Physics 2028: Great Ideas in Science II: The Changing Earth Module Notes

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Edition 2.0

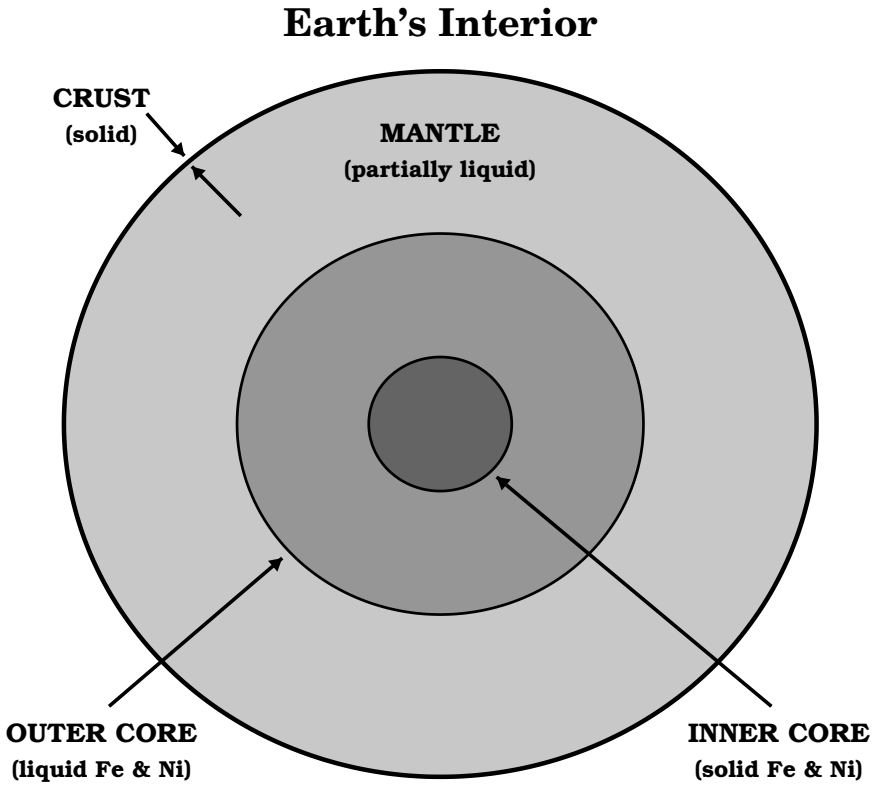
Abstract

These class notes are designed for use of the instructor and students of the course Physics 2028: Great Ideas in Science II. This edition was last modified for the Spring 2009 semester.

II. The Earth-Moon System

A. The Earth's Interior

1. The Earth's interior is layered into 4 distinct zones:



a) Inner core (radius of 1200 km) which is solid and composed primarily of Fe & Ni.

b) Outer core (thickness of 2270 km) which is liquid and composed primarily of Fe & Ni.

c) Mantle (thickness of 2900 km) which is partially liquid and composed primarily of O, Si, Mg, and some Fe.

d) Crust (thickness of 8-70 km) which is solid and composed of the lightest elements (H, C, N, & O) with traces of heavy elements.

2. We know the interior structure through **seismology**: using sound waves from Earthquakes as a probe.

a) Seismic waves travel at different velocities through different types of materials.

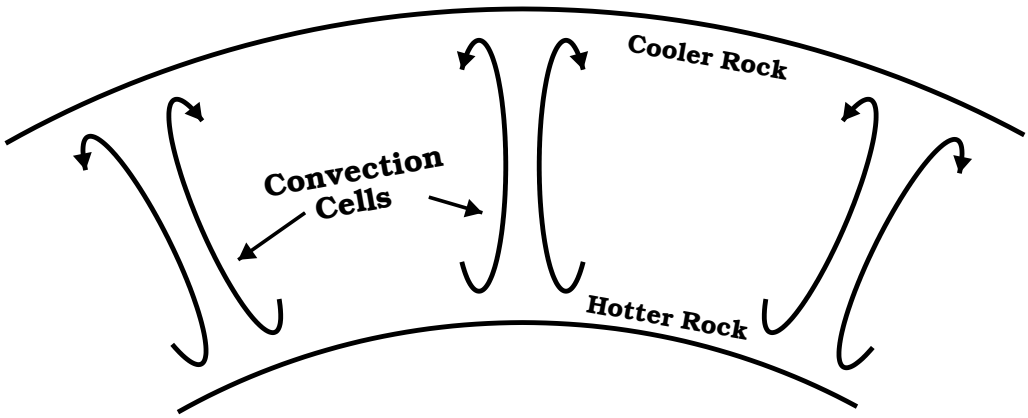
b) Density, composition, and even temperature can be deduced from seismic waves.

3. The outer core is hot which ionizes much of the liquid Fe & Ni. The core rotates just as the surface does.

a) Charged particles in motion produce a magnetic field.

b) The spinning outer core produces the Earth's *dipole* magnetic field that we measure at a strength of 0.5 gauss at the surface.

4. The mantle is also hot. Energy (heat) must flow outward towards cooler regions. This heat flow happens via **convection**.



a) This convection breaks the thin crust into plates and moves the plates about the surface.

b) This plate motion is called **plate tectonics**.

B. Activity on the Earth.

1. Over its 4.6 billion year history, the interior of the Earth should have completely cooled.

a) Should be a solid body throughout, but it is not.

b) Radioactive decay of certain elements (U for instance) continually warms the interior of the planet.

c) This is the main driving force of the Earth's surface activity!

i) Earthquakes.

ii) Volcanos.

iii) Shape of the crust through plate tectonics.

2. The effects of plate tectonics.

a) Approximately 200 million years ago, all of the continents were together which formed a supercontinent called **Pangaea**.

i) Before this time, Pangaea didn't exist and separate continents existed, but moved towards each other.

ii) The Appalachian Mountains formed during the continent collision that formed Pangaea!

b) The mantle's convection broke Pangaea apart forming the present day continents.

i) Pangaea broke apart at a line which is now called the **Mid-Atlantic Ridge**.

ii) At this ridge, new rock is brought up from the mantle to form new crust.

iii) This pushes the American continents away from Europe and Africa at nearly 5 cm/yr.

iv) Such a plate boundary is called a **divergent plate boundary**.

c) This sea-floor spreading pushes North America toward and northward of the Pacific plate, which is moving southward.

i) These 2 plates slide along each other in opposite motions $\Longrightarrow$ **transform plate boundary**.

ii) These plate motions are not uniform, but occur in sporadic lurches due to friction between the plates.

iii) Each *lurch* that occurs causes an **earthquake** to occur!

$\Longrightarrow$ Lurch causes vibration which propagates through the rock in waves.

$\Longrightarrow$ The measurement of these waves is the science of **seismology**.

d) The Indian plate is running head-on into the Eurasian plate $\Longrightarrow$ **convergent plate boundary**.

i) This collision causes the Himalayan Mountains to form.

ii) One plate can sink below another plate (called **subduction**) $\Longrightarrow$ the rock that sinks, heats up to

a molten state and rises through the rock of the other plate causing **volcanos** to form.

e) Convection *hot spots* can form under the centers of some plates pushing mantle material through the crust causing **shield volcanos** (*e.g.*, Hawaii).

C. The Earth's Magnetic Field

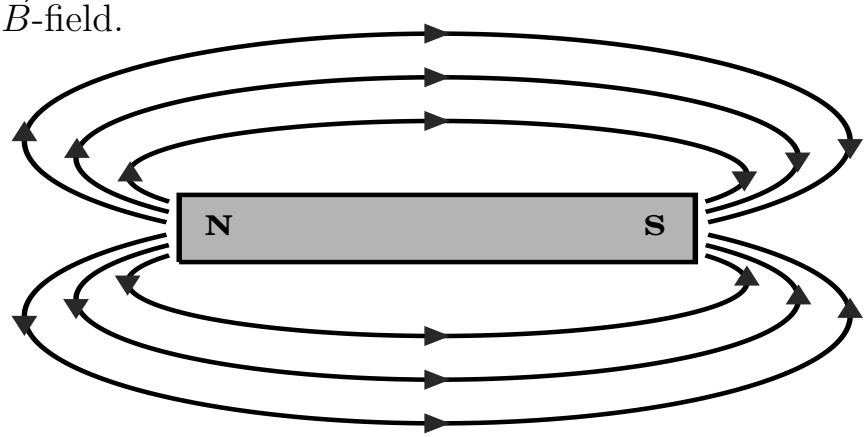
1. Ancient people discovered a rock that when placed close to a similar rock, the rocks would move either closer or farther apart from each other $\Longrightarrow$ these rocks were called **loadstones** or **magnets**.

2. *Like* **poles** repel each other and *unlike* poles attract each other.

a) Magnets have to be asymmetrical for this to work $\Longrightarrow$ preferably the shape of a bar.

b) One pole is called **north** (N), the other **south** (S).

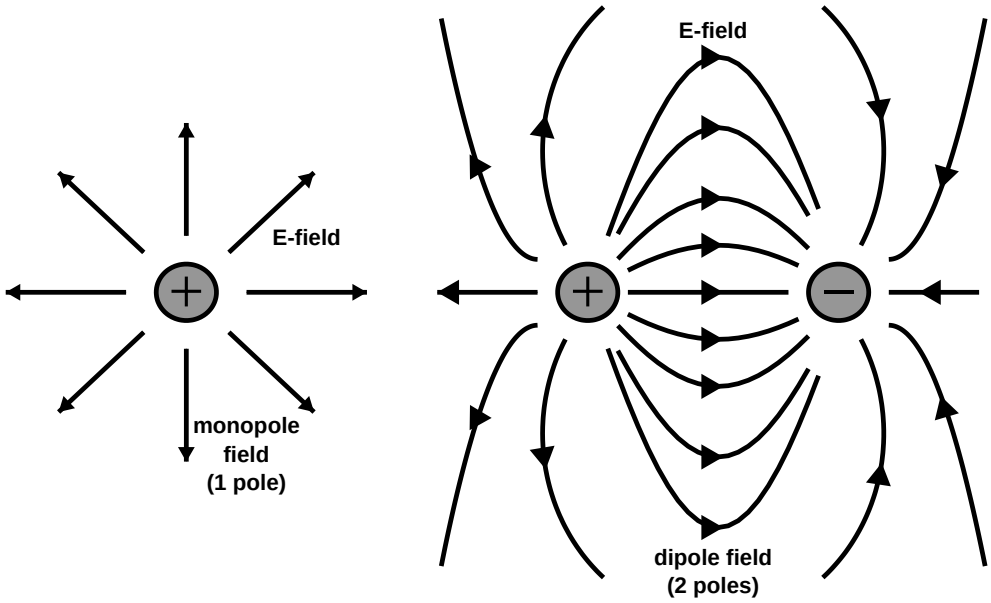
3. Like the electric field ($\vec{E}$), magnets have a **magnetic field** called the $\vec{B}$-field.



a) The B-field points <u>away</u> from the north pole (hence is analogous to a + electric charge).

b) The B-field points <u>towards</u> from the south pole (hence is analogous to a − electric charge).

4. Unlike the electric field, there are no **monopoles** in magnetism $\Longrightarrow$ magnets are always **dipoles** (2 poles).



5. The Earth has a magnetic field!

a) Currently, the magnetic N pole corresponds to the S geographic pole (which is why your compass's N points to geographic N, remember, like poles repel, opposites attract).

b) The magnetic S pole corresponds to the N geographic pole.

c) The magnetic axis is not aligned with the spin axis!

6. Devices used to measure the direction of the magnetic field are called **compasses**. The designation 'N' and 'S' for either pole on a compass was assigned based on which end pointed to the Earth's north pole $\Longrightarrow$ 'N' *seeks* Earth's North pole.

7. An imaginary line joining the magnetic poles is currently inclined by approximately 11.3° from the planet's axis of rotation.

8. The Earth's magnetic field is generated by electric currents in the liquid outer core of the planet which is composed of mostly nickel and iron $\Longrightarrow$ a process known as the **dynamo theory**. The electric currents arise from the Earth's rotation. The details of the geomagnetic field source is still not well understood.

9. Dynamo theory describes the process through which a rotating, convecting, and electrically conducting fluid acts to maintain a magnetic field. Dynamo theory of astrophysical bodies uses magnetohydrodynamic equations to investigate how the fluid can continuously regenerate the magnetic field.

10. The magnetic field is induced and constantly maintained by the convection of liquid iron in the outer core. A requirement for the induction of field is a rotating fluid. Rotation in the outer core is supplied by the **Coriolis effect** caused by the rotation of the Earth. The coriolis force tends to organize fluid motions and electric currents into columns (called **Taylor columns**) aligned with the rotation axis. Induction or creation of magnetic field is described by the induction equation:

$$\frac{\partial \vec{B}}{\partial t} = \eta \nabla^2 \vec{B} + \vec{\nabla} \times \vec{u} \times \vec{B} \ , \qquad \text{(II-1)}$$

where u is the rotational velocity of the core, t is time, $\eta = 1/(\sigma\mu)$ is the magnetic diffusivity, σ is electrical conductivity and μ is the permittivity constant.

11. Magnetic fields extend infinitely, though they are weaker further from their source. The Earth's magnetic field, which effectively extends several tens of thousands of kilometres into space, is called the **magnetosphere**.

12. Geomagnetic field measurements over the past few hundred years show that the B-field strength of the Earth is decreasing and the magnetic poles are changing in position with respect to the spin axis poles.

a) The Earth's magnetic field strength was measured by Carl Friedrich Gauss in 1835 and has been repeatedly measured since then, showing a relative decay of about 5% over the last 150 years.

b) The Magsat satellite and later satellites have used 3-axis vector magnetometers to probe the 3-D structure of the Earths magnetic field.

c) The two poles wander independently of each other and are not at directly opposite positions on the globe. Currently the magnetic north pole is farther from the geographic south pole than the magnetic south pole is from the geographic north pole.

13. Based upon the study of lava flows of basalt throughout the world, there is observational evidence that the magnetic field of the Earth flips polarity (*i.e.*, reverses direction) in random intervals over time.

a) It has flipped 171 times over the past 76 million years. The average period between flips is about 10^4 to 10^5 years (with a peak average period of 200,000 years).

b) The last such flip event, called the Brunhes-Matuyama reversal, occurred approximately 780,000 years ago.

c) We know this from the volcanic rocks near the Mid-Atlantic Ridge. As the sea-floor spreads as mantle material flows upward at that location, the rock solidifies when it hits

the water. The metallic compounds in the lava "freeze" the direction of the magnetic field as the liquid lava turns to solid basalt rock.

d) We may be on our way to another polarity flip within the next few thousand years.

e) There is no clear theory as to how the geomagnetic reversals might have occurred.

i) Some scientists have produced models for the core of the Earth wherein the magnetic field is only quasi-stable and the poles can spontaneously migrate from one orientation to the other over the course of a few hundred to a few thousand years.

ii) Other scientists propose that the geodynamo first turns itself off, either spontaneously or through some external action like a comet impact, and then restarts itself with the magnetic "North" pole pointing either North or South.

iii) External events are not likely to be routine causes of magnetic field reversals due to the lack of a correlation between the age of impact craters and the timing of reversals.

iv) Regardless of the cause, when magnetic "North" reappears in the opposite direction this is a reversal, whereas turning off and returning in the same direction is called a **geomagnetic excursion**.

D. The Moon's Surface

1. The Moon (in Latin the word for the Moon is **Luna**, hence features of the Moon are often referred to as "lunar") is Earth's only natural satellite and the fifth largest natural satellite in the Solar System. When referring to the Earth's moon, the "M" in moon is capitalized. When referring to the other planet's moon, the "m" in moon is kept in lowercase.

2. Physical characteristics:

a) The average center-to-center distance from the Earth to the Moon is 384,403 km, about thirty times the diameter of the Earth.

b) The Moon's diameter is 3,474 km, a little more than a quarter of that of the Earth. Thus, the Moon's volume is about 2 percent that of Earth; the pull of gravity at its surface is about 17 percent that at the Earth's surface.

c) The Moon makes a complete orbit around the Earth every 27.3 days (the orbital period), and the periodic variations in the geometry of the EarthMoonSun system are responsible for the lunar phases that repeat every 29.5 days (the synodic period).

3. The Moon's surface can be subdivided into 2 main type of topology:

a) **Highlands**: Mountainous regions with numerous craters (the brighter regions, the oldest surface of the Moon).

b) **Maria**: Smooth lava plains with relatively few craters (the darker regions).

4. The Moon is in **synchronous orbit** with the Earth $\Longrightarrow$ rotation period = revolution period.

a) One side always points towards the Earth.

b) The *near* side has many maria.

c) The *far* side has no maria.

d) **The far side is <u>not</u> the same as the dark side!**

5. The craters are a result of impacts, most of them resulted from the final epochs of the planetesimal bombardment.

a) The largest impact basin on the Moon is Mare Imbrium.

b) Some of the more recent impact craters show bright *rays* of material radiating from them (*e.g.*, Tycho and Copernicus).

E. The Moon's Interior

1. We have learned much about the Moon from the rocks returned and seismographs left on the Moon by the **Apollo** manned-Moon missions (*i.e.*, Apollo 11 – 17 [13 never landed]).

2. We have learned that the oldest rocks from the Moon (from the highlands) are 4.4 billion years old — slightly younger than the age of the meteorites.

3. The maria are a bit younger from 3.1 to 3.8 billion years old.

4. The Moon has virtually the same average density as the Earth's mantle $\Longrightarrow$ composition must be similar.

5. The Moon's interior is subdivided into 3 distinct layers:

a) Small, solid **iron-rich core** ($R < 700$ km).

b) Plastic **asthenosphere** (650 km thick).

c) Solid **lithosphere** (800 km thick) which includes the solid mantle and a solid crust.

i) Moon's crust is thicker on the far side (100 km).

ii) Moon's crust is thinner on the near side (60 km).

iii) This is why the maria is only seen on the near side.

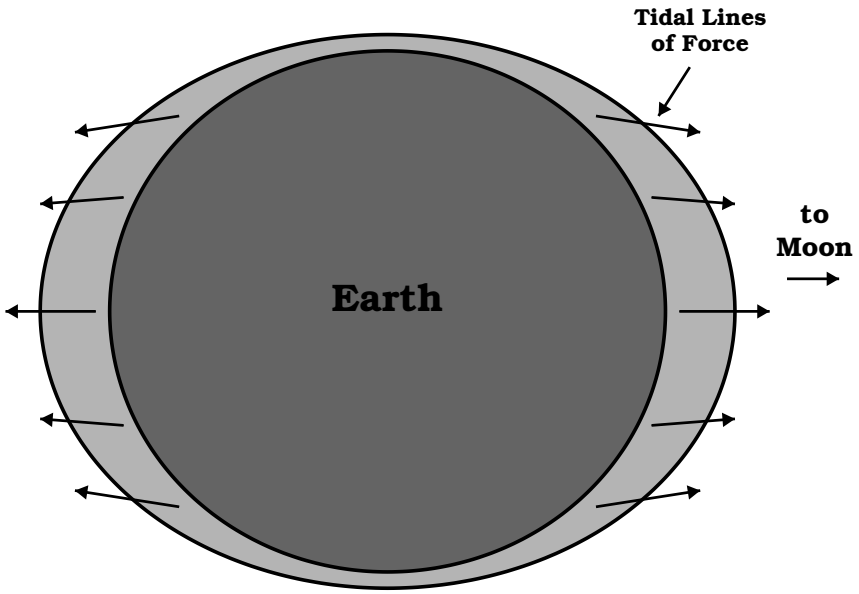
6. The maria lava plains are made up of denser material than the highlands. As a result, the Moon is a bit more massive on the side towards the as compared to the far side. This is the reason the Moon is tidally locked to the Earth (*i.e.*, synchronous rotation).

7. Since the Moon's interior is solid and spins slowly (once every 27.3 days), the Moon doesn't have a magnetic field.

F. The Earth's Tides

1. Just as the Earth has tidally locked the Moon into always pointing one face towards it, the Moon's gravitational field rises tides on the Earth.

2. **Tidal forces** are the differences in the gravitational pull at different points on an object.



3. The Sun also causes tides on the Earth.

a) When the Sun and Moon are co-aligned with the Earth (new or full phase), **spring** or high tides are produced.

b) When the Sun and Moon are at quadrature (90° angles, 1st or 3rd quarter phase) with each other, **neap** or low tides result.

4. Due to the Earth's rapid rotation, the tides are a little ahead of the overhead position of the Moon.

a) The tidal bulge on the leading side of the Earth produces a small forward force on the Moon that causes it to slowly spiral away from Earth (4 cm per year), which has been confirmed by instruments left on the Moon by the Apollo astronauts.

b) Since angular momentum must be conserved, as the Moon's orbital period increases, the Earth's spin rate must slow down (0.0016 seconds per century).

c) As a result, early in its history, the Moon was closer to the Earth and the Earth spun much faster in the past.

Example II–1. What was the distance of the Moon in 3000 BC and how long did the day last?

$\Delta T = 5000$ yrs = 50 centuries

$\Delta P_{\oplus} = 0.002$ sec/cen * 50 cen = 0.1 sec $\Longrightarrow$ tenth of a second shorter day!

$\Delta r = 4$ cm/yr * 5000 yr = 20,000 cm = 200 m = 0.2 km closer to the Earth!

G. The Moon's Formation

1. There have been many hypotheses presented for the formation of the Moon.

2. Any accepted theory of the Moon's formation must take into account the following constraints:

a) Moon's composition must be matched (not much Fe & Ni, nor light elements).

b) Angular momentum problem — Moon must form with its relatively low total angular momentum of the Earth-Moon system.

c) Moon's mass must be obtained.

3. There used to be 3 main competing theories (prior to the Apollo missions) for the Moon's formation $\Longrightarrow$ none of them pass the above constraints set by the Apollo missions.

a) **Fission theory**: The Moon was pulled out of the Earth from the rapid rotation of the proto-Earth.

i) Supporting: (1) Moon's average density (3340 kg/m^3) is similar to the Earth's outer layers; (2) Perhaps the Pacific basin was the original site of the ejection.

ii) Against: (1) The Moon has no water, unlikely to have spun out of the Earth due to fission; (2) The Moon has more **refractory elements** (*i.e.*, those that melt at a higher temperature) than **volatile elements** (*i.e.*, those that melt at lower temperature) — formation occurred at high temperatures; (3) The Earth-Moon system would have a much higher angular momentum than observed; (4) The surface of the Earth is always changing due to plate tectonics, as such, the Pacific basin didn't even exist when the Earth was young.

b) Capture theory: The Moon formed elsewhere in the solar system and was later captured by the Earth's gravitational field during a close encounter.

i) Supporting: (1) The refractory to volatile element ratio may indicate that the Moon formed closer to the Sun than Earth; (2) The Moon's orbital plane is similar to the ecliptic plane — suggests Moon formed in the planetary disk around the Sun.

ii) Against: (1) The Moon would have to have coasted to within 50,000 km from the Earth at exactly the right speed to put it into Earth orbit from a solar orbit <u>without</u> hitting the Earth; (2) Again, the Earth-Moon system would have a much higher angular momentum than it currently has.

c) **Cocreation theory**: The Earth-Moon formed at the same time as a double planet from the solar nebula in the same location from the Sun.

i) Supporting: (1) Moon in virtually same plane as the ecliptic; (2) Water could have been baked out of small planetesimals by the early Sun before accreting into the Moon.

ii) Against: Why doesn't Venus and Mars have such a large Moon too?

4. The results from the Apollo mission has presented a new theory which is the currently accepted theory of the Moon's formation: the **collisional ejection theory**.

a) The Earth was struck by an object perhaps as big as Mars towards the end of the planetesimal bombardment, after the Earth had differentiated.

b) This collision ejected mantle debris from which the Moon formed.

c) Supporting: (1) Apollo mission found that lunar craters resulted from impacts (some very large) and not volcanos, such large impacts surely took place on Earth as well, including perhaps a Mars-sized object; (2) Collision would have vaporized any water and volatile elements from the ejected material; (3) Density of Moon similar to Earth's mantle — Moon's small amount of iron results from the Earth already being (partially) chemically differentiated; (4) Debris would lie in the same plane as the ecliptic since the colliding body would have been in the ecliptic (*i.e.*, a large planetesimal); (5) Such an impact could have given rise to the Earth's axis tilt; (6) Earth-Moon total angular

momentum could be produced by such a collision.

d) Against: Planetesimal would have to be in a relatively small range of masses to eject enough material to form the Moon, yet not be large enough to completely destroy the Earth.

5. Once the material was ejected from the Earth, the rocks accreted into the Moon. As the Moon solidified from the outside in, the still molten mantle of the Moon caused much volcanism in the regions of the Moon's crust that were relatively thin over the first billion years of the Moon's life $\Longrightarrow$ great lava plains formed in these lower basins (*i.e.*, the maria).

6. The low crater density on the maria indicates that the planetesimal bombardment ceased very rapidly during the first half billion years of the solar system's life $\Longrightarrow$ **number of craters on a planetary surface gives us some clues of the age of a surface**.