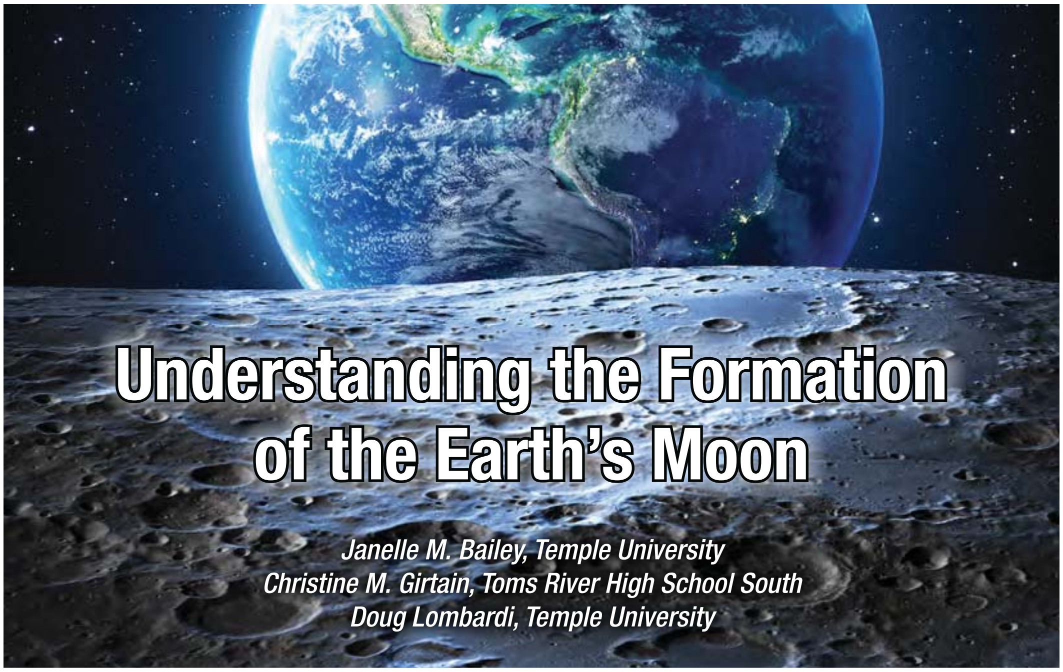

Understanding the Formation of the Earth's Moon

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Abstract

Understanding how the Moon formed supports understanding of Earth's formation and early history. The Moon Model-Evidence Link (MEL) diagram is an activity that has students weighing the connections between four lines of evidence and two different models explaining the Moon's formation—capture theory and giant impact theory. By evaluating alternative models, students can improve upon their scientific literacy and understanding of scientific practices. Suggestions from classroom use of the Moon MEL will help teachers use this activity in a productive manner.

The Science of the Moon's Formation

Four main theories of the Moon's formation have been considered over the years (Clery, 2013). The capture theory suggests that the Moon may have been a traveling body, such as an asteroid, that was pulled into a stable orbit by Earth's gravity. Co-formation is the idea that the Moon formed simultaneously as Earth in the primordial solar system, about 4.5 billion years ago, much in the same way that Earth itself formed through a process of collisions and accretions. Similarly, the fission theory suggests that the Moon was formed at the same time as Earth—not through accretion but by a spinning Earth ejecting a large blob of material into space which then developed into the shape and orbit of the Moon. These three theories seemed largely unsettled until a fourth was proposed by Hartmann and Davis (1975): the giant impact or collision theory, in which a large impactor crashed into Earth and material from both mixed to create the Moon.

Today, planetary scientists generally agree that the giant impact theory is the likely scenario for our Moon's formation, though the other theories are still viable mechanisms for the formation of other planets' moons. Evidence from the Apollo missions, including the collection and analysis of lunar samples, have propelled the giant impact theory into the forefront. Determination of the details—such as the size of the impactor, the percentage of material from each original body (proto-Earth and impactor) ending up on each final body (Earth and Moon), or the spin

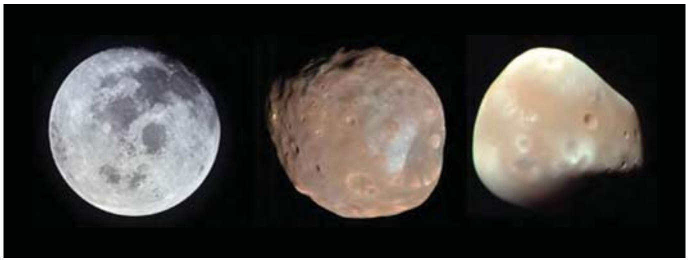

Figure 1. Images of Earth's Moon (left) and Mars's moons Phobos (center) and Deimos (right). Not to scale. The photos of Phobos and Deimos are color-enhanced.
Credit: NASA.

rate of the proto-Earth at the time of the collision—is an active area of research within planetary science.

Moon's Formation in the High School Classroom

The formation of the Moon is not a large part of the typical high school Earth science curriculum, but it is a piece of the discussion of Earth's formation (see Table 1 for the relevant NGSS). The Moon's formation can also be a springboard to understanding the relationship between other planets and their satellites—for example, Mars's moons Phobos and Deimos are very different in appearance than the Moon (Figure 1), so should another formation theory be considered for them? This type of discussion can also support understanding and implementation of scientific and engineering practices such as engaging in argument from evidence (NGSS Lead States 2013; NRC, 2012).

Table 1: Connections to the Next Generation Science Standards (NGSS Lead States, 2013, p.119)

NGSS performance expectations related to the Moon Model-Evidence Link (MEL) diagram
HS-ESS1-6: Earth's Place in the Universe
Apply scientific reasoning and evidence from ancient Earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history.

Creating a Model-Evidence Link (MEL) Diagram on Moon Formation

The Model-Evidence Link (MEL) diagram provides a scaffolded approach for students to compare competing models and to what extent evidence supports each model, leading to a critical evaluation of each model and ultimately an informed judgment about which model is more plausible. The MEL was originally designed by Clark Chinn and colleagues (Chinn & Buckland, 2012) for use in middle school life science, and has since been adapted for use in Earth science topics in middle and high school grades[1] (Lombardi, Sibley, & Carroll, 2013; Lombardi, Sinatra, & Nussbaum, 2013; and other articles in this issue). A more detailed description of how to use the MEL in high school classrooms is provided by Lombardi (this issue).

The MEL requires that students make judgments about how certain evidence supports, contradicts, or has nothing to do with each of two different models that explain the topic at hand. Although there have been four major models proposed for the Moon's formation, the MEL contains only two—the giant impact model (considered the scientifically correct model) and the capture model. Capture was chosen over the co-formation and fission models because it provides a clearer distinction from the giant impact model, although it would be possible to create a MEL with either of these other two models instead.

Using the Moon Formation MEL

The Moon MEL includes three components: the MEL diagram itself (Figure 2), supporting Evidence Texts, and an associated Explanation Task (Figure 3). We generally have students work in groups of two to four to share the Evidence Texts and discuss their ideas, although

[1] All MEL activities and associated materials may be downloaded for free at our project website: (https://sites.temple.edu/meldiagrams/materials/).

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we have each student complete their own MEL diagram and Explanation Task. Students should look at the MEL diagram and read the two models and the four evidence boxes. They will then draw one of four arrow types between each evidence box and each model, for a total of eight arrows.

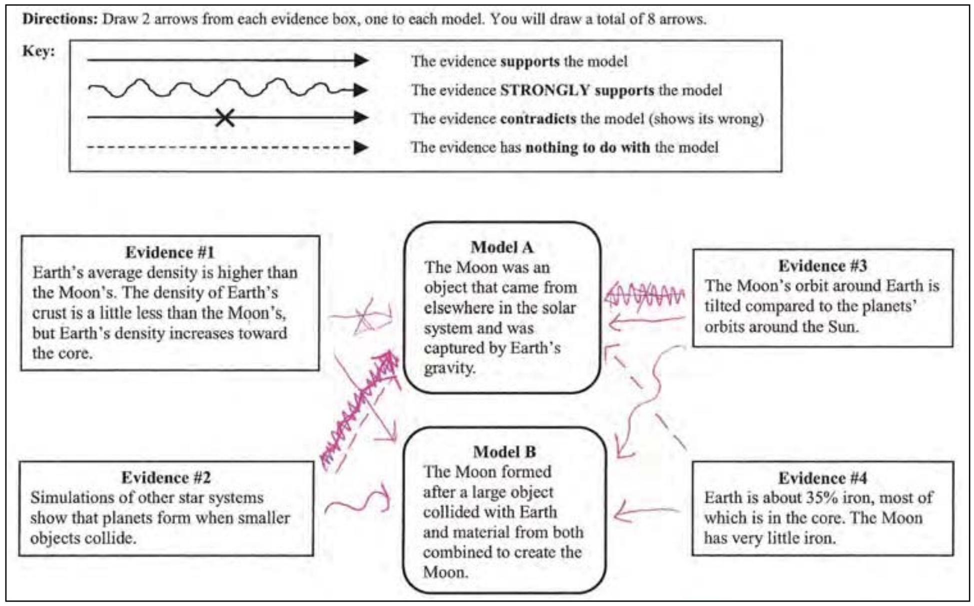

Figure 2. Example of a student-completed Moon MEL diagram.

Each page of Evidence Text expands upon one of the evidence boxes; each includes a figure, graph, or table to further support students' understanding of the evidence and their scientific reading skills. Some students will want to read the supporting Evidence Text before making a judgment about how the evidence connects to each model and drawing the appropriate arrow; others will want to jump into drawing the arrows and change them later if needed. You might have students simply share the pages of evidence text among themselves, or you might use a jigsaw or round-robin strategy for reading them in a more systematic approach.

Figure 3. Student example of the Moon MEL explanation task.

Please work on this individually.

Provide a reason for three of the arrows you have drawn. **Write your reasons for the three most interesting or important arrows.**

A. Write the number of the evidence you are writing about.
B. Circle the appropriate word (**strongly supports | supports | contradicts | has nothing to do with**).
C. Write which model you are writing about.
D. Then write your reason.

1. Evidence # 3 strongly supports | supports | contradicts | has nothing to do with Model B because:

Rocks coming from earth can create its own orbit

2. Evidence # 2 strongly supports | supports | contradicts | has nothing to do with Model B because:

Because it states dust and other material begin to coliade as it orbits around the center of the cloud

3. Evidence # 4 strongly supports | supports | contradicts | has nothing to do with Model B because:

Because it talks about earth and the moon having the same type of material

Circle the plausibility of each model. [Make two circles, one for each model.]

	Greatly implausible or even impossible									Highly Plausible
Model A	1	2	3	4	5	6	7	8	9	10
Model B	1	2	3	4	5	6	7	8	9	10

After they have completed the MEL diagram (i.e., drawn all eight arrows), students should now complete the Explanation Task. Students should select three model-evidence combinations, i.e. arrows drawn, and write about what kind of arrow they drew and why. We recommend that they choose arrows that they feel are particularly important or interesting, such as ones where there was disagreement among the group. You should encourage as much detailed writing as possible on this portion of the activity.

Management Tips and Other Suggestions

Because there are four evidence boxes and thus four supporting texts, a group size of four can work well—but groups larger than four should be avoided because some students may be left with nothing to do while their group members read the Evidence Texts. Smaller groups (two or three) can also work well. The extent to which you let students explore the Evidence Texts and MEL diagrams on their own versus provide them some kind of structure for the reading and discussion of them depends on your own style as well as your students' experience working in small groups. Both approaches have been successfully used across various classrooms.

Students might want to use different colors for their arrows to help distinguish between the two models (e.g., use red for Model A and black for Model B, or pen versus pencil or highlighter). This can make it easier for them to identify which is which when they begin working on the Explanation Task, as well as to verify that they have completed all of the required arrows. It can also help you review their drawings quickly if arrow colors are assigned ahead of time. Be careful to make the color options appropriate if you or any of your students are colorblind.

When working on the Explanation Task, students may want to choose arrows of "nothing to do with" because it is easy to write about, but this has limited utility for both their understanding and your assessment of it. You might suggest that these arrows should not be used or perhaps limited to a single explanation (not two or three). This part of the activity is what could be used for assessment, if so desired, thereby encouraging rich and robust explanations that would help you better determine students' understanding and reasoning processes. A discussion of a rubric that can provide insights into students' reasoning and evaluation processes is found later in this issue (Bickel & Lombardi, this issue).

You should have a general debriefing of the activity, but it is not necessary to go through each of the eight arrows to ensure that students get "the right answer." In other words, reducing the activity to a discussion of each arrow would be counterproductive because it moves students away from the scientific practice of evaluating several lines of evidence with alternative models. Focus instead on completion of all eight arrows and providing detailed responses on the explanation task, encouraging students to back up their claims with material from the evidence text (and prior knowledge). However, at the end of the explanation task, make sure you discuss that the scientifically accurate model, supported by overwhelming consensus of astronomers and planetary scientists, is the giant impact theory (Model B).

Potential Problem Areas and Extensions

Students have many alternative conceptions about the Moon (see Kavanagh, Agan, & Sneider, 2005, for a review of this literature); most of this research is focused on lunar phases and the nature of the Sun-Earth-Moon system rather than the Moon's formation. That doesn't mean, however, that students will be free of alternative conceptions that can interfere with this activity!

Evidence Statement #1 focuses on the density of the materials that make up Earth and the Moon. Students' understanding of density and why it makes a difference in the structure of these bodies could create challenges in their understanding and use of this evidence. Pilot studies have shown some students think Evidence Statement #1 has nothing to do with Model A or Model B, perhaps because of a lack of sufficient understanding that molten materials will separate into layers based on density. If Earth and the Moon had the same densities this evidence could support co-formation, whereas different densities support both Model A capture and Model B giant impact.

Other students may have prior knowledge that Earth's density is higher than the other inner planets. As a post-activity discussion, teachers may want to show a graph of the densities of the inner planets. It is important to note that not only is Earth's density higher than the Moon's, Earth's density is higher than all the other inner planets—thus Earth's density is an outlier from the trend in the densities of the other planets. Could Earth's higher density imply added materials from an impact? The teacher could then revisit each model and discuss how the trend in densities of the inner planets relates to each model. For Evidence Statement #4 students may miss the connection between the percentage of iron on Earth and the Moon. Most students do not have previous knowledge that silicates (SiO4)4- from Earth's crust would vaporize more easily on impact and be put into orbit whereas heavy metals like iron would not, making the silicon and oxygen amounts higher and iron lower for materials that coalesced to form the Moon. As a result, in our experience some student groups thought Evidence Statement #4 had nothing to do with either model. Instead, the different percentages of the various materials implies different origins of Earth and the Moon—thus supporting both Models A and B.

The Moon MEL is a tool that can be used to discover student alternative conceptions and lack of knowledge, spurring important classroom debates. A follow up activity, such as one described by Murphy and Bell (2013), could focus on understanding how the Moon's surface has changed over time.

Conclusions

The Moon MEL enables students to explore the Moon's formation and relates to a larger discussion of the solar system formation, a topic important to astronomy and Earth sciences as evidenced by its inclusion in the NGSS but that may not have been addressed through an engaging activity in the past. Additionally, as part of a broader approach to provide students the opportunity to critically evaluate different models within science, the Moon MEL can contribute to students' scientific literacy and critical thinking skills.

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