NATIONAL CENTER FOR CASE STUDY TEACHING IN SCIENCE

The Moon:

What's It Made of? Where Did It Come From?

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It's like no cheese I've ever tasted.
Wallace, A Grand Day Out (Nick Park)

Part I – The Standard Model

Hester O'Ryan loved working on puzzles; a good thing, too, because her first night in Washington, DC, was a rainy one, and she could not sleep. Hester had just won a summer internship at the History Division of NASA. She had never been this far from home, and she knew little about spaceflight, so her mind was filled with unformed queries.

She arrived promptly at NASA headquarters at 8:00am the next morning and was greeted by one of the archivists, who had some surprising news. "After several days of rain, water has seeped into our basement and damaged some files," explained the archivist. "We need you and the other interns to sort through the damaged files and fill in any information that was washed away. Specifically, we need you to walk step by step through the history of our maturing knowledge of how Earth's Moon came to be, reviewing the hypotheses in the era of the NASA Apollo missions of the 1960s and 1970s. What hypotheses existed? Were any of them correct? Was the evidence from Moon rocks sufficient to reach a conclusion? What conclusions were reached by Moon researchers?"

Hester silently contemplated this information for a moment, so the archivist continued. "Don't worry, you and the other interns have a broad background in many different subject areas. You have exactly the skill set we need. And be sure to check in with me at every stage of your investigation." After being shown to a room full of tables and filing cabinets, Hester and the other interns began to work. The first document found was some lecture notes on how the solar system formed. This information seemed like a good place to begin, so Hester and her colleagues began reading.

Document A – The Solar System Formed from the Collapse of a Cloud of Gas and Dust

Using our telescopes to peer into the heart of giant interstellar gas clouds, we see an uncountably large number of stellar systems in various stages of formation. There is good evidence that our solar system formed in a coherent way, i.e., all of the objects in our solar system—Sun, planets, moons, asteroids, and comets—formed at the same time from the same parent cloud.

The standard model for solar system formation is a simple one, and accounts for the gross properties of our system. The model runs like this: a large interstellar cloud begins to collapse under its own weight. While collapsing, higher-density knots of gas in the cloud begin to collapse on their own. These knots are spinning, and continue their collapse by flattening out to become wide, thin disks. Each disk has a central condensation: the protostar. Surrounding the protostar is a protoplanetary disk or "proplyd."

The proplyd is a mixture of two types of substance: volatiles, and refractories. Volatile substances evaporate readily, even at low temperatures, whereas refractory substances resist evaporation until a high temperature is reached. Common volatiles are hydrogen, helium, ammonia, and methane; volatiles also include many non-metal oxides like water, and carbon dioxide. Common refractories are iron, and tungsten; refractories also include many metal oxides like silicon-oxygen minerals and iron-oxygen minerals.

When the protostar becomes a bona fide star it shines very brightly, thus heating its proplyd. Close to the star, volatiles in the proplyd evaporate and are effectively removed to the outer disk. What remains in the inner disk are refractories, which condense to form rocky or terrestrial planets. In the outer disk the temperature is low enough that volatiles can condense and form Jovian or gas giant planets. At the very edge of the disk, the temperature is so low that volatiles freeze to become cometary bodies, i.e., objects of mixed rock and ices.

The evolution of the inner disk, where Mercury, Venus, Earth, and Mars formed, is of particular interest. Once the volatiles are removed to the outer disk, the remaining refractories are in the form of dust grains; tiny clumps of many dozens of atoms. These grains experience random hit-and-stick collisions with other grains, in a lengthy process that produces pebbles from grains, then boulders from pebbles, and so on until large 1,000 km sized objects are formed. Throughout this process of agglomeration the inner disk is said to be populated by planetesimals. The last few collisions between these largest planetesimals produce protoplanets; protoplanets will settle down to become planets, evolving mostly via internal processes.

After reading through the notes, Hester and the others checked in with the archivist. “Good start,” said the archivist. “Let’s make sure we all understand the standard model before moving to the next step. Here are some questions we should be able to answer.”

Questions

1. What is a proplyd?

2. What two substances are found in proplyds?

3. What is the difference between a volatile and a refractory substance?

4. What is the difference in temperature between the center of the proplyd and the outer edge?

5. Why do volatile and refractory substances separate from each other in the proplyd?

6. The standard model predicts that objects at the same distance from the Sun will have the same composition; how?

Part II – A Problem

"I see how the standard model explains a relationship between distance from the Sun, temperature, and what a planet is made of," said Hester. The other interns nodded in agreement. "Let's return to the file room and look at that second document we found, the lecture notes that were written before Moon rocks were returned by the Apollo astronauts." They began reading.

Document B – The Moon Does Not Easily Fit into the Standard Model

As stated earlier, the standard model accounts for gross properties, e.g., for why all the major bodies in our solar system orbit the Sun in the same direction and in the same thin plane, and why there is a progression from more refractory material to more volatile material as one moves outwards from the Sun (i.e., why terrestrial planets are closer to the Sun than Jovian planets).

The question is, where does the formation of the Earth's Moon fit into this model?

Clearly, we need to know the mix of volatile and refractory material on the Moon to say something about its origin. A big clue comes from the Moon's average density; it is 3 g/cc (grams per cubic centimeter), much lower than 5 g/cc for both Earth and Venus. A difference in density reflects a difference in composition; having objects of different composition at the same distance from the Sun seems to contradict the prediction made by the standard model. For the sake of comparison, the densities of water-ice, granite, and iron are 1 g/cc, 3 g/cc, and 8 g/cc respectively. As of the 1960s, the Moon was recognized as a unique object of mysterious origin.

After reading Document B, Hester again led the interns back to the archivist for discussion. "Very good work," said the archivist. "Let's make sure we understand what was puzzling the scientists in the 1960s."

Question

7. How was the value of the Moon's average density not predicted by the standard model?

Part III – Hypotheses Pre-Apollo

"I see the problem," said Hester. "What is the origin of the Moon? The Moon is different enough from Earth to suggest a different composition, but in the 1960s we had no Moon rocks, so we didn't know for sure what the Moon was made of. We needed to analyze Moon rocks. Only by comparing Moon rocks with other rocks in the solar system could the Moon's origin be found."

Hester and the other interns returned to the file room. They found that researchers had proposed several scenarios for the formation of the Moon, each of which made specific, differing predictions about the types of rocks that would be found there. These scenarios were called (i) the fission hypothesis, (ii) the accretion hypothesis, (iii) the capture hypothesis, and (iv) the ring condensation hypothesis.

Document C – Competing Hypotheses

The Fission Hypothesis

The fission hypothesis proposed that a rapidly-spinning proto-Earth spun off rock from its equator; this spun-off rock collapsed to form the Moon. The Moon would therefore have formed from rocks in Earth's crust and mantle. The Moon would have formed at a relatively low temperature, and thus also would have retained the water that was embedded in crystalline form in crustal and mantle rock.

The Accretion Hypothesis

The accretion hypothesis proposed that the Earth and Moon formed together, always having shared an orbit around the Sun. In this case, Moon rocks would be identical in composition to Earth rocks, and the Moon should form a core, mantle, and crust similar to that of Earth.

The Capture Hypothesis

The capture hypothesis proposed that the Moon formed in the outer solar system. Its orbit evolved to cross Earth's, eventually bringing it into orbit around the Earth. This scenario is almost identical to the history of meteorites; they originate from the rocky debris between Mars and Jupiter, experience an orbital evolution that takes them on an Earth-crossing path, and collide with the Earth. Therefore, this hypothesis predicts that Moon rocks would more resemble meteorite rocks than Earth rocks.

The Ring Condensation Hypothesis

In this hypothesis, the proto-Earth was heated to a very high temperature, so much so that a thick, volatile atmosphere surrounded the Earth. Upon cooling, a ring of ices remained to coalesce and form the Moon. In this case, the Moon would be composed of mostly frozen water and other volatiles.

Hester and the others stopped reading. "And here is where the water damage begins," said Hester. "The next few pages were erased by the water." They returned to the archivist. Hester explained, "The scientists in the 1960s had made predictions of what Moon rocks would be composed of before the Apollo astronauts collected any. But their predictions have been erased."

The archivist said, "Let's see what the scientists would have concluded based upon the descriptions of the four hypotheses, and the data they had."

Questions

8. Examine Table 1 and Table 2. Which elements and/or oxides would be relevant to measure for the Moon for the purpose of determining the Moon's origin?

9. For each of the four Moon formation hypotheses, predict the composition of the Moon. Refer directly to the species in Table 1 and Table 2. You can speak of groups (e.g., lithophilic elements) instead of individual elements. You can use words like "greater than," "less than," or "equal to," instead of actual numbers.

   Fission:

   Accretion:

   Capture:

   Ring condensation:

	Volatile elements		Lithophilic elements						Siderophilic elements		Other	Total
	H	He	Si	O	Mg	Ca	Al	Na	Fe	Ni		
Earth, crust	0	0	28	47	2	4	8	3	5	0	3 (K)	100
Earth, mantle	0	0	23	44	19	2	2	1	10	0	0	101
Earth, core	0	0	5	0	3	0	0	0	85	3	4 (S)	100
Meteorites (avg)	0	0	17	33	14	1	4	1	29	2	2 (S)	100

Table 1. Percent by mass elemental composition. Meteorite "average" composition is most indicative of stony or typical (non-carbonaceous) chondrite meteorites. Volatile elements evaporate easily, i.e., at low temperatures. Lithophilic elements are those that combine preferentially with silicon. Siderophilic elements are those that combine preferentially with iron. Values across a row may not add to 100% due to measurement uncertainties. This table is adapted from Table 9-2 of Hartmann (2005).

	SiO_2	Iron Oxides	MgO	Al_2O_3	Other metal oxides	H_2O	Total
Earth, crust	57	8	5	16	14	1	101
Earth, mantle	44	8	40	3	2	?	100
Meteorites (avg)	40	27	25	2	3	0	97

Table 2. Percent by mass composition of oxides, i.e., oxygen-containing rocks and minerals. Oxygen is the third most abundant element in the universe after hydrogen and helium. It is expected that oxides are among the most common molecules generally, and oxide-based minerals are among the most common. Water (H_2O) would be embedded in minerals in crystalline form. Values across a row may not add to 100% due to measurement uncertainty. This table is adapted from Table 9-3 of Hartmann (2005).

Part IV – Results from Apollo

Hester and the other interns read that a primary science objective of the Apollo missions was to bring back rocks from a variety of places on the Moon's surface. Between 1969 and 1972, six Apollo missions brought back 382 kg (842 lb) of Moon rock. Partial results of these rocks are listed in Table 3 and Table 4.

"Right," said Hester. "Each of the four hypotheses made specific predictions of the composition of Moon rocks. The next stage would be to compare each prediction with the real composition of Moon rocks and see which hypothesis was correct."

"We have to be careful here," said the archivist. "As scientists we are never able to think of every possible hypothesis. It might be that none of the four hypotheses are correct."

	Volatile elements		Lithophilic elements						Siderophilic elements			
	H	He	Si	O	Mg	Ca	Al	Na	Fe	Ni		
Moon, bulk	0	0	20	42	18	5	4	0	8	0	0	97

Table 3. Percent by mass elemental composition of the Moon, as inferred from lunar landers (Surveyor missions) and sample returns (Apollo missions). For details refer to the caption to Table 1. This table is adapted from Table 9-2 of Hartmann (2005).

	SiO_2	Iron Oxides	MgO	Al_2O_3	Other metal oxides	H_2O	Total
Moon, bulk	43	9	28	11	9	0	97

Table 4. Percent by mass composition of oxides of the Moon. For details refer to the captions for Table 2 and Table 3. This table is adapted from Table 9-3 of Hartmann (2005).

Questions

10. Do these results eliminate any of the four Moon formation hypotheses? Which?

11. Do these results support any of the four Moon formation hypotheses? Which?

12. Can you come to a definite conclusion concerning the Moon's origin?

Part V – Post-Apollo

"I'm quite surprised," said Hester. "None of the four hypotheses were able to describe correctly the composition of Moon rocks. There were other papers after the Apollo missions that we have not read yet. We should read those."

Hester and the other interns discovered that, indeed, a detailed analysis of the composition of the Moon ruled out all four formation hypotheses. A fifth hypothesis was proposed by W.K. Hartmann and D.R Davis (1975). Called the giant impact hypothesis, they proposed that in the late planetesimal phase a Mars-sized object struck the Earth a glancing blow, sending a debris field into Earth orbit that coalesced to form the Moon. This hypothesis predicts that the Moon formed from rock from Earth's crust and mantle, and the resultant heat of the collision evaporated all of the volatile content. Moon rocks should therefore closely resemble Earth crustal and mantle rock and be devoid of water.

The net result is that today, although imperfect, the giant impact hypothesis is the generally accepted explanation for Moon formation. This conclusion would not have been possible without the return of Moon rocks from the Apollo program. The Apollo program is thus heralded as a great scientific success.

The interns sat down with the archivist at the end of a long day. "Whew," said Hester. "It takes a lot of imagination and a lot of data to answer even the most basic of questions."

"Yes," said the archivist. "But our job as scientists is never done. We are constantly checking and revising our conclusions. That's why science is so good at describing our universe."

Question

13. Explain how the Moon's composition best matches the prediction of the giant impact hypothesis.

Part VI – Reflection

Discuss the following topics with members of your group. Appoint someone to take minutes of the discussion.

Questions

14. The giant collision hypothesis involves an extremely unlikely event, in that all of the conditions—like the size and trajectory of the collider—must be just right to produce Earth's Moon. Is this extreme unlikelihood a disadvantage of the hypothesis?

15. Sample return missions are rare; why? Do you think the information gained would be worth the effort?

16. Exoplanets are planets orbiting stars other than our Sun. Some of these exoplanets are called "hot Jupiters"; these are massive gas planets orbiting close to their parent stars where only terrestrial planets should be. Does the existence of hot Jupiters make false the standard model of planet formation?

Part VII –Further Research

Extend your knowledge! Refer to textbooks, course notes, or other published materials on planetary science to respond to the following questions.

Questions

17. What evidence is there for (i) captured moons, and (ii) moons that accreted around other planets in our solar system?
18. What other sample return missions have there been? What others are in the planning stage?
19. How do proplyds in the Orion star formation region support the standard model of planet formation?
20. One proposed solution to the existence of hot Jupiters is to modify the standard model for planet formation by introducing a process called planet migration. What evidence is there for planet migration within our own solar system?

Reference

Hartmann, W.K. 2005. *Moons and Planets,* 5^{th} ed. Belmont, CA: Brooks-Cole.