The Moon

Question

If the Moon is the Earth's partner, why is it so different?

Earth & Moon Comparison

Table 9-1 Moon Data

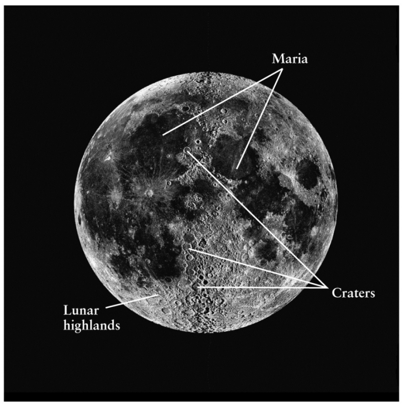
Distance from Earth (center to center):	Average: 384,400 km = 238,900 mi Maximum (apogee): 405,500 km Minimum (perigee): 363,300 km
Eccentricity of orbit:	0.0549
Average orbital speed:	3680 km/h
Sidereal period (relative to fixed stars):	27.322 days
Synodic period (new moon to new moon):	29.531 days
Inclination of lunar equator to orbit:	6.68°
Inclination of orbit to ecliptic:	5.15°
Diameter (equatorial):	3476 km = 2160 mi = 0.272 Earth diameter
Mass:	7.349×10^{22} kg = 0.0123 Earth mass
Average density:	3344 kg/m^3
Escape speed:	2.4 km/s
Surface gravity (Earth = 1):	0.17
Albedo:	0.11
Average surface temperatures:	Day: 130°C = 266°F = 403 K Night: −180°C = −292°F = 93 K

Basic Properties

The Moon has 1/80 (= 0.012) the mass of the Earth.

The Moon has no atmosphere. In fact, there is no evidence to suggest that it ever had an atmosphere or any water. Consequently, the Moon lacks volatile gases, such as hydrogen, helium, and oxygen.

Surface Features

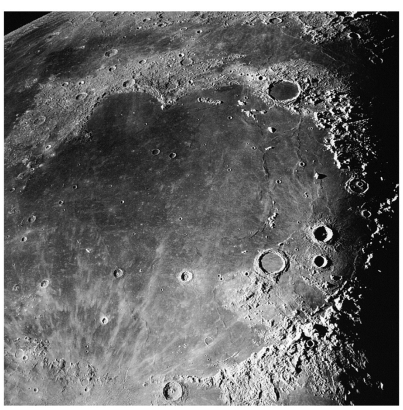


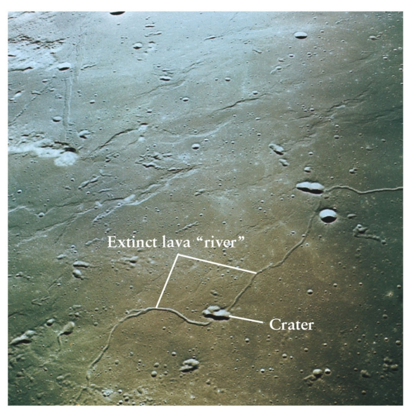
Galileo saw the smooth, dark regions with his telescope. He called these **maria** (singular is **mare**), meaning “sea.”

Besides the dark regions, there are lighter, rough areas called **highlands**.

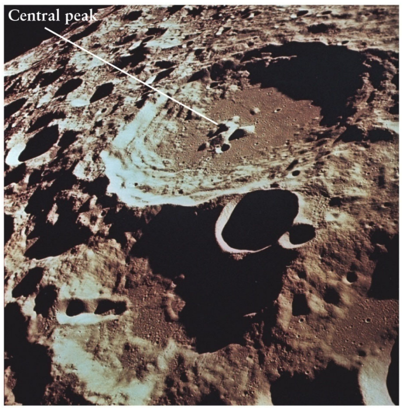
There are numerous, circular **craters**.

Maria





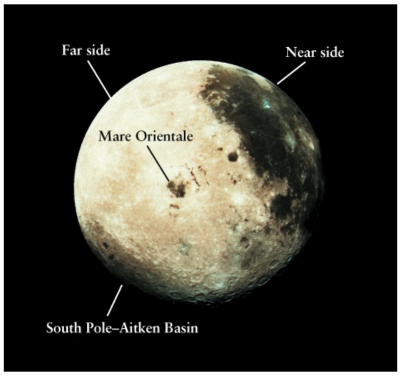
Craters



Pre-Apollo Exploration

Ranger series	USA	Early 1960's	Landed
Lunar Orbiter (5)	USA	1966-67	Orbited
Surveyor (5)	USA	1966-68	Landed

Hemispheres are Different



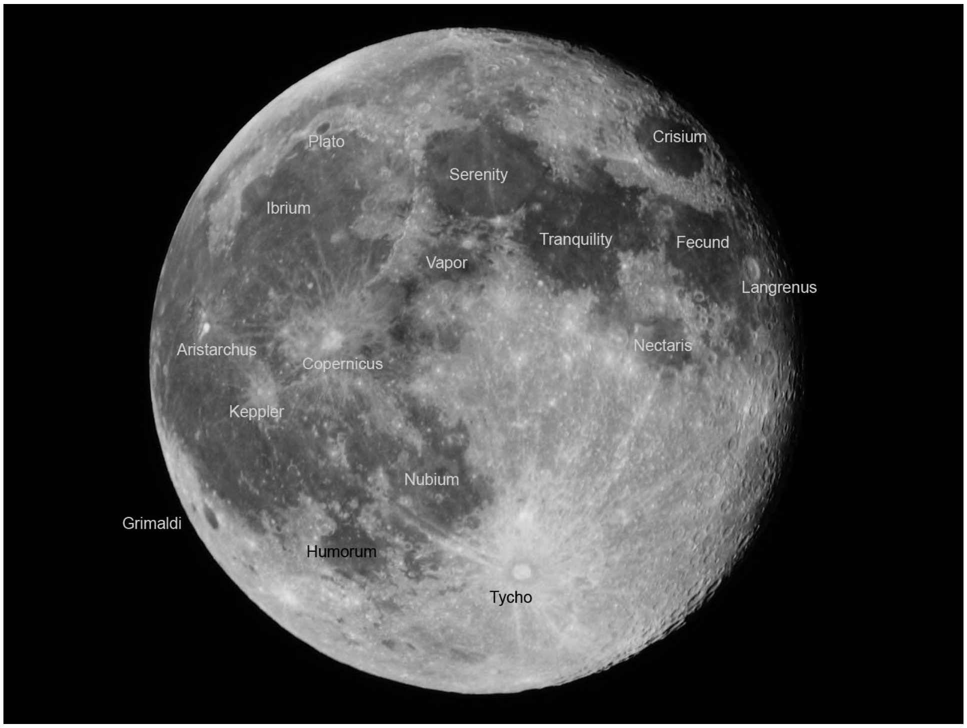
The Earth-facing (near-side) hemisphere is dominated by numerous, large maria.

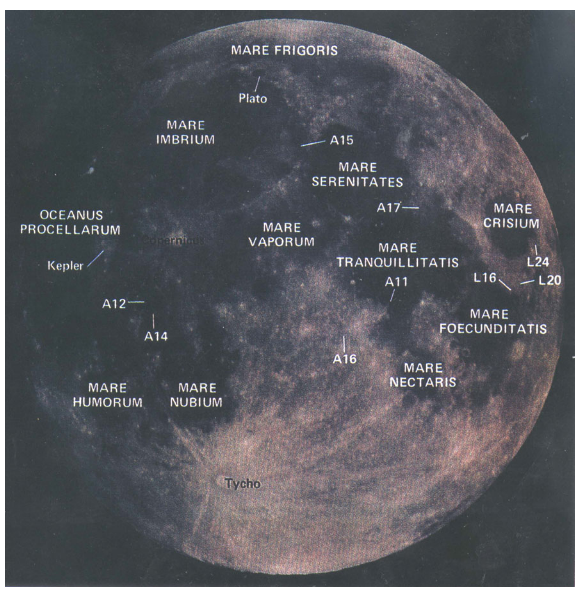
But on the Earth-opposite (far-side) hemisphere, there is only one small mare (Orientale).

The far-side hemisphere is dominated by lunar highlands.

Apollo-Era Exploration

Apollo 11	USA	1969	Manned
Apollo 12	USA	1969	Manned
Luna 16	USSR	1970	Robotic
~~Apollo 13~~	~~USA~~	~~1970~~	~~Manned~~
Apollo 14	USA	1971	Manned
Apollo 15	USA	1971	Manned
Luna 20	USSR	1972	Robotic
Apollo 16	USA	1972	Manned
Apollo 17	USA	1972	Manned
Luna 24	USSR	1976	Robotic

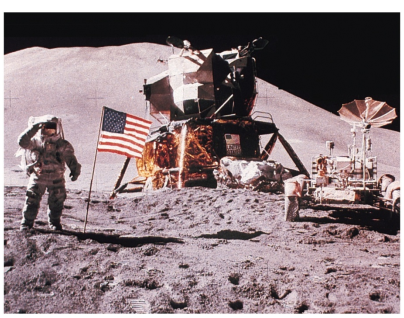

Plato
Crisium
Serenity
Ibrium
Tranquility
Fecund
Vapor
Langrenus
Aristarchus
Copernicus
Nectaris
Keppler
Nubium
Grimaldi
Humorum
Tycho


MARE FRIGORIS
Plato
MARE IMBRIUM
A15
MARE SERENITATES
A17
MARE CRISIUM
OCEANUS PROCELLARUM
MARE VAPORUM
MARE TRANQUILLITATIS
L24
Kepler
A11
L16
L20
A12
MARE FOECUNDITATIS
A14
A16
MARE NECTARIS
MARE HUMORUM
MARE NUBIUM
Tycho

Post-Apollo Exploration

Galileo		1990	Flyby
Clementine		1994	Polar Orbiter
Lunar Prospector		1998	Orbiter
Lunar Reconnaissance		2009	Orbiter
GRAIL (Interior)		2011-12	Orbiter
LADEE (Atmosphere)		2013-14	Orbiter
China			3 Landers
Israel			1 Lander
India			2 Landers

Lunar Exploration



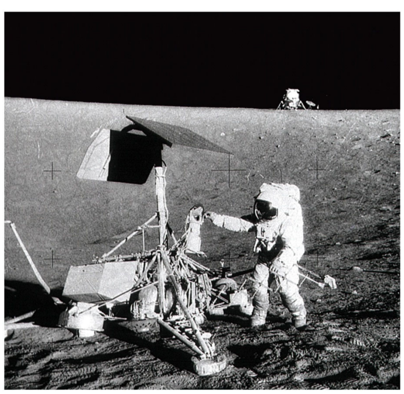
1. Astronauts collected ~400 kg (800 lbs) of samples for detailed analysis.

2. Each landing after the first deployed an ALSEP (Apollo Lunar Surface Experiment Package), which included seismometers.

3. Orbiting Command Module carried a wide range of instrumentation to photograph and analyze the surface.

The Moon's Interior

Average Density



Moon's average density is 3.2 g/cm^3

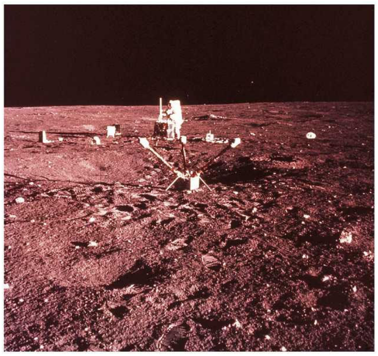
Earth's is 4.5 g/cm^3 (*uncompressed*). This density is characteristic of many kinds of silicate rocks, such as the crust of the Earth.

The Moon's interior composition must be dominated by rocky material and have only a very small metallic core.

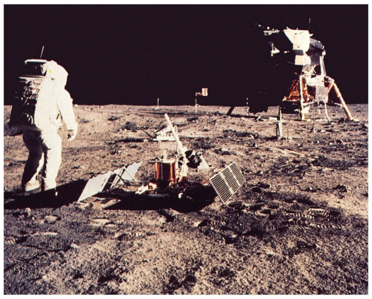
The Moon therefore differs from the Earth in being depleted of metals (primarily iron).

Seismic Waves

Seismometers recorded much fewer and weaker **moonquakes** than correspondingly on the Earth. Note that moonquakes are correlated with Spring Tides – tidal forces are at work.



Magnetic Field

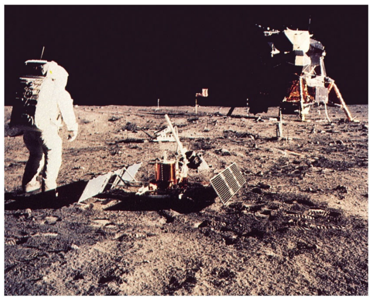


All of the Apollo missions carried **Magnetometers**.

Up until recently, with more sensitive detectors, these indicated that the Moon has no magnetic field, suggesting that the Moon today does not have a molten core.

However, careful magnetic measurements of lunar rocks later returned to the Earth indicate that the Moon did have a weak magnetic field when the rocks solidified billions of years ago.

Magnetic Field



Hence the Moon must originally have had a small, molten, iron-rich core.

The core presumably solidified at least partially as the Moon cooled, so that the lunar magnetic field disappeared.

Lunar Prospector Results

Around 2000, scientists used **Lunar Prospector** to probe the character of the Moon's core. The spacecraft made extensive measurements of lunar gravity and of how the Moon responds when it passes through the Earth's magnetosphere.

When combined with detailed observations of how the Earth's tidal forces affect the motions of the Moon, the data indicated that the *present-day* Moon has a **partially liquid, iron-rich core** about 700 km in diameter.

While 32% of the Earth's mass is in the core, the core of the Moon contains only 2 to 3% of the lunar mass.

Lunar Reconnaissance Results

In 2011, analyses by the **Lunar Reconnaissance** team suggested the Moon possesses an iron-rich core with a **solid inner core** nearly 300 miles in diameter and with a 55-mile thick **outer fluid shell**.

http://asunews.asu.edu/20110106_lunarcore

Current Thoughts

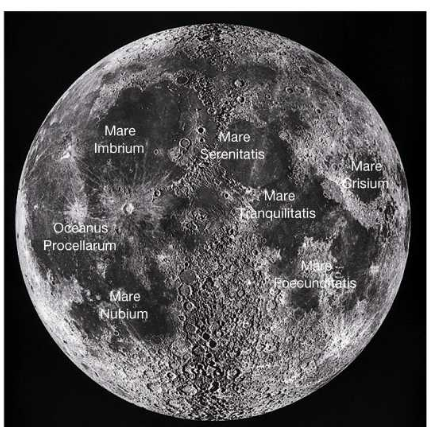
Core is layered: inner solid; middle liquid; outer partially melted.

Does not circulate so it does not generate the small magnetic field.

Magnetic field is localized at the crust.

The Surface – Large Scale

Lunar Maria



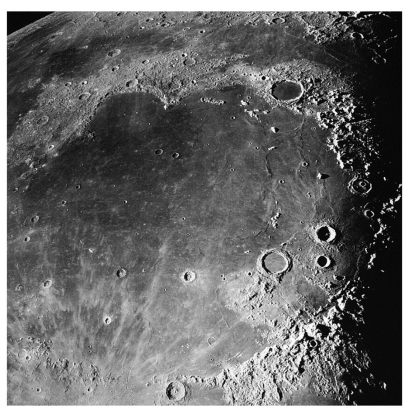
These dark plains, which are much less cratered than the highlands, cover 17% of the lunar surface, mostly on the side facing the Earth. They are volcanic plains, roughly circular in shape.

Lunar Maria – Basalt

The lunar maria are all composed of **basalt**, which is very similar in composition to the oceanic crust of the Earth or to the lavas erupted by many terrestrial volcanoes.

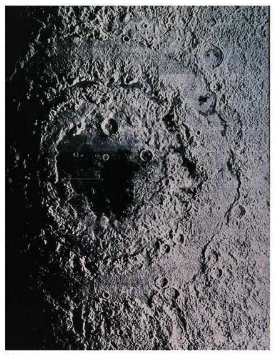
Lunar Maria

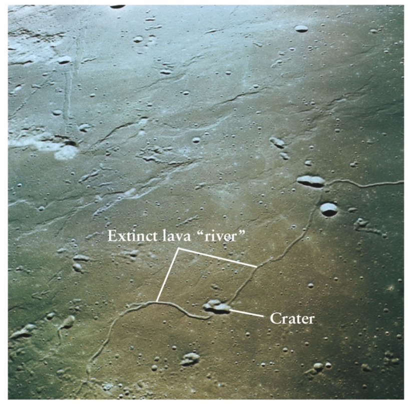
The creation of lunar maria is a two step process. Their low elevation and roughly circular shapes reveal most of them to lie within impact basins. But the impacts themselves did not produce the lava that later filled these basins. Within the maria are a number of large craters that are flooded by lava. **More than a hundred million years elapsed** between the basin-forming impacts and the major era of volcanic eruptions.



Lunar Maria

Maria volcanism was largely confined to the interval between **3.8 and 3.3 billion year ago**. After that, the Moon's interior cooled, and by **3 billion years ago all volcanic activity ceased**.



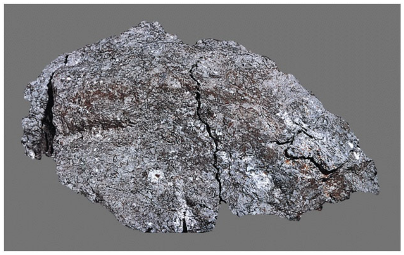


Lunar Highlands

The **highlands** are the oldest surviving part of the lunar crust. They are material that solidified on the crust of the cooling Moon within a hundred million years or so of its formation. Because they are so old, the highlands are extremely cratered. Craters are seen on top of craters.

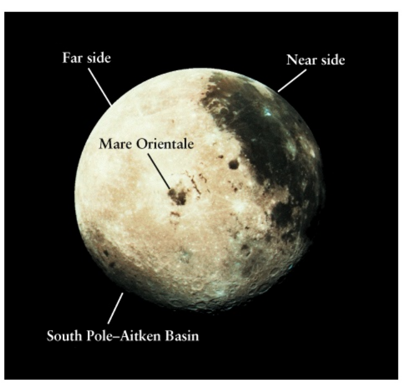
Although none of the Apollo landings took place directly in the highlands, several were close to highland regions, and all brought back samples of highland rock distributed over the Moon as ejecta from cratering impacts.

Lunar Highlands – Anorthosite



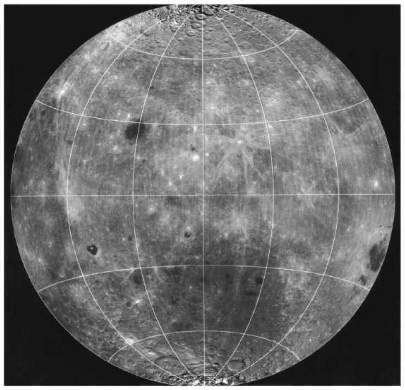
Like floating slag, the **anorthositic** rocks are the lowest density part of the Moon. These rocks are light-colored silicates. Oldest rocks returned by the Apollo astronauts were 4.4 billion years old.

Hemispheres are Different



The Earth-facing (near-side) hemisphere is dominated by numerous, large maria. But on the opposite (far-side) hemisphere, there is only one small mare. This hemisphere is dominated by lunar highlands.

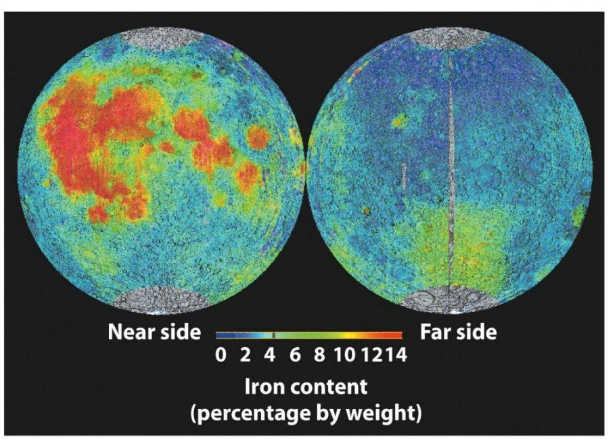
Far Side of the Moon



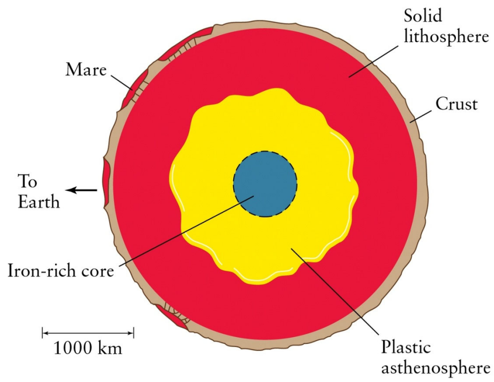
Detailed observations by Apollo astronauts in lunar orbit showed that the maria on the Moon's Earth-facing side are 2 to 5 km below the average lunar elevation.

In contrast, the cratered land on the lunar far side are typically at elevations up to 5 km above the average.

Iron Content



Crust is Not Uniform



The crust is much thicker on the farside than it is on the nearside. Large objects hitting the nearside were able to produce cracks that reached molten regions of the Moon.

The same number of large projectiles should have hit the farside, too, but the cracks did not reach molten regions. Hence, maria were only produced on the nearside.

Surface Features

Types of Surface Features

Craters

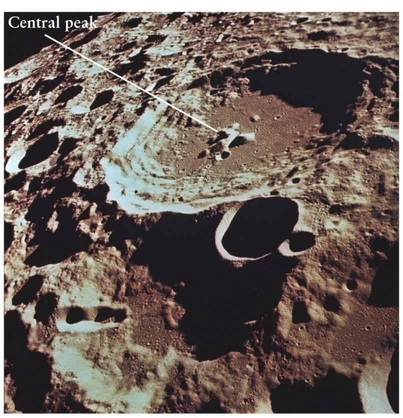
Rays

Mountains

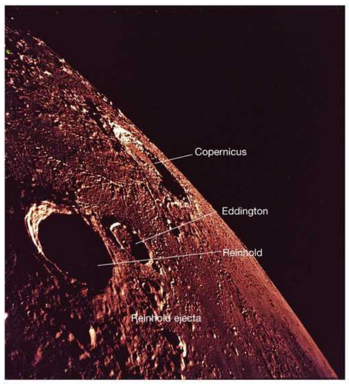
Valleys

Rilles

Craters



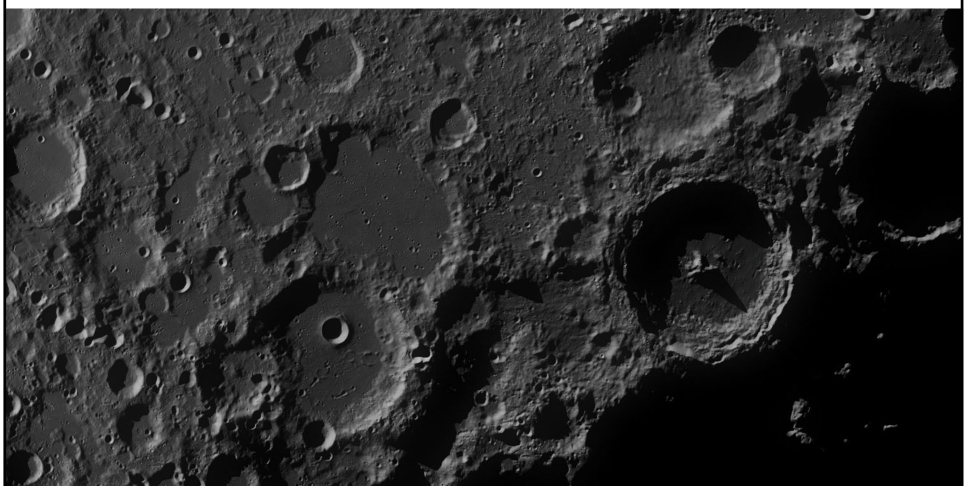
Craters



Origin of Craters

The origin of all lunar craters was **originally thought to be volcanic** well into mid-20th century, because scientists extrapolated Earth's processes to the Moon. However, there are no plate tectonic (or erosional) processes on the Moon, so impacts are preserved.

The difficulty was understanding why all impact craters are **round** – as opposed to elliptical for glancing strikes. Why? Because projectiles are attracted by the gravity of the much more massive world, they impact the surface with speeds at least equal to the escape velocity, which is 11 km/s for the Earth and 2.4 km/s for the Moon. Most projectiles are traveling at speeds greater than 20 km/s. The corresponding energy of impact leads to an ***explosion***.

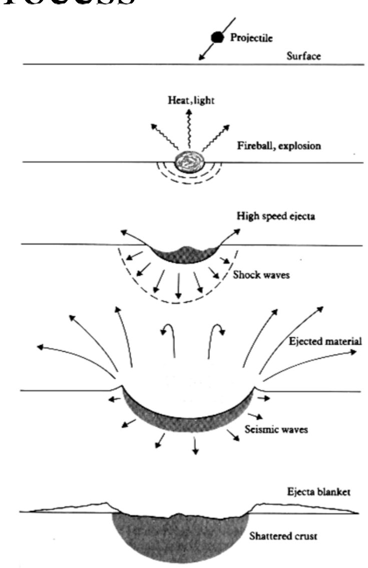


Cratering Process

When an impacting projectile strikes the surface, it penetrates two to three times its own diameter before it stops.

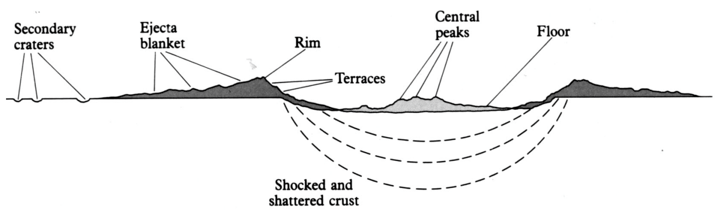
Its kinetic energy of motion is transferred into a shock wave and into heat, which vaporizes most of the projectile and some of the target.

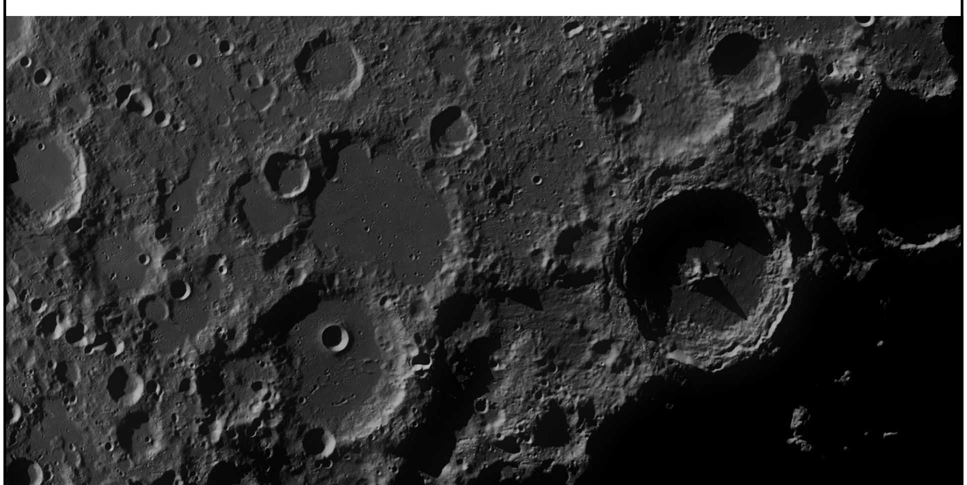
The shock wave fractures the rock of the target, while the superheated vapor generates an explosion.



Cratering Process

The central cavity of a 50 km crater is initially bowl-shaped, but the gravitational rebound of the crust partially fills it in, producing a flat floor and sometimes creating a central peak. Around the rim, landslides create a series of terraces. The floor is generally below the level of the surrounding terrain. The rim of the crater is turned up by the force of the explosion. Surrounding the rim is a blanket of ejecta, which forms secondary craters and **rays**.

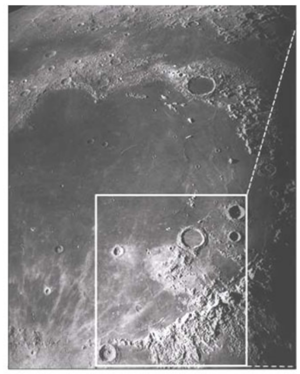




Lunar Rays

Rays are produced by ejected material. They are lighter in color because the material was originally under the surface and had been exposed to less UV light, which darkens rocks.

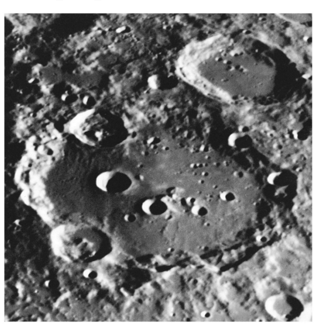
Having no atmosphere to affect the trajectories, the ejecta follow the ballistic trajectories shown by the cratering process.

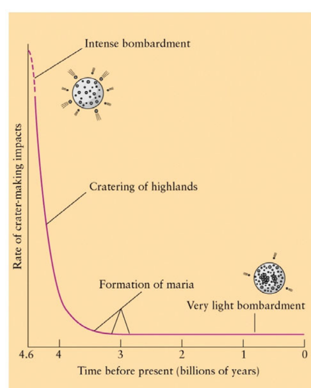


Secondary Craters

Crater Counts and Rates

The more heavily cratered areas are always the older. Most of the heavy bombardment was prior to 3.8 billion years ago. Maria are not that old and do not have nearly as many impacts (**superposition**).



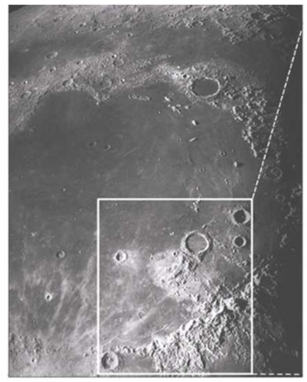


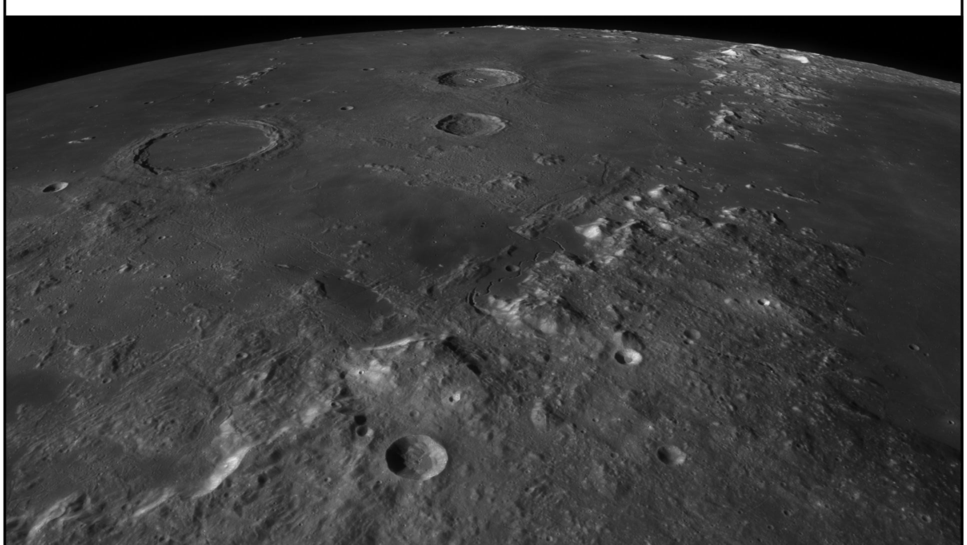
Crater count rates per unit surface areas are used to estimate ages.

Lunar Mountains

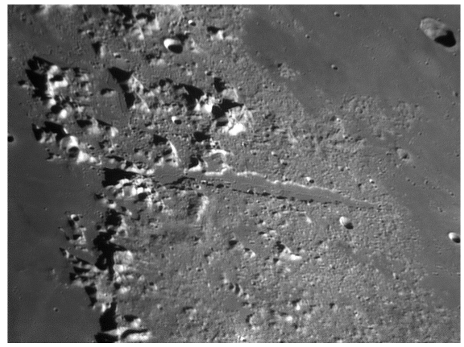
The major **lunar mountains** are all the **result of impacts**, such as the borders of maria are ejecta.

Lunar mountains have low, rounded profiles that resemble old, eroded mountains on the Earth. However, the mountains of the Moon have not been eroded, except for the effects of meteoritic impacts. They are rounded because there has been no water or ice to carve them into cliffs and sharp peaks.



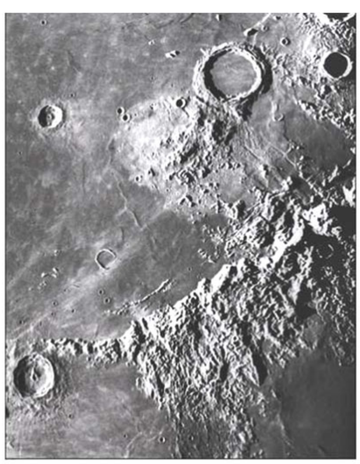


Valleys

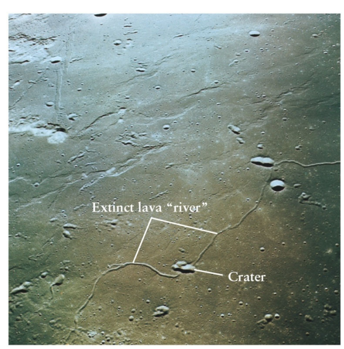


Valleys are wide, shallow runoff areas.

Rilles



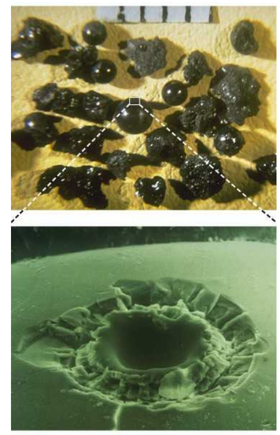
Cracks are called **rilles**. These were lava-flow channels.



Lunar Soil

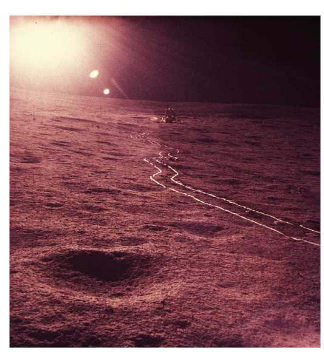
The lunar soil consists of tiny, fine-grained, shattered rock fragments. This lunar “dust” is the product of impacts, including those by **micrometeorites**.

The larger impacts have shattered the crust to a considerable depth to produce a layer called the **regolith**. This material consists of rock fragments and small glass spheres produced in the heat of impacts.



Regolith

The regolith can be as deep as about 10 meters. No similar layer exists on the Earth because water and various chemical processes act to cement loose material together to form new sedimentary rocks.



Regolith – Breccias

The force of large impacts fuses some loose rock together to form re-cemented rocks called **breccias**. Almost all highland rock samples are breccias, providing further evidence of their long history of violent impacts.

Theories of the Moon's Origin

Compositional Comparison

	Light	Intermediate	Heavy
Earth	33%	33%	33%
Moon		100%	

Fission Theory

This theory suggests that the Moon spun off from the Earth.

Cons:

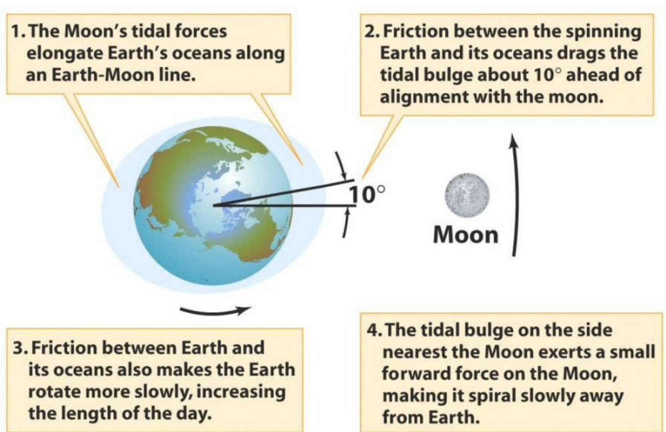
This is very unlikely to occur because of the angular momenta needed.

The compositions (densities) are different, for the Moon does not have the lighter volatiles or the heavier metals that the Earth has.

Pros:

The Moon is slowly moving away from the Earth!

Increasing Separation



Capture Theory

This theory suggests that the Moon was formed elsewhere in the Solar System and later captured by the Earth.

Cons:

This is a very hard gravitational maneuver to accomplish.

A study of isotopes indicate that the Moon had to have formed near the Earth's position in the Solar System.

Pros:

The Moon's orbit is close to the *ecliptic* as opposed to the Earth's *equator*.

Co-Creation Theory

This theory suggests that the Moon formed at the same time as the Earth but separately – it accreted from rock fragments orbiting the Earth very soon after the Earth itself formed.

Cons:

The Moon should have the same ratio of heavy, medium, and light abundances as the Earth has, but it does not.

Pros:

Binary objects are very common, so this process must be relatively easy.

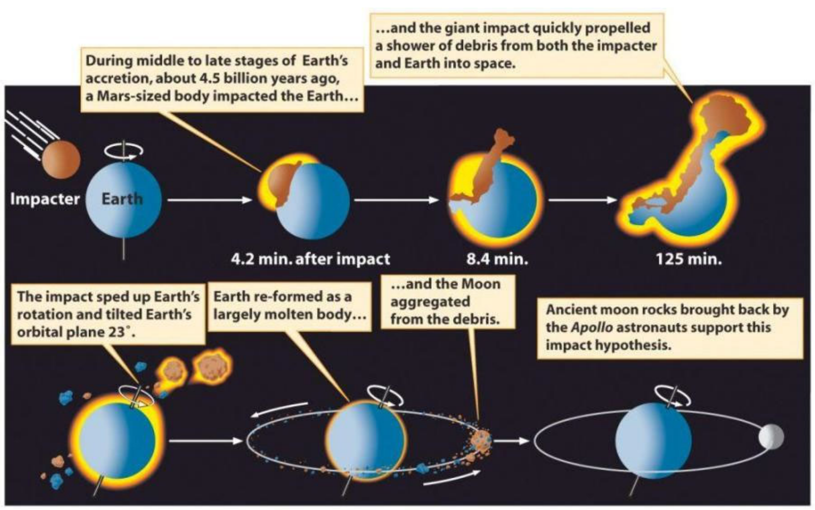
Giant Impact Theory

This theory suggests that a Mars-sized object hit the Earth, penetrating into the mantle.

Light and moderate density materials were ejected. The light materials dispersed, but the moderate ones condensed to form the Moon. This theory explains the compositional and isotopic values.

The possibility that the projectile was moving in the ecliptic would handle why the Moon's orbit is relatively near it, too.

The theory *suggests* that the impact gave the Earth its tilt!



Two Collisions?

"Scientists have long thought that the Moon formed with a bang, when a protoplanet the size of Mars hit the newborn Earth. Evidence from Moon rocks and simulations back up this idea.

But a new study suggests that the protoplanet most likely hit Earth twice. The first time, the impactor (dubbed "Theia") only glanced off Earth. Then, some hundreds of thousands of years later, it came back for the final blow.

The study, which simulated the literally Earth-shattering impact thousands of times, found that such a "hit-and-run return" scenario could help answer two longstanding questions surrounding the creation of the Moon."

https://skyandtelescope.org/astronomy-news/two-impacts-not-just-one-may-have-formed-the-moon/

First Issue

"The Moon's creation was the last major episode in Earth's formation, a catastrophic event that set the stage for the rest of our planet's evolution.

The first has to do with the speed of Theia's impact. (1) If Theia had hit our planet too fast, it would have exploded into an interplanetary plume of debris and eroded much of Earth. (2) Yet if it had come in too slowly, the result would be a Moon whose orbit looks nothing like what we see today. The original impact theory does not explain why Theia traveled at a just-right speed between these extremes.

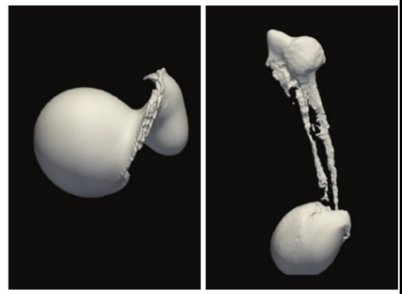
Initially, Theia could have been going much faster, but the first impact would have slowed it down to the perfect speed for the second one."

https://skyandtelescope.org/astronomy-news/two-impacts-not-just-one-may-have-formed-the-moon/

Second Issue

"The other problem with the original Impact Theory is that our Moon ought to be mostly made of primordial Theia. But Moon rocks from the Apollo missions show that Earth and the Moon have nearly identical compositions when it comes to certain kinds of elements. How could they have formed from two different building blocks?

A hit-and-run return would enable Earth's and Theia's materials to mix more than in a single impact, ultimately forming a Moon chemically more similar to Earth."

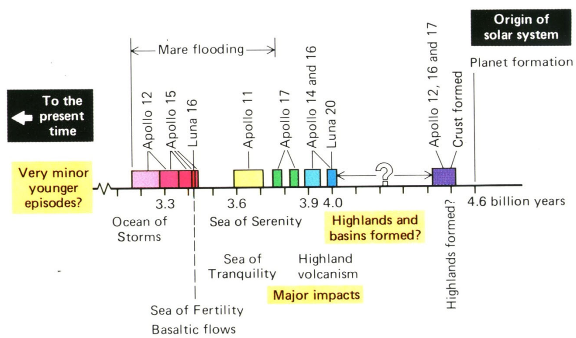


https://skyandtelescope.org/astronomy-news/two-impacts-not-just-one-may-have-formed-the-moon/

Geologic Summary

A. 4.4 billion years ago

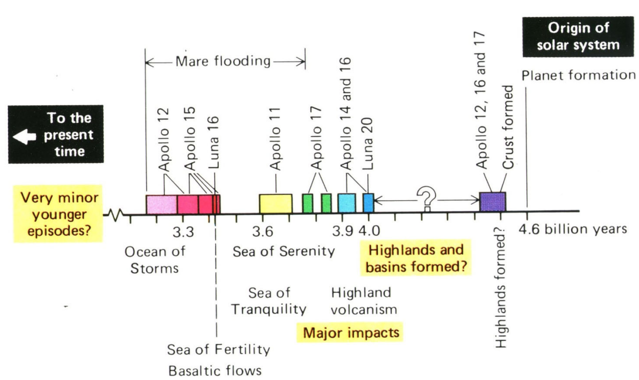
1. Highlands are created
2. Surface is gouged by impact explosions
3. Regolith and breccias are produced



Geologic Summary

B. 4.0 billion years ago

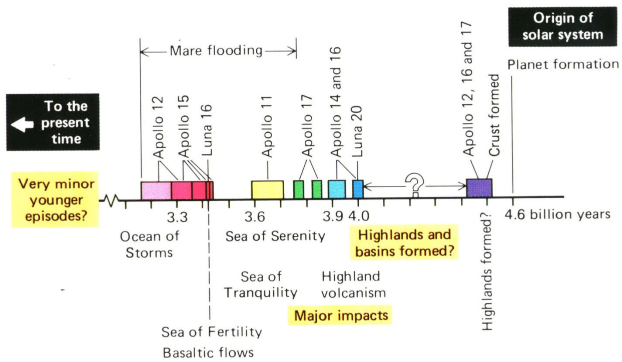
1. Heavy bombardments end
2. Large impact basins are created



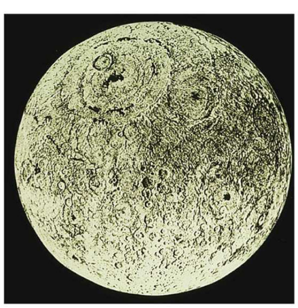
Geologic Summary

C. 3.8 - 3.3 billion years ago

1. Moon is volcanically active, but there are no volcanoes
2. Maria are formed

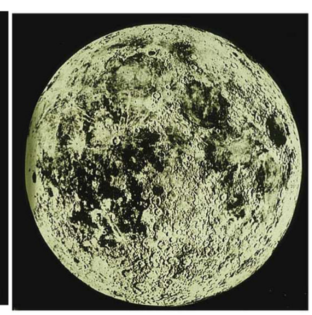


Changing Face of the Moon



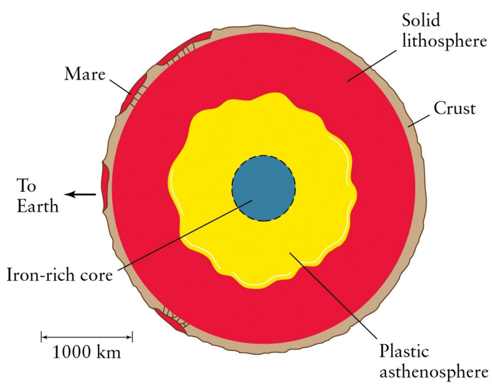
(a) 4 billion years ago

(b) 3 billion years ago



(c) Today

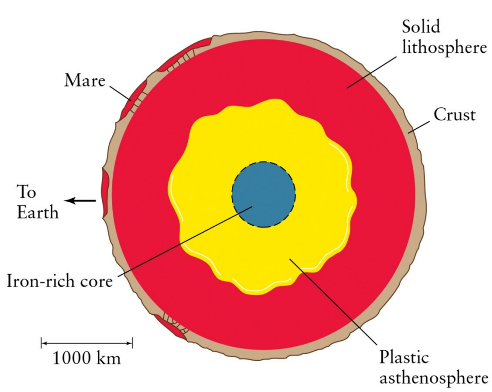
Why the Crust is Not Uniform



The crust is much thicker on the far side than it is on the near side. Large projectiles hitting the nearside were able to produce cracks that reached to molten regions but such cracks on the far side were not deep enough.

Maria were only produced on the nearside.

Why the Crust is Not Uniform



One theory to explain the non-uniform crust thickness states that (a) the Earth and Moon were 10 times closer when they formed and (b) the hot Earth kept the near-side of the Moon significantly warmer than the far side.

The far side cooled quickly but the near side did not.