spun off” from the Earth; this would result in an unstable lunar orbit

The most plausible theory is the Collision Scenario, in which a Mars-sized object hits Earth early in its development:
It was originally believed that Mercury was tidally locked to the Sun, in a synchronous orbit with an 88-day sidereal period. This was based on observations made by the Italian astronomer Giovanni Schiaparelli (1835-1910).

Mercury’s Rotation

However, in 1965, Doppler radar was used to accurately measure the rotation speed of Mercury for the first time. Part of the reflected radar signal was redshifted and part was blueshifted. These measurements indicated that the sidereal rotation period of Mercury is actually 59 Earth days!
Mercury’s Rotation

- This was an unexpected result, which requires a little thought to understand.
- Mercury displays a spin-orbit resonance that is more complex than in the case of the lunar orbit.
- For Mercury, we find that the spin and orbit periods are related by the ratio $2/3$:

$$\frac{59 \text{ Earth days}}{88 \text{ Earth days}} = \frac{2}{3}$$

- Hence, 3 Mercury sidereal days equals 2 Mercury sidereal years.

This is a $2/3$ spin-orbit resonance.
Mercury’s Rotation
- The resonance is 2:3 instead of 1:1 because Mercury has a highly eccentric orbit.
- Therefore, Mercury can’t be tidally locked (it can’t show the same face towards the Sun at all times).
- This is because the orbital speed varies in an elliptical orbit:

Synchronous Orbit of the Moon
- The Moon always keeps the same face pointed towards the Earth.
- The spin period relative to the stars is exactly equal to the orbital period, 27.3 Earth days.
- Since these periods are equal, we say that the Moon is tidally locked, in a synchronous orbit around the Earth.

Synchronous Orbit of Mercury
- The spin-orbit resonance of Mercury is enforced by the presence of a bulge that points towards the Sun every other perihelion.
- If the spin-orbit resonance “slips” a little, the Sun will pull the bulge to re-create the resonance.
- The spin and orbit angular rates are equal at perihelion.
Mercury's Surface

- The Caloris Basin points towards the Sun every other perihelion.
- This is where the massive bulge is that enforces the 2:3 spin-orbit resonance.
- The Caloris Basin resulted from a huge, ancient impact.

![Diagram of Mercury's Surface]

- Seismic waves from the impact traveled through Mercury and were focused and absorbed on the other side.
- The energy from these waves probably formed the "weird terrain" on the far side of Mercury from the Caloris Basin.

![Diagram of Caloris Basin and Weird Terrain]
Mercury’s Surface

• The surface temperature on Mercury is determined by a balance between solar heating and infrared cooling

The surface temperature on Mercury varies between extremes during one solar day

The Moon & Mercury

• The Moon and Mercury have no atmospheres, no water, and no sound. Both are completely desolate

• The daily temperature variation on the Moon is extreme:
  \( T_{\text{day}} = 400 \text{ K} \)
  \( T_{\text{night}} = 100 \text{ K} \)

• The daily temperature variation on Mercury is more extreme:
  \( T_{\text{day}} = 600 \text{ K} \)
  \( T_{\text{night}} = 100 \text{ K} \)

• The surfaces of the Moon and Mercury have been altered by thousands of meteorite and asteroid impacts

• The crater evidence has been preserved on both, since there is no wind or water erosion
• The typical temperature change between noon and midnight is about 600 K
• This is the largest temperature variation observed anywhere in the solar system!
• The largest variation on Mercury, 700 K, occurs in the Caloris Basin
• However, ice sheets may exist at the poles of Mercury!

Mercury’s Surface

• The Moon also has ice at its south pole...with implications for lunar exploration...
• The Moon and the Moon are covered with craters of all sizes
  ◦ Caused by large and small impacts
  ◦ Lead to erosion of surface features

Mercury’s Surface

• Mercury has no atmosphere
• But, particles from the Solar Wind do impact the planet, and can “hang around” for a while
• These particles form a temporary plasma sheath around the planet, but this is not an atmosphere since the particles all escape
• It’s just too hot for Mercury to retain an atmosphere because it has a very low mass
• This is the same for the Moon
• Mercury does have a magnetic field, which is unexpected because it spins so slowly...

The Moon & Mercury

• Mercury and the Moon are covered with craters of all sizes
  ◦ Caused by large and small impacts
  ◦ Lead to erosion of surface features
The Moon & Mercury

- The impact of the meteorite or asteroid forms a shock wave that melts the underlying rock, producing glassy material.

- New craters can form at any time as a result of impacts.

Crater Formation
Crater Formation

- The impact velocity of a meteorite or asteroid is usually close to the escape velocity:

\[ v_{impact} = v_{esc} = \sqrt{\frac{2GM}{R}} \]

- We have for the mass and radius of Mercury and the Moon:
  - \( R_{mercury} = 2,439 \text{ km} \)
  - \( M_{mercury} = 3.3 \times 10^{23} \text{ g} \)
  - \( R_{moon} = 1,700 \text{ km} \)
  - \( M_{moon} = 7.4 \times 10^{23} \text{ g} \)

- Using the masses and radii of Mercury and the Moon, we obtain for the impact velocity:
  - \( v_{impact} = 4.3 \text{ km / sec for Mercury} \)
  - \( v_{impact} = 2.4 \text{ km / sec for the Moon} \)

- Hence the impacts are more violent on Mercury.
So why are craters more compact on Mercury than on the Moon?

The ejecta fly farther on the Moon because of the lower surface gravity.