

Origin of Earth's moon

Short Course Notes

I gave this short course several times to groups of high school earth science teachers, 1994-1998. The information herein was derived from many sources, some of which are listed at the end. I have updated this document on occasion.

Samples returned from the Moon

6 U.S. Apollo landings	382.0 kg
3 U.S.S.R. Luna robot landers	0.32 kg
Over 366 known lunar meteorites	>249 kg
Total	>632 kg

Although the robot lander sample set is small, it is important because the samples came from parts of the moon different from the Apollo landings. The meteorite sample set is important, but where they came from on the Moon is unknown.

Types of samples collected on the Apollo missions

Soil	Loose particles on and near the surface that have been excavated and thrown about by meteorite impacts. This is made of mineral and rock fragments, volcanic glass, impact glass, and fragments welded together with impact glass.
Breccia	Aggregates of rock, soil, and other breccias that were welded together by meteorite impacts. Some of these have been partly melted by impact heating.
Basalt	Dark, fine-grained, iron- and magnesium-rich, silica-poor volcanic rock that makes up the dark floors of the largest lunar impact basins (maria).
Other	Small breccia and rock fragments, anorthosite (plagioclase-rich plutonic rock), and gabbro (coarse-grained equivalent of basalt). Granite and other rock types are very rare.

Minerals in lunar samples

There are fewer minerals in lunar rocks than on the Earth, partly because of the more limited range of rock compositions of the Moon. The absence of water and other volatiles is an important factor that limits the number of minerals too. The most abundant minerals in the moon are listed below.

Silicates	plagioclase (feldspar), calcium-rich pyroxene (augite, pigeonite), calcium-poor pyroxene (enstatite), olivine. These minerals are found in terrestrial rocks, principally in gabbro, basalt, and the Earth's upper mantle. Quartz, alkali feldspars, and related minerals are rare on the Moon but rich in Earth's continental crust.
Oxides	ilmenite (FeTiO_3), ilvospinel (TiFe_2O_4), chromite (FeCr_2O_4), and ferropseudobrookite (FeTi_2O_5). These minerals are found in many terrestrial rocks, although the latter three only in basalt, gabbro, the Earth's mantle, and related rocks.
Sulfides	troilite (FeS). This mineral is extremely rare on the Earth, though its iron-deficient relative pyrrhotite (Fe_{1-x}S , where X is a value between 0 and 0.1) is common.
Metals	iron (Fe). Metallic iron is extremely rare on the Earth (except in the core, of course).

Ages of lunar rocks

The oldest rocks are anorthosites in the lunar highlands (ancient crust, 4.3-4.46 billion years old). Impact breccias are mostly derived from the giant maria-excavating impacts (3.9-4.3 billion years old). Mare basalt that covers the mare floors was formed by melting of the lunar mantle. These basalts gradually filled the maria as a series of lava flows (3.1-3.9 billion years old). Volcanic glass is scattered throughout the lunar regolith, although relatively few volcanoes, as such, have been positively identified. This glass (1.3-3.5 billion years old) largely post-dates the mare basalts. Since 1.3 billion years ago there is no evidence of any geologic processes except meteorite impacts and some mass wasting processes such as landslides.

Comparison of the Moon with the other inner planets

Characteristic	Mercury	Venus	Earth	Moon	Mars
Distance from sun*	0.39	0.72	1	1	1.52
Length of day*	59**	243 (retrograde)	1	27.3**	1.03
Diameter*	0.38	0.95	1	0.27	0.53
Mass*	0.055	0.816	1	0.012	0.107
Density, g/cc	5.46	5.23	5.52	3.35	3.92
% of mass in the iron core	~54%	~28%	32%	~2%	~25%
Rotation angular momentum/mass*	0.01	0.01	1	<0.01	0.7
Earth + Moon angular momentum***	11				
* Earth = 1.					
** Tidal effects have slowed the spins of Mercury and the Moon, and possibly Venus. Mercury's day is 2/3 the length of its year, and the moon's day equals its orbital period about the Earth, so the Moon always has the same face toward the Earth. Venus always has the same face toward earth on closest approach, which is difficult to understand without at least some tidal effect.					
*** Including the angular momentum of the Moon's spin and orbit about the Earth.					

The inner planets of the solar system are largely composed of rocky silicate material in their crusts and mantles, surrounding a metallic iron core. The inner planets contrast with the outer planets, which are gas giants composed largely of hydrogen and helium.

The most popular hypotheses three or four decades ago held that the inner planets accreted by the accumulation of huge numbers of relatively small meteorites, asteroids, comets, etc. The larger each planet grew, the more meteorites its gravitational field, and target area, swept up. Eventually, most stray objects were used up and the inner planets stopped growing. Because of presumed mixing of debris in different parts of the solar system due to orbital perturbations, this view predicted that the inner planets should have similar chemical compositions, similar core sizes, no significant moons, long days (slow rotation rates), and, as a consequence of the long days, similar and low rotational angular momentum.

Comparison of the inner planets shows that there are some dramatic differences between the inner planets that are contrary to the uniformitarian accretion concept. Venus spins very slowly (and in a retrograde direction!) compared to the other planets. Venus, Earth, and Mars have proportionally similar size iron cores, but the core of Mercury is proportionally huge and the core of the Moon almost nonexistent. Lastly, the angular momentum of the Earth-Moon

system is anomalously large, and that of Venus anomalously small. Most of these differences are difficult to explain given the uniformitarian viewpoint. Furthermore, the Earth, with its proportionally giant moon, is unique in the inner solar system and its origin has been controversial for more than 200 years.

Introduction to lunar geology

The basic geology of the Moon has been worked out from telescope and satellite images of the lunar surface, samples returned by the U.S. Apollo and Soviet Luna missions, from lunar meteorites, from seismic sensors and other devices left by Apollo missions, and measurements from lunar-orbiting satellites. The following summarizes the conclusions.

1. The Moon's density, measured chemistry, and seismic structure is compatible with a lunar mineralogy of mostly pyroxene, olivine, plagioclase, and iron-titanium oxides, with a tiny iron core.
2. The overall chemistry of the Moon is much like the Earth's mantle, but the Moon has much less of chemical components that are volatile at modest temperatures, including H₂O, CO₂, and elements with low boiling points such as sodium, lead, and arsenic.
3. The Moon's oldest crust is 4.4 billion years old, about 60 km thick on the near side and thicker on the far side, and is composed mostly of anorthosite and other related plagioclase-rich rocks. This anorthosite crust is thought to have formed by floating of plagioclase crystals as they crystallized during cooling of a global magma "ocean". The crust has been heavily "churned up" by numerous large meteorite impacts early in the Moon's history.
4. The Moon's mantle is largely composed of pyroxene, olivine, and iron-titanium oxides. The deeper parts of the mantle were probably always mostly solid, whereas the upper parts of the original mantle were formed by sinking of dense minerals during cooling and crystallization of the magma ocean at the same time the crust formed.
5. After the crust formed and the magma ocean solidified, several huge meteorite impacts excavated large basins and created large quantities of impact melt and breccia.
6. The earliest giant impact basins were probably erased by subsequent impacts, like the South Pole-Aitken basin on the lunar far side almost is, despite being the largest impact structure in the solar system.
7. Somewhat younger large impact basins became partly filled with enormous basaltic lava flows. These "mare basalts" erupted over a period of hundreds of millions of years. The basalts formed by melting of the lunar mantle.
8. Volcanic activity decreased with time, and evidence indicates that volcanism ceased about 1.3 billion years ago.
9. Impact cratering continues at a slow rate to this day.
10. The Moon is gradually moving away from Earth as tidal interactions gradually transfer angular momentum to the Moon. As a result, Earth's rotation rate is gradually slowing and its day is gradually getting longer.

Hypotheses for the origin of the Moon

Capture hypothesis. The moon formed by accretion like the other planets somewhere in the inner solar system. Gradual changes in the Moons' orbit about the sun by gravitational interaction with other planets eventually caused the Moon to pass close to the Earth and be captured into orbit about the Earth.

- Doesn't explain why the Moon has so little iron (so small a core).
- Doesn't explain why the Moon is so poor in volatile materials, such as H₂O, CO₂, sodium, etc.
- Doesn't explain the origin of the early magma ocean, which would have required a very hot early lunar history.
- Capture is unlikely from an orbital dynamics standpoint. It is much more likely that the moon would have collided with an inner planet, been moved into a different, probably eccentric orbit about the sun, or ejected from the solar system.

Fission hypothesis. The moon split (fissioned) from the Earth as a blob when the Earth was spinning very fast in its early history (the day had to have been only 2.5 hours long). The very fast spin may, in part, have resulted from sinking of metallic iron in the Earth to form the core.

- Does explain why the moon has such a small core, because the portion of the Earth that fissioned to form the Moon would have been the mantle, with little iron metal.
- Does explain the proximity of the Earth and Moon.
- Doesn't explain why the Moon is so poor in volatile materials, such as H₂O, CO₂, and sodium.
- Doesn't explain the origin of the early magma ocean, which would have required a very hot early lunar history.
- Calculations show no easy way to get the Earth spinning so fast. Indeed, several theories for planet formation indicate that slow spins should be the norm.

Sister planet hypothesis. The moon accreted from a disk of material that surrounded the proto-Earth, much as planets accreted from a much larger disk of material surrounding the Sun, and the way the major moons of Jupiter appear to have accreted.

- Does explain the proximity of the Earth and Moon.
- Doesn't explain the origin of the early magma ocean, which would have required a very hot early lunar history.
- Doesn't explain why the Moon has so little iron (so small a core).
- Doesn't explain why the Moon is so poor in volatile materials, such as H₂O, CO₂, and sodium.

Giant impact hypothesis. The Moon formed from debris thrown into Earth orbit during an oblique collision of the proto-Earth with a smaller, but still planetary-sized body (perhaps the size of Mars).

- Explains the proximity of the Earth and Moon.
- Explains why the Moon has little or no iron core. Computer models indicate that the debris thrown into orbit came mostly from the rocky mantles of the proto-Earth and the impacting body.
- Explains why the moon has a low volatile content. The very hot debris (silicate vapor and liquid) thrown into orbit by the giant impact would initially be dispersed and then form a

disk, or ring, about the Earth. Gaseous materials, like H₂O, CO₂, sodium, and some other elements, would evaporate into space and be lost. When the ring gradually accreted to form the Moon, the material would have been poor in volatile materials.

- Explains the formation of the early magma ocean. The material thrown into orbit would have been very hot, probably mostly gas and liquid initially, and would have released gravitational potential energy as the material eventually accreted on the growing Moon. The result would have been a moon with a thick layer of liquid, the magma ocean from which the lunar anorthosite crust and early upper mantle formed.
- Explains the very high angular momentum of the Earth-Moon system. The extra angular momentum came from the oblique impact, which converted part of the orbital momentum of the impacting body to orbital momentum of the ring about the Earth (which became the Moon), and part to make the Earth spin faster.

How lunar origin relates to the accretion of the Earth

As mentioned above, older ideas about the formation of the inner planets were rather uniformitarian in nature. The early solar nebula was shaped like a disk and contained gas and dust. The dust gradually clumped together to make pebbles, the pebbles clumped to make boulders, the boulders clumped to form asteroids, and the asteroids accreted by gravity and collision to form the planets:

1. Dust of the early solar nebula.
2. A great many pebbles.
3. Zillions of boulders.
4. Trillions of asteroids.
5. Asteroids accrete to form the four inner planets.

This idea holds that the planets basically formed from the accumulation of a “rain” of fairly small boulder to asteroid size fragments. Recent computer models and other evidence suggest a somewhat different course of events. The beginning is the same, with tiny particles gradually clumping together to form larger bodies. The difference is that the last stages of accretion include mammoth collisions of planet-size bodies:

1. Dust of the early solar nebula.
2. A great many pebbles.
3. Zillions of boulders.
4. Trillions of asteroids.
5. Thousands of planetesimals.
6. Dozens of protoplanets.
7. Four inner planets.

The large, random collisions involved in the last stages of planetary accretion can explain many of the inner planet anomalies pointed out above:

- Mercury may have its proportionally large core because half of its mantle may have been blown away (greater than escape velocity) by one or more giant impacts. However, why the

silicate debris didn't eventually find its way back onto the surface of Mercury is an outstanding question with this idea.

- Venus may have its slow, retrograde rotation because its last big collision may have, by chance, almost eliminated its spin.
- Earth's moon and the large angular momentum of the Earth-Moon system may have been caused by an oblique giant impact on the proto-Earth. This impact, by chance, put enough material into orbit to create our moon.
- Although Mars has no similarly dramatic anomalies, the geology of Mars is amazingly [asymmetric](#), which may have been instigated by one or more large late collisions.

References and further reading

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