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T. M. Davison

Constructing the Solar System

Compton Lectures – Autumn 2012
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## The Moon

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<tr>
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<tr>
<td>Orbital distance</td>
<td>238854 miles</td>
</tr>
<tr>
<td>Average radius</td>
<td>1079 miles ((0.27 \times \text{Earth}))</td>
</tr>
<tr>
<td>Mass</td>
<td>(7.34 \times 10^{22} \text{ kg}) ((0.012 \times \text{Earth}))</td>
</tr>
<tr>
<td>Average density</td>
<td>(3346 \text{ kg/m}^3) ((0.61 \times \text{Earth}))</td>
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Image courtesy of Gregory H. Revera/Wikimedia Commons
Galileo 1609 showed Moon is rocky

- Observed hills and what he thought were oceans

Leads to our names for:

- the bright highlands (Terra)
- and dark basins (Mare)
Features on the Lunar surface

- **Maria** are large, dark, basaltic plain on the Moon
  - Formed by ancient volcanic eruptions
- **Terrae** are the lighter, anorthositic highlands
  - Older than the Mare

Image courtesy of the United States Geological Survey
Impact craters are a dominant surface feature.

- Craters cover the surface of the Moon.
- Smooth areas are the younger Mare which often infill large craters.

Images courtesy of NASA.
Craters still forming today

New Crater Discovered in LROC Image

Image courtesy of NASA/GSFC/Arizona State University
Part 1:
Classical formation mechanisms

Image courtesy of NASA
1878: G.H. Darwin

- Suggested a large chunk of material split from the Earth
- Requires fast rotation of Earth

Four years later: Osmond Fisher

- Thought that Pacific basin represents the scar left behind
1909: Thomas Jefferson Jackson See
- Moon formed as a planetesimal elsewhere in the Solar System
- Later captured by Earth’s gravity

Image courtesy of William Larkin Webb/Wikimedia Commons

Image courtesy of Black Cat Studios
1873: Édouard Roche
- Earth and Moon formed together
- Formed from swarm of planetesimals as a **double planet**
Part 2:
Properties of our Moon

Image courtesy of NASA
Angular Momentum

Earth and the Moon: the view from Mars

- The Earth–Moon system has a high angular momentum
- The Moon has a greater mass fraction compared with other planet–satellite systems

Image courtesy of NASA/JPL-Caltech/University of Arizona
We have samples of the Moon

- NASA’s Apollo program in the 1960s to 1970s
- Collected samples from the Moon
  - Also have lunar meteorites
- Can measure ages, composition, structure, etc.

Images courtesy of NASA
The Moon formed relatively late (given its size)

- Radiometric age of lunar rocks from hafnium/tungsten isotopes
  - Moon formed > 30 million years after Solar System formation

- Other objects this size formed in a few hundred thousand years

Harrison H. Schmitt collects lunar rocks during the Apollo 17 mission

Image courtesy of E.A. Cernan/NASA
The Moon has a small core

- Apollo astronauts left seismometers on the Moon
- Recorded moonquakes from 1969 to 1977
- Using moonquake data, the size of the lunar core is estimated to be $\sim 330$ km
  - $\sim 20\%$ of the Moon’s radius
  - Compare to Earth’s core ($\sim 50\%$ Earth’s radius)
- Explains low density of Moon:
  - Moon is depleted in iron

Image courtesy of NASA/MSFC/Renee Weber

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The Moon had an early magma ocean

- The crust of the Moon is composed of a rock called **anorthosite**
- Anorthosite is a rock made up of low-density components
- This implies that the Moon had a magma ocean
  - The low-density components floated to the surface, and cooled as the crust
Summary of Constraints
A model of how the Moon formed should explain each of these

1. High angular momentum
2. Low density/small core
3. Late formation
4. Oldest rocks appear to come from magma ocean
   - Energetic start occurred after decay of short-lived radionuclides
5. Oxygen and titanium isotope data identical to Earth
   - Asteroids and planets differ
   - Common origin

How do these constraints fit with the classical formation hypotheses?
Fission

- Can explain:
  - Lack of large core
  - Oxygen isotope similarity

- But, problems exist:
  - Earth would have had to spin very fast before fission event
  - Pacific Basin only formed 70 million years ago
  - Moon’s orbit and Earth’s equator not co-planar
  - Cannot account for lack of volatiles on the Moon
Fission

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But, problems:
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- Isotopic similarities
- Unlikely to be captured:
  - More likely to impact or by hurled back out to space
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But, problems:
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Image courtesy of Black Cat Studios
Co-accretion

- Most popular theory until 1970s
  - Doesn’t require low frequency event like capture
- But, cannot explain:
  - Difference in iron content
  - Large angular momentum of Earth–Moon system
Co-accretion

- Most popular theory until 1970s
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- But, cannot explain:
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  - Large angular momentum of Earth–Moon system
New theory required

- Not fission, capture or co-accretion

- After Apollo, we needed a new theory to explain the origin of the Moon
Part 3:
Giant Impact Hypothesis

Image courtesy of NASA
Giant impact hypothesis

- Mid 1970’s to 1980’s: New theory
- First suggested by Hartmann & Davis

- Giant impact with Earth
  - Debris disk
  - Coalesced to form the Moon

Image courtesy of Black Cat Studios
Giant impact

- 2004: Robin Canup’s model of the giant impact
- Impact of a ~ Mars–sized body with Earth
  - Theia
- Impact angle 42–50°
- Moon is composed of > 60% impactor material

Images courtesy of Canup (2004) *Icarus*
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In the lecture, I showed a movie of this collision. That movie, and other resources from Canup (2004), can be found at: http://www.boulder.swri.edu/~robin/moonimpact/
Success?
Does this model match the observational constraints?

- Explains a lot of the constraints on Moon formation

1. Angular momentum ✓
2. Low iron content/small core ✓
3. Late formation time ✓
4. Magma ocean ✓
One constraint cannot be easily explained by this model

- Measurements of oxygen and titanium isotopes — now a lot more accurate
- As the error bars on the measurements shrunk, isotopic composition of the Moon and Earth became indistinguishable
- This means that:
  - They must come from a single body, or
  - They were well mixed during/after the impact

Image courtesy of Zhang et al. (2012) *Nature Geoscience*
Can we save the Giant Impact Hypothesis?

1. Earth and Theia came from the same orbital distance
   - Explains similar isotopic composition
   - But, can’t account for late formation time

2. Material stayed hot for a long time, allowing exchange in the vapor phase
   - Could reach isotopic equilibrium for volatile elements like oxygen
   - However, refractory elements like tungsten and titanium and silicon are not readily explained

This is where things stood, up to around a month ago
Part 4: Giant Impact Hypothesis: Updated

Image courtesy of NASA
Moving the goalposts

In the original scenario, the angular momentum of the Earth–Moon system was generated by the impact:
- This limited the types of impact that could be studied.
- A month ago, two papers removed this limitation.
- They assumed that the Earth was spinning rapidly before the impact.
  - A resonance with the Sun after the impact was able to remove the excess angular momentum.

Image courtesy of Čuk & Stewart (2012) Science
In one of the new models, a smaller impactor is invoked
- It doesn’t need to generate angular momentum
- Small mass — lower fraction of Moon’s composition
- Helps explain isotopic similarities
- Think of it as a hybrid of the Giant Impact hypothesis and Darwin’s Fission hypothesis
Canup’s new model

- In another updated model, Canup also invokes a fast spinning Earth
- But, rather than a smaller impactor, uses an impactor more similar in size to proto-Earth
- Assumption is that the resultant bodies are a mixture of Earth and Theia
- Works well for Theia of ~ 40% the size of Earth

Image courtesy of Canup (2012) *Science*
A hit-and-run collision

- One final alternative doesn’t need to invoke resonance with the Sun to slow down the Earth’s spin
- Instead, it assumes a **hit-and-run** type collision
  - High velocity, low incidence angle
- Most of the impactor mass continues downrange
- Moon forms from debris disk that is composed primarily of Earth material

Image courtesy of Reufer et al. (2012) *Icarus*
Impacts, once again, played a key role in shaping the Solar System.

The full details of the impact that formed our Moon are still not resolved.

Exciting work to come in the next few years.

Which of the possible models best fits our observations?
Thank you

Questions?