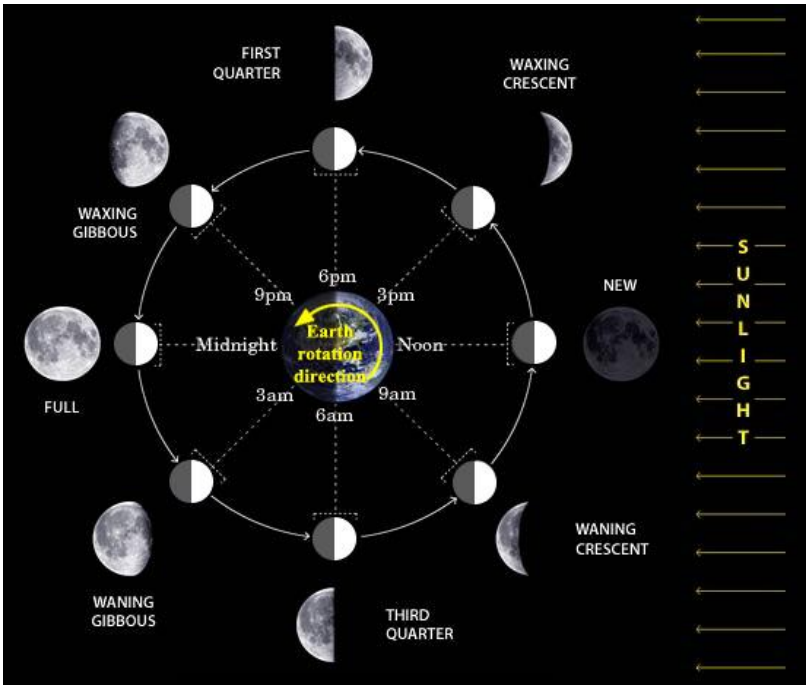
V. ASTRONOMY: EARTH AND THE MOON

A. All planets and moons in the Solar System shine at optical wavelengths only because they reflect light from the Sun; they are too cold to emit thermal visible radiation.
   1. At any given time, only that half of a spherical object facing the Sun is illuminated.
   2. At any given time, we see only the half of a spherical object that is facing us.
   3. The sequence of lunar phases is a consequence of changes in our viewing perspective of the Moon's illuminated hemisphere as it orbits the Earth over 1 month.



   4. Popular misconceptions are that the lunar phases are caused by the Moon entering Earth's shadow, or by clouds in earth's atmosphere, or by clouds on the Moon.
   5. Since the lunar phases are often misunderstood, they are described in detail here.
      a. Consider parallel rays of sunlight reaching the Earth-Moon system.
         i) Note that the diagram above remains the same even as the Earth-Moon system orbits the Sun; only the relative position of the Sun changes.
         ii) For simplicity, assume we are observing from a location not too near the Earth's poles.
      b. When the Moon is between the Earth and the Sun, the Moon's illuminated half faces away from Earth; only the dark half is exposed to us.
         i) This is called "new moon".
         ii) Being roughly aligned with the Sun, the new moon rises and sets approximately with the Sun, and crosses the meridian (it's highest point in the sky) around noon.
         iii) Notes that the Earth, Moon, and Sun are generally not exactly collinear (i.e. in a straight line) at this position because the Moon's orbital plane is tilted by about

5^0 with respect to Earth's orbital plane. Thus, a solar eclipse generally does not occur.

c. A few days later, when the Moon has moved eastward along it's orbit to a new position, the half that we see intersects the illuminated half by a small amount. Since the Moon is spherical, this illuminated part looks curved.
   i) This is called the "crescent moon".
   ii) Since the visible illuminated region is growing larger each day, we call it a "waxing crescent".
   iii) It rises around 9 am, crosses the meridian at approx. 3 pm, and sets in the west around 9 pm, a few hours after sunset. It is most prominent in the evening.

d. About a week after new moon, the Earth-Moon-Sun angle is 90^0. We see half of the illuminated side of the Moon.
   i) This is called the "quarter moon", (actually first quarter), the Moon has moved through ¼ of it's orbit, and we see one quarter of the Moon's entire surface.
   ii) Some people call this the "half moon", since we see half of the side facing us, and it is more consistent with the "full moon" terminology.
   iii) It rises around noon (6 hours later than at new moon), crosses the meridian at about 6 pm, and sets around midnight.

e. A few day later, we see more than half of the illuminated side of the Moon.
   i) This is called the "gibbous moon" (in fact "waxing gibbous" since the illuminated region grows larger each day).
   ii) It rises around 3 pm, crosses the meridian at 9 pm, and sets around 3 am.

f. About two weeks after new moon, the Earth is between the Moon and the Sun; the Moon is opposite the Sun in the sky. The Moon illuminated side faces Earth, and we therefore see all of it.
   i) This is called the "full moon," since the Moon appear fully lit up, even though we actually see only half of it (and "half moon" would be more consistent with the "quarter moon" terminology used earlier).
   ii) It rises at sunset, crosses the meridian around midnight, and sets at sunrise.
   iii) As with the new moon, note that the Moon, Earth, and Sun are usually not exactly collinear at this position due to the 5^0 tilt of the Moon's orbital plane. Thus, a lunar eclipse generally does not occur.

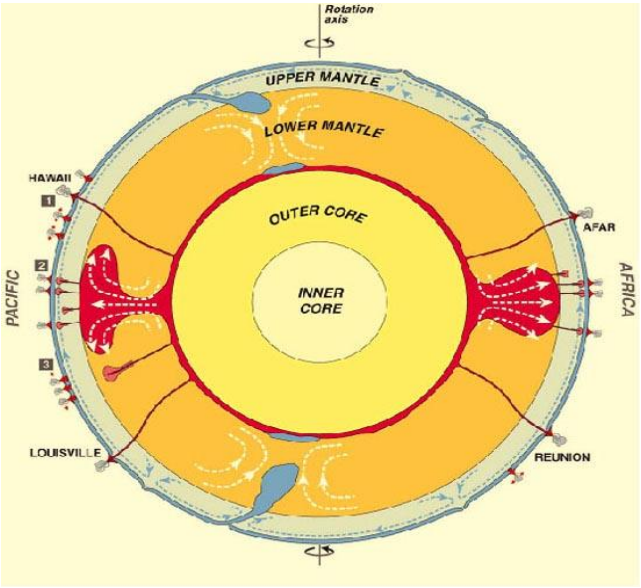
g. From the figure above, it is easy to see that the Moon subsequently goes through the waning gibbous, third quarter, and waning crescent phases before reaching new moon once again.

6. One can deduce from the above discussion that the Moon rises (and sets) an average of about 50 minutes later each day, due to it's eastward motion of about 12^0. Over the course of it's orbit (about 29.5 days), the total necessarily adds up to 24 hours.
7. Note that the Moon can often be seen during the day. For example, the first quarter moon is up and easily visible in the afternoon.
8. When the Moon is in it's crescent phase, it's "dark side" is sometimes easily visible.
   a. This phenomenon is called "earthshine".

b. From the Moon's perspective, the Earth is nearly fully illuminated –it is in it's gibbous phase.
c. Light reflected by the Earth reaches the Moon and is reflected back toward the Earth; thus, the Moon's dark side is indirectly illuminated.
d. During the quarter and gibbous lunar phases, earthshine is more difficult to see.
    i) A smaller portion of the illuminated Earth is visible from the Moon, so there is less reflected light.
    ii) The visible illuminated portion of the Moon is larger and brighter, and the glare drowns out the fainter earthshine.

9. The Moon looks larger when it is near the horizon than when it is high in the sky.
    a. This is just an illusion; it is easier to compare the Moon's angular size with that of known objects (distant trees, buildings, etc.) when it is rising or setting.
    b. The illusion persists even when the Moon rises over the ocean, probably because our brains still remember how big objects appear near the horizon.
    c. The Moon actually has a smaller angular diameter when near the horizon, because we view it from a distance of one Earth radius farther than when it is almost overhead.

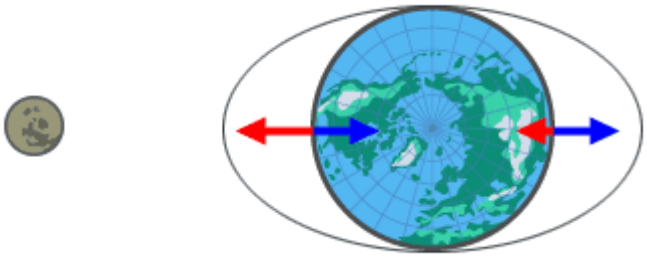
B. Earth, the third planet from the Sun, is the only in the Universe known to sustain life.
1. For reference, Earth's radius is 6400 km, it's mass is 6.0×10^{24} kg, and 1 A.U. = 1.5×10^{8} km.
2. The internal structure of the Earth is determined largely by measuring the transmission of seismic waves through different regions.
    a. Earth clearly went through the process of *differentiation*: dense substances like iron sand to the center when the Earth was young and completely molten, leaving lighter materials (silicates, etc.) on top.
        i) The inner iron core is solid, while the outer iron core is molten.
        ii) The iron core is surrounded by a viscous but fluid mantle, above which lies the crust.
        iii) The Earth remains partly molten because of the release of energy by radioactive elements within it.
    b. The soft, churning layer below the crust produces the phenomenon of continental drift.
        i) Mountain ranges, volcanoes, and earthquakes tend to occur at the boundaries of "plates" that move relative to each other.
        ii) An excellent example of this is the "Ring of Fire" that surrounds the Pacific ocean.
        iii) "Hot spots" are sometimes found within a plate, where molten rock (magma) reaches the surface and cools. This is the origin of the Hawaiian islands.



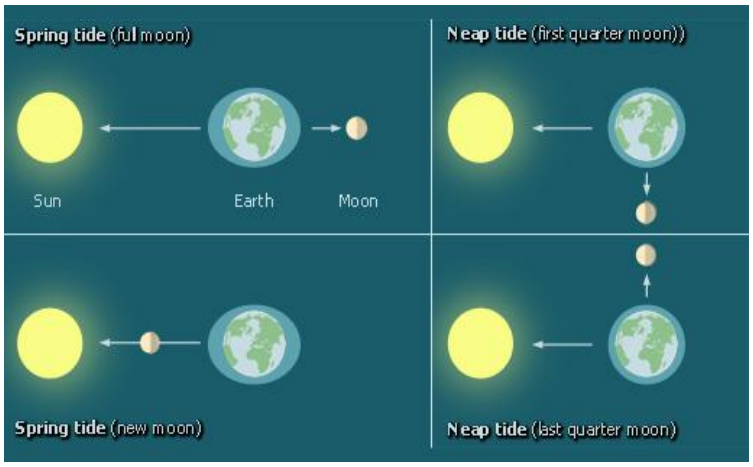
3. Earth's thin atmosphere (<100 km thick) consists of 79% nitrogen molecules (N_2) and 20% oxygen molecules (O_2), with small quantities of carbon dioxide (CO_2), water vapor (H_2O), and argon (Ar).
    a. There is so much free oxygen due to the presence of life: plants, algae, and some plankton produce it.
    b. The early atmosphere of the Earth did not have free oxygen. Rather, the oxygen content started to increase about 2 billion years ago, a consequence of life.
    c. Complete decay of dead organisms uses up as much oxygen as they produced during their lives.
        i) The net increase in oxygen occurs because sediments often cover the organic material before it has had time to fully decompose.
        ii) This is the source of coal and petroleum.
4. Earth's magnetic field, sustained by motions in the partially molten iron core, looks like that of a bar magnet (i.e., a "dipole") centered on the planet.
    a. The magnetic polarity of the Earth (that is, the direction of it's north and south poles) flips irregularly, with average intervals of about ½ million years between reversals. This is clearly seen in the alternating magnetic polarity of solidified lava in the mid-Atlantic ridge, a mountain range that is growing due to the progressive separation between two plates.
    b. Most ionized atoms (predominantly protons) and electrons from the Sun and outer space get trapped in Earth's magnetic field, far from Earth's surface or atmosphere.
        i) This helps life by decreasing the rate of mutations, most of which are harmful.
        ii) The charged particles are guided along the field lines toward the poles, where they approach the Earth and interact with it's atmosphere.
        iii) Collisions with atoms and molecules in the upper atmosphere kick bound electrons to higher energy levels, and they subsequently emit light when they

jump back down to lower levels. The resulting displays are called auroras (northern and southern lights).

5. The Earth's tides are a consequence of differential forces, mostly by the Moon.
   a. The side of the Earth closest to the Moon feels a greater gravitational force than the Earth's center, which in turn feels a greater force than the side farthest from the Moon.
   b. This is called a **differential** force, or a tidal force.
   c. Thus, relative to Earth's center, the "near side" of the Earth feels a force toward the Moon, while the "far side" of the Earth feels a force away from the Moon.
   d. The Earth consequently tends to get stretched out on both sides.



   e. Since water flows, while rocks are difficult to deform, most of the resulting bulge is due to the flow of water toward and away from the Moon. In between these regions, there is a deficit of water.
   f. As Earth rotates about it's axis during the course of a day, most points on (or adjacent to) an ocean experience 2 high tides and 2 low tides.
      i) One tide is usually bigger than the other, due to the tilt of Earth's axis.
      ii) The presence of land, bays, and other geographical features complicates things, but the fundamental picture is correct.
   g. The Sun's total gravitational force on earth is stronger than that of the Moon, but the differential force is only about ½ that produced by the Moon; the Sun is so distant that the near side of the Earth is not much closer than the far side.
   h. Tides tend to be extreme (very high and very low) when the Sun, Earth, and Moon are aligned, since the Sun's and Moon's tidal effects act along the same axis. These are known as "spring tides," but they have nothing to do with the spring season.



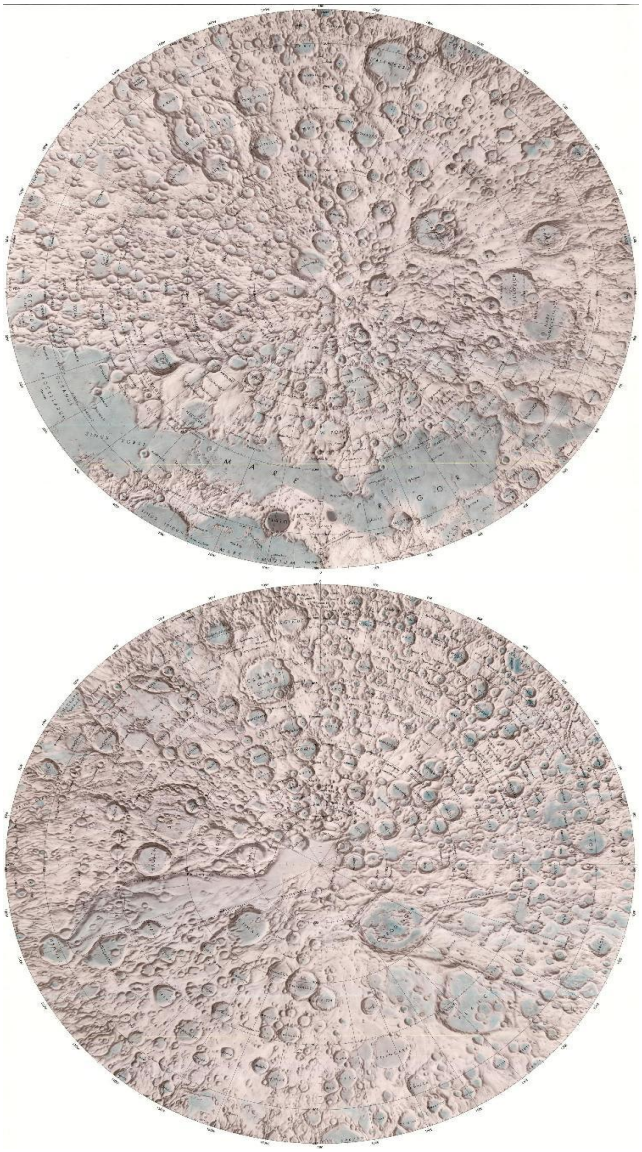
i. Differences between high and low tide are smaller when the Sun, Earth, and Moon form a right (90^0) triangle, since the Sun's and Moon's tides are perpendicular to each other. These are known as "neap tides".

6. Just as the Moon produces tides on Earth, the Earth produce tides on the Moon.
   a. Since the Earth is 80 times more massive than the Moon, the tidal forces on the Moon are 80 times larger than on the Earth.
   b. However, the Moon has no oceans, so only the rocks were able to deform.
   c. In the past, the Moon rotated more rapidly than it does now. Thus, different parts of the Moon deformed at various times during the Moon's rotation period.
   d. The resulting "tidal friction" between different parts heated them, releasing energy at the expense of the Moon's rotational energy.
   e. Thus, the Moon's rotation rate gradually slowed down, until the rotation period became **equal** to the Moon's orbital period.
   f. In this configuration, the same sides of the Moon (those facing directly toward and away from the Earth) are always bulging out due to tidal forces; there are no periodic changes in the deformation of the Moon.
   g. Tidal heating therefore stopped, and there was no reason for the Moon's rotation to continue slowing down.
   h. The Moon became locked in "synchronous rotation": we see the same side at all times.
7. The Earth also loses rotational energy, but at a far slower rate than the Moon did: the tidal forces are smaller, and water is able to flow (so less energy is dissipated).
   a. However, this effect is causing Earth's day (rotation period) to increase by about 1 second every 100,000 years.
   b. To keep the overall angular momentum (total spin) of the Earth-Moon system constant, the Moon is gradually receding from the Earth.

C. Earth's Moon give important clues to the history of the Solar System.
1. A few basic facts about the Moon are that it's average distance is 384,000 km (center of Earth to center of Moon), it's mass is 1/80 of Earth's mass, and it's radius is 1/3.7 of Earth's radius.
   a. The gravitational force per unit mass on the Moon's surface, GM/R^2 (where M is the mass of the Moon and R is it's radius), is therefore $(1/80)/(1/3.7)^2 = 1/6$ times that on the Earth's surface.
   b. Since the weight of an object of mass m is a measure of the gravitational force on it, objects weigh about 1/6 as much on the Moon as they do on Earth.
   c. This is why astronauts had a relatively easy time jumping around on the Moon, or hitting golf ball a great distance.
2. The time between two consecutive full moons is 29.5 days.
   a. Given the Moon's synchronous rotation, this means that any given point experiences nearly 15 consecutive day of sunlight followed by an equal interval of darkness. There is no perpetual "dark side of the Moon".

b. More importantly, the Moon has no atmosphere to trap and redistribute heat; thus, the Moon's surface temperature goes through extremes of -110^{0}C (night) to 130^{0}C (day). (Recall that at sea level on Earth, water freezes at 0^{0}C and boils at 100^{0}C).
c. There is essentially no water on the Moon, except perhaps in the extreme polar regions that are shaded from the Sun.
    i) Instruments aboard recent satellites suggest the presence of ice crystals.
    ii) More controversial is the claimed evidence for a frozen lake in a shielded crater at the Moon's south pole.
    iii) Any traces of water on the Moon probably come from comets that hit it.

3. The Moon is heavily cratered.
    a. The evidence (shapes, distributions, detailed characteristics) strongly implies that most of the craters are of impact origin, rather than volcanic.
    b. The most heavily cratered areas are the oldest (that is, solidified longer ago than less heavily cratered areas).



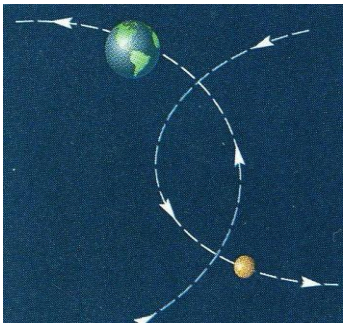
c. Lava flows produced the maria ("seas"; singular mare) and presumably covered previously existing craters.
d. Since there is very little erosion on the Moon, we can measure the relative ages of features.
e. For example, craters superposed on maria must be younger (i.e., created most recently) than the maria.

4. A glorious time in history of space exploration was the era of the lunar landings of Apollo 11 through Apollo 17 (1969-1972).
   a. The astronauts did a number of experiments on the Moon.
   b. They also left equipment (e.g. seismographs; radar reflectors).
   c. Moon rocks from various regions were returned to Earth.
5. The absolute ages of the rocks (i.e. the time since they were last in the molten state) is derived by radioactive dating.
   a. A radioactive element such as uranium decays into daughter products (e.g. lead) with a certain half-life.
   b. After a time interval of one half-life, half of the original quantity of the substance remains; after two such time intervals, half to half.
   c. If the rock is solid, the daughter and parent products won't be able to mix with their surroundings and become diluted.
   d. By measuring the ratios of parent and daughter products, the age of the rocks can therefore be determined.
6. It was found that the heavily cratered areas of the Moon are 3.9-4.4 billion years old, while the maria have ages of 3.1-3.9 billion years old.
   a. There are few craters on the maria; hence, the intense bombardment of the Moon must have happened very soon after the formation of the Moon.
   b. Presumably other bodies in the Solar System, including the Earth, also experienced this onslaught.
   c. Given the ages of the oldest lunar rocks (4.4 billion yrs old) and the asteroids (4.6 billion yrs old), the Moon itself must have formed at the same time as, or shortly after, the rest of the Solar System.
   d. The intense cratering era was probably the tail end of the accumulation of planetesimals into planets.

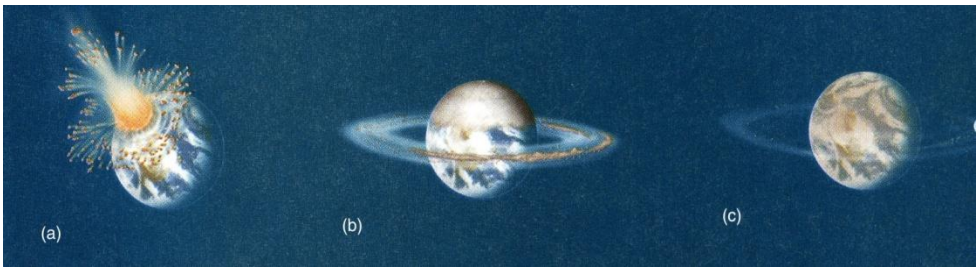
D. Origins of the Moon:
   1. Four Theories: Double Planet, Fission, Capture, and Impact
      Facts: (i) One-fourth of Earth's Diameter (ii) Surface craters were caused by meteorite impacts. (iii) Maria was caused by lava flow. (iv) No atmosphere. (v) Weak magnetic field.
      a. Double Planet Theory:
         i) Suggested in the 1800s that the Earth formed from a spinning disk of material. A small part of that material was left orbiting the Earth and formed into the Moon.
         ii) If the Moon formed along with the Earth, the two bodies should have about the same density. (Earth density = 5.5 g/ cm^3 ; Moon density = 3.3 g/cm^3)

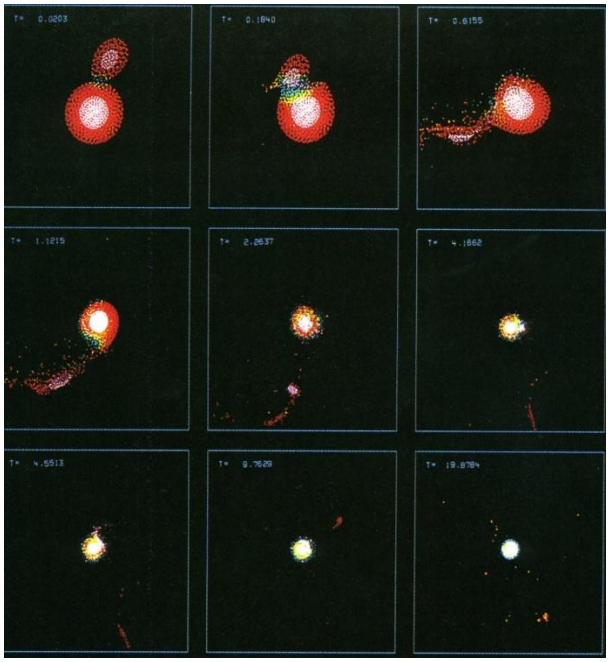
b. The Fission Theory:
   i) George Howard Darwin, 1878, proposed that the Moon was once part of the Earth and broke from it due to forces caused by a fast rotation and solar tides.
   ii) The density of the moon is similar to the Earth's crust.
   iii) No satisfactory mechanism for this event has been proposed.
   iv) The Moon does not orbit in the plane of the Earth's equator, as it should if it were ejected from a spinning earth.
   v) The Moon has higher proportions of nonvolatiles than the Earth's crust, which require a very high temperature to vaporize.

c. The Capture Theory:
   i) 1900s: Holds that the Moon was originally solar system debris that was captured by the Earth.
   ii) One astronomical object will not capture the other unless there is contact between the two or unless a third object is involved to slow down the other's orbital speed.



d. The Large Impact Theory:
   i) In the 1970s, A.G.W. Cameron and William Ward proposed that the Earth was struck at a glancing angle by a large object.
   ii) The impact resulted in a fusion of the two objects, and material was thrown off from the combined object to form the present Moon
   iii) Computer simulations of such collisions show that if the impacting object has a mass nearly as great as Mars, heat resulting from the collision would vaporize material and eject enough of it into orbit to account for the mass of the Moon, once the material coalesced in orbit.





iv) Since the impact would have vaporised the rocks, they should be depleted in water and volatile elements.

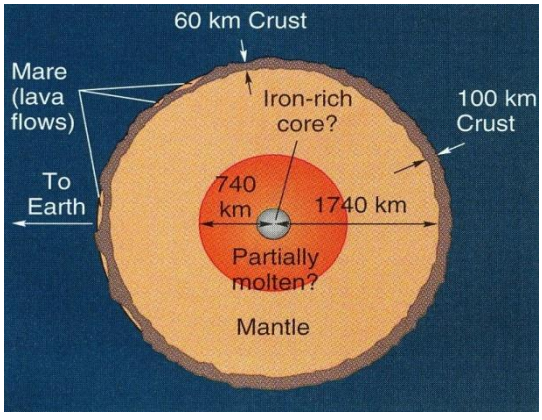
v) If the collision occurred after the Earth was chemically differentiated, then the resulting Moon would have proportionally much less iron than the Earth.

vi) If the plane of the impacting object were close to the ecliptic, so would be the plane of the resulting debris and thus the Moon.

vii) The impact would most likely tip the Earth's rotation axis in the process.

viii) Computer models show that the Earth should rotate every 200 hrs without the impact.

2. The Probable History of the Moon:
   a. Formed 4.6 bya
   b. The surface was molten a few million years after formation.
   c. Most craters were formed 4.2-3.9 mya.
   d. After most of the cratering ended, the interior of the Moon became hot enough from radioactivity, that molten lava flowed from beneath the surface to gather in the floors of the giant craters,(3.1 & 3.8 mya). (Hence the Maria)



E. QUESTIONS: Moon and the Earth

1. Describe the phases of the Moon and what produces them.

2. Show that the visibility of the Moon (time; location in the sky) is related to it's phase.

3. What would be the phase of the Earth, as seen from the Moon at each lunar phase?

4. Describe some of the main characteristics of Earth's atmosphere:

5. Describe some of the main characteristics of Earth's internal structure:

6. Describe some of the main characteristics of Earth's magnetic field:

7. Explain how the tides on Earth are produced, and why the Moon's pull dominates that of the Sun in this process.

8. Calculate your weight if you were standing on the Moon.

9. Explain how the age of an object is determined through radioactive dating.

10. State the evidence for believing that there was a period of heavy bombardment early in the history of the Solar System.

11. Discuss why the Moon keeps essentially the same face toward the Earth.

12. Given that the Moon is slowly receding away from the Earth, discuss the visual appearance of total solar eclipses in the past. Were the chromosphere and inner corona more difficult to see? Will it be possible to view total solar eclipses far in the future?

13. It is sometimes said that the U.S. mission to the Moon was entirely motivated by the Soviet Union's launch of the Sputnik satellite in 1957. Do you think the scientific benefits of lunar landings would have been sufficient reason to take the risks and spend the funds? Why?