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2. Physical characteristics and relief of the surface of the Moon

Introduction

The Moon, our only natural satellite; it is the closest and most studied celestial body after Earth. Its surface preserves a unique geological history of the Solar System, offering a wide range of data on the processes of planetary evolution [25, 26]. A detailed study of the physical characteristics of the surface layer (regolith) and the relief of the Moon's surface is key to understanding its formation history, tectonic activity (or lack thereof), the impact of space weathering, and the potential for future exploration [32] and colonization [6, 9, 11, 14, 17, 19]. The surface relief is characterized by two main types of terrain, which contrast sharply in color, elevation, and age.

2.1. Methods for obtaining data on the physical characteristics and relief of the lunar surface

Knowledge of the lunar surface has been accumulated over centuries of research, starting with telescopic [8, 12, 13] visual observations and reaching its peak with space missions [22].

Telescopic observations. The first systematic visual observations by Galileo Galilei in 1609 revealed the presence of mountains, craters and so-called "Mare" (dark plains) on the lunar surface. Over time, telescopes became more powerful, allowing an increasing number of surface details to be mapped.

Analysis of the *spectra* [10, 21, 22] of reflected sunlight allows the identification of the mineral composition of surface rocks, since different minerals absorb and reflect light at different wavelengths. This gave the first ideas about the presence of basalts in seas [3] and anorthosites in mountainous areas.

The emission of radio waves to the Moon and the analysis of the reflected signal during ground-based radar surveys made it possible to obtain information about the topography, surface roughness and even about some subsurface structures at a depth of several meters.

Space missions. The ***missions of the "Luna" series (USSR)*** and ***"Ranger", "Surveyor" (USA)*** in the 1960s provided the first close-up images of the Moon, confirming the cratered nature of the surface and its unevenness. The Surveyor missions made a soft landing and sent the first images of the lunar soil.

The "***Lunar Orbiter" series*** of missions (USA) provided almost complete photographic coverage of the Moon's surface with high resolution. It became the basis for detailed mapping; with their help, detailed maps of the surface were created with a resolution of up to 0.5 meters per pixel

The astronauts of the "***Apollo" manned missions (USA)*** made six successful landings on the Moon between 1969 and 1972. They conducted visual observations, took photographs, installed scientific instruments such as seismometers and laser light reflectors on the surface, and most importantly, collected and delivered 382 kg of lunar soil and rock samples to Earth.

Laboratory analysis of these samples in Earth laboratories provided the most reliable data on the mineralogical, chemical, isotopic composition, age of rocks, and physical properties of the lunar regolith [4]. This allowed for the development of a detailed geological chronology of the Moon [18].

The "***Clementine" mission (USA, 1994)*** was the first orbital mission to provide global topographic mapping of the Moon using a laser altimeter and a multispectral camera. It also provided the first evidence of water ice in permanently shadowed craters near the poles.

The neutron spectrometer on the "***Lunar Prospector" (USA, 1998-1999***) confirmed the presence of hydrogen (presumably in the form of water ice) in the polar regions, and also detected gravitational field anomalies: the so-called mascons.

The "***Kaguya" mission (Japan, 2007-2009***) provided high-quality images, topographic data, and data on the Moon's gravitational field.

The "***Lunar Reconnaissance Orbiter" (LRO) mission (USA, 2009-present***) is currently the most advanced orbital mission. LRO is equipped with a set of instruments that allow you to obtain a wide range of observational data. The LROC (Lunar

Reconnaissance Orbiter Camera) cameras create high-resolution images with a resolution of up to 0.5 m/pixel, which allows you to study craters, individual boulders, lunar vehicles and even astronaut tracks in detail.

The LOLA (Lunar Orbiter Laser Altimeter) laser altimeter using laser altimetry created the most accurate topographic map of the Moon, revealing the smallest irregularities and allowing you to measure the depth of craters and the height of mountains. The Diviner (Lunar Radiometer Experiment) instrument measures surface temperature, which allows you to create temperature maps; they provide information about the thermal properties of the regolith and the presence of frozen volatiles.

Using ***neutron spectroscopy***, LEND on LRO continues to detect hydrogen (and therefore potential water) by measuring the flux of neutrons from the surface. This is how maps of water ice distribution in the polar regions have been constructed [33-35].

The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument measures radiation levels on the lunar surface. This radiation data is important for future manned missions.

The **"Chang'e"** series of missions (China's space program) includes orbiters, landers, and lunar rovers. In particular, "Chang'e-3" and "Chang'e-4" (the first landing on the far side of the Moon) provided new data on the composition of the regolith and subsurface structures using ground-penetrating radar. And the "Chang'e-5" mission successfully returned lunar soil samples in 2020, collecting samples of relatively young rocks [1].

2.2. Physical characteristics of the lunar surface layer (Regolith)

Unlike the Earth, the Moon does not have a dense atmosphere and hydrosphere, so its surface is not protected from cosmic radiation and constant bombardment by micrometeorites. These processes over billions of years have transformed the upper layer of bedrock into a unique formation - regolith. Regolith is a layer of loose, crushed material that covers the entire surface of the Moon. It was formed as a result of centuries of bombardment of the Moon by meteorites, micrometeorites, and particles of the solar wind.

The regolith consists of a mixture of dust, sand, gravel, and larger rock fragments (breccias). The particle size varies from micrometers to tens of centimeters. Small fractions (< 1 mm) constitute about 50% of the mass. That is, the lunar regolith consists of rock fragments, minerals, glass spherules, and sintered particles (agglutinates). Its thickness varies from 2–8 meters in young seas to 10–20 meters or more on ancient continents and in very old craters. Although the regolith appears homogeneous at the macroscopic level, studies of many cores have revealed its complex layered structure, reflecting a history of meteorite impacts and mixing. In the deeper layers of the regolith, breccias are often found - rocks consisting of fragments of various lunar rocks cemented by fine-grained material; they indicate intense impact processes [20, 44].

The average bulk density of the regolith is approximately 1.3–1.7 g/cm^3, which is significantly lower than the density of solid rocks (about 3 g/cm^3). This low density is explained by its high porosity. That is, the regolith is a very porous material (40-50%), which explains its low thermal conductivity and high insulating properties. The color of the regolith varies from light gray to dark gray or brown, depending on the mineral composition and the presence of glassy particles formed as a result of micrometeorite impacts.

The particles of the regolith have low cohesion under vacuum conditions, which makes it very loose. However, electrostatic forces (due to the influence of the solar wind) can cause it to “stick together” and form dust pillars.

Regolith is an excellent insulator. The lack of an atmosphere to retain heat and the low thermal conductivity of the regolith means that the temperature at the Moon's equator fluctuates in extremes, leading to extreme temperature drops on the Moon's surface: from +127°C during the day to -173°C at night. In permanently shaded regions near the poles, the temperature can drop to -240°C, creating “cold traps” for volatile substances. This property is important for the design of lunar bases.

Regolith is a good dielectric. Under the influence of solar ultraviolet and X-ray radiation, dust particles on the dayside of the Moon acquire a positive electrical charge. This leads to their electrostatic repulsion and levitation, forming a kind of “dust atmosphere” at a height of several centimeters to tens of meters.

The regolith has a low bearing capacity, which requires special designs for lunar landers and vehicles. Traces of astronauts and lunar rovers on the Moon indicate its friability and ability to compact.

The lunar regolith, like other lunar rocks, is predominantly diamagnetic or paramagnetic material. However, some samples also show weak residual magnetism [24]. This indicates the presence of an ancient magnetic field of the Moon in the early stages of its history, which later disappeared.

2.3. Relief of the Moon's surface

The surface of the Moon is a kind of chronicle of the history of the Solar System, which has preserved traces of events that occurred billions of years ago. The relief of the Moon's surface is characterized by two main types of terrain, which contrast sharply in color, height and age: light, high-altitude continents (terrae) and dark, low-altitude seas (maria).

Data on which conclusions about changes in the physical state of the Moon's surface are based. Conclusions about changes in the physical state of the Moon are based on data obtained from the study of lunar soil samples. Laboratory analysis of these samples, collected by the “Apollo” and “Luna” missions, provided information about the age of the rocks, chemical and mineralogical composition, the presence of glassy particles and their transformation under the influence of space weathering. The presence of nanophase iron (nFe0) is direct evidence of space weathering. Impact crater density (i.e., the number of craters per unit area) is used to date lunar surfaces [5]. The more craters there are in an area, the older it is. This method is calibrated by radioisotope dating of lunar rock samples from known geological regions.

Modern orbiters, such as LRO, continuously acquire high-resolution images of the surface. Comparing images taken years apart allows the detection of new craters and rifts, which indicates ongoing activity [30]. And a network of seismometers installed by Apollo astronauts has been operating for many years, recording lunar earthquakes. Analysis of these data has provided insight into the internal structure of the Moon and its ongoing tectonic activity [7, 15, 45].

High-precision topographic maps obtained using laser altimeters (LOLA on LRO) have allowed us to study the morphology of the relief, identify landslide cliffs and other small tectonic features. Maps of the lunar gravity field (obtained, for example, by the GRAIL mission) allow us to detect mascons (concentrations of mass in certain regions), which are the result of filling basins with dense basaltic lavas. These data provide an idea of the history of volcanic activity [27, 28, 31, 38, 40]. And observations of the lunar exosphere and dust cloud phenomena provide information about volatiles and dust movement.

Data on changes in the physical state of the lunar surface throughout the historical past and to the present. Changes in the physical state of the lunar surface occur on different time scales. With long-term changes over billions of years, the regolith becomes darker over time. This phenomenon, known as "space weathering," occurs as a result of micrometeorite impacts. This forms nanophase iron (nFeO) in glassy particles, which changes the optical properties of the regolith.

Ion bombardment, or solar wind, changes the chemical composition of the surface of the particles. Meteorite impacts also eject lighter, fresh material from deep within, temporarily illuminating areas; but then they darken again. Craters are eroded over time, leading to the smoothing of their rims and the filling of the bottom. This process occurs much more slowly than on Earth, due to the absence of an atmosphere and water.

The thickness and structure of the regolith are constantly changing as a result of bombardment. Tectonic processes, although very slow, affect the formation of rifts and lead to minor displacements of crustal blocks [47, 49]. In the case of short-term changes (years, decades, centuries), new impact craters continue to form on the Moon as a result of meteorite impacts. After all, modern spacecraft [50] (for example, LRO) regularly record the formation of new, small craters. This is direct evidence of ongoing changes in the relief. Seismometers installed on the surface of the Moon as part of the Apollo program recorded lunar earthquakes. They are divided into deep lunar earthquakes associated with the Earth's tidal forces acting on the Moon. They occur regularly - about 3000 per year - but are weak.

Surface lunar earthquakes are rarer and more powerful; they are probably associated with tectonic movements along cliffs and cracks. Seismometers have also recorded meteorite impacts.

Electrostatic forces induced by the solar wind and ultraviolet radiation can cause lunar dust to move across the surface, especially at the terminator (the day-night line). This dust can leave fine trails or settle on spacecraft. Also, the constant heating and cooling cycles of the surface cause expansion and contraction of surface rocks; this leads to their gradual destruction and a kind of "loosening" of the regolith.

How has the relief of the Moon's surface changed historically? The evolution of the lunar relief is closely related to its geological history, which is divided into several geological eras.

Pre-Nectarian period (up to 3.92 billion years ago). The Moon was formed approximately 4.51 billion years ago, probably as a result of a giant collision. At this stage, there was a magma ocean, intensive accretion of material and the formation of a primary crust. Lighter minerals (plagioclase) floated, forming a primary anorthosite crust - the future continents.

The surface of the Moon at that time was subjected to intense bombardment by asteroids and cometary nuclei, which led to the formation of many large impact basins and craters. Today, they form continental areas. Some of these basins were so large that they caused repeated regional melting. During this same period, differentiation of lunar material occurred, and lighter, less dense rocks (anorthosites) surfaced, forming the primary lunar crust.

The Nectarian period (3.92–3.85 billion years ago) was a period of particularly intense bombardment, during which most of the large impact basins were formed. They were later filled with lava, forming seas such as Mare Nectaris and Mare Imbrium.

The Imbrian period (3.85–3.2 billion years ago) is a period when, after the late intensive bombardment, a period of massive eruptions of basaltic lavas began, which filled the low-lying impact basins, forming dark seas. This lava flowed through faults in the crust formed as a result of numerous impacts. It was during this period that the basic appearance of the lunar surface, which we see today, was formed. At the same time, the compression of solidified lavas formed wrinkled ridges.

During the *Eratosthenian period (3.2–1.1 billion years ago*), there was a period when volcanic activity [39] decreased significantly; although occasional eruptions still occurred, producing some of the youngest marine basalts. Surface bombardment also continued, although at a lower intensity. Therefore, craters were formed that could not be filled with lava. However, the regolith continued to build up.

During the *Copernican period (1.1 billion years ago – present*), the intensity of meteorite impacts decreased significantly. Therefore, during rare impact events, craters formed during this period are relatively "fresh", with bright ray systems. Examples of these are the craters Copernicus and Tycho. Their ejecta has not yet darkened by space weathering.

At this time, the Moon's surface continues to be subjected to continuous micrometeorite bombardment, which leads to slow but constant mixing of the regolith, its darkening and the formation of glassy particles. Extreme temperature fluctuations on the surface (from -173°C to +127°C) lead to significant "fatigue" of rocks, which causes their destruction and the formation of new regolith particles.

The Moon, in comparison with the Earth, is geologically inactive. However, there are still minor tectonic processes that lead to the formation of "lobate scarps". These are small faults that arose as a result of the Moon's compression as it cooled, and the core contracted [45]. These structures indicate that the Moon is still slowly contracting.

Major landforms. *The lunar continents (Terrae)* are the dominant type of terrain on the Moon. These are bright, high-altitude areas that cover about 83% of the entire surface of the Moon and are mostly located on the far side. They are characterized by a highly rugged relief and a high density of craters. That is, they are old, heavily cratered, bright areas composed mainly of anorthosite rocks, rich in aluminum and calcium. These rocks are the remains of the primary lunar crust, which was formed during the crystallization of the magma ocean. The average height of the continents is much higher than the seas. They are the oldest parts of the lunar crust, whose age reaches 4.4–4.5 billion years. The high density of craters on their surface indicates that these areas were subjected to intense bombardment in the early history of the Solar System.

The lunar Marias, despite their name, are large dark, relatively flat lowlands. They occupy about 17% of the surface, mostly on the visible side (about 31-40% of its area). These are ancient impact basins that were filled with liquid basaltic lavas during a period of intense volcanic activity (3.9–3.2 billion years ago, although some volcanic processes could have lasted up to 1 billion years ago). They are composed mainly of dark basalts, rich in iron, which determines their dark color and low albedo. Some seas are also rich in titanium. They contain fewer craters than continents; this indicates their younger age. The largest sea is the Oceanus Procellarum.

Impact craters – are the most prominent and widespread features of the lunar landscape. They are formed by impacts from meteorites, asteroids, and cometary nuclei. Craters vary greatly in size and morphology, depending on the size and energy of the impactor. Craters cover almost the entire surface of the Moon, from microscopic pits to giant basins. There are about 300,000 craters over 1 km in diameter on the visible side, and over a million on the entire surface. In ancient continental areas, the density of craters is so high that the surface has reached a saturation point, where new impacts destroy as many old craters as they create new ones.

A typical fresh crater has the following main elements*:* a well-defined shaft (raised rim), a floor (inner depression), inner slopes (often with terraces in complex craters), and a central hill (in complex craters). Around the crater is an ejecta blanket – a layer of debris thrown out during the impact. Light rays – bands of lighter material thrown out over long distances – radiate from young craters. Secondary craters can also form around large craters from the fall of large debris. The study of craters (their morphology, distribution, density) is a key method for determining the relative and absolute age of different areas of the lunar surface and reconstructing the history of meteorite bombardment in the Solar System.

Simple craters are small, cup-shaped depressions up to 15–20 km in diameter, with a smooth bottom and steep slopes.

Complex craters are somewhat larger (~15–20 km to ~150–200 km), with flat floors, central hills formed by crustal uplift after impact, and terraced inner slopes of the shaft formed by collapses; the flat floor is often filled with solidified melt.

Examples include the craters Copernicus, Aristarchus, and Tycho.

Impact basins are very large impact structures with diameters of over 300 km and up to over 1000 km; they often have several concentric ring shafts (mountain ranges); examples include the Eastern Sea and the Sea of Rains (Imbrium). Most sea basins are also impact basins filled with basaltic lavas. The impacts that formed the basins were so powerful that they could have pierced the lunar crust and caused the uplift of mantle material or subsequent lava flows that formed the seas. The largest known impact basin in the Solar System is the South Pole-Aitken Basin on the far side of the Moon.

Mountain ranges are often remnants of ridges around craters and large impact basins. Unlike Earth, where mountains are mainly formed by tectonic activity (plate collisions) or volcanism, most lunar mountains are of impact origin. They are mainly the uplifted edges (ridges) of large impact basins and craters. The giant collisions that created the basins lifted and deformed the surrounding crust, forming mountain ranges surrounding these structures. The central peaks of complex craters are also mountains of impact origin. The most famous lunar mountain ranges have terrestrial names: Apennines (ridge of the Mare Rainii basin, peaks up to 5 km high), Alps (with the Alpine Valley), Caucasus. Some lunar peaks reach considerable heights, up to 9 km above the surrounding terrain, exceeding the height of Mount Everest relative to the base level. The so-called *Rilles* are long, narrow, sinuous or straight depressions on the lunar surface, resembling channels or cracks [2]. They are classified by morphology, which reflects different mechanisms of formation.

Sinuous rilles are the most common type. They have a characteristic meandering, river-like shape. They can be hundreds of kilometers long and a few kilometers wide. They often start from small crater-like depressions, which are considered volcanic vents. Their formation is associated with lava flows: they can be either open lava channels or collapsed lava tubes through which molten basaltic lava once flowed during the formation of the seas. That is, they were formed by lava flows in lava tubes that later collapsed. An example is Hadley Rille, explored during the “Apollo 15” mission. *Straight rilles* are often associated with tectonic faults. They are linear, straight, or slightly curved depressions that resemble grabens - lowered blocks of crust between two parallel faults. Their origin is associated with tectonic processes - stretching of the lunar crust. Examples are the Ariadaeus Rille (Fig. 2.1), Vallis Alpes (Fig. 2.2), Cauchy Rille (Fig. 2.3).

Fig. 2.1. Image of the Ariadaeus Rille, which is hundreds of kilometers long. Photo of the "Apollo 10" crew in 1969 as they approached an altitude of 14 km above the lunar surface (https://apod.nasa.gov/apod/image/0210/rille_apollo10_big.jpg).

Fig. 2.2. Vallis Alpes, as seen by the "Lunar Reconnaissance Orbiter" (https://c02.purpledshub.com/uploads/sites/48/2019/08/Vallis_Alpes_4115_h3-147c260-e1566997446657.jpg?webp=1&w=1200).

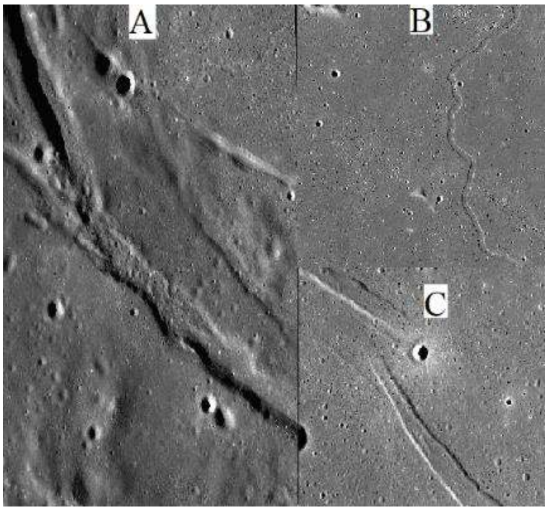

Рис. 2.3. Sinuous, Straight and Arcuate Rilles: A – Rille Sulpicious Gallus (20°N Lat, 10°E Lon), B – Rille Sharp (46°N Lat, 309°E Lon), C – Rille Cauchy (10°N Lat, 38°E Lon) (https://lroc.im-ldi.com/ckeditor_assets/pictures/893/content_Rilles_rilles_rilles_anote.png).

Arcuate rilles have a smooth arcuate shape and are usually located at the edges of lunar seas, sea basins and are associated with the lowering of the basin floor; therefore, they are located parallel to the sea-continent boundary. They are believed to have formed as a result of the subsidence and compression of heavy basaltic layers in the center of the basin after their cooling and solidification, which caused stretching and faults at the periphery. Example: *Rille Hippalus* on the edge of *Mare Humorum*.

The variety of groove types (Table 3.1) indicates the complex nature of geological processes on the Moon, which included both large-scale volcanism (Sinuous rilles) and tectonic stresses in the lithosphere (*Straight* and *Arcuate rilles*).

Formations such as *Domes* are quite low and have rounded shapes; they are considered volcanic formations of the shield volcano type [29, 41-43, 49].

Table 2.1.

Types of Rilles on the Moon.

Type of rilles	Appearance	Likely Formation Mechanism	Examples
Sinuous	Meandering, river-like, often begins in a crater-like depression	Lava channel or collapsed lava tube	Hadley Rille, Schroeter Valley
Arcuate	Smooth bend, parallel to the sea edge	Subsidence/compression of lava in the basin	Hyppal Rille
Straight	Linear, straight or slightly curved depression	Tectonic fault (graben)	Ariadea Rille, Alpine valley

Wrinkle Ridges are long, winding ridges that cross the surface of seas. They are the result of tectonic compression of basaltic lavas after they have cooled and solidified.

Global topography of the Moon. The visible side of the Moon is dominated by seas; this gives it a darker appearance; the Sea of Rains, the Sea of Tranquility, and the Sea of Clarity stand out in particular. Continental regions are less common, but still present.

The *far side* of the Moon is mainly composed of heavily cratered continents. Seas are much rarer and smaller here; examples include the Mare Moscoviense and the Mare Desiderii. This asymmetry is explained by the thickness of the lunar crust, which is much thicker on the far side; this is what prevented magma from reaching the surface and filling impact basins.

The *lowest point* on the Moon is located in the South Pole-Aitken Basin on the far side of the satellite. It is one of the largest impact basins in the Solar System: about 2500 km in diameter and up to 13 km deep. It is the lowest and one of the oldest and largest impact structures on the Moon. The *highest point* is located at the edge of the South Pole-Aitken basin, at an altitude of up to 8-10 km above the mean level of the Moon.

2.4. Mineralogical composition of the surface layers of the Moon

The mineralogical composition of the surface layers of the Moon reflects its geological history [36, 37] and differentiation processes.

The ***main minerals*** on the surface of the Moon are the following ***feldspars***:

a) Plagioclase dominates in continental rocks (anorthosites), giving them a light color. Anorthite ($CaAl_2Si_2O_8$) is the main mineral of the primary lunar crust, formed by upwelling during the crystallization of the magma ocean.

b) Pyroxenes: $(Ca,Mg,Fe)_2(Si,Al)_2O_6$.

c) Clinopyroxenes (e.g., augite) are common in marine basalts.

d) Orthopyroxenes (e.g. enstatite, hypersthene) are found in both marine and continental rocks.

e) Olivine $(Mg,Fe)_2SiO_4$ is common in marine basalts, also found in some continental breccias.

Ilmenite (***$FeTiO_3$***) is an important mineral in some marine basalts, especially in basalts with a high titanium content. Its presence gives some seas a darker hue. Ilmenite is also considered a potential resource for obtaining oxygen and titanium on the Moon.

Chromite, Ulvospinel and other oxides are found in basalts.

Iron-nickel metals are found in small quantities in the form of particles originating from meteorites or formed as a result of the reduction of iron from minerals under the influence of the solar wind. ***Glass*** is formed as a result of meteorite impacts that melt local rocks. Lunar glass can be of different colors (brown, green, yellow) depending on its chemical composition. It is a common component of the regolith.

Typical rocks in the surface layer of the Moon are ***Basalts***. These are dark, fine-grained igneous rocks that make up the seas. They are rich in pyroxenes, olivine and plagioclase (with a relatively high content of iron and magnesium). ***Anorthosites*** are light, coarse-grained igneous rocks that make up the continents. They consist almost entirely of plagioclase (anorthite).

Breccias are rocks composed of fragments of various lunar rocks (basalts, anorthosites, impact glass) cemented by a fine-grained matrix. They are very common in the regolith, especially in continental areas, and are evidence of intense impact bombardment. ***Regolith breccia*** is a type of breccia composed of regolith fragments cemented by pulsed melting.

KREEP lands are unique areas (the largest of which is the Burr Ocean) enriched in incompatible elements such as **K** (potassium), **REE** (rare earth elements) and **P** (phosphorus). They are believed to be the remnants of the last fractions to crystallize from a former magma ocean.

Observational data from “LRO”, “Chandrayaan-1” and “LCROSS” have confirmed the presence of ***water ice*** in permanently shadowed regions near the poles (Fig. 2.4). Ice is mixed with the regolith in concentrations ranging from a few to tens of percent by mass [16]. Its sources are thought to be comets, asteroids, and chemical reactions involving hydrogen from the solar wind.

Space weathering, such as bombardment by micrometeorites and the solar wind, also significantly alters the mineralogical composition of particles on the surface. One of the most important consequences of such weathering is the formation of nanophase iron (nFeO).

Iron atoms from minerals are reduced to form nanometer-sized particles of metallic iron, which settle on the surface of dust particles. This leads to a darkening of the regolith and a decrease in its reflectivity. As a result of meteorite bombardment, the crystal structure of minerals can be disrupted, transforming them into amorphous glass.

And solar wind particles (mainly hydrogen, helium, carbon, nitrogen) can be implanted into the surface layers of minerals; this is of great importance for the potential extraction of resources, such as helium 3.

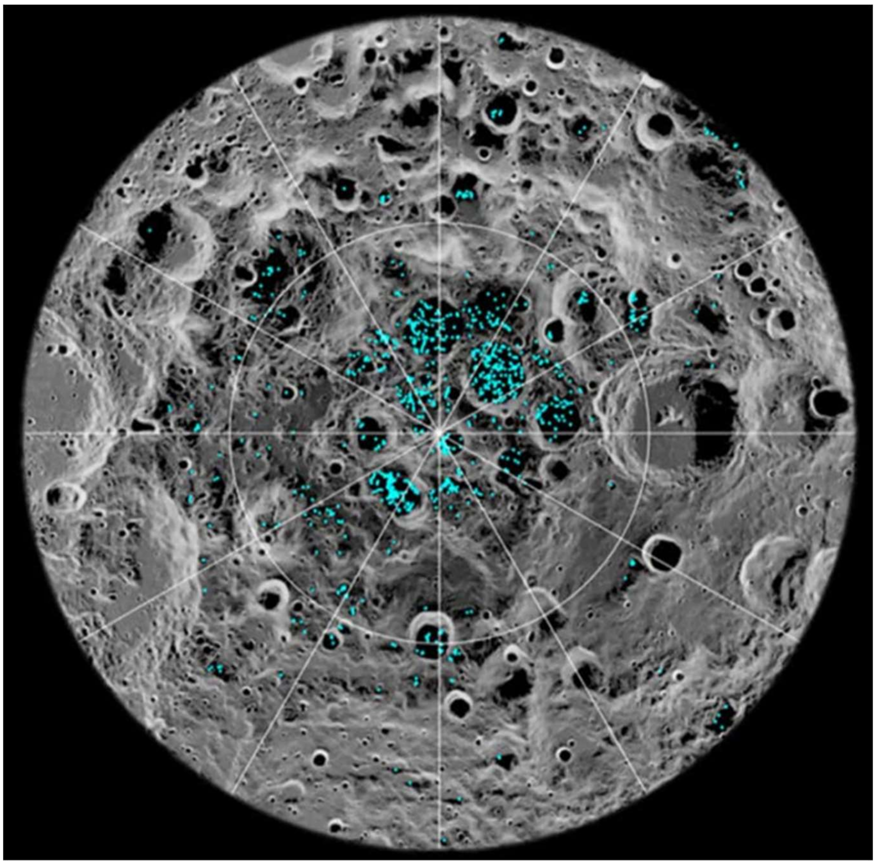

Fig. 2.4. Extensive hydrogen deposits in the Moon's shadowed regions have been revealed. It is unveiled extensive hydrogen deposits in the Moon's shadowed regions (https://www.thebrighterside.news/uploads/2024/12/ice-1-scaled.webp?format=auto&optimize=high&width=1200).

Conclusions

The Moon is a unique natural object, whose surface carefully preserves the history of intensive bombardment and volcanic activity in the early stages of the development of the Solar System. A detailed study of its regolith, relief and mineralogical composition has allowed us to build a comprehensive model of lunar evolution. The continued acquisition of data from new missions such as "LRO" and the "Chang'e" mission, along with re-evaluations of existing samples and data, continues to deepen our understanding of this amazing celestial body and its role in Earth's history. Future lunar missions, including the Artemis program, promise new discoveries and an even more detailed look at the physical characteristics and evolution of our closest neighbor.

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