Origin of Earth and Moon

PA STEM
monthly meeting

CCIU

September 15, 2015

High-school standard HS-ESS1-6 focuses on the evidence for Earth's early history

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HS-ESS1-6. 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.

[Clarification Statement: Emphasis is on using available evidence within the solar system to reconstruct the early history of Earth, which formed along with the rest of the solar system 4.6 billion years ago. Examples of evidence include the absolute ages of ancient materials (obtained by radiometric dating of meteorites, moon rocks, and Earth's oldest minerals), the sizes and compositions of solar system objects, and the impact cratering record of planetary surfaces.]

(It's one of the greatest stories ever told!)

Evidence in science is identified through the process of the scientific method

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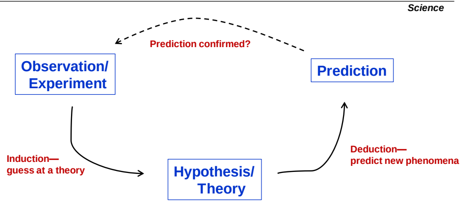

If the prediction is false, the hypothesis (or theory) is false!

The approach to understanding Earth's origin depends on an operational hypothesis

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The composition of each celestial body indicates the distribution of elements at its current location when the body formed (unless evidence implies the contrary)

Question: What does this hypothesis predict about the compositions of the various planets as a function of their distance from the sun?

Heavy elements like iron and nickel are smoothly distributed throughout the solar system, but predominate close to the sun

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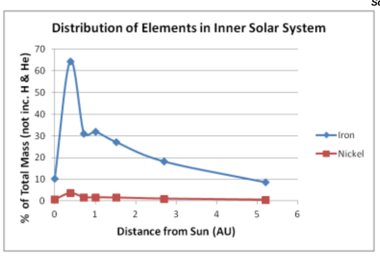

This smooth distribution supports the operational hypothesis

Intermediate-mass elements like silicon and oxygen are mostly found farther out, but are also smoothly distributed

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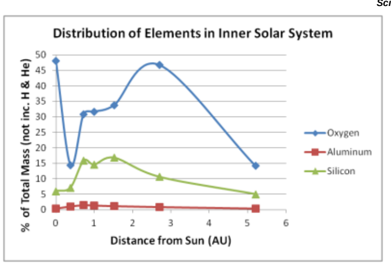

Earth and nearby planets have similar compositions

Venus, Earth, and Mars have nearly identical compositions, supporting the idea that they formed in their current positions at the same time

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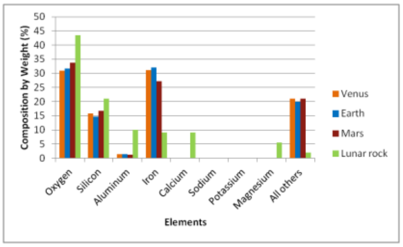

The Moon is very different, indicating formation at another time or place (possibly contradicting the hypothesis)

The mystery of the Moon's origin might be explained if we can test two hypotheses

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The Moon might have formed

- at another place
  (where the composition was different—Hypothesis 1)
- at another time
  (when the composition had changed—Hypothesis 2)

Question: What are some predictions each of these hypotheses imply?

The ages of celestial bodies are determined by two main methods

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Age of surface of body—density of craters

more craters = older surface

→ body is older OR less active

Age of material in body—radiometric dating

more radioactive elements = younger material

Compare the cratering on these surfaces. What does it tell us about the surface? How do you know?

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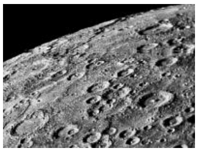

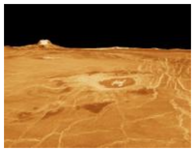

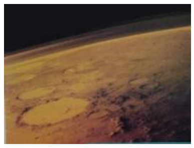

The Moon's pattern of cratering is distinctive. Which surface does it most resemble? Is the surface young or old?

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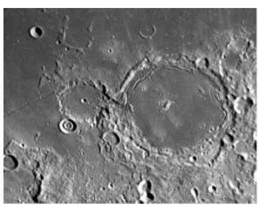

The Moon's surface is most similar to Mercury's, which is very old and inactive

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- Mercury and the Moon show little evidence of active surface processes
- Venus, Earth, and Mars have younger surfaces, but show evidence of surface activity

→ **Evidence from cratering is inconclusive about the relative ages of the bodies**

Radiometric dating uses the radioactive decay of heavy nuclei to tell time

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- Radioactive decay is mostly independent of external influences
- Decay times span a large range:

  < 1 s to > billions of yrs

- Heavy elements are found in a wide range of materials

Time of decay is measured by the ***half-life***, which is the time for half of the current radioactive nuclei to change into stable nuclei

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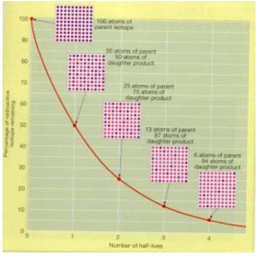

# of half-lives	parent	daughter
1	1/2	1/2
2	1/4	3/4
3	1/8	7/8
4	1/16	15/16

Total number of parent and daughter nuclei remains constant

Let's do some sample problems to see how radiometric dating works

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Carbon 14 nuclei decay into Nitrogen 14 nuclei with a half-life of 5730 years. How old is a sample containing 125 nuclei of C-14 and 375 nuclei of N-14?

Another sample begins with 10 g of Carbon 14. After 20,000 years, how much Carbon 14 will remain?

A number of radioactive nuclei have half-lives of use in dating celestial bodies

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Parent	Half-life (years)	Daughter
$^{87}Rb_{37}$	48.8 billion	$^{87}Sr_{38}$
$^{232}Th_{90}$	14.0 billion	$^{208}Pb_{82}$
$^{238}U_{92}$	4.47 billion	$^{206}Pb_{82}$
$^{40}K_{19}$	1.25 billion	$^{40}Ar_{18}$
$^{235}U_{92}$	0.704 billion	$^{207}Pb_{82}$

Material from a wide range of celestial bodies has been dated very precisely

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Celestial body	Source	Age (years)
Meteorites	CAIs, chondrules	4.5673 billion
Earth's surface	Zircons (Jack Hills)	4.404 billion
Mars' surface	Zircons (Black Beauty)	4.428 billion
Lunar surface	Highland samples	4.3 – 4.5 billion

The Moon is as old as Earth and Mars

→ Hypothesis 2 is false !

Four possible hypotheses have been proposed to explain the Moon's origin

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- Capture Hypothesis (Hypothesis 1)
- Condensation Hypothesis
- Fission Hypothesis
- Large Impact Hypothesis

The capture hypothesis proposes that the Moon formed elsewhere and was later caught in orbit around Earth

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Question: What predictions does this hypothesis make?

Prediction 1:

Prediction 2:

Though different from Earth as a whole, the Moon's composition is remarkably similar to Earth's *crust*

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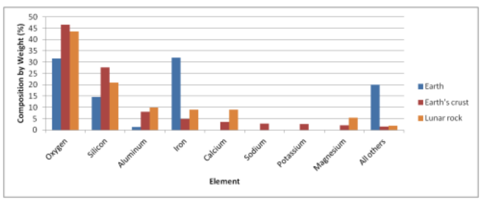

There is also no evidence of bodies with Moon-like compositions elsewhere in the solar system

→ **Hypothesis 1 is false!**

Two other hypotheses fail to make correct predictions

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- **Condensation Hypothesis**

  Moon formed with Earth from the same material

  Prediction:

- **Fission Hypothesis**

  Moon spun off from molten Earth

  Prediction:

The Large-Impact Hypothesis says the differentiated Earth (iron sunk to core) was struck by a large body that splashed up debris to form the Moon

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Predictions:

- **Moon should lack iron √**
- **Moon similar to Earth's crust √**
- **Moon made of both Earth and impactor material √**
- **Earth should have more iron and less silicon than Venus and Mars √**
- **Thermal impact should be seen in Earth isotope distribution √**
- **Thermal impact of debris should be seen in asteroids √**

Latest research shows that likely debris from the Moon's creation heated asteroids 4.47 billion years ago

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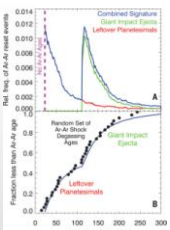

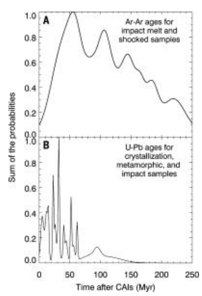

W. F. Bottke et al. Science 348, 321-323 (2015)

Hypothesis is fully supported!