76th Arthur H. Compton Lecture Series

Constructing the Solar System: A Smashing Success!

Lecture 7: Constructing the Moon

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1 Introduction

The Moon is our closest neighbor, and therefore one of the most intensely studied bodies in the Solar System. It is the only planetary body that humans have set foot on, other than the Earth. However, despite our intense interest in the Moon, its formation still remains somewhat of a mystery. After NASA's Apollo missions to the Moon, all previous theories were considered unlikely. The prevailing theory today is that a giant impact between a planet-sized body and the Earth led to the Moon's construction. In recent years, advances in numerical modeling have allowed us to better understand this significant event in Earth's history.

Figure 1: The Moon. Image courtesy of Gregory H. Revera

2 Constraints on formation hypotheses

Based on our knowledge of the Moon's orbit and composition, we have several constraints that a formation mechanism must be able to explain.

1. The high angular momentum of the Earth–Moon system
2. The Moon has a lower density and smaller iron core than the Earth
3. The Moon formed later that most other objects in the Solar System (at least 30 million years after the formation of the Solar System)
4. The Moon sustained a magma ocean on its surface in its early history, required a large input of energy
5. Oxygen and titanium isotopes are identical between Earth and the Moon, meaning the material has a common origin

3 Classical formation mechanisms

Three classical formation mechanisms had been proposed for the Moon in the pre-Apollo era. However, we now know that problems exist for each of these hypotheses.

Fission: A large fraction of its mass tore away from the fast spinning Earth to form the Moon

- Does not account for depletion of volatiles on the Moon
- Requires very rapid rotation
- The Moon's orbit is not in coplanar with the Earth's equator

Capture: The Moon formed elsewhere and was captured in orbit around the Earth

- Slowing down the Moon enough to keep it in orbit is hard
- More likely that the Moon would have collided with Earth or been hurled away

Co-accretion: The Moon and Earth form concurrently in the primordial accretion disk

- Does not account for compositional differences between Earth and the Moon (e.g. iron)

4 Giant impact hypothesis

The evidence we gained from the Apollo missions to the Moon showed that the classical formation hypotheses did not match all the observations. A new theory was needed, and in the late 1970s and 1980s, the giant impact hypothesis started to gain traction.

In this theory, the Moon formed as the result of a giant impact between the young Earth and a large impactor, possibly around the size of Mars. During the early stages of the Solar System, impacts were frequent events. The giant impact hypothesis can explain the low density and small core of the Moon, and the energetic birth of the Moon (which led to the formation of the magma ocean).

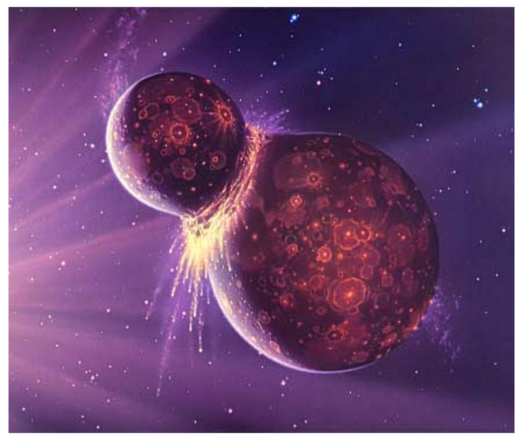

Figure 2: Artist's impression of the giant impact that it is thought led to the formation of the Moon. Image courtesy of Joe Tucciarone

Original models of the giant impact led to a Moon with a significant fraction of its mass coming from the impactor. However, recent measurements of oxygen and titanium isotopes suggest that the majority of the Moon must have originated from the Earth's mantle. Several studies have suggested some possible ways to overcome this difficulty:

1. The Earth was spinning very fast before the impact: this means that less angular momentum needs to be delivered by the impact, and therefore a smaller impactor is possible (and thus less material in the Moon came from the impactor, leading to similar isotopic compositions)
2. The impactor and the Earth were actually very similar in size, leading to a large degree of mixing during the impact, explaining the similar isotopic composition
3. The impact was of the hit-and-run class, where the impact was at a very oblique angle; the impactor kept moving past the Earth, and most of the lunar material came from the material ejected from the Earth during the impact

These mechanisms are all still very new, and the next few years will be very exciting in helping to determine which of them offers most likely scenario for the formation of the Moon.

5 Next lecture

In the next lecture (December 15), we will look at impacts on the Earth, and how they have shaped the planet we live on today.