Giant Impact: The Leading Scenario of the Origin of the Moon

Ziyi Song*
Wardlaw-Hartridge School, Edison, New Jersey, 08820, United States

*Corresponding author e-mail: lsong@whschool.org

Abstract. Moon, an astronomical body hanging in the sky, has been recorded and studied by mankind for thousands of years, even before the invention of the word “moon”. There are numerous varying theories about its origin. The aim of this article is to compare and further analyze the common theories of the origin of Moon. First, we provide basic information about the moon, the moon's soil, and the basic elements of the moon and offer an introduction to solar and lunar eclipses and why they exist, as well as human efforts to explore the moon, including the Apollo program and the Chang’E program. Finally, we analyze and compare the four most common theories about the origin of the Moon: the split theory, homologation theory, capture theory, and impact theory. Among all, the more accepted theory is the big collision theory though there is still no scientific basis for it. This article introduces the origins of the Moon by analyzing the pros and cons and describing possible future directions.

Keywords: The Moon, Origin of the moon, Apollo program, Chang’E program, Giant Impact theory, Lunar Eclipse, Moon resource

1. Introduction
The Moon, Earth's Io, is Earth's only natural satellite and is the fifth largest satellite in the Solar System. The Moon is slightly larger than a quarter of the Earth's diameter and about 1/81th of the Earth's mass, which makes it the largest moon in size and mass relative to the planets it orbits, and the second most dense moon in the solar system [1]. The Moon formed about 4.5 billion years ago, shortly after the Earth appeared. The Moon is an already differentiated celestial body, meaning it has a crust, a mantle, and a core. Moreover, the Moon's core is rich in solid iron and has a radius of about 240 kilometers, in addition to a fluid outer core that is primarily composed of liquid iron and has a radius of about 300 kilometers. In addition, the Moon is the Earth's synchrotron satellite, and it rotates on its axis at the same period as it does around the Earth, which makes it almost always face the Earth on the same side.
1.1. Lunar Soil

The entire lunar surface is covered with a layer of lunar soil of varying thickness, except for a few very steep mountains ranges, impact craters and volcanic craters (where bedrock may be exposed). Contrary to the process of soil formation on Earth, the formation of lunar soil is caused by the thermal expansion of lunar rocks in the absence of O2, water, wind, and life activity, due to the impact of small and large meteorites and micrometeorites, continuous bombardment caused by cosmic rays and solar wind, and large temperature differences at the lunar surface [2]. In conclusion, the formation is the result of a combination of factors such as condensation and fragmentation. Therefore, the formation of lunar soils is dominated by mechanical crushing. The basic constituent particles of a moon soil are: mineral clasts (defined as particles containing more than 80% of a mineral, mainly olivine, diorite, pyroxene, ilmenite, spinel, etc.), primary crystalline rock clasts (basalt, plagioclase, olivine, soda-lite, etc.), breccia clasts, various types of glass (molten rock, micro breccia, percussive glass, yellow or black). The eclipses are caused by a variety of factors, such as the presence of a large number of small particles (pyroclastic glass), unique lunar soil components - clay aggregates, meteorite fragments, etc [3].
1.2. Solar and Lunar Eclipses

A solar eclipse occurs when the moon moves between the sun and the earth, and if the three are in a straight line, the moon blocks the light from the sun towards the earth, and the dark shadow behind the moon falls right on the earth.

1.2.1. Total Solar Eclipse. The Sun is 400 times the diameter of the Moon but is also 400 times farther away from the Earth than the Moon is. Because of symmetry, the moon's dark shadow, the shadow that falls on the Earth's surface, is just wide enough to cover the entire sun such that the sun's solar sphere is completely obscured by the moon, and the otherwise bright disk of the sun is obscured by the black shadow of the moon. However, it is still possible to observe the fuzzy corona (coronal layer) with the naked eye only when a total solar eclipse occurs. In addition, total solar eclipse only occurs when the Moon is at perigee, when the Moon's umbra cone is longer than the distance between the Moon and Earth, and the umbra cone is able to sweep across the Earth's surface. Because the actual size of the Sun is much larger than that of the Moon, a total solar eclipse is usually seen only in a very small area of the Earth, since the Moon's umbra is only a small dot for the Sun.

1.2.2. Partial Solar Eclipses. The cause of a partial solar eclipse is because the observer falls in the penumbra of the Moon and sees part of the Sun obscured by the Moon's shadow while the rest continues to shine. The Sun and the Moon are only partially coincident, and the size of the eclipse is measured by the apparent distance between their centers (the maximum diameter of the Sun obscured by the Moon).

1.2.3. Annular Solar Eclipse. When the Moon is at apogee, the Moon's shadow cone cannot reach the Earth; instead, it is extended by the shadow cone out of the pseudo-shadow cone. The apparent diameter of the Moon at this time is slightly smaller than that of the Sun. Therefore, the ball of light at the edge of the Sun is still visible, forming a bright ring around the Moon's shadow.

Total annular eclipse occurs only when the Earth's surface is very close to the tip of the lunar umbra, or when the distance between the Moon and the Earth's surface is very close to the length of the lunar umbra [4]. Because the Earth is a sphere, and the umbra of the umbra is in total solar eclipse when it touches the Earth (usually in the middle of the eclipse band), the shadow cones at the two ends of the eclipse band fail to touch the Earth, so only a pseudo-umbra can reach below the Earth, and what is seen is an annular solar eclipse.

| Lunar phase | Waxing | Waning | 3rd | Waning | New | Waxing | 1st | Waxing |
|-------------|--------|--------|-----|--------|-----|--------|-----|--------|
|             | moon   | gibbous| quarter | crescent | moon | crescent | quarter | gibbous |
| DFM         | 28, 29, 2, 3, 6, 7, 9, 10, 13, 14, 17, 18, 21, 22, 24, 25, 0, 1 4, 5, 8, 11, 12, 15, 16, 19, 20, 23, 26, 27 |
| Rank        | 4 3 2 1 0 1 2 3 |

Figure 3. Illustration of each phase of solar eclipse.

1.2.4. Eclipse of the Moon. A lunar eclipse is a special astronomical phenomenon that occurs when the Moon orbits to the shadowed part of the Earth. It appears as a piece of the Moon is missing because
the Sun's light is blocked by the Earth. At this point the Sun, Earth, and Moon are exactly (or almost) in the same line. Lunar eclipses can be divided into three types: partial, total, and penumbral eclipses.

1.3. Resource Energy
The Moon is rich in mineral deposits and has more reserves of rare metals than the Earth. There are three main types of rocks on the Moon: (1) lunar sea basalt rich in iron and titanium, (2) oblique feldspar, rich in potassium, rare earths and phosphorus, mainly distributed in the lunar highlands, and (3) conglomerate composed of 0.1-1 mm of rock particles [5]. Lunar rocks contain all the elements of the earth and about 60 kinds of minerals, six of which are not found on earth.

The lunar soil is also rich in helium 3. The uses of deuterium and helium 3 for helium fusion can be used as energy for nuclear power plants. Such fusion does not produce neutrons, which are safe and non-polluting and easy to control. Nuclear fusion therefore not only useful for ground nuclear power plants but also particularly suitable for space travel.

The content of helium 3 in the lunar soil is estimated to be 715,000 tons. For every ton of helium 3 extracted from the lunar soil, 6300 tons of hydrogen, 70 tons of nitrogen and 1600 tons of carbon can be obtained. Based on the information we have on the Moon, due to the large amount of helium 3 contained in the moon, the possibility of an energy-scarce Earth in the future is slim to none. Many space powers have made the acquisition of helium 3 as one of the important goals for the development of the moon.

Table 1. Estimated Composition of Crust and Mantle.
Credit: lsintspl3.wgbh.org

| Element  | Earth (%) | Moon (%) |
|----------|-----------|----------|
| Oxygen   | 45.2      | 44.7     |
| Silicon  | 22.1      | 22.5     |
| Magnesium| 21.9      | 20.3     |
| Iron     | 6.0       | 8.2      |
| Calcium  | 2.3       | 2.0      |
| Aluminum | 2.1       | 1.9      |
2. Lunar Programs

In recent decades, there have been continuous efforts to explore the Moon. In fact, mankind has been trying to explore the moon since very early times, and the first person to try to land on the moon with a flying rocket was Wando of the Song Dynasty, who created his own flying rocket by strapping 47 homemade rockets to a chair and sitting on it himself, holding a large kite in both hands. Imagine using the rocket's thrust to fly up into the sky, and then using the kite to land smoothly. Unfortunately, the rocket explodes, and Manto gave his life for it. Either way, this is a reflection of man's desire to explore the moon within.

2.1. Apollo Program

The Apobaylo manned lunar landing project began in May 1961 and the first lunar landing was expected to take place between 20 and 21 July 1969. Since then, the United States has launched the "Ado-Polo" spacecraft six times, five of which were successful, with a total of 12 astronauts on the moon [6]. The entire project lasted about 11 years, ending in December 1972, costing $25.5 billion. At the peak of the project, there were 20,000 enterprises, more than 200 universities and more than 80 scientific research institutions participating in the project, the total number of more than 300,000 people. It is one of the most ambitious human projects of this century.

The first step of the project was to determine the lunar landing program, which included demonstrating the lunar flight trajectory and determining the general layout of the manned spacecraft. Finally, the lunar orbital rendezvous program was selected, and accordingly the general layout of the spacecraft, consisting of the command module, the service module and the lunar module, was determined. The development of the Apollo spacecraft is the most important part of the project. The command module is the place where the astronauts live and work, as well as the control center of the whole spacecraft; the service module is equipped with the main engine and other systems; the lunar module consists of descending stage and ascending stage.

For the purpose of manned lunar landings, the United States first implemented four auxiliary programmes for various purposes: (1) the launch of nine lunar orbiters, from 1961 to 1965, to learn about the possibility of future Apollo landings on the lunar surface, (2) the launch of the Apollo missions, from 1966 to 1965, to learn about the possibility of future Apollo landings on the lunar surface, (3) the launch of five Prospector lunar landers in 1968 to learn about the physical and chemical properties of lunar soil and (4) the launch of three Lunar Orbital Collimators in 1966-1967 to make detailed observations of more than 40 pre-selected landing sites, which lead to the selection of 10 sites. In addition, 10 Gemini spacecraft were launched for biomedical research and training in spacecraft maneuvers, docking and extravehicular activities in 1966 to 1967.

"The third aspect of the Apollo project was the development of the Saturn V launch vehicle with a low orbital carrying capacity of 127 tons and a high thrust." The first manned lunar landing was accomplished by the Apollo 11 spacecraft [7]. When the spacecraft separated from the third stage of the Saturn 5 rocket with three astronauts on board and the Apollo 11 lunar module spacecraft flew along the transition orbit for 2.5 days, it began to approach the Moon, at which time the main engine of the spacecraft's service module slowed down, putting the spacecraft into a circumlunar orbit. Then, two astronauts entered the lunar module and drove the lunar module separated from the spacecraft, at this time the spacecraft command module of an astronaut continued to drive the spacecraft around the moon orbit, while the other two astronauts took the lunar module landing on the surface of the moon. After the lunar landing, the astronauts collected rock and soil (22 kg), deployed the solar array, installed the lunar seismometer, etc. After the mission was completed, they returned to lunar orbit on the upper stage of the LEM, docked with the spacecraft, and finally returned to Earth.

From November 1969 to December 1972, the United States launched six spacecrafts- the Apollo 12-17- one after another. Except for Apollo 13, the other five spacecraft were successfully landed on the moon. The astronauts of Apollo 15 to 17 also drove the lunar rover on the lunar surface to collect rocks.
2.2. Chang’E Program
China's lunar exploration project, also known as the "Chang’E Project", first started in 2004. The Chang’E project is divided into three stages: unmanned lunar exploration, manned lunar landing and establishment of a lunar base. At 18:05 on October 24, 2007, "Chang’E-1" was successfully launched into the sky. After the successful completion of various missions, a scheduled plan for a controlled collision with the moon was made in 2009. In 2010, "Chang’E-2" launched successfully, exceeding the completion of the various established mission. Later, after leaving the Larangiri point L2 point in 2012, “Chang’E-2” moved toward deep space delving into development of deep space communication system. One year after, the lunar exploration project conducted the Chang’E 3 satellite and Yutu lunar rover lunar surface survey mission. And Chang’E 4 is the backup star for Chang’E 3. The main scientific objectives of Chang’E-5 included on-site investigation and analysis of the landing zone, as well as analysis and research after the return of lunar samples to Earth.[8] The logo of this project abstractly outlines a round moon with Chinese calligraphy strokes, a pair of footprints on it, symbolizing the ultimate dream of lunar exploration. The starting point of the arc naturally forms a
dragon head symbolizing China's space like a giant dragon soaring into the sky, and the ending stroke of the flying white consisting of a flock of peaceful doves expresses China's good wishes for the peaceful use of space. Pei Zhaoyu, the deputy director of the lunar exploration project and the official of the Defense Science and Industry Agency, said on December 2, 2014 that the lunar exploration project phase three- re-entry of flight test vehicle at the scheduled landing site was a complete success.

![Chang'e 5](image)

Figure 6. Image of Chang'E probe. Credit: Spaceflight 101.

3. The Origin of the Moon
Research on the formation of the Moon has been conducted extensively. The hypothesis about the origin of the Moon can be broadly categorized into four types of resonance tide (1) the Fission theory, (2) the Co-accretion theory, (3) the capture theory and (4) the impact causation theory [9].

3.1. Fission theory
The Moon split from the Earth. Scientists who adhere to this hypothesis believe that in the early days of Earth's formation, when the Earth was in a molten state and its rotation was unstable due to tidal resonance. With the tidal impact of the Sun, the period of Earth's rotation could be shortened to 2 hours even considering only the angular momentum of the Earth and the Moon [10], the period of Earth's rotation was only 4 hours. Therefore, it is reasonable to believe that early in Earth's history, the Earth spun so fast that its rotation rate was so much higher than at present. Supporters of this theory believe that if the Earth had been in a molten state in the early period, an expansion zone would have appeared on the equatorial plane of the Earth causing a part of the molten material on the equatorial plane to separate and this part of the molten material would have been thrown out of the equatorial zone by the high-speed rotation of the Earth, condensed in the interplanetary space near the Earth and further forming the Moon after condensation. People who hold this hypothesis also believe that the Pacific Ocean on Earth is the "scar" left by the splitting of the Moon. Since this hypothesis proposes that the Moon was separated from the Earth, it appears be similar to "mother-daughter theory"[11]. However, due to the large age difference between the Earth and the Moon -- the Moon may even be the same age as the universe -- and the different geology of the Earth and the Moon, it has now been rejected by most scientists.
3.2. Co-accretion theory

Scientists who advocate this hypothesis believe that in primitive solar nebulae, temperature and chemical composition depend on the distance from the Sun. The planets of the solar system were formed in different regions of the nebula by the condensation and accretion of nebulosity with different chemical compositions. The Moon and the Earth are close to each other in the solar nebula, with similar formation processes, and are "brothers" that formed at the same time. The differences between the composition of the Earth and the Moon help explain that the formation of planets began with the coalescence, accretion and formation of iron [12], the main component of the planetary nucleus. After the further growth of the metal nucleus, the remaining non-metallic materials in the nebula before coalescence started to form. The homology theory attempts to explain the difference between the composition of the Earth and the Moon and the composition of the Moon's nucleus, mantle and shell. However, findings have shown that the hypothesis does not match the coalescence process of the solar nebula and the motion characteristics of the Earth-Moon system. Therefore, this hypothesis is also unsatisfactory.

3.3. Capture Theory

Scientists who advocate the capture theory believe that the Earth and the Moon are in different parts of the solar nebula and were formed by the condensation of nebular material with different chemical compositions. The original orbital plane angle of the Moon and the Earth is very small (about 5 degrees) such that when the Moon orbits near the Earth (within the Earth-Moon distance of 10 Earth radius), the Moon may be captured by the Earth and become a satellite of the Earth [13].

The famous astronomer Alphen believes that the Moon was once an independent planet and that when it was captured by the Earth, the Moon was about 26 Earth radii away from the Earth and had a 149-degree angle of intersection with the plane of the Earth. If the Moon had entered the Earth's Losh limit, the tides would have created a strong non-uniform gravitational field and the rocks on the Moon's surface would have broken up and entered the orbital space where the Moon orbited. Also, the bulk of the debris material would have returned to the Moon and struck the Moon creating a large lunar sea basin on the surface of the Moon. 3.9 billion years ago, the Rain Sea event (the Moon's frontal excavation of the lunar sea) may be important evidence for the capturing theory. Fine calculations of the Earth-Moon orbit and data from laser ranging indicate that the Moon's present-day orbit is moving further and further away from the Earth, retreating by about 3.8 centimeters per year. However, the capturing theory can only explain part of the observed facts, which is unsatisfactory. As a result, new hypotheses are constantly being put forward.

3.4. Giant-Impact theory

According to the impact causation theory, in the early stages of the formation of the solar system, there were a large number of nebulae in interplanetary space, and these nebulae grew in size through collision and accretion. Around the space where the Earth-Moon system existed, a "proto-Earth" with a mass equivalent to 9/10 of the present mass of the Earth and another Mars-sized object, the "proto-Lunar", were formed [14]. In the course of their respective evolution, these two objects formed a metallic nucleus dominated by iron and a mantle and shell composed of silicates. Since these two objects were not far apart, there is a chance that they would have collided. The violent collision not only deflected the rotation of the "proto-Earth", but also caused the "proto-Moon" to break up, the mantle and shell to heat up and evaporate, and the expanding gas to "trap" dust and small amounts of mantle and shell. Also, Matter flew off the proto-Earth moon. The separated metal nuclei, decelerated by the obstruction of expanding gases, were absorbed by the "proto-Earth" and became part of the Earth. Since the late 1960s and early 1970s, around when American astronauts brought back samples of moon rocks from the Apollo missions to the Moon, planetary scientists put tremendous efforts in examining and studying these samples. It is surprising how similar moon rocks are to rocks found deep in the Earth's outermost regions. As more scientists took a closer look at the moon rocks, the question of lunar origins became even more suspenseful, and scientists discovered that the rocks deep
within the Moon are still very different from those found deep within the Earth. Most importantly, the isotopes found in moon rocks did not match those found in rocks on Earth [15] [16].

Some scientists speculate that a planet the size of Mars struck Earth early in the Earth's history, causing debris that later gathered to form the Moon. If that were the case, the Moon would have a lower iron content than Earth, and a higher content of lighter elements such as magnesium and aluminum.

4. Summary and Future Works
In this article, the basic introduction to the moon extends from the development of human exploration to a detailed explanation of the pros and cons of each formative theory. Based on the analysis and comparison, several points can be made.

In the solar system, we divide natural satellites into moons of Earth-like planets and moons of wood-like planets. We first compares the moon of the Earth with the moons of Jupiter, an Earth-like planetary structure that is primarily a metal center of iron surrounded by a silicate mantle. Gas giants, on the other hand, are planets or giants outside of Jupiter, large planets that are not composed primarily of rock or other solids. Jupiter and Saturn are huge and massive, but less dense and composed mainly of light elements such as hydrogen, helium, and neon. So, it is quite possible that the moons of the two planets were formed for different reasons.

Most of the previous work has focused on dynamical simulations by varying various collision conditions to cater for the mass ratio, angular momentum, tilt angle, etc. of the two after the collision, while little has been done to limit the chemical similarities and differences of the Earth-Moon system to limit the collision conditions.

The age of the Earth's moon has been determined by the dynamics of the collision. Dynamical simulations of collisions show that both early and late impact models are theoretically capable of forming the current Earth-Moon system. The collision model can also be constrained if further precise data on the age of formation of the Earth-moon system can be derived.

Conflict of Interest
The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

References
[1] Lowrie, William (1997). Fundamentals of Geophysics. Cambridge: Cambridge University Press. p. 5.
[2] Stuart Ross Taylor (1979). Structure and evolution of the Moon. Nature.
[3] Taylor, L. A. (1992). Resources for a lunar base: Rocks, minerals, and soil of the Moon. In NASA. Johnson Space Center, The Second Conference on Lunar Bases and Space Activities of the 21st Century, Volume 2 p 361-377 (SEE N93-13972 03-91)
[4] Richard Pogge (2010). An Introduction to Solar System Astronomy.
[5] Randy L. Korotev (2020). How Do We Know That It’s a Rock from the Moon? Washington University in St. Louis
[6] Flint Wild (2019). What Was the Apollo Program? NASA.
[7] Nadia Drake and Jenny Howard (2020). A brief history of moon exploration. National Geographic.
[8] (2019) “Chang’e-4 finds moon's far side colder than expected during night,” XinhuaNet
[9] Kristen Bobst (2017). 4 Theories About How the Moon Formed. Treehugger.
[10] Wiechert, U.; Halliday, A. N.; Lee, D.-C.; Snyder, G. A.; Taylor, L. A.; Rumble, D. (2001). "Oxygen Isotopes and the Moon-Forming Giant Impact". Science.
[11] Jewitt, David; Haghighipour, Nader (2007), "Irregular Satellites of the Planets: Products of Capture in the Early Solar System", Annual Review of Astronomy and Astrophysics
[12] Stephen Himson, Co-Accretion Theory. How the moon formed.
[13] Katie Silver (2015). Where did the Moon come from? BBC
[14] Robin M. Canup (2019). Giant Impact Hypothesis: An evolving legacy of Apollo. Astronomy.com
[15] Kerry Lotzof. How did the Moon formed. SPACE.
[16] Xu Yingkui, Zhudan, Wang Shijie, Liu yun (2012). Recent Advances of Lunar Formation Theories. Bulletin of Mineralogy, Petrology and Geochemistry.