How Did Our Moon Form?

Many theories have been proposed for how our Moon formed. Any valid scientific model must explain several observations:

- Relative to Earth and other terrestrial planets, the Moon has less iron and few components that evaporate easily, such as water — volatiles — but it is enriched in aluminum and titanium.
- Rocks collected by the Apollo astronauts tell us that the Moon has essentially the same oxygen-isotope signature as Earth (isotopes are varieties of an element that have different masses).
- The plane in which our Moon orbits Earth is slightly tilted relative to Earth's plane of orbit around the Sun — the ecliptic.
- The Earth-Moon system has a large amount of mass, spin, and orbital motion — angular momentum — compared to other planets and moons.

Scientists developed different theories to explain these observations, but none could explain all of them. One theory was that Earth "captured" the Moon as it passed by, but this did not explain their similar isotopic compositions. Another theory was that Earth "threw off" the Moon, but calculations suggest that there was not enough angular momentum to do so. The third theory proposed that Earth and the Moon formed separately but close to each other. If this was true, however, they should have very similar compositions; this model cannot explain the differences in volatiles, iron, titanium, and aluminum between Earth and the Moon.

After the Apollo missions, a new model was proposed: the "giant impact theory." In this model, an impactor, half the size of Earth, collided with Earth during the early stages of solar system formation, about 4.5 billion years ago. The impactor was obliterated. Rocky debris, primarily from the impactor and some of Earth's outer layer, was hurled out into orbit around Earth. This material came together — accreted — to form the Moon.

The giant impact theory explains the Moon's relative lack of iron. Earth's iron core was untouched and much of the impactor's metallic core is thought to have been mixed into the Earth. Scientists still debate why the Moon is enriched in aluminum and titanium. Perhaps the impactor was enriched in these elements, or enrichment occurred as the materials condensed after impact. Scientists also debate why Earth and the Moon have similar oxygen-isotope signatures. Either the impactor had a similar isotopic composition, or the heat from the impact and accretion caused the isotopes to equilibrate between Earth and the debris band. Volatiles such as water and gases were driven out of the system by high temperatures caused by the impact. The theory also explains the tilt of the Moon's orbital plane and the greater angular momentum; the impactor struck Earth at an angle and added its own momentum to the system.

The giant impact theory best explains the current scientific evidence. Future planetary scientists — the students of today — may refine this model or even propose new models as new data are collected!

Meet A Lunar Geologist — Dr. Jeff Taylor, University of Hawaii

I try to figure out how things work on planetary bodies. I examine data from various instruments, instruments on spacecraft or instruments in the laboratory, to solve scientific problems. I also spend time helping future scientists — students — explore their research questions.

Well, I always liked science and math. I did well in school and I went to college to be a journalist. I wanted to be a newspaper reporter. But in the summer of my first year, I got a job working with engineers planning roads. The survey crew marked the road position, but then the engineers had to plan the actual "up and down" of the road, and what the road would be made of, and how to prepare the ground. I had to figure out where dirt had to be added and where it had to be removed. It involved numbers and details, and I felt I was doing something useful with people who liked what they were doing.

Because of that job, I decided to become an engineer and began to study physics to prepare for engineering. In my senior year I took a course in geophysics from a great teacher! The entire course was about figuring out what Earth was made of using instrument measurements and other kinds of data. When I started graduate school, the space program was underway, and my interests took me to trying to figure out what other planets were made of and how they have changed with time.

What was our early solar system like as the planets and our Moon were forming? There has been a big change in the way we are looking at planet formation because of the giant impact theory for forming our Moon. Before, we thought that the planets just grew as more stuff slammed into them. But now we are thinking that it was a messy solar system with stuff of all different sizes that was smashing into each other, sometimes clumping together and sometimes ripping each other apart, and sometimes even missing altogether. All this colliding and mixing is making us rethink why the planets have the compositions they do, and where they are, and how they have changed.

Yes! The Moon is a scientific treasure. It records the early history of Earth and our solar system that has been erased from planets like Earth and Mars by erosion and tectonic activity. More importantly, I think we should go back to the Moon because it is hard to do and we learn a lot by doing hard things. We get different perspectives on new problems and learn new ways to solve them that will benefit everyone. It's the trying that really matters.

The most important thing is to be open to new ideas and to keep your imagination humming. Examine your world and ask how it works. Learn everything you can about math and science, and learn how to speak and write well. But science is important even if you don't become a scientist. The solutions to many of the issues challenging humans come down to science — from global climate change to battling disease to deflecting incoming asteroids. To make good decisions it is important to know how science works. You need to understand why scientists think Earth is warming and what that means to our future, and that scientific debate is part of the process of building understanding.

Evolution Of Our Moon

Early Stages: A Magma Ocean — As the rocky materials orbiting Earth accreted, the Moon grew larger and hotter. Heat from accretion caused the outer surface, and perhaps more, of the Moon to melt, forming an ocean of magma.

The evidence for a magma ocean comes from the layering of the Moon's interior. The uppermost part of the Moon's crust is mainly the rock anorthosite, which is primarily made of a single mineral: low-density, aluminum-rich, plagioclase feldspar. This rock forms the "lunar highlands," the brighter, light-colored, heavily cratered regions we see on the Moon. Deeper parts of the Moon's crust and mantle include larger amounts of other minerals, such as pyroxene and olivine. As the magma ocean cooled and crystallized over a period of 50–100 million years, low-density minerals such as plagioclase floated to the top, while denser minerals such as pyroxene and olivine sank. The oldest rocks collected by Apollo astronauts are 4.5 billion years old, which is thought to indicate when the Moon's crust solidified.

As the outer layers solidified, the interior of the Moon also differentiated. The heavier iron separated from the less-dense rock in the mantle and sank, forming a small core surrounded by the rocky mantle and crust.

Big Impacts, Big Basins — Our early solar system was a messy place! An abundance of material remained in space and debris of all sizes constantly pummeled the Moon and all other planetary bodies. The impactors left their mark; huge impact basins such as Imbrium, Crisium, and Serenitatis, hundreds of miles across, occur where they struck the Moon. The upturned rims of these basins form mountain chains on the lunar landscape. The impacts broke apart the rocks at the surface of the Moon and fused them into impact melt breccias — rocks made of angular, broken fragments, finer matrix between the fragments, and melted rock. These rocks, collected by Apollo astronauts, provide scientists with the timing of basin formation, ranging from 3.8 to 4.0 billion years ago. By 3.8 billion years ago, the period of intense bombardment came to a close; impact events became less frequent and were generally smaller. Impacts still occur today.

Basin Filling — Although cooling, the Moon was still hot, heated by radioactive decay of unstable isotopes of elements, such as uranium and thorium, and the processes of accretion and differentiation. Isolated pockets of hot mantle material slowly rose to the surface, melting at lower pressures. This magma poured out through cracks in the lunar surface — fissures — many of which were created by the earlier impacts. The magma flooded across the lowest regions on the lunar surface to fill the impact basins. It crystallized quickly, forming basalt, a dark, fine-grained, volcanic rock. The composition of the basalt varies because the magma formed in different places in the lunar interior. Some basalts have more titanium, others are more enriched in other elements such as potassium and aluminum. The large, smooth, dark regions we see on the Moon are the basaltic "lunar maria." "Maria" is Latin for "seas," as these areas looked like seas to early astronomers. They are smooth because they are less cratered than the lunar highlands. The smaller number of craters in the maria suggests that these regions have not been impacted as much and therefore are younger. Mare basalts have been radiometrically dated to be between 3.0 and 3.8 billion years old.

Imagine standing on the Moon at this time. Hot basalt lava flowed from long fissures, filling regions of low elevation. Fountains of lava sporadically erupted along the fissures, spewing molten rock high above the lunar surface. Chilled magma droplets fell back as beads of colored volcanic glass, later sampled by Apollo astronauts. Flowing lava cut channels into the landscape. In a few locations, small volcanic domes built up on the surface of the maria. Gradually, as the Moon's interior cooled, volcanism ceased.

Recent History — For the last one billion years, our Moon has been geologically inactive except for small meteoroids pummeling its surface, breaking the rocks and gradually adding to the layer of fine lunar dust — regolith — that covers the surface. In some places the regolith may be thicker than 50 feet (15 meters). The Moon has no atmosphere, flowing water, or life to erode or disturb its surface features. Other than impactors, only a few spacecraft, and the footsteps of 12 humans, have reshaped its landscape.

The data returned by orbiting spacecraft and the Apollo program reveal much about the formation and evolution of our Moon and, in turn, of our own Earth. Resurfacing processes active on Earth have obscured our planet's early history of formation, differentiation, and asteroid bombardment. New missions will help scientists piece together details of the history and evolution of the Moon (and Earth) and will help us better understand lunar processes and the distribution of resources in preparation for humans to live and work on the Moon.

RY HIS —
Make an Impact!

Students model impact events and develop an understanding of the processes that cause cratering on the lunar surface.

What's Needed

An image of the Moon
(example: http://photojournal.jpl.nasa.gov/jpegMod/PIA00405_modest.jpg)

For each group of 4–6 students:
- A sturdy box at least 2' × 2' wide and 6" deep
- Sand or oatmeal to fill the box to a 3" depth
- Flour to cover the sand to a 1" depth
- Cocoa to cover the flour to a 1/8" depth
- Several impactors of different sizes and weights (marbles, pebbles, golf balls, etc.)
- Eye protection

Prepare the impact box with a bottom layer of sand or oatmeal, a middle layer of flour, and top layer of cocoa. Smooth each layer before you add the next layer.

Getting Started

Show the students an image of the Moon.

What to Do

- Invite the students to drop an impactor into the box.
- Experiment by dropping an impactor from different heights, simulating different velocities of incoming impactors.
- Experiment with different impactors dropped from the same height.

Wrapping Up

Return to the images of the Moon. Discuss how impact basins and craters form. When meteoroids strike the Moon, they create a circular depression and eject material onto the surrounding landscape. What remains is a crater, surrounded by a raised rim, and a debris blanket of ejecta. Sometimes the debris can be seen as long, bright rays radiating great distances from the crater. If a crater is greater than 185 miles (300 kilometers) in diameter, it is called a "basin." Different basin and crater sizes result from different sizes and velocities of impactors. The larger and faster the impactor, the larger the crater that results.

Invite the students to observe the Moon.

This activity can be made more quantitative by having students carefully perform the experiments and measure the resulting crater dimensions. An expanded classroom lesson plan can be found in NASA's Exploring the Moon Teacher's Guide, available at http://ares.jsc.nasa.gov/Education/Activities/ExpMoon/ImpactCraters.pdf.

Exploration Timeline

Humans have been asking questions about our Moon since we first looked up at it in the sky.

What is our Moon made of? What are the light and dark markings? Does the Moon have oceans and an atmosphere?

As telescopes became ever more powerful, the Moon's rugged surface was revealed in increasing detail, but observations from Earth could not answer many scientific questions.

What caused the craters on the Moon? Is the Moon geologically active?

It was not until 1959 that the first spacecraft flyby, launched by the Soviet Union, captured close images of the lunar landscape. Over the next decade, orbiters and landers with increasingly sophisticated instruments gathered information. These spacecraft provided high-resolution images of the Moon's surface, including the farside, as well as information about the Moon's gravity field and surface radiation levels. These missions helped scientists understand the geologic processes that shaped the Moon's surface, especially impact cratering and volcanic activity, and helped scientists and engineers select landing sites. The new instruments yielded new information, and lots of new questions.

How did the Moon form? How has the Moon evolved? What is the age of the Moon?

NASA's Apollo program landed 12 astronauts on the Moon in 6 missions between 1969 and 1972. The astronauts collected seismic and magnetic data, investigated soil properties, and collected 842 pounds (382 kilograms) of rock and regolith — lunar "soil." These samples, brought back to Earth, revealed a surprising history, especially concerning the age of the Moon. The composition of the lunar highlands crust suggested that a magma ocean once covered the Moon. The samples confirmed that the Moon's craters are not volcanos, but were created by asteroid impacts. The astronauts found that rock ejected from impact basins and craters blankets much of the lunar surface. The Apollo missions provided astounding insights into the formation and evolution of our Moon — and Earth. But the missions landed on only a few places on the Moon; in fact, less than 1% of the lunar surface has been visited!

What is the compositional variability of Moon rocks? What resources might be available?

Between 1994 and 2006, lunar orbiters Clementine (Department of Defense and NASA), Lunar Prospector (NASA), and SMART-1 (European Space Agency) applied new technologies to study the lunar surface. They measured reflected "light" — electromagnetic radiation — of different wavelengths to give global information about elemental and mineral abundances on the Moon's surface. This information, validated by the Apollo sample analyses, allowed scientists to map the chemical composition of rocks across the whole Moon. One result of this work is the suggestion that frozen water, possibly delivered by comets, may be present near the Moon's poles!

As new data are collected and analyzed, new questions arise to drive exploration, and new objectives are identified to focus scientific and engineering efforts. In 2004, the President of the United States declared that astronauts will return to the Moon to live and work. Several missions will prepare the way, including the Japan Aerospace Exploration Agency's orbiter Kaguya and Chang'e-1 of the China National Space Administration, already in orbit at the Moon. The Indian Space Research Organization's Chandrayaan-1 orbiter carries two NASA instruments to characterize lunar resources and search for ice at the poles. NASA's paired missions, the Lunar Reconnaissance Orbiter and the Lunar Crater Observation and Sensing Satellite, will permit scientists and engineers to characterize the hazards and resources of the lunar environment, test equipment for human habitation, and select landing sites for our return to the Moon. The Moon will be a "test bed" for new technologies that will allow our exploration of the solar system. Human exploration of the Moon will allow scientists to address exciting unanswered questions about our Moon — and to come up with new questions.

Is the current model of the Moon's formation correct? Why are the basalts in the basins so variable?
Is the Moon still volcanically active?

INA OVES O HE OON:
A Hawaiian Story About Our Moon

Hina fashioned the finest and softest kapa cloth in Hawaii. She made this cloth from the bark of the banyan tree. Because her cloth was so fine, it was in great demand. She worked long, long hours with little rest and eventually grew tired. She was also tired because her sons were unruly and her husband was lazy and none of them ever helped her.

One day, Hina decided to leave Hawaii, so she traveled up a rainbow into the sky. She went to the Sun, but found it so hot and inhospitable that she could not live there. The next night, she climbed the rainbow to the Moon and was so pleased with what she found that she made it her home. The Hawaiian name for the Moon, "Mahina," is derived from her name.

In some stories, the dark regions on the Moon are said to be a banyan tree from which Hina makes cloth for the gods. Once, when Hina was up in the banyan tree, she broke off a branch for its bark. It fell to Earth, took root, and was the first tree of its kind ever seen in the world.

The clear space in the Moon is where the branch once was, and beneath the tree in that area is where Hina has her home.

On a clear night, when you are outside, look up at the Moon and see if you can find the banyan tree, and recall the story of Hina and the wonderful cloth she makes for the gods.

Contributed by:
Paul Coleman, Ph.D.
University of Hawaii, Institute for Astronomy

An Earth-Based Tour Of The Moon

A quick look at the Moon in the night sky (even without binoculars) shows light areas and dark, somewhat circular areas. These different features record our Moon's history. Can you find them? Use the map to help guide your viewing.

The binoculars symbol means that the feature is too small to see with just your eyes and you will need binoculars (a tripod will help) or a telescope.

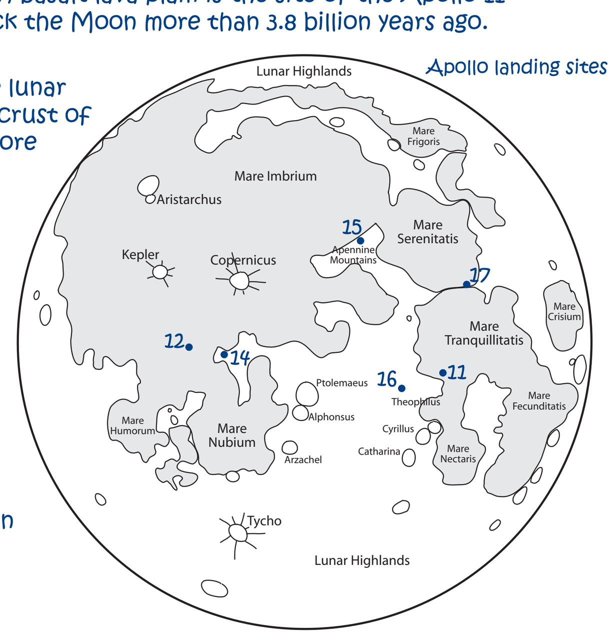
I have seen it! **Sea of Rains (Mare Imbrium)** — Imbrium Basin, one of the largest impact basins on the Moon, formed when a huge impactor hit the lunar surface a little more than 3.8 billion years ago. Floods of lava filled the basin floor 500 million years later. This cooled to form a dark, fine-grained igneous rock — basalt — creating the dark, smooth surface of the mare.

I have seen it! **Apennine Mountains** — The lunar surface is punctuated by mountain ranges — the uplifted rims of impact basins. Apollo 15 astronauts worked in the shadow of Mount Hadley, one of the peaks of the Apennine Mountains that form the rim of Imbrium Basin. Mount Hadley is almost 3 miles (4.6 kilometers) high!

I have seen it! **Sea of Serenity (Mare Serenitatis)** — Apollo 17 astronauts sampled some of the oldest rocks on the Moon from the basin walls surrounding the Sea of Serenity. These ancient rocks formed in the Moon's magma ocean 4.5 billion years ago. They were exposed at the lunar surface when a huge impactor struck the Moon 3.9 billion years ago, forming Serenitatis Basin.

I have seen it! **Sea of Tranquility (Mare Tranquillitatis)** — This 500-mile-wide (800-kilometer) basalt lava plain is the site of the Apollo 11 landing in 1969. It fills an ancient basin, created when a huge impactor struck the Moon more than 3.8 billion years ago.

I have seen it! **Lunar Highlands** — The brighter, light-colored regions on the Moon are the lunar highlands. These areas, formed from the magma ocean, make up the oldest crust of the Moon. Because they are so old, they have been hit by impactors many more times than the dark, smooth basalt plains, making the highlands very rough.



I have seen it! **Copernicus Crater** — A small, bright circle south of Imbrium Basin, with rays spreading up to 500 miles (800 kilometers) in all directions, marks Copernicus Crater. Its sharp rays and crisp rim indicate Copernicus is geologically young. Rocks suspected to have been formed by the impact are 800 million years old.

I have seen it! **Tycho Crater** — A bright star of material stands out on the light-colored lunar highlands of the Moon's southern hemisphere. This is Tycho Crater, which is 53 miles (85 kilometers) wide, and has ejecta rays stretching over 1200 miles (2000 kilometers) north to the Apollo 17 landing site. The age of material collected near this site suggests the crater formed about 110 million years ago.

How many features can you identify on a clear night?

RTHER XPLORATION

Additional Reading

Team Moon: How 400,000 People Landed Apollo 11 on the Moon. Catherine Thimmesh, 2006, Houghton Mifflin, ISBN: 0618507574. Children ages 10 and older will enjoy this well-illustrated exploration of the events and people who made it possible to put humans on the Moon.

Earth and the Moon. Ron Miller, 2003, Twenty First Century Books, ISBN: 0761323589. Written for young teens, this book examines the formation and evolution of the Earth and Moon.

Stories of the Moon. Joan Marie Galat, 2004, Whitecap Books, ISBN: 1552856100. A beautifully illustrated collection of stories about the Moon from cultures around the world for children ages 9 to 12.

Apollo: The Epic Journey to the Moon. David Reynolds, 2002, Harcourt, ISBN: 0151009643. A captivating history of the people and events leading up to, and involved in, the Apollo lunar exploration missions. Young adults and adults will enjoy this well-illustrated adventure.

The Scientific Legacy of Apollo. G. Jeffrey Taylor, 1994, Scientific American, volume 271, number 1, pages 40–47. Rocks retrieved during the Apollo missions provided a new view of our Moon's — and Earth's — origin and evolution.

The Modern Moon: A Personal View. Charles Wood, 2003, Sky Publishing Corporation, ISBN: 0933346999. The perfect companion to lunar telescope viewing, Wood works his way across the lunar surface, identifying features of scientific importance and the people involved in unraveling their story.

MO E C AS OOM ESO RCES

Exploring the Moon — http://ares.jsc.nasa.gov/Education/Activities/ExpMoon/ExpMoon.htm An integrated portfolio of hands-on activities that explore what we know about the Moon, what we have learned through lunar samples from the Apollo missions, and where we may go next. Upper elementary through high school.

Exploring Planets in the Classroom: The Moon — http://www.spacegrant.hawaii.edu/class_acts/MoonDoc.html A suite of hands-on activities and supporting materials that investigate lunar landforms, regolith formation, and more.

Educator Resources — http://www.lpi.usra.edu/education/resources/s_system/moon.shtml Explore lunar phases and eclipses, formation of the Moon, lunar processes, future lunar outpost sites, and more through hands-on activities, background information, and presentations.

Online Discovery

Explore NASA's Apollo Program.
http://www.nasm.si.edu/collections/imagery/apollo/apollo.htm
http://history.nasa.gov/apollo.html

NASA's Lunar and Planetary Science pages provide an overview of past, present, and future lunar missions. http://nssdc.gsfc.nasa.gov/planetary/planets/moonpage.html

The Lunar and Planetary Institute has compiled a comprehensive site of existing lunar images, data, studies, and information. http://www.lpi.usra.edu/lunar

The research of NASA's Science Mission Directorate focuses on understanding the origin, evolution, and nature of our solar system, including our Moon. http://nasascience.nasa.gov

About This Poster

This is one of a three-poster set that examines how our geologic understanding of the Moon will be used as we plan to live and work there in the future. The poster **front**, designed for **sixth- to ninth-grade students**, explores how our Moon formed and has changed through time; this history is recorded in the features the students see when they look at the Moon. The poster **back** is designed to provide **educators** with background information, ideas for lessons, and resources to support further student exploration. The complete set of posters can be found at http://www.lpi.usra.edu/education/moon_poster.shtml.

Content Development: Stephanie Shipp and Christine Shupla, Lunar and Planetary Institute; *Scientific Oversight:* David Kring, Allan Treiman, and Walter Kiefer, Lunar and Planetary Institute; *Graphic Design:* Leanne Woolley, Lunar and Planetary Institute.

Concept Development and Content Review: Cassandra Runyon, E/PO Lead, Moon Mineralogy Mapper, College of Charleston; Stephanie Shipp, Lunar and Planetary Institute; Jaclyn Allen, Astromaterials Research and Exploration Science, NASA Johnson Space Center; Marilyn Lindstrom, NASA Headquarters. Appreciation is extended to the students and teachers of McWhirter Elementary in Webster, Texas, and Sugarland Middle School in Sugarland, Texas, for their insightful critique of the poster design and content.

Content Review: Dr. Carlton Allen, Astromaterials Curator, Astromaterials Research and Exploration Science, NASA Johnson Space Center; Dr. Ben Bussey, Deputy Principal Investigator, Miniature Synthetic Aperture Radar (Mini-SAR), Johns Hopkins University, Applied Physics Laboratory; Mr. Brian Day, E/PO Lead, Lunar Crater Observation and Sensing Satellite, NASA Ames Research Center; Dr. Clive Neal, Chair, Lunar Exploration Analysis Group, University of Notre Dame; Dr. Carlé Pieters, Principal Investigator, Moon Mineralogy Mapper Instrument, Brown University; Ms. Stephanie Stockman, E/PO Lead, Lunar Reconnaissance Orbiter Mission, NASA Goddard Space Flight Center; Dr. Paul Spudis, Principal Investigator, Miniature Synthetic Aperture Radar (Mini-SAR), Lunar and Planetary Institute; Dr. Jeffrey Taylor, Hawaii Institute of Geophysics and Planetology, University of Hawaii.

Image Credit: NASA, United States Geological Survey, Lunar and Planetary Institute.