

How Did the Moon Form?

Exploring Formation Hypotheses through Evidence and Observation

Objectives:

- Provide experience in critical analysis of data
- Identify the characteristics of hypotheses and compare hypotheses to theories
- Explore and compare lunar formation hypotheses

In Advance:

Students should already have an understanding of the Moon's orbit, and of accretion.

Procedure:

1. Invite your students to spend some time in pairs developing some ideas on how the Moon formed. Invite each pair of students to jot down the ideas on a sheet, and then gather them to discuss as a class. Record the ideas and for each one presented discuss:
 - Are there any observations that support this idea? (Does this idea explain something we see or know about the Moon?)
 - Could science test this idea?
 - Is it a logical idea?
 - Is this idea supported by any other experiences (for instance, our ideas of how the Earth or other objects formed?)
 - Does your own experience support this idea?
2. Ask the students to help you determine which ideas fit these criteria, and share that those specific ideas are hypotheses. If the student's hypotheses do not include the four common lunar formation hypotheses, please share them to include them within the discussion. Let the students know that a hypothesis is a proposed explanation for a narrow set of phenomena (like the formation of the Moon). A theory is the broader explanation for a wide range of phenomena—a theory is more broadly applicable (like our theory of gravity.) *For more information about hypotheses and theories, check out http://undsci.berkeley.edu/article/0_0_0/howscienceworks_19 and <http://undsci.berkeley.edu/teaching/misconceptions.php#a4>.*

3. Origin of the Moon: Hypotheses

There have been four major hypotheses regarding the formation of the Moon; some of these past models have been discredited through data and observations. Your task is to analyze these hypotheses and their strengths and weaknesses, based on that data.

Examine each of the hypotheses in turn. What predictions does the hypothesis make? Invite the students to share and record their thoughts, then provide additional input as needed.

1. The *co-formation hypothesis* states that the Moon formed in orbit around Earth at the same time as the Earth formed.
 - What predictions does this hypothesis make for the Moon's composition compared to Earth, if it formed from the same initial materials in the same location of our solar system? *[Their composition should be similar—they should be made of the same materials in the same relative amounts, unless something happened later to change one of them.]*
 - If the Moon formed in orbit around the Earth, how should its density compare to Earth's? *[They should have similar densities, unless something major happened later to change one of them.]*

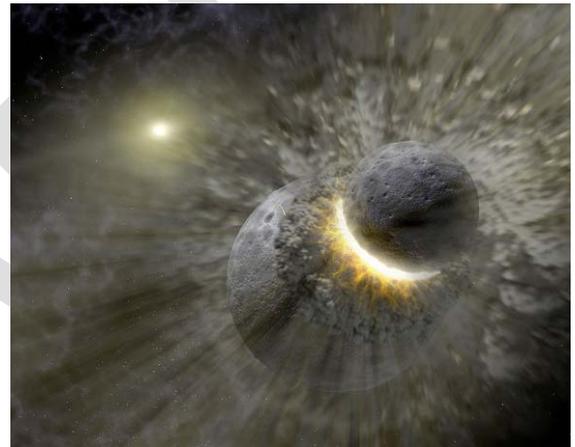
- How should the Moon's orbital plane compare to Earth's and other planets in this model? *[The Moon should orbit the Earth's equator, just as other planets' moons orbit their equators, unless something happened later to change the Moon's orbit.]*
 - How much angular momentum in the Earth-Moon system (the combined energy of Earth's and Moon's rotations and the Moon's orbit) does this hypothesis require? *[This would require about the same amount of angular momentum as other planet-moon systems.]*
2. The *capture hypothesis*, states that the Moon formed somewhere else in the solar system with less iron, and was captured by Earth's gravity and began to orbit around the Earth.
- What predictions does this hypothesis make for the Moon's composition compared to Earth, if it formed from the different materials in a different location of our solar system? *[Their composition should be different—they should be made of different materials, with different isotopic ratios.]*
 - If the Moon formed somewhere with less iron, how should its density compare to Earth's? *[It should have a lower density.]*
 - How should the Moon's orbital plane compare to Earth's and other planets in this model? *[The Moon might orbit the Earth in a different plane or the same plane that Earth and the other planets orbit the Sun.]*
 - How much angular momentum in the Earth-Moon system (the combined energy of Earth's and Moon's rotations and the Moon's orbit) does this hypothesis require? *[The Moon would be moving very fast when it was captured, giving a very large angular momentum to the Earth-Moon system. There should be an extremely large amount of angular momentum in the system now.]*
3. The *fission hypothesis* states that early molten Earth spun so fast that material spewed off and formed the Moon.
- What predictions does this hypothesis make for the Moon's composition compared to Earth? *[Their compositions should be similar in some ways; the Moon should be made of the same materials as the Earth's crust and mantle.]*
 - What predictions does this hypothesis make for the Moon's density compare to Earth's? *[It should have a lower density.]*
 - How should the Moon's orbital plane compare to Earth's and other planets in this model? *[The Moon should orbit in the same plane as the Earth's rotation (around its equator), not the plane of its orbit around the Sun.]*
 - How much angular momentum in the Earth-Moon system (the combined energy of Earth's and Moon's rotations and the Moon's orbit) does this hypothesis require? *[The Earth would have had to rotate extremely fast initially, so this predicts an extremely large amount of angular momentum.]*
4. The *giant impact hypothesis* states that when the Earth formed, about 4.5 billion years ago, a nearby newly-formed object half as wide as Earth collided with it. A fraction of the debris from the crust and mantle (from both Earth and the colliding object) spewed into orbit around Earth and accreted to form the Moon.
- What predictions does this hypothesis make for the Moon's composition compared to Earth? *[Their compositions should be similar in some ways; the Moon should be made of the same materials as the Earth's crust and mantle.]*
 - What predictions does this hypothesis make for the Moon's density compare to Earth's? *[It should have a lower density.]*
 - How should the Moon's orbital plane compare to Earth's and other planets in this model? *[The Moon might orbit the Earth in a different plane or the same plane that Earth and the other planets orbit the Sun, depending on the angle of the impact.]*
 - How much angular momentum in the Earth-Moon system (the combined energy of Earth's and Moon's rotations and the Moon's orbit) does this hypothesis require?

[This requires a somewhat high angular momentum of the Earth-Moon system, but not as high as is predicted by capture or fission.]

4. Invite the students to examine the data handout to determine whether it supports, negates, or is unrelated to the predictions from each hypothesis. Ask them to fill in the data table correlating to their analysis, and then to discuss their conclusions with the others in their group.
5. Discuss the students' analyses, and how they relate to our understanding of the Moon's formation:
 - Which model(s) are most supported by the data? *[The Giant Impact is currently the most supported by the data and widely accepted by scientists, but they continue to investigate the other models. The fission hypothesis has some new evidence that suggests it might be possible, however problems exist with the fission hypothesis regarding the angular momentum of the Earth-Moon system and how fast the Earth would have needed to spin in order for fission to occur.]*
 - Does this mean we have conclusive evidence that one hypothesis (the Giant Impact) is correct? When will scientists be able to conclude that they have the exact correct model? *[No, scientists continue to test this model and the other hypotheses, and compare new data to their predictions.]*

More on the Giant Impact Hypothesis

In 1984, the Giant Impact Hypothesis emerged (it was really announced as early as 1974, but was not considered acceptable at the time). This model stemmed from the recognition that the early solar system was a more violent place than originally thought. Scientists realized that matter formed the seeds of planets with a large range of sizes within closely spaced orbits. The final stages of planetary formation would involve the merging of often rather large bodies, punctuated with giant impacts in which bodies of comparable size crashed into one another at high speeds. The chaos of this era explains the wide variations in orbital inclinations, eccentricities of orbits, rotational periods and spin axis and directions observed among the inner planets.



This illustration is not to scale in size or distance. It is an artistic rendition that illustrates the giant impact theory of the formation of the Moon. Credit: NASA.

A giant impact theory provides the right circumstances for a body with the Moon's peculiar chemical composition to form. The vapor that was squirted from the contact point between the proto-Earth and the impacting smaller proto-planet would be mostly the material from the mantles of the two objects. It would not include the metals from the core. Condensing in space, the high-speed cloud of rock vapor would incorporate refractory elements, while volatile elements would be slow to condense, and hence, be greatly depleted.

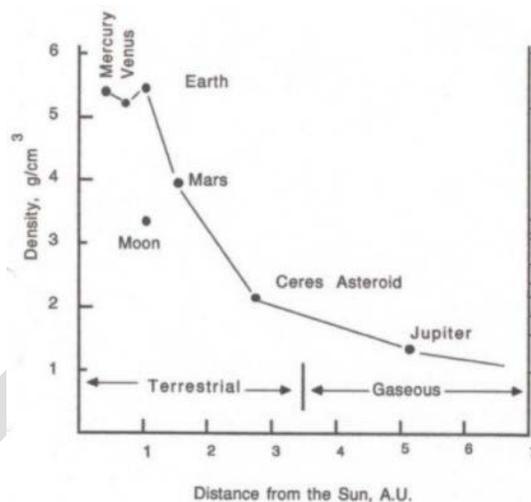
In addition, the large amount of angular momentum brought in by the projectile would be mainly in the orbiting debris, although the proto-Earth would also be spun up. From the angular momentum of the present Earth-Moon system, the projectile must have had a mass comparable to that of the planet Mars. However, the Moon's formation is still a debated topic, with newer models that have modified the Giant Impact Hypothesis.

Student Data Sheet

Data related to the Moon's formation

- A. **Density:** examine the density of Earth's layers in the table below, and the Earth's density relative to the Moon's on the graph to the right.

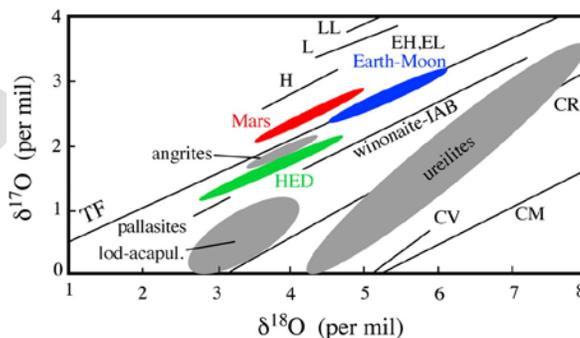
Crust	2.8 g/cm ³
Mantle	4.6 g/cm ³
Outer Core	10.5 g/cm ³
Inner Core	13 g/cm ³



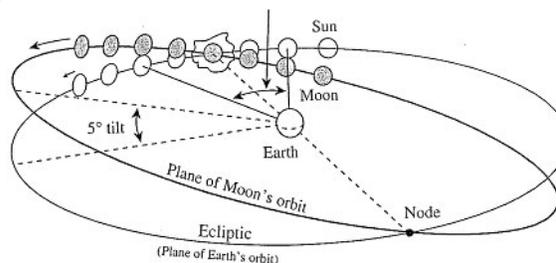
- B. **Composition:** compare the elemental composition of the Moon and Earth.

Element	Earth	Moon
Iron	34.6%	3.5%
Oxygen	29.5%	60.0%
Silicon	15.2%	16.5%
Magnesium	12.7%	3.5%
Titanium	0.05%	1.0%

- C. **Oxygen Isotopes:** scientists have measured the ratio of different oxygen isotopes for meteorites from the Moon, Mars, and from many asteroids and compared them to Earth. The Earth and Moon have identical oxygen isotope ratios (seen in blue). New research (2012) shows that the titanium isotopes for Earth and the Moon are also identical compared to Mars and asteroids.



- D. **The Moon's Orbital Plane:** the Moon orbits the Earth at a 5 degree tilt relative to the planets' orbits around the Sun.



- E. **Energy in the Earth-Moon system:**

Angular momentum = $L = mrv$ (mass*radius of system* spin velocity). With the large mass of both the Earth and Moon and its distance, the Earth-Moon system has a relatively high angular momentum, but not an extraordinary amount. Extrapolating backwards in time, we can estimate how fast the Earth could have been spinning when the Moon formed, given that the Moon is getting farther from the Earth and the inference that at one point it was very near Earth.

	Earth's Period of Rotation
Earth-Moon System Today	24 hours
Earth-Moon System When Moon Formed	4-5 hours
Needed for Fission Hypothesis	1.5 hours

Student Worksheet

1. The **co-formation hypothesis** states that the Moon formed in orbit around Earth at the same time as the Earth formed.
 - What predictions does this hypothesis make for the Moon's composition compared to Earth, if it formed from the same initial materials in the same location of our solar system?
 - If the Moon formed in orbit around the Earth, how should its density compare to Earth's?
 - How should the Moon's orbital plane compare to Earth's and other planets in this model?
 - How much angular momentum in the Earth-Moon system (the combined energy of Earth's and Moon's rotations and the Moon's orbit) does this hypothesis require?
2. The **capture hypothesis**, states that the Moon formed somewhere else in the solar system with less iron, and was captured by Earth's gravity and began to orbit around the Earth.
 - What predictions does this hypothesis make for the Moon's composition compared to Earth, if it formed from the different materials in a different location of our solar system?
 - If the Moon formed somewhere with less iron, how should its density compare to Earth's?
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 - How should the Moon's orbital plane compare to Earth's and other planets in this model?
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4. The **giant impact hypothesis** states that when the Earth formed, about 4.5 billion years ago, a nearby newly-formed object half as wide as Earth collided with it. A fraction of the debris from the

crust and mantle (from both Earth and the colliding object) spewed into orbit around Earth and accreted to form the Moon.

- What predictions does this hypothesis make for the Moon's composition compared to Earth?
- What predictions does this hypothesis make for the Moon's density compare to Earth's?
- How should the Moon's orbital plane compare to Earth's and other planets in this model?
- How much angular momentum in the Earth-Moon system (the combined energy of Earth's and Moon's rotations and the Moon's orbit) does this hypothesis require?

Fill in the table using the evidence above by labeling each piece of evidence (A-E) as supporting, not supporting, or unrelated to a formation hypothesis. Not all columns (support, not support, or not relevant) will have evidence.

Hypothesis	Evidence Supports	Evidence Does Not Support	Evidence Not Relevant
1. Co-formation			
2. Capture			
3. Fission			
4. Giant Impact			

Which hypotheses are most supported by the data?

Which hypotheses are least supported by the data?

Given the evidence, which hypothesis or hypotheses *most likely* explains the formation of the Moon? Please explain your answer.

Student Worksheet - Answer Key

1. The **co-formation hypothesis** states that the Moon formed in orbit around Earth at the same time as the Earth formed.

- What predictions does this hypothesis make for the Moon's composition compared to Earth, if it formed from the same initial materials in the same location of our solar system?

Their composition should be similar—they should be made of the same materials in the same relative amounts, unless something happened later to change one of them.

- If the Moon formed in orbit around the Earth, how should its density compare to Earth's?

They should have similar densities, unless something major happened later to change one of them.

- How should the Moon's orbital plane compare to Earth's and other planets in this model?

The Moon should orbit the Earth's equator, like other planets' moons orbit their equators, unless something happened later to change the Moon's orbit.

- How much angular momentum in the Earth-Moon system (the combined energy of Earth's and Moon's rotations and the Moon's orbit) does this hypothesis require?

This would require about the same amount of angular momentum as other planet-moon systems.

2. The **capture hypothesis**, states that the Moon formed somewhere else in the solar system with less iron, and was captured by Earth's gravity and began to orbit around the Earth.

- What predictions does this hypothesis make for the Moon's composition compared to Earth, if it formed from the different materials in a different location of our solar system?

Their composition should be different—they should be made of different materials.

- If the Moon formed somewhere with less iron, how should its density compare to Earth's?

It should have a lower density.

- How should the Moon's orbital plane compare to Earth's and other planets in this model?

The Moon might orbit the Earth in a different plane or the same plane that Earth and the other planets orbit the Sun.

- How much angular momentum in the Earth-Moon system (the combined energy of Earth's and Moon's rotations and the Moon's orbit) does this hypothesis require?

This predicts an extremely large amount of angular momentum for the Earth-Moon system, because it includes the speed that the Moon would have been moving at when it was captured.

3. The **fission hypothesis** states that early molten Earth spun so fast that material spewed off and formed the Moon.

- What predictions does this hypothesis make for the Moon's composition compared to Earth?

Their compositions should be similar in some ways; the Moon should be made of the same materials as the Earth's crust and mantle.

- What predictions does this hypothesis make for the Moon's density compare to Earth's?

It should have a lower density.

- How should the Moon's orbital plane compare to Earth's and other planets in this model?

The Moon should orbit in the same plane as the Earth's rotation (which is tilted but changes over time), not the plane of its orbit around the Sun.

- How much angular momentum in the Earth-Moon system (the combined energy of Earth's and Moon's rotations and the Moon's orbit) does this hypothesis require?

The Earth would have had to rotate extremely fast initially, so this predicts an extremely large amount of angular momentum.

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It should have a lower density.

- How should the Moon's orbital plane compare to Earth's and other planets in this model?

The Moon might orbit the Earth in a different plane or the same plane that Earth and the other planets orbit the Sun, depending on the angle of the impact.

- How much angular momentum in the Earth-Moon system (the combined energy of Earth's and Moon's rotations and the Moon's orbit) does this hypothesis require?

If much of the mass of the Moon originated from Earth, then the angular momentum of today's Earth-Moon system would be about the same today as it was then.

Fill in the table using the evidence above by labeling each piece of evidence (A-E) as supporting, not supporting, or unrelated to a formation hypothesis. Not all columns (support, not support, or not relevant) will have evidence.

Note: students may have different interpretations of these data. It may be worth discussing that scientists also sometimes interpret data differently.

Hypothesis	Evidence Supports	Evidence Does Not Support
1. Co-formation	C, E	A, B, D
2. Capture	A, B, D	C, E
3. Fission	A, B, C,	D, E
4. Giant Impact	A, B, C, D, E	

Which hypotheses are most supported by the data?

The Giant Impact hypothesis (Note: Students responses may vary. Science allows room for discussion and argument.)

Which hypotheses are least supported by the data?

Co-formation, Capture, and fission hypotheses. (Note: Students responses may vary. Science allows room for discussion and argument.)

Given the evidence, which hypothesis or hypotheses *most likely* explains the formation of the Moon? Please explain your answer.

The Giant Impact is currently the most supported by the data and widely accepted by scientists, but they continue to investigate the other models. The fission hypothesis has some new evidence that suggests it might be possible, however problems exist with the fission hypothesis regarding the angular momentum of the Earth-Moon system and how fast the Earth would have needed to be spinning in order for fission to occur.

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