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1. General characteristics of the Moon and features of its internal structure

Introduction

The Moon, Earth's only natural satellite. It is the closest large celestial body to us and one of the most studied objects in the Solar System. Its proximity and lack of a dense atmosphere make it a unique natural laboratory for studying the processes that shaped the terrestrial planets [17] billion years ago. Unlike the geologically active Earth, where plate tectonics [25], erosion, and the biosphere [4, 8] are constantly changing the landscape, the Moon's surface has preserved evidence of its turbulent youth, including traces of intense meteorite bombardment [22] and large-scale volcanism. Studying the Moon, from its general physical parameters to the details of its internal structure and volcanic evolution, allows us not only to reconstruct its own history, but also to shed light on the early stages of the development of the Earth and other planets. Let us dwell on a detailed overview of current knowledge about the Moon, covering its astronomical and physical characteristics, a model of its internal structure, major landforms, evidence, and features of past volcanic activity, its influence on the formation of the lunar surface, and the current geological state of the satellite.

1.1. General characteristics of the Moon

The Moon differs significantly from the Earth in its physical and orbital parameters, which determines its unique properties and appearance.

Astronomical and physical parameters. The Moon has an average radius of 1737.1 km, which is about 27% of the Earth's radius. Its diameter (about 3475 km) is about four times smaller than that of the Earth. [17] The Moon's total surface area is about 38 million square kilometers. Although the Moon is much smaller than the Earth, it is an unusually large satellite relative to the size of its parent planet. This ratio (about 1/4 the diameter) is much larger than that of most other satellite systems in the Solar System, resulting in strong gravitational interactions between the Earth and the Moon. The Moon's mass is estimated to be 7.3477×10^{22} kg, which is only about 1.2% (or 1/81) of the Earth's mass.

The Moon's average density is 3.346 g/cm³, which is much less than the average density of the Earth (about 5.51 g/cm³). This relatively low density indicates a lower iron content and a smaller metallic core compared to Earth. This fact is one of the key arguments in favor of the giant impact theory, according to which the Moon formed mainly from lighter, mantle materials of the proto-Earth and the impactor, while the heavy iron core of the impactor was mostly incorporated into the Earth's core [18].

The acceleration of gravity on the Moon's surface is about 1.62 m/s², which is about six times less than on Earth. This means that objects on the Moon weigh six times less. The second cosmic velocity (the speed required to overcome gravitational attraction) is 2.38 km/s. Low gravity significantly affects geological processes on the satellite: emissions from meteorite impacts are scattered over much greater distances, and volcanic structures have a different morphology. Also, weak gravity is unable to maintain a dense atmosphere.

The Moon has a very low reflectivity. Its Bond albedo is about 0.11, and its geometric albedo is about 0.12. This means that the lunar surface reflects only 11–12% of the sunlight that falls on it [3, 5, 6]. Despite this, the Moon is the brightest object in the night sky (after the Sun) due to its proximity to the Earth. The dark color of the regolith surface [11, 12] is the result of processes of space weathering - the long-term impact of the solar wind and micrometeorite bombardment on lunar rocks.

Due to the lack of an atmosphere to regulate temperature, the Moon experiences extreme temperature fluctuations. During the day at the equator, temperatures can reach +120°C to +130°C, while during the long lunar night it drops to -160°C or even -170°C. The average surface temperature is estimated to be approximately -20°C. Such extremes are a direct result of the Moon's lack of atmosphere [14] and its slow rotation on its axis.

Orbit and Rotation. The Moon orbits the Earth in an elliptical orbit. The average distance between the centers of the Earth and the Moon is 384,400 km. Due to the ellipticity of the orbit, this distance varies: at perigee (the point closest to Earth), it averages 363,300 km, and at apogee (the point furthest away), it averages 405,500 km.

The average eccentricity of the orbit is 0.0549. This change in distance causes variations in the apparent size of the Moon in the sky and is the main factor determining the tides on Earth.

The time it takes the Moon to complete a complete revolution around the Earth relative to distant stars is approximately 27.32 Earth days (27 days 7 hours 43 minutes).

The time between two identical phases of the Moon (for example, from full moon to full moon) is approximately 29.53 Earth days. This period is longer than the sidereal period, because during the Moon's rotation, the Earth also moves in its orbit around the Sun. A unique feature of the Moon is its synchronous rotation. The Moon's period of rotation around its axis is exactly equal to its sidereal period of rotation around the Earth (~27.32 days). As a result, the Moon always faces the Earth with the same hemisphere. This condition, known as tidal capture, is the result of tidal forces between the Earth and the Moon over billions of years, which have gradually slowed the Moon's axial rotation until it is fully synchronized with its orbital motion.

The Moon's orbit is inclined to the plane of the ecliptic (the plane of the Earth's orbit around the Sun) at an angle of approximately 5.145°. The inclination of the orbit to the plane of the Earth's equator varies from 18.28° to 28.58°. The Moon's axis of rotation is inclined to the plane of its orbit at an angle of 6.68°. The inclination of the orbit to the ecliptic is the reason why solar and lunar eclipses do not occur every month, but only when the Moon, in the new or full phase, crosses the plane of the ecliptic.

1.2. Comparing the characteristics of the Moon and Earth

A comparison of the basic characteristics of the Moon and Earth reveals both significant differences and certain similarities that reflect their common, yet unique, history. As can be seen from Table 1.1, the Moon is significantly smaller than the Earth in size, mass, and density. Its gravity is much weaker, which does not allow it to maintain a dense atmosphere. The absence of an atmosphere and a global magnetic field leads to extreme temperature changes on the surface and unprotected from cosmic radiation and meteorite impacts. Synchronous rotation is also a significant difference from the rapid rotation of the Earth. Despite the differences, both bodies have an almost spherical shape and a differentiated internal structure (crust, mantle, core).

Table 1.1.

Comparative characteristics of the Moon and Earth.

Characteristics	Moon	Earth	Ratio (Moon/Earth)
Average radius (km)	1 737.4	6 371.0	0.2727
Mass (10^{22} kg)	7.3477	597.24	0.0123
Average density (g/cm^3)	3.346	5.514	0.607
Surface gravity (m/s^2)	1.62	9.80	0.165
Second cosmic velocity (km/s)	2.38	11.2	0.213
Surface temperature (°C)	from -170 to +130	from -89 to +57 (average +15)	-
Albedo (Bond)	0.11	0.294	0.37
Atmosphere	Very thin exosphere (almost vacuum)	Dense (N_2, O_2, Ar...)	~10^{-14} Earth's pressure
Global magnetic field	None (weak local fields)	Present (dipole)	~0
Rotation	Synchronous (27.3 days)	23.9 hours	-

The isotopic composition of some elements (for example, oxygen) in lunar rocks is very similar to that of Earth, which supports the theory of their common origin as a result of a giant collision.

1.3. The internal structure of the Moon

The Moon, our closest cosmic neighbor and Earth’s only natural satellite. Current models of the Moon’s internal structure are based on data from the Apollo seismic experiments, measurements of the Moon’s gravitational field and laser ranging, and analysis of lunar samples. These data suggest that the Moon, like the Earth, is a differentiated celestial body consisting of geochemically distinct layers [17]: a crust, a mantle, and a core (Fig. 1.1). This structure likely formed as a result of the crystallization of a global magma ocean that existed early in the Moon's history. Its average density of 3346.4 kg/m^3 is significantly lower than that of Earth (5510 kg/m^3). This relatively low modern density is a key indicator of its unique composition and formation history, indicating a much lower iron content than Earth. This layered structure is thought to have resulted from fractional crystallization of a global magma ocean shortly after its formation approximately 4.5 billion years ago.

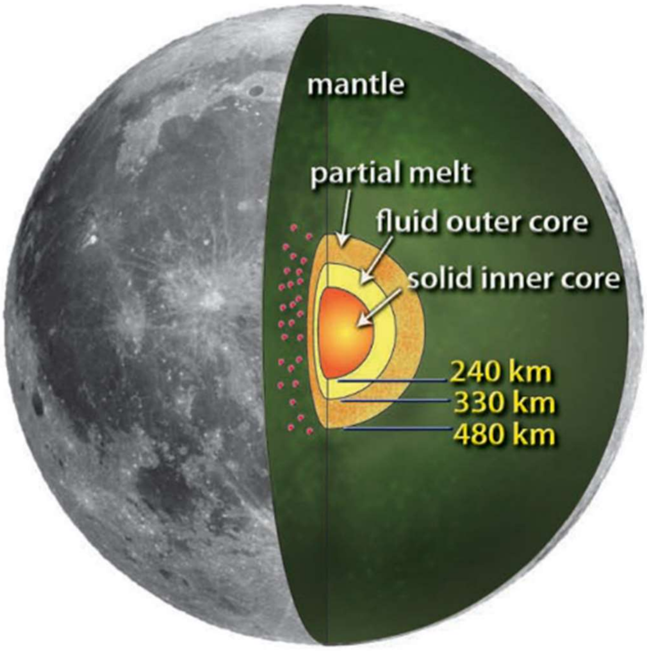

Fig. 1.1. The interior of the Moon, as observed by lunar earthquakes (red dots); a liquid iron core (yellow) and a solid iron inner core (orange) have been discovered there (https://www.science.org/do/10.1126/article.29453/full/sn-lunarcore-1644929015487.jpg).

Understanding of the Moon's interior has evolved significantly over many decades of research. The first direct data were obtained during the Apollo program with the deployment of seismometers on the lunar surface.These initial measurements laid the foundation for further, more detailed studies, which included gravity mapping from orbit by the Lunar Prospector and GRAIL missions, and analysis of lunar samples. Current models are the result of the integration and reanalysis of these diverse data sets [1]. The following is a detailed description of the physical characteristics of the Moon's interior, explains some of the methods by which these characteristics were obtained, and outlines the main current models of the interior.

1.4. Methods for studying the interior of the Moon

Our knowledge of what is inside the Moon is based not on direct observations, but on the interpretation of data obtained by several key methods.

a) ***Seismic studies***. The most direct data on the interior of the Moon have been obtained by seismic experiments during the "Apollo" program and by passive seismic experiments. For example, the Apollo program deployed four passive seismic experiments (PSEs) on the lunar surface at the landing sites of "Apollo 11, 12, 14, 15, and 16". The purpose of these experiments was to measure vibrations of the lunar surface, caused by both natural and artificial sources of seismic energy, in order to determine the internal structure and composition of the Moon.

The PSE instruments consisted of three long-period seismometers, aligned orthogonally to measure the vertical and two horizontal components of surface motion, and one short-period vertical seismometer. The "Apollo 11" seismometers operated only during lunar days due to their dependence on solar panels, while later, more advanced seismometers deployed by "Apollo 12 through 16" transmitted data until September 1977 and measured all three components of ground displacement. Radioisotope heaters were used to protect the instruments from the extreme temperatures of the lunar night. Thus, lunar seismology is the most powerful tool for studying the interior. The "Apollo" seismometer network operated from 1969 to 1977. The seismometers recorded several types of seismic events. Natural "moonquakes" were detected deep in the mantle, at depths of approximately 700-1100 km, and occurred with a monthly periodicity associated with tidal stresses from the Earth. A few weak moonquakes were also recorded at a depth of about 100 km. In addition, the instruments recorded impacts of meteoroids when they fell on the surface of the satellite (Fig. 1.2); these impacts could create quite powerful seismic vibrations. Artificial impacts, such as the fall of spent S-IVB rocket stages and lunar landing modules after missions, were used as calibration sources. The impact of the "Apollo 12" lunar module caused the Moon to vibrate for more than 55 minutes, and seismometers recorded signals that resonated for a long time. Spent "Saturn V" rocket stages and "Apollo" modules were also deliberately directed at the Moon to create seismic events with known coordinates and energies. Data collected by Apollo seismometers were used to study the propagation of seismic waves through the entire body of the Moon.

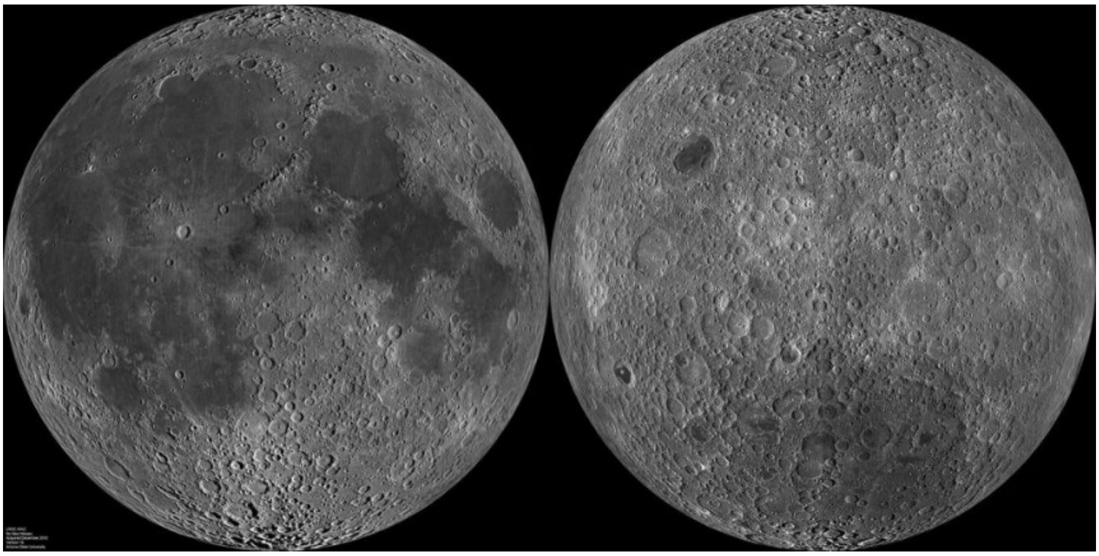

Fig. 1.2. Near and far hemispheres of the Moon (https://universemagazine.com/wp-content/uploads/2025/05/there-might-be-a-hot-s-1024x512.jpg).

By analyzing the arrival time and characteristics of P-waves (longitudinal) and S-waves (transverse), as well as their reflection and refraction, it was possible to determine the boundaries between the main layers of the Moon and the internal structure, density and physical state of individual layers of the Moon. The key is the fact that S-waves cannot propagate in liquids. Their attenuation at a certain depth became direct evidence of the existence of a liquid outer core. And it was the reanalysis of old seismic data from the Apollo spacecraft using modern processing methods that confirmed the presence of an iron-containing core and a partially molten layer in the lower mantle. To overcome the problems of “noise” caused by multiple reflections of signals in the fractionated crust of the Moon, approaches such as digital separation of seismic data signals were used. These methods allowed us to identify how and where seismic waves passed through or reflected from elements of the lunar interior, indicating the composition and state of layer boundaries at different depths. Seismic profiles obtained from these data provided constraints on the thickness of the crust and mantle, as well as on the values of seismic wave velocities in these layers.

b) ***Gravimetry and laser altimetry***. Gravity mapping from orbit is another powerful tool for studying the internal structure of the Moon, since variations in the gravitational field reflect the distribution of mass and density inside the celestial body under study. After all, orbiters orbiting the Moon since even slight changes in its gravitational field, caused by the uneven distribution of mass inside. The "Gravity Recovery and Interior Laboratory" (GRAIL) mission, consisting of two identical spacecraft ("Ebb" and "Flow") orbiting the Moon, measured the changes in the distance between the two spacecraft, and was able to detect these changes with an accuracy of one micrometer, and provided a very detailed map of the Moon's gravitational field. The twin satellites flew in an extremely low orbit, constantly measuring the distance between them (Fig. 1.3). The data obtained allowed for the creation of the most detailed map of the Moon's gravitational field, which was able to reveal the structure of the crust, mantle and core density. Laser altimetry (e.g., on the "LRO" spacecraft) was able to make precise measurements of surface elevation and allowed the topography of the lunar surface to be correlated with the obtained gravity data.

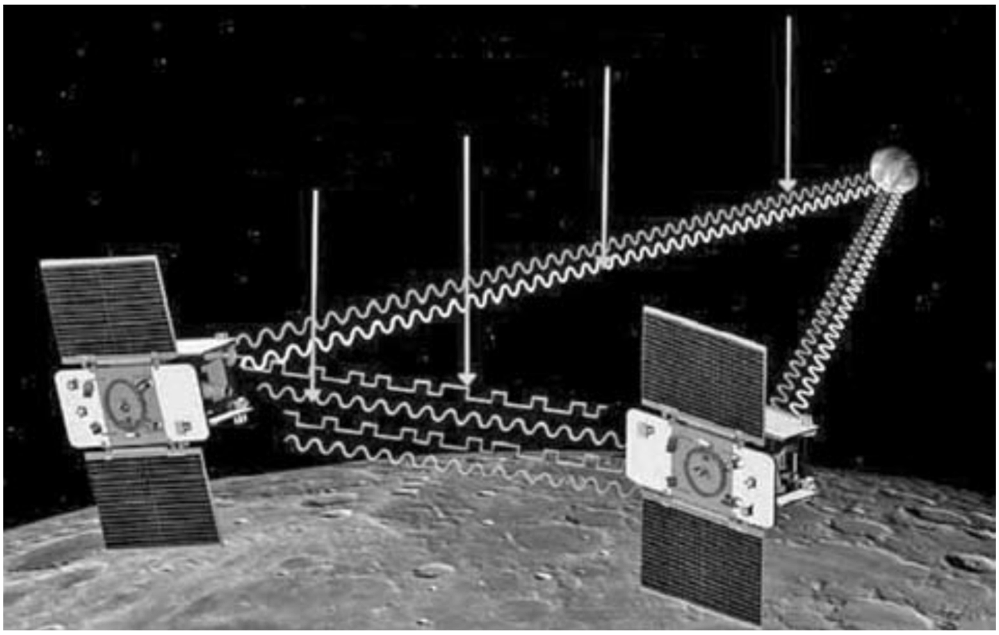

Fig. 1.3. "GRAIL" data transmission scheme [2]

The “Lunar Prospector” mission (1998-1999) also included a Doppler Gravity Experiment, which used S-band radio signals to monitor changes in the spacecraft's orbit; this allowed the lunar gravity field to be measured and mapped with high precision. Analysis of the data obtained by the “GRAIL” mission allowed for a significant improvement in the resolution of the lunar gravity field. Combined with topographic data, these data were used to determine variations in crustal thickness and mantle density. By subtracting the gravitational effect caused by topography from the observed field, it was possible to confirm that the lunar crust is asymmetric, with a thicker crust in mountainous areas and a thinner one under sea basins.

Gravity data also allowed the identification of increased mass concentrations or “mascons”; these are strong positive gravitational anomalies; they are most often associated with large impact basins. Such mascons are explained by the lifting of a central block of dense mantle material during the impact, as well as the subsequent filling of the formed basins with dense basalts of the seas.

c) ***Lunar Laser Ranging***. Since the Apollo missions, so-called corner reflectors have remained on the Moon. Powerful laser pulses were directed at them from Earth, and their return time was measured with an accuracy of a few millimeters. These long-term measurements allowed us to track the smallest fluctuations in the Moon’s rotation, the so-called librations. The nature of these fluctuations depends on how the inner layers “slip” relative to each other. Analysis of librations confirmed that the Moon’s outer core is liquid and is not rigidly connected to the mantle.

d) ***Analysis of lunar samples***. The samples delivered by the Apollo missions (a total of over 382 kg of rock) and the automatic Luna stations from their landing sites (Fig. 1.4) made it possible to determine the chemical and mineral composition of the lunar crust and, indirectly, the mantle. For example, the prevalence of anorthosite in the crust supports the theory that the Moon was covered by a global magma ocean at an early stage.

1.5. Physical characteristics of the layers in the middle of the Moon

Overall average density and differentiation. The average density of the Moon is

3346.4 kg/m³, making it the second densest satellite in the Solar System after Io. This relatively low density compared to Earth (5510 kg/m³) indicates a significantly lower iron content in its composition. The Moon's differentiated structure – with its distinct crust, mantle, and core – is a direct result of the fractional crystallization process of a global magma ocean that existed shortly after its formation.

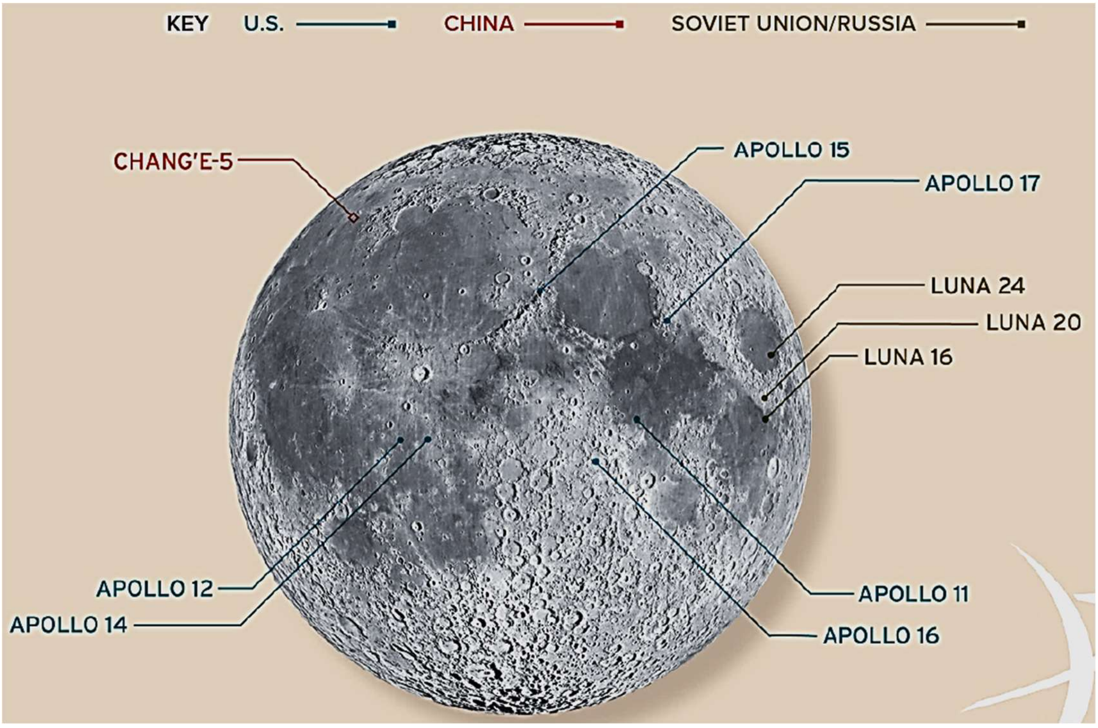

Fig. 1.4. The map shows the locations of lunar sample collection sites delivered from the near side of the Moon by missions from the United States, the Soviet Union, and China from 1969 to 2020. In 2024, the Chinese mission "Chang'e-6" delivered the first lunar samples from the far side (not visible) (https://knowablemagazine.org/docserver/fulltext/g-map-lunar-sample-sites.png)

This process caused heavier minerals, such as olivine and pyroxene, to sink to the center, forming the mantle, and lighter minerals, such as plagioclase and silica-rich crystals, to rise to the surface, forming the crust.

This resulted in a dense metallic core containing a lot of iron, some nickel, and traces of lighter elements such as sulfur. The core has two components: an inner core and an outer core. The inner core is a solid, iron-rich mass ~480 km in diameter, while the outer core is a liquid that increases the diameter of the core to ~660 km. It is the outer core that generates the magnetic field as the material rotates around the inner core. The Earth's outer core is still active and hot, creating a strong magnetic field that protects life from intense solar radiation and storms. However, on the Moon, the outer core is no longer active, and its magnetic field has greatly diminished. Compared to the entire diameter of the Earth, the Moon's core is small (only 20% of the Moon's total diameter). Above the core are the Moon's mantle and crust. These components are of particular interest because the differences in their composition tell the story of when the Moon was completely, or almost completely, covered by a magma ocean. The mantle and crust formed when this magma ocean began to cool and crystals sank and rose to the surface. Heavier minerals, such as olivine and pyroxene, sank to the bottom of the magma ocean, while lighter minerals, such as plagioclase feldspar, rose to the surface, forming the lunar anorthosite crust. The mantle is approximately 1338 km thick (for comparison, the Earth's is ~2900 km).

Lunar crust: composition, thickness and variations. Geochemical mapping from orbit indicates that the lunar crust has a predominantly anorthosite composition; this is consistent with the hypothesis of the existence of an ancient magma ocean. It is composed mainly of oxygen, silicon, magnesium, iron, calcium and aluminium. Some minor and trace elements, such as titanium, uranium, thorium, potassium, sulfur, manganese, chromium and hydrogen, are also present in the crust. Water has been found in the peripolar regions [9, 19]. Detailed studies have shown that the upper crust consists of 88±4% plagioclase by volume, while the lower, more mafic part of the crust contains 65±8% plagioclase and includes norite or gabbronorite [27].

The uppermost part of the crust is composed mainly of anorthosite, a light-colored rock rich in aluminum and calcium. This is essentially the "continental" crust of the Moon. Dark areas, known as lunar seas, are filled with solidified basalt, the result of volcanic activity [20, 21] in the past. The upper part of the crust is hard, brittle, with a density of ~2900 kg/m^3. According to geophysical data, the lunar crust is thinner on the near side and thicker on the far side; the crust has an average thickness of ~60 km on the near side and ~100 km on the far side (Fig. 1.4).

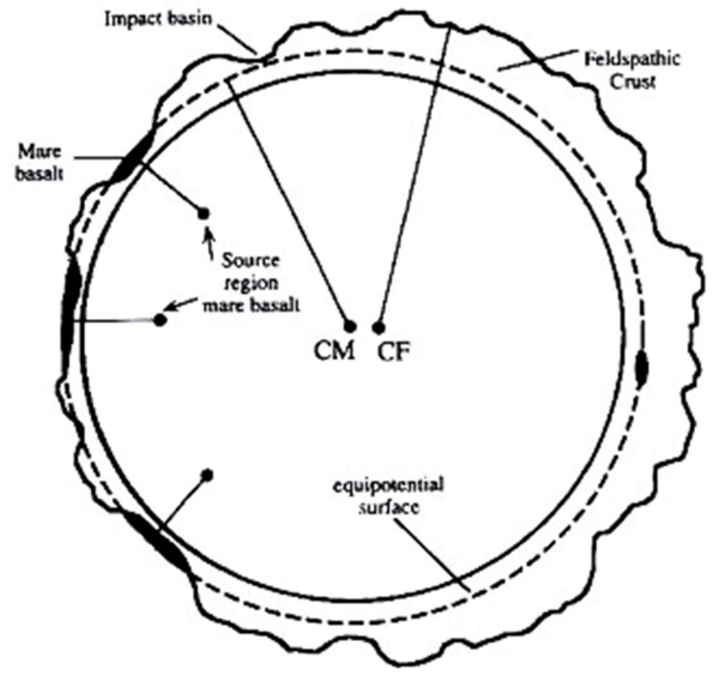

Fig. 1.4. Schematic cross-section of the Moon in the equatorial plane, showing the displacement of the Moon's center of mass towards the Earth (left in the figure) due to the presence of a thicker crust on the far side (right). The thickness of the crust is exaggerated for clarity. The equipotential surface is indicated by a dashed line [23].

The origin of the heterogeneous thickness of the crust is still a matter of debate, but the most accepted hypothesis is that the near side was struck by several large meteoritic bodies, which struck, lifted and absorbed a significant part of the crust, while the far side was affected very little. This asymmetry is a significant factor in the synchronous rotation of the Moon around the Earth. GRAIL data have shown that the upper crust of the Moon is 35–40 km thick and is less dense, and therefore more porous, than previously thought [26]. Large ancient impacts have significantly fragmented and homogenized the density structure of the upper crust. At the same time, lunar basalts, which are products of lunar volcanism, are predominantly found on the near side. This crustal asymmetry is also a major factor contributing to the Moon’s synchronous orbit around the Earth. The thinner crust on the near side facilitates the release of magma to the surface. Thus, the observed asymmetric crustal thickness is not simply a geometric feature but a critical causal factor in the distribution of lunar volcanism. Magmas generated in the mantle, even if they originate from similar depths, would encounter significantly greater resistance as they rise through the much thicker crust on the far side. This directly explains the prevalence of marine basalts on the near side, providing a compelling link between early lunar differentiation (which established this crustal asymmetry during the crystallization of a magma ocean) and its subsequent magmatic history. Understanding this correlation is fundamental to reconstructing the magmatic and thermal evolution of the Moon.

Lunar mantle: composition, layering, and seismic properties. The lunar mantle, which formed from the crystallization of a magma ocean, is mafic. Analyses of basalts indicate that it is composed primarily of the minerals olivine, orthopyroxene, and clinopyroxene. The lunar mantle is richer in iron than the terrestrial mantle. Some lunar basalts contain high levels of titanium (in the mineral ilmenite), indicating significant heterogeneity in the composition of the mantle. Moonquakes have been detected deep in the Moon's mantle, approximately 1000 km below the surface.

These deep moonquakes occur with a monthly periodicity and are associated with tidal stresses caused by the Moon's eccentric orbit around the Earth. Modern reanalysis of Apollo seismic data has revealed that the core is partially (10-30%) surrounded by a molten layer of lower mantle with a radius of 480 ± 20 km (about 150 km thick). Mantle models assume a pyroxenitic composition for the upper mantle and a magnesium-rich composition for the lower mantle, with increasing Mg content with depth. The composition of the Moon's mantle, characterized mainly by olivine and pyroxene, is also noticeably rich in iron. However, the discovery of lunar basalts with significant titanium content indicates that the mantle is not chemically homogeneous.

This compositional heterogeneity of the lunar mantle, especially the variable titanium content of marine basalts, provides important evidence for its complex history of partial melting. This implies that the mantle contains distinct geochemical reservoirs that melted at different times or under different pressure and temperature conditions, rather than being a uniformly mixed source.

The presence of a partially molten layer in the lower mantle serves as a direct physical mechanism for the generation of magma at depth. The ascent of these magmas, influenced by the heterogeneous composition of the mantle, then leads to the eruption of marine basalts onto the lunar surface, especially where the crust is thinner. Understanding this mantle heterogeneity is fundamental to reconstructing the magmatic and thermal evolution of the Moon [24]. This suggests that the dynamics of the lunar interior involve more complex processes than simple, uniform cooling and convection, with distinct compositional regions that influence the timing, volume, and chemistry of volcanism.

The mantle thus extends from the base of the crust to the core. It is heterogeneous and is divided into the upper mantle, which is a solid, rigid layer that extends to a depth of about 700 km and, together with the crust, forms the lunar lithosphere; and the lower mantle (asthenosphere), which extends to the boundary with the core; seismological data indicate that this layer is partially molten (1-5% melt); and this zone is the region where deep moonquakes originate.

The mantle is mainly composed of minerals such as olivine and pyroxene, which are rich in iron and magnesium. The density of the mantle increases with depth from ~3000 to almost 4200 kg/m³.

The lunar core: size, condition, and chemical composition. Recent reanalysis of seismic data from the Apollo missions, using modern processing techniques, has confirmed that the lunar core is quite small, with a radius of about 330 ± 20 km; this is only about 20% of the diameter of the Moon itself. The solid inner core consists of almost pure iron, and has a radius of 240 ± 10 km. A liquid outer core, about 90 km thick, surrounds the solid inner core, and has a radius of 330 ± 20 km. These results indicate that 40% of the volume of the core is now solidified. The density of the liquid outer core is about 5000 kg/m³. The composition of the lunar core is not well established, but it is believed (Table 2.1) to consist of a metallic iron-nickel alloy with a small amount of sulfur. The liquid outer core may contain up to 6% sulfur by weight. Studies also indicate the presence of light elements in the core, which has parallels with recent seismological studies of Earth, which also suggest the presence of light elements, such as sulfur and oxygen, in a layer around the Earth's core. Analysis of changes in the Moon's rotation period also indicates that the core is at least partially molten. Its temperature is estimated at 1570–1720 K.

Table 1.2.

Internal structure of the Moon

Layer	Approximate thickness/radius (km)	Main composition	Physical state
Crust	50 - 100 (average ~50-70)	Anorthosite (rich in plagioclase, Al, Ca, Si)	Solid
Mantle	~1350 (thickness)	Silicates (olivine, pyroxenes), richer in Fe	Mostly solid, possible partial melt near the core
Outer core	Radius ~330-480	Iron (Fe), Nickel (Ni), Sulfur (S)	Liquid (molten)
Inner core	Radius ~240-258	Mostly Iron (Fe)	Solid

1.6. Modern models of the Moon's internal structure

The current understanding of the Moon's interior is based on the integration of all available geophysical data, lunar samples, and theoretical models developed to date.

The layered model of the Moon's interior suggests that the satellite is a differentiated body consisting of three main layers: the crust, mantle, and core.

The lunar crust is predominantly anorthosite and is globally asymmetric: it is thinner on the near side of the Moon (on average ~60 km) and thicker on the far side (on average ~100 km). This model assumes a two-layer crust, in which the upper layer is anorthosite and the lower, more mafic layer, containing norite or gabbro-norite. The Moon's mantle is mafic and is believed to consist mainly of minerals such as olivine, orthopyroxene, and clinopyroxene. It is richer in iron than the Earth's mantle. Seismic data indicate the presence of a partially molten layer in the lower mantle surrounding the core. Deep moonquakes occur in the mantle at a depth of about 1000 km.

The lunar core is relatively small, with a radius of about 330 km. It is differentiated into a solid inner core of pure iron (radius 240 ± 10 km) and a liquid outer core (radius 330 ± 20 km), consisting of a metallic iron-nickel alloy with a small amount of sulfur (up to 6% by weight). This means that about 40% of the core volume is solidified. The lunar magma ocean hypothesis is a cornerstone of modern models of the formation and differentiation of the Moon. According to this hypothesis, shortly after its formation, approximately 4.5 billion years ago, the Moon was largely or completely molten. The energy required to melt the Moon's outer surface is usually attributed to the giant impact event that is postulated to have formed the Earth-Moon system, and the subsequent re-accretion of material in Earth's orbit.

This magma ocean underwent fractional crystallization: denser minerals such as olivine and pyroxene sank to the ocean floor, forming the mantle, while lighter minerals such as plagioclase rose to the surface, forming the anorthosite crust. This process explains the observed anorthosite composition of the lunar crust and the overall differentiated structure of the Moon. The details of the Moon's post-magmatic ocean structure are sensitive to assumptions about the composition, depth of the magmatic ocean (shallow or full), and the crystallization process (fractional or equilibrium), each of which is imperfectly known. Thermal evolution models – seek to explain its thermal history and its effects on internal structure and surface features.

Cooling and heat sources. Due to its small size, the Moon is thought to have undergone rapid early cooling. However, the present-day heat flux from the Moon [15] is mainly the result of heat generated by radioactive isotopes such as uranium, thorium, and potassium, which are found in the interior at depths of up to 300 km. These radionuclides play a key role in maintaining the Moon's internal heat and influencing its long-term cooling.

Impact on magmatism. The thermal evolution of the Moon is directly related to partial melting processes in the mantle, which lead to the eruption of marine basalts to the surface. Studies show that enrichment with radioactive elements can keep the upper mantle hotter, even billions of years after the Moon's formation [14]. This explains why younger magmas may have originated from shallower depths than previously thought, since these "pockets" of mantle remained hot enough to partially melt even during the late stages of the Moon's cooling.

Conclusions

Thus, the Moon's internal structure is the result of a complex history of differentiation that may have begun with a hypothetical global magma ocean. Today, the Moon is a well-differentiated body consisting of an anorthosite crust, a mafic mantle, and a small, partially molten iron-nickel-sulfur core.

The Moon's crust exhibits a significant thickness asymmetry, being thinner on the near side and thicker on the far side, which has profound implications for the distribution of lunar volcanism and its synchronous rotation around the Earth. The mantle, although composed primarily of olivine and pyroxene, exhibits compositional heterogeneity. This suggests a complex history of partial melting.

The presence of a partially molten layer in the lower mantle and a liquid outer core confirms that the Moon is still not a completely solid body.

Understanding these physical characteristics has been made possible by interpreting disparate data obtained by different methods. The “Apollo” seismic experiments, which recorded moonquakes and artificial impacts, have provided fundamental data on the layering of the internal structure and on the different values of the propagation velocities of seismic disturbances in different layers of the Moon.

Gravity mapping, in particular by the “Lunar Prospector” and “GRAIL” missions, has made it possible to determine in detail the variations in crustal thickness and identify mascons. Heat flux measurements by the “Apollo” missions and mapping of radioactive elements from orbit have provided critical constraints on the thermal evolution of the Moon and on the distribution of internal heat over its surface. Finally, laser ranging of the Moon has provided information on the state of the core and its oblateness. Current models of the Moon's internal structure continue to be refined [1] by re-analyzing the “Apollo” archive data using new computational methods and by receiving new data from current and future missions [7, 10, 16]. These studies are key to a better understanding of the formation and evolution of the Moon, as well as to expanding our knowledge of the differentiation and dynamics of other celestial bodies in the Solar System.

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