

CONTENTS

Introduction	Page 2
Figure 1 – Picture of Apollo Moon landing	
The Moon's Structure	3
Figure 2 – Picture of internal structure	
Figure 3 – The distinction between terrain types	
Figure 4 – Table of Moon facts	
Theories of Origin	5
Evolution of the Moon	9
Conclusion	10
References	11

INTRODUCTION

Human beings have wondered about the Universe since the beginning of civilization. It is such a vast place, yet much about our own solar system and closest neighbours still remains a mystery. Learning how the solar system formed and evolved is critical to our understanding of how typical the Earth is in terms of planetary systems. The study of our moon, from its origin and evolution to the many effects that it has on the Earth is important in learning about the history of our planet and even its possible future. The Moon is also able to provide evidence about the early history of the Solar System, which is not available on Earth.

The gravitational forces between the Earth and Moon cause some huge effects, with the most obvious being the tides. The force of gravity from the Moon causes the Earth to be slightly stretched out along the line towards the Moon. The effect is seen particularly clearly with the oceans. As the Earth rotates, the bulges move, creating high and low tides. Another interesting effect comes from the fact that the force between the Earth and Moon is not exactly along the line between their centres. This produces a net torque, and the Moon accelerates. The acceleration is not a change in speed however; it is a change in direction causing the Moon to move in an increasing orbit at a rate of about 3.8 centimetres per year. Interestingly, the opposite effect happens with the satellites of some of the other planets. Due to the conservation of angular momentum, the acceleration has an effect on the Earth and its rotational period is increased. This effect is too small to be noticeable, although eventually the Earth's rotation will be slowed to match the Moon's period.

The Moon has been studied for many centuries from the ancient civilizations of the Romans, Greeks and Egyptians who worshipped the Sun, Moon and planets, believing they were gods or the home of gods. The Greeks were probably the first culture to study the Moon scientifically and by looking up at it with the naked eye they were able to identify two types of terrain, which they believed to be seas and land (or maria and terrae as they are now known in Latin). Amazingly in the third-century B.C. astronomer Aristarchus made an estimate of the distance to the Moon that is remarkably accurate considering their lack of technology. It wasn't until 1610 when Galileo used his telescope to view it, uncovering the true nature of its maria and terrae, showing that it is a rocky body that the modern search for answers began. Recent technological advances have made it possible to study the Moon closer than ever before. The Soviet spacecraft Luna 2 was the first visitor to the Moon. It flew by the Moon in 1959 and was able to photograph it from all sides providing information about the side of it that is not visible from Earth. Then in 1969 came the first manned landing with subsequent Apollo and Luna missions to carry out detailed experiments. Nuclear powered seismic stations were installed in order to collect data about the interior of the satellite. Crashing lunar modules into the Moon would simulate results from the impacts of meteors. The most detailed knowledge, however, comes from the samples of rock and soil collected on the missions from different regions of the Moon. In more recent years spacecraft have been able to extensively map its surface and structure. Details of the composition and age of the samples, along with seismic data has been revolutionary in influencing the current theories about the formation and evolution of the Moon.

This dissertation will discuss some of the past and present theories of the origin of our moon and the possible evolution into its current state, looking at the evidence of its structure and composition from experiments and results from modern studies.

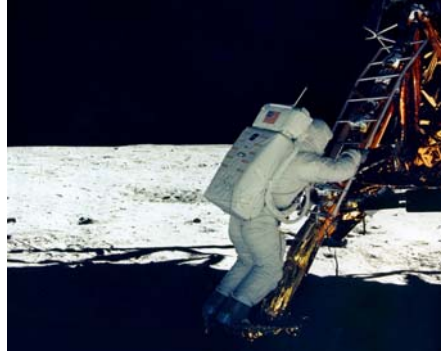


Figure 1: Picture of the Apollo 11 landing on the Moon

THE MOON'S STRUCTURE

The Moon has been known since prehistoric times. It is the closest object to the Earth and our only natural satellite. It is the second brightest object in the sky after the Sun, although it does not emit any light of its own, it is simply illuminated by the Sun's light. The Moon orbits the Earth approximately once per month, but as the angle between the Earth, Moon and Sun changes, we see different phases. A full cycle of phases takes 29.5 days, which is slightly different from its orbital period due to the movement of the Earth around the Sun. We actually only ever see one side of the Moon because its rotation and revolution around the Earth take the same length of time. This is defined as a synchronous rotation and is caused by an unsymmetrical distribution of mass. In fact the centre of mass of the Moon is 2 kilometres off centre, towards the Earth.

There is no atmosphere on the Moon, so the lunar sky is always black because the diffraction of light required a medium to travel through. There are also no vast amounts of water, although evidence from recent moon mapping missions suggests that there may be small amounts of ice trapped in the craters at the poles. Experiments carried out on the Moon and studies of the samples show that most of the rocks on the surface are between 3 and 4.6 billion years old. Its crust varies from a thickness of 0-107km with an average depth of 68 kilometres. Seismic studies suggest a layered structure with a mantle below the crust, and although no there is no evidence for an iron-rich core, it is probable that there is a very small one of about 2% of the Moon's mass.

By observing the Moon it is possible to see three types of surface material. The regolith is a fine-grained debris, or lunar soil. It is a mixture of dust and rock fragments produced by meteor impacts that have been welded to form impact-generated glass. It covers most of the Moons surface, with the exception of steep crater and valley walls and varies in thickness from 2-15 metres. The dark, smooth regions, visible from Earth are called maria and cover about 16 percent of the lunar surface, mainly on the nearside. They are huge impact craters, which were later flooded by molten lava. The location of

the maria can be explained by the Moon's offset centre of mass and by the fact that the crust is thicker on the far side. This means that the basalt magma from the interior was able to reach the surface more easily on the side facing Earth. These areas are on average only a few hundred metres deep, but are so massive that they deformed the crust beneath them causing huge depressions and raised ridges. The brighter, heavier, cratered highlands are called terrae. The fact that these regions have accumulated more craters from meteorite impacts show that they are older than the maria. The rocks in these regions contain high contents of minerals rich in calcium and aluminium. Nearly all the samples analysed from this region date from 3.8-4.6 billion years ago, which is the estimated time of the Moon's origin.

The figure below shows the distinction between the maria and terrae regions.

Figure 1:

The lack of water or atmosphere on the Moon means that there is no weathering of soils, so rocks from more than 4 billion years ago are still able to exist there. Also, the fact that there is no global magnetic field (although some of the surface rocks exhibit magnetism, indicating there may have been one at some stage), or significant tectonic activity of the Moon's interior mean that it is considered to be geologically dead. Figure 2 below shows some more statistics for the Moon:

CHARACTERISTIC	MEASUREMENT
Mass (kg)	7.35×10^{22}
Radius (km)	1737
Mean density (g/cm^3)	3.34
Mean distance from Earth (km)	384400
Rotational period (days)	27.3
Orbital period (days)	27.3
Equatorial surface gravity (m/s^2)	1.62
Mean surface temperature – day ($^{\circ}\text{C}$)	107
Mean surface temperature – night ($^{\circ}\text{C}$)	-153

Figure 2: Some statistics for the Moon (Adapted from source 4)

THEORIES OF ORIGIN

Before the modern age of space exploration, scientists had great trouble accounting for the origin of the Moon. Many theories have existed in the past from ancient beliefs to more modern scientific hypotheses, but although space exploration has been revolutionary in solving some of the Moon's mysteries, no absolutely conclusive evidence has been found for its origin.

Thousands of years ago, the Egyptian astronomers tried to make sense of the Solar System and universe as a whole. They came up with a theory for the Earth-Moon system and as a result worshipped their planet and its satellite. They believed that the Earth was egg shaped because of the curved horizon line visible from their isolated, flat country and if they walked far enough they would fall off. They also believed that inside their egg-shaped world was a baby bird, and the Moon was therefore the birds mother! This theory is of course ridiculous, but the Egyptians used the knowledge that they had at the time, and came up with what they thought was a reasonable explanation. The Moon theories have come a long way over the last couple of centuries, and up until recently three main ideas existed to try and explain the origin of the Earth's closest companion. These theories will be outlined below:

1. 1. Fission Theory

Astronomer George Darwin, who was also the son of Charles Darwin, invented this theory. He proposed that in an early stage of the Earth's evolution the planet rotated so rapidly that a chunk broke off and was thrown into orbit. This fission idea was thought to be a good theory partly because the density of the Moon is the same as that of the rocks just below the Earth's crust (or the upper mantle). It was thought that a rapidly spinning planet would be able to split due to the solar tides, forming two parts, and in this case the Pacific Ocean was the probable scar. The theory could also be modified to account for the possibility that the Earth had been in a molten state at the time.

A difficulty arises, however, when the dynamics of the situation are considered. The original single planet would have had to rotate so fast to fission into two pieces, so in order to achieve rotational instability the angular momentum would have to be much greater than that of the present Earth-Moon system. The law of conservation of angular momentum does not allow this. Also it is thought that the Moon is too chemically different from the Earth. Finally, it is thought that the escaping Moon would have been shattered while within the Roche limit. Roche limit is defined as 'the maximum orbital radius for which tidal disruption occurs' (source 2). This theory is universally discarded today.

2. 2. Capture Theory

This early theory suggests that the Moon was once an independent planet, which formed elsewhere in the Solar System, far from Earth and where there was little iron. The orbits of the Earth and Moon carried them near each other so that the Moon was captured into a permanent orbit about the Earth by its gravitational field.

This theory posed both dynamical and composition problems, however. Firstly, rock samples collected from the Apollo and Luna missions showed that although Capture theory explained why the Moon has little iron content, it could not disguise the fact some of the samples showed the same isotope composition as the Earth. This would suggest that the Moon would have to have formed somewhere near the Earth. Secondly, by studying the dynamics of the two bodies it was discovered that for one approaching body to enter into orbit around another, it would need to lose a lot of energy, otherwise the approaching planet would simply be slingshot around the second planet, rather than

captured by it. Even a successful capture would have resulted in an elongated comet-like orbit. Although this theory has also been discarded, some of the issues that arose with the dynamics have provided many good tools, which are utilised in space travel today. For instance the Voyager probes exploited the slingshot phenomenon, allowing the spacecraft to travel past most of the nine planets, photographing them along the way. This effect also explains why spacecraft sent to orbit a planet are designed with retro-rockets.

3. 3. Condensation/Co-creation Theory

Another early theory assumes that the Moon and Earth formed near each other and at the same time. It was proposed that all objects in the Solar System condensed independently out of the huge cloud of cold gases and solid particles that constituted the solar nebula in its early stages of evolution. Most of the material collected at the centre to form the Sun, while the Earth and Moon were a double planet system, with the Moon forming from a ring of material that was orbiting around where the Earth was evolving.

This theory broke down because it failed to explain the composition of the Moon. If the two objects formed in the same place at the same time, why does the Moon lack iron compared to the Earth? It is also very unlikely that the gravitational attraction could have been strong enough to pull together all the material orbiting the Earth.

The aim of the Apollo missions was to gather information, samples and evidence from the Moon in order to shed light on its structure, composition and origin. Scientists were expecting the experiments that they carried out to support one of the three theories above, but to their surprise, the study of the moon rock samples and close-up pictures did show much evidence to fit any of their theories. Then in 1975 a new theory was proposed, which supports a lot of the evidence obtained so far, and it is widely accepted (although still not absolutely conclusive) today.

4. 4. Giant Impact Theory

This theory is a more modern version of the fission idea and proposes that early in the Earth's history, about 50 million years after the start of the Solar System, other small planetesimals were also forming. A roughly Mars-sized planetesimal then collided with the Earth late in its growth process, and the catastrophic impact blasted portions of the Earth's mantle and other rocky debris out into orbit around our planet. While the core of the original body proceeded into the Earth and merged with its existing core, the small percentage of ejected material coalesced to form the Moon. This hypothesis is consistent with the ideas about how the planets were assembled, and can explain some of the features of the current Earth-Moon system. It is thought that in the early stages of the Solar System, as the larger objects were forming (or the planets as they are today) there would have been several smaller bodies, up to half the size of the planet, around the general vicinity of them. This made the probability of collisions quite large. In the Earth's case the collision is thought to have happened late enough, and in such a direction relative to the Earth's rotation, that enough material was thrown out to make a Moon. A slight variation on the idea is the Impact-triggered Fission hypothesis, which suggests

that the Moon was formed from the debris of multiple impacts of smaller planetesimals, although it is generally accepted that the single collision is the more likely event.

There are a number of factors, which suggest it is a good theory, such as the fact that it can explain why the Moon lacks a substantial iron core. Also it is known that the Moon is less dense than the Earth, at a value roughly the same as the material in Earth's mantle, as suggested by Giant Impact theory. Evidence that shows exactly the same oxygen isotope composition for the Moon and Earth, (but not any of the other planets) can only support the hypothesis, and it also offers a reason for the scenario leading to a Moon as unique as ours.

Since the idea was first presented, many studies and simulations have been carried out to find out the plausibility of the event, and possible scenarios. The isotopic composition of several of the elements in the lunar rock samples indicate that the Moon was actually derived from the Earth itself, with the colliding body having a similar composition. Other samples also indicate that the Moon formed relatively late compared to the Earth and Solar System. In order to narrow down the choice of different collision scenarios and the early Earth-Moon evolution, many complicated computer simulations have been, and are still today being carried out using different sets of initial conditions so that some insight into the details of the collision can be found. Simulations of angular momentum have suggested that for the current state of the Earth and Moon, the initial impacting body would have needed to have a mass roughly that of Mars. It is also indicated that the impacting body would have been in an orbit similar to that of the current Earth.

There are still a few problems with the theory though because the computers can only provide very simplified models of what went on before the Moon's formation, and while some simulations have shown very reasonable results, others have not been quite so successful. Some of the studies show that rather than debris going into orbit, it may actually rain back down onto Earth. In this situation the impacting object would need to be much bigger, which causes a problem with the angular momentum of the system. Results also require that the Earth was molten throughout following the impact, but there is no evidence from studies of geochemistry to suggest this was the case.

EVOLUTION OF THE MOON

From its initial formation about 4.6 billion years ago, to present day, the Moon has gone through a number of stages in its evolution. These stages are discussed below along with some of the evidence obtained from lunar exploration.

1. Pre-Imbrian Period

It is generally accepted that the formation of the Moon occurred 4.6 billion years ago. It would have been formed in very hot conditions, and was possibly entirely molten, which is consistent with the idea that an ocean of magma surrounded the Moon when it formed. Melting and separation of the crust produced the lunar highlands, which today contain some of the oldest rock samples. As the molten rocks cooled down, they crystallised and rose to the surface, as they were the least dense of the materials. Although most of the

original crust has been destroyed by bombardment and cratering, some of the samples from these highland regions have been radioactive dated at around 4.5-4.6 billion years, showing that the Moon is only just younger than the Earth itself.

2. Cataclysmic Bombardment

The Moon was heavily bombarded in its early history, between 4.5 – 3.8 billion years ago. These impacts caused many of the original rocks of the ancient crust to be scrambled, melted and buried, allowing magma oceans to be formed and maintained. Rocks with different compositions (from the impacting bodies) were added to the surface and interior of the Moon, which can explain why samples from only a few locations can provide many different rock types for study.

3. Imbrian Period

The underlying crust of the large impact craters or maria regions thinned and cracked due to the heavy bombardment, allowing molten basalt from the Moon's interior to reach the surface and flood the basins. This occurred in successive stages, between 3.9 – 3.2 billion years ago, forming layers of more material and leaving the maria regions looking smooth and flat, much as they do today.

4. Eratosthenian Period

The lava-flooding period finished rather abruptly, restricting the formation of craters. Although volcanism continued between 3.2 – 1 billion years ago, with minor eruptions and the continued formation of the regolith, nothing much else happened in terms of the evolution of the Moon, apart from the occasional impacting meteorites.

5. Copernician Period

The Moon's recent history, over the last billion years has been extremely quiet and still for both meteoric and volcanic activity. It continues to expose its stony face to cosmic weather and has accumulated a few new scars in this period, as some of the craters have been dated back less than 1 billion years, but this has occurred at a diminishing rate. With such a violent and active early history, with the heavy bombardment period ending abruptly, the Moon still shows evidence of all these stages and is considered to be fossilised in time.

CONCLUSION

Since space travel and the lunar missions in the fifties and sixties, the understanding of our Moon and Solar System has come a long way. The pictures taken, models used and samples collected have given scientists a great insight into the structure of the Moon, providing them with a great deal of evidence for the stages of the Moon's life and

evolution. It has not been quite so simple to account for the Moon's origin on the other hand.

After the Moon landings, scientists expected to find conclusive evidence pointing to one of their three existing theories. These were Fission theory Capture theory and Condensation theory. However, the many studies that were carried out did not make the picture quite as clear as they were expecting. Although each of the hypotheses had a number of good points supported by the evidence, they all had insoluble flaws involving the composition of the Moon and its dynamics. These problems lead planetary scientists to rethink their theories, and they arrived at the Giant Impact theory. It explains a lot about the Earth and Moon, and accounts for the evidence of structure, angular momentum and the Moon's evolution process. But in spite of the support this idea receives, there are still a few problems that need to be ironed out and it is by no means conclusive.

The last few decades have bought us closer than ever to understanding our planet and its neighbours, but it will be a hard task to resolve the uncertainties of the origin of Earth's satellite, as the Moon has existed for all of human history, so the only way to ever truly know what happened over four billion years ago is to speculate and create models and theories based on all the evidence available at the time.

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