Frontier Interdisciplinary Strategy

Research Report on Frontier Interdisciplinary Assessment Based on Key Scientific Issues Related to Crewed Lunar Exploration

Frontier Interdisciplinary Assessment Based on Key Scientific Issues Related to Crewed Lunar Exploration Research Team

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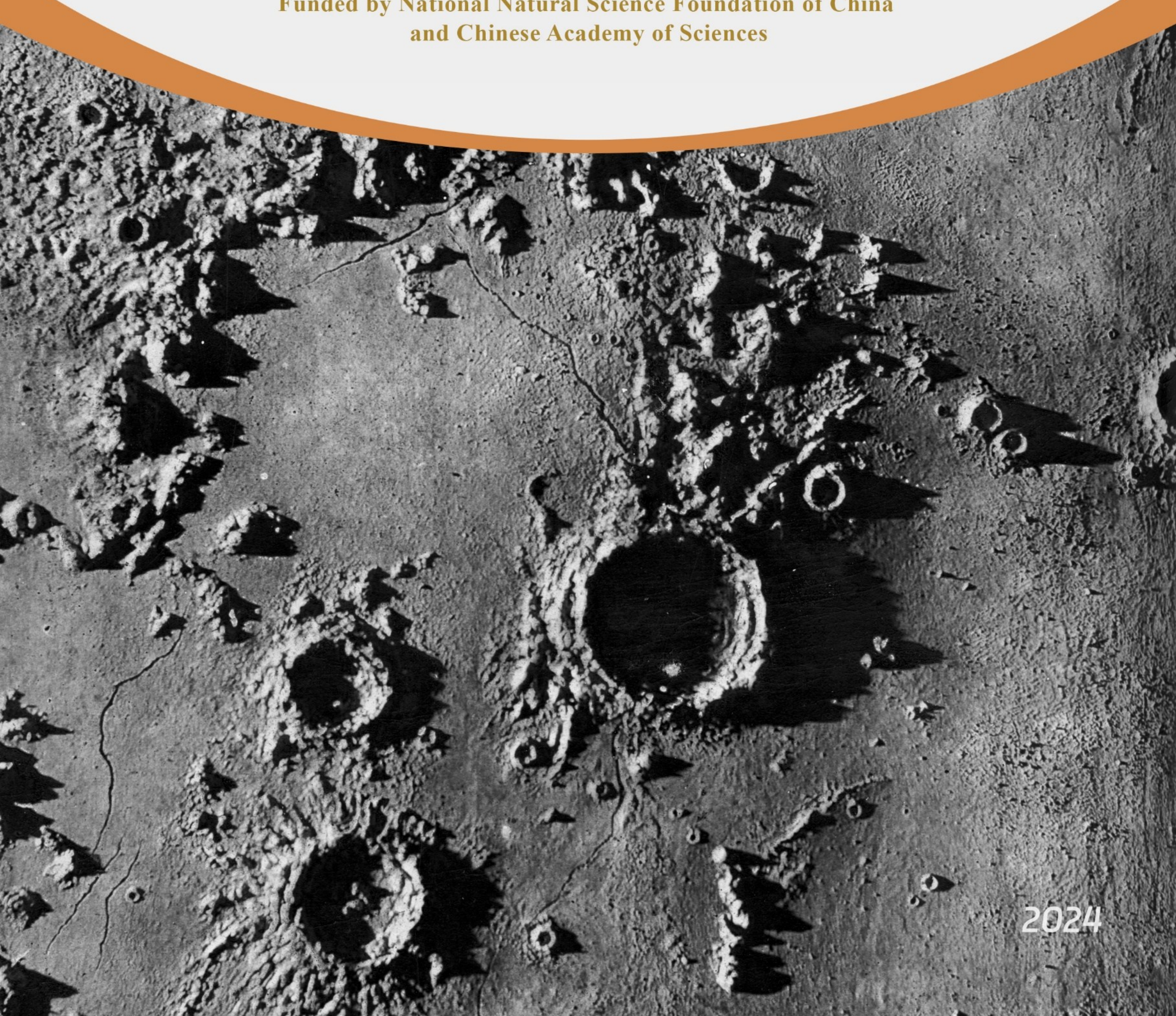

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Report Writing Group

Principal Investigator
LI Xianhua
Institute of Geology and Geophysics, Chinese Academy of Sciences

Main Participants

LIN Yangting, YANG Wei, ZHANG Hui, ZHANG Jinhai, HU Sen, LIN Honglei, DU Aimin, HE Huaiyu, YUE Zongyu, GOU Sheng, HE Yuyang
Institute of Geology and Geophysics, Chinese Academy of Sciences

LIU Jianzhong, LI Xiongyao, LIU Yun, YANG Jing, ZENG Xiaojia
Institute of Geochemistry, Chinese Academy of Sciences

LIU Yang, XU Lin, ZHANG Xianguo, GUO Dijun
National Space Science Center, Chinese Academy of Sciences

HE Hongping, WANG Guiqin, ZHU Jianxi
Guangzhou Institute of Geochemistry, Chinese Academy of Sciences

CAO Jinbin, LIU Hong
Beihang University

HUI Hejiu, ZHANG Aicheng
Nanjing University

XIAO Long, HUANG Jun
China University of Geosciences

QIN Liping, WANG Yuming
University of Science and Technology of China

DI Kaichang, LIU Guang
Aerospace Information Research Institute, Chinese Academy of Sciences

XIAO Zhiyong
Sun Yat - Sen University

KANG Zhizhong
China University of Geosciences, Beijing

LONG Mian
Institute of Mechanics, Chinese Academy of Sciences

DENG Yuanyong
National Astronomical Observatories, Chinese Academy of Sciences

LING Zongcheng
Shandong University, Weihai

FA Wenzhe
Beijing University

ZHANG Zhaofeng
Chengdu University of Technology

ZHANG Peng, MOU Lingli
Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences

Abstract

Lunar exploration is deemed crucial for uncovering the origins of the Earth-Moon system and is the first step for advancing humanity's exploration of deep space. Over the past decade, the Chinese Lunar Exploration Program (CLEP), also known as the Chang'e (CE) Project, has achieved remarkable milestones. It has successfully developed and demonstrated the engineering capability required to reach and return from the lunar surface. Notably, the CE Project has made historic firsts with the landing and on-site exploration of the far side of the Moon, along with the collection of the youngest volcanic samples from the Procellarum KREEP Terrane. These achievements have significantly enhanced our understanding of lunar evolution. Building on this foundation, China aims to achieve its first crewed lunar landing by 2030, leveraging astronauts' advantages to advance lunar exploration. Moving forward, the country will further integrate crewed and uncrewed missions to conduct comprehensive scientific investigations across the entire Moon, marking a new era of scientific exploration and utilization of the Moon. This report explores the benefits of crewed lunar exploration while leveraging synergies with robotic exploration, refining fundamental lunar scientific questions that could lead to significant breakthroughs and proposing the respective engineering and technological requirements. This research lays a crucial foundation for defining the objectives of future lunar exploration, emphasizing the importance of crewed missions and offering insights into potential advancements in lunar science.

Content

1. The Strategic Importance of Scientific and Applied Research for Crewed Lunar Exploration

Modern civilization has journeyed from the Age of Discovery to the Age of Air and Space. Each era brought about significant progress and transformations in science, technology, and economics. Now, humanity has embarked on a thrilling new chapter, venturing beyond near-Earth space to explore the vast cislunar and deep space realms. We are standing at another pivotal moment in history. The Apollo program's grand success and lasting impact were fueled by the scientific discoveries and research accomplishments it made possible. The success of a series of increasingly complex Chang'e missions, marked by the "orbiting, landing, and returning" of lunar probes, has made China the third nation to possess the capabilities of returning samples from the lunar surface. Lunar and deep space exploration is a major strategic priority for China's plans for scientific and technological developments. China has officially announced a preliminary plan for crewed lunar exploration, with the goal of accomplishing crewed lunar landing and scientific exploration before 2030.

The scientific and applied research for the crewed lunar exploration bears tremendous strategic importance as it provides scientific guidance and enables the objective realization of the missions. In the meantime, China's crewed lunar exploration also faces enormous challenges, considering the incredible legacy of the Apollo program and the competition from the Artemis project. It is an urgent subject for China's Earth and planetary science community to leverage the advantages of crewed lunar exploration and its synergy with the Chang'e project to position China at the forefront of lunar scientific exploration and applied research.

1.1 Scientific Guidance and Objective Realization for National Strategy

General Secretary Xi Jinping noted, "To explore the vast cosmos, develop the space industry, and build China into a space power is our eternal dream." Scientific and applied research for crewed lunar exploration is a key link in accomplishing this goal, providing scientific guidance and enabling objective realization for this strategy. The scientific accomplishments of the Apollo moon-landing program established the framework for modern lunar science. Amidst a new wave of lunar exploration over half a century later, fully leveraging the advantages of crewed lunar exploration to conduct lunar science research will contribute Chinese wisdom to the body of human knowledge.

The equal emphasis on scientific exploration and applied research marks a new transformation of lunar exploration in the new era. The Moon is a new frontier for long-term sustainable development for humanity. It serves as a base and launchpad for humans to venture beyond Earth, our cradle, and enter deep space. The Moon possesses unique environmental elements, making it a super platform distinct from artificial Earth satellites and is expected to enable new breakthroughs in areas like astronomical observation, Earth observation, life sciences, and fundamental physics experiments. Meanwhile, in situ resource utilization on the Moon has emerged as a game-changer, which will support the long-term sustainability of lunar bases and turn the Moon into a launching pad for further exploration into deep space.

1.2 A Frontier and Commanding Height of Scientific and Technological Development

Lunar and deep space exploration, as exemplified by crewed lunar exploration, has always been a frontier and commanding height of scientific discovery. The Apollo Moon landing missions made ten major discoveries about the Moon [*ref-1*], establishing the main theories and hypotheses about lunar formation and evolution. From there on, planetary science has extended the research discipline of traditional Earth sciences to another dimension, and it is a world-wide consensus now that comparative planetology is an ultimate direction for the future development of Earth sciences. However, the nine landing and sampling sites of the Apollo and Luna programs represent only a very small portion (about 4% ~ 8% for ideal representativeness) of the lunar surface, mostly in low latitude regions on the nearside. Chang'e-5 landed and sampled the youngest basalt from a region far from the previous sites, making a disruptive new discovery about recent volcanic activities. The new wave of lunar exploration, especially crewed lunar exploration, holds the promise of groundbreaking discoveries that could reshape our understanding of the Moon, potentially establishing a whole new framework for lunar science, and serving as an opportunity for China to become a space science and technology powerhouse.

Space technologies are the foundation and safeguard for human activities on Earth, Moon, and deeper space. A key feature in the development of planetary science is the mutual support between it and space technology. The scientific and applied research for lunar exploration serves as the scientific guidance and objective realization for crewed lunar exploration. The Apollo era developed a suite of technologies for crewed lunar landing, including more powerful and reliable rockets and launch systems, efficient and dependable energy systems, advanced design and manufacturing techniques for spacecraft, and precise real-time deep space navigation, measurement and control communication. The implementation of a new crewed lunar exploration project would act as a powerful catalyst, significantly accelerating advancements in space technologies.

1.3 A Driver of the Sustainable Development of Global Economy and Society

Crewed lunar exploration can greatly facilitate the development of economy and society. At its peak, the Apollo program involved over 300,000 personnel. 1,000 of the over 3,000 patented technologies from the program have been applied for civilian purposes, with long-term economic return ratios up to 1:7–8 [*ref-2*]. The Apollo program demonstrated America's enterprising spirit in pioneering space on behalf of humanity, and its tremendous social impact has been unmatched by any other program [*Monastersky*, 2009]. China's crewed lunar exploration will also ignite progress in various scientific and technological fields, leading to significant societal benefits. It will greatly stimulate the interest in science for the youth not only in China but also in the entire world, enhance the scientific literacy of humanity, demonstrating China's responsibility as a major power.

1.4 Promoting the Integration of Planetary Science and Earth Science, and the Advancement of Natural Science Disciplines

The modern lunar formation theory holds that the Moon formed from the collision between a protoplanet and the early Earth [*Canup and Asphaug*, 2001; *Stevenson*, 1987; *Wiechert et al.*, 2001], an event that also dramatically transformed the Earth. The early traces on Earth have been severely obscured, if not completely erased, by later geological activities, while early asteroidal and cometary impacts and solar radiation of the Earth-Moon system have been well recorded on the lunar surface. New discoveries and achievements from lunar exploration provided fresh perspectives on understanding Earth's formation and evolution [*Day et al.*, 2007; *Dickey et al.*, 1994; *Jacobson et al.*, 2014; *Johnson et al.*, 2022; *Lagos et al.*, 2008; *Schönbächler et al.*, 2010; *Wood and Halliday*, 2005; *Yuan et al.*, 2023].

The scientific and applied research for crewed lunar exploration stands out for its multidisciplinary approach. Lunar and Earth science research share noticeable similarities in techniques, platforms, research methods, and ideas. It is both an opportunity and a historic responsibility for Earth science researchers to conduct scientific research based on crewed lunar exploration, especially assisting astronauts in conducting lunar surface geological surveys, sample collection, laboratory analyses of returned samples, and interpretation of detection data. The crewed lunar exploration based scientific research will facilitate the synergy of China's planetary science and Earth science, ushering Earth science into a new phase. In addition to planetary and Earth science, this collaboration also encompasses astronomy, life sciences, physics and other disciplines. Besides space technologies, lunar applications also involve the R&D of diverse new technologies including energy, communications, intelligent manufacturing, materials, and in situ resource utilization.

2. Key Scientific Issues

The Moon is the most extensively explored and best understood extraterrestrial body. However, due to engineering and technical constraints, there are still five major deficiencies in our understanding of the Moon: (1) temporally, they were limited to samples formed in the "middle age" era, lacking samples formed in the "ancient" and "young" periods; (2) spatially, the "central part" of the nearside of the Moon was a focus, neglecting areas such as the "farside" or the "north and south poles"; (3) in terms of depth, there was an inability to explore deeper into the "interior," including deep lunar regolith and mantle; (4) for samples, only "relocated rocks or boulders" were collected, resulting in a lack of samples from native rock outcrops; (5) the explored areas are "scattered," lacking the "integration and continuity coverage of traverse and regions," such as through lava flows or across different strata. China's crewed lunar exploration will be able to achieve major breakthroughs and establish a new modern framework for lunar science by identifying key scientific issues for understanding lunar formation and evolution from these deficiencies, tackling key technologies and innovating exploration strategies.

China's crewed lunar exploration program consists of two main stages. The first stage is a crewed lunar landing mission. The landing sites are located in the region within 20 degrees north to south latitude on the nearside of the Moon, similar to the sampling sites adopted by the Apollo and Luna projects, situated within the Procellarum KREEP Terrane (PKT). The landing site of Chang'e-5 was at 43 degrees north latitude, also within the PKT, but with rocks about one billion years younger than Apollo samples. China's first crewed lunar landing faces formidable challenges against this backdrop. The second stage, currently under discussion, focuses on large-scale lunar geological investigations. Through the research and development of a high-performance mobile lunar laboratory, this stage will feature the first-ever thorough investigation of over one thousand kilometers on the lunar surface. Meanwhile, in collaboration with focused missions at key regions and robotic exploration of the Chang'e project will establish a long-term monitoring network across the full Moon. The missions in this stage will mark an unprecedented advanced level of China's lunar exploration capability, providing critical technical support and assurance for establishing a new framework of lunar science. The mobile lunar laboratory will have strong mobility on the lunar surface and can support short-term crew stay. It is also capable of in situ detection, sample collection, processing and preparation, and sample analyses along their routes. Therefore, it is necessary to fully leverage the complementary advantages of crewed and robotic exploration missions and identify key scientific issues for crewed lunar exploration, considering the engineering constraints and strengths of the two stages.

The equal emphasis on scientific exploration and applied research marks another prominent change in lunar exploration in the new era and an inevitable leap for humanity's expansion into cislunar space and deeper space. Compared to Earth orbits, the Moon offers unique characteristics like ultra-high vacuum, platform stability, low seismic activities, low gravity and weak magnetic fields, making possible unrivaled platforms for astronomical observation, monitoring global phenomena of Earth, and basic science experiments. Meanwhile, research has to be pursued in areas like lunar in situ resource utilization and lunar-surface life science to sustain long-term lunar base operations and ensure the survival and activities of astronauts on the lunar surface.

2.1 Exogenic Processes for Lunar Evolution

2.1.1 Interaction between radiation particles and lunar surface and the mystery of lunar swirls

Particle radiation is a major exogenic factor determining the habitability of Earth, Mars and other planets and a key element of the research of the space environment of the Earth-Moon-Sun system. Meanwhile, the lunar surface environment and its evolution are critical considerations in future lunar base construction and operations, ensuring safety aspects of astronaut activities on the lunar surface. The interaction between the radiation environment and the lunar surface mainly involves particles reaching the lunar surface (composition, energy and flux) under different spatial and temporal conditions, lunar morphology and electromagnetic field, as well as lunar regolith properties and composition (Figure 1).

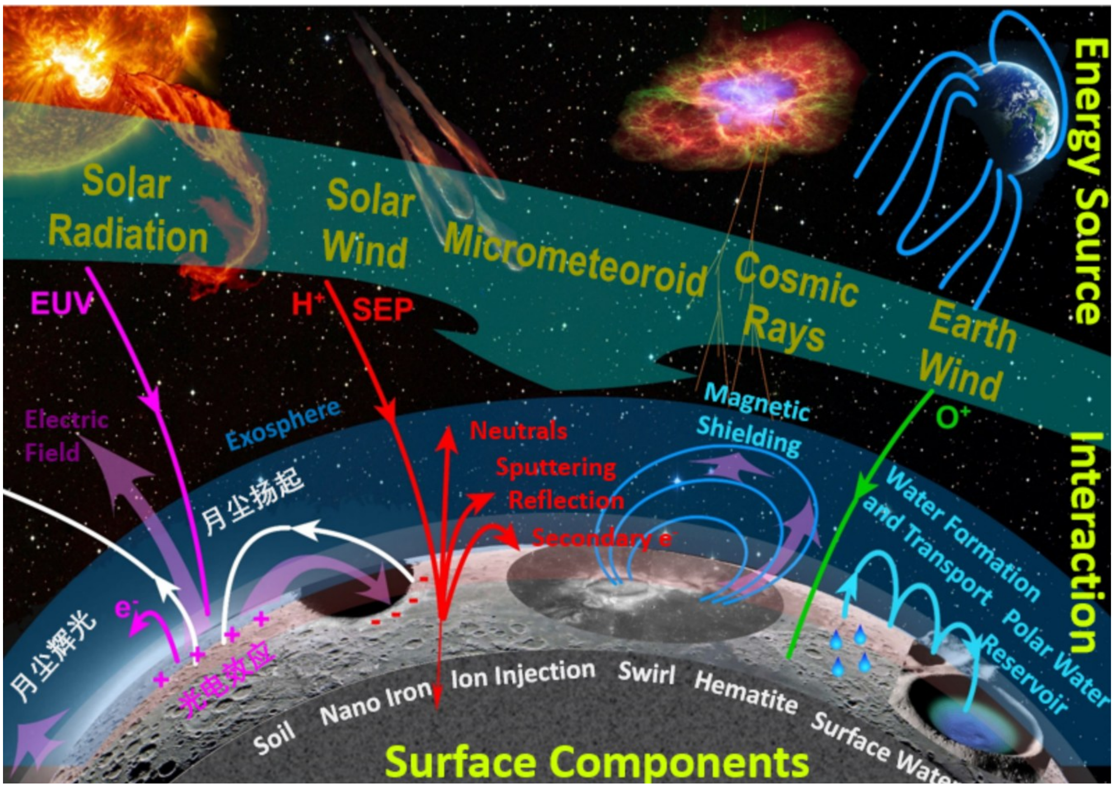


Figure 1. Interaction between particles and the lunar surface. Radiations reaching the lunar surface include solar EUV, solar wind and highly energetic particles, cosmic rays, micrometeorites, and possibly Earth wind. Their effects include dust migration (levitation and glow), secondary radiation, and changes in surface composition and physical properties (albedo, swirls, lunar regolith, nanophase iron, H, He and other ion implantation). These processes are modulated by the surface electric field and local magnetic anomalies.

Key scientific issues:

(1) The origin of lunar swirls: the microscopic morphology, crystal structure, composition and physical properties of lunar surface materials (lunar regolith) change (in a process called space weathering) due to long-term bombardment by various types of particles. One notable result of space weathering is the alteration of lunar regolith's optical properties. High-resolution optical images reveal large bright spots (swirl) in some regions of the Moon [*Denevi et al.*, 2016; *Hemingway and Garrick-Bethell*, 2012] and exhibit complex brightness patterns on lava flow surfaces of the same periods. The origin

of swirls remains an unsolved mystery about the lunar surface, requiring interdisciplinary research.

(2) Fine structures and origin of lunar magnetic anomalies: The Moon has no global intrinsic magnetic field, and only localized magnetic anomalies exist with strength up to hundreds of nT, which can effectively shield the solar wind and form locally shielded environments. The magnetic anomaly data have mainly be detected by satellites, lacking information of detailed 3D structures of the mini-magnetospheres. The origin of lunar magnetic anomalies is a topic of debate among scientists. Some suggest that the magnetic shielding of the solar wind has caused the swirls, but the two do not match completely in terms of spatial distribution [*Richmond and Hood*, 2008]. Others relate magnetic anomalies to asteroid impacts, but there is no clear spatial association between them.

(3) Spatiotemporal changes in the lunar environment: The lunar surface is continually bombarded by solar wind, solar energetic particles, cosmic rays, etc. What are the composition, flux and velocity of these particles? How do they vary over time across different longitudes, latitudes and terrains on the lunar surface? How do these particles, especially high energy particles and cosmic rays, interact with lunar surface materials? The composition and flux of resulting secondary particles are also mysteries.

(4) Lunar dust levitation and migration: Apollo astronauts observed the horizon glow on the Moon, which was interpreted to be scattered sunlight by floating dust. However, neither orbital remote sensing [*Horányi et al.*, 2014; 2015] nor surface surveys and sample returns have observed dust levitation and migration on the Moon under natural conditions. Does natural lunar dust levitation and migration occur on the lunar surface? What are the particle size distribution, height and flux for the naturally lofted dust? What are the external conditions necessary for dust levitation? What's the mechanism giving rise to the Moon's horizon glow?

(5) Presence or absence of Earth wind: Upward flux of particles from Earth's ionosphere/upper atmosphere form ion flows in the magnetosphere and bombard the lunar surface together with the solar wind, known as "Earth wind". Observations suggest the Earth wind mainly comprises ions like H^+、O^+、NO^+、N^+、and O^{2+}, whereas the solar

wind consists of H^+ and He^+ ions. However, whether the lunar surface is irradiated by the Earth wind is an scientific issue needed to be tested [*Ozima et al.*, 2005]. In geological history, what effect did the Moon have on the Earth wind when the Moon was closer to the Earth? Can the effect of the Earth wind be detected from lunar regolith cross-sections to infer the evolution of the Earth's ancient atmosphere composition and magnetic field?

Current state of researches: (1) Scientists have tried to explain the origin of lunar swirls by suggesting differences in space weathering due to deflection of solar wind particles, cometary impacts exposing fresh subsurface regolith of the Moon, and separation of lunar regolith particles caused by lunar dust migration. Orbital probe data showed some correlation between lunar swirls and magnetic anomalies. The degree of space weathering is generally low in the swirl regions, which appear to be brighter with stronger ferrous absorption. These observations support both the view of space weathering differentiation and that of fine-grained or feldspathic dust coverage. By now, no in situ detection has been conducted to identify the composition and space weathering characteristics in regions with magnetic anomalies and light/dark belts of swirls. (2) Fine structures and origin of lunar magnetic anomalies. Regions with magnetic anomalies have been detected by orbital probes, but without in situ detection, the fine structures are only simple models based on interactions between the solar wind and the lunar surface. (3) Spatiotemporal changes in the lunar environment. Interactions between space particles and the lunar surface have resulted in remarkable differences between the radiation environment on the Moon and the cislunar space environment. Current detection lacks long-term monitoring of the composition, energy and flux of space particles on the Moon, especially secondary particles. (4) Lunar dust levitation and migration. The origin of the lunar horizon glow remains unsolved, commonly attributed to lofted dust without observational verification. Surveys by the Chang'e-3 and Chang'e-4 probes did not reveal obvious effects of dust deposition on optical sensors and solar panels. (5) Presence or absence of Earth wind. This scientific issue is studied largely based on theoretical predictions and model constructions. The M^3 spectral data from Chandrayaan-1 revealed evidence of lunar surface water and hematite [*Li et al.*, 2020]. It may be interpreted as the result of bombardment by O^+ ions of the Earth wind, but lacking validation by in situ detection.

Significance: Lunar surface radiation particles and their interactions with lunar regolith are not only urgent fundamental space science issues pending solution but also critical considerations supporting lunar exploration as well as the construction and long-term operations of future Moon research bases. The interactions between radiation particles and lunar surface materials have dramatically altered the properties of lunar surface materials, serving as the basis for correctly interpreting remote sensing data, inferring surface composition and physical properties of substances across the lunar surface, and inferring the lunar surface exposure history recorded in lunar regolith cross-sections. The H^+ and He^+ ions from the solar wind constitute a major part of the particles bombarding the lunar surface and are implanted into lunar regolith. They are important resources on the Moon. By comprehensively detecting and studying the lunar surface environment, we may unravel scientific mysteries like the origin of lunar swirls, magnetic anomalies and their fine structures, lunar dust levitation and migration, presence of the Earth wind, and early Earth atmospheric composition and magnetic field.

2.1.2 History of meteoritic impacts and solar radiation recorded in lunar regolith cross-sections

The major exogenic processes influencing the Earth-Moon system's evolution are meteoritic impacts and solar radiation. Early intensive impacts with high flux directly shaped the interior structure evolution of both Earth and the Moon, while the impact flux variations were largely recorded by means of spatial distributions of impact craters on the surface. With diminishing flux with time, later impacts have remained a key factor for the Earth's habitability. In addition, variations in impact flux were directly related to orbital changes of Solar System bodies, preserving records for the dynamical evolution of the Solar System. Crater size-frequency distribution is also widely used for determining model ages of geologic units on both the Moon and other planetary bodies. Impact records are also widespread in lunar regolith by means of melt spherules and residual impactor fragments. Analyzing impactor fragments in different-aged samples can reveal the impact flux of different types of impactors. On the other hand, lunar regolith samples at different depths were repeatedly exposed due to impact gardening and they record the history of radiation by various energetic particles. Theoretically, deep cores of lunar regolith materials are capable to provide complete records on the impact flux, history of solar and cosmic ray activities, and other major astronomical events in the Earth-Moon space over 4 billion years (Figure 2).

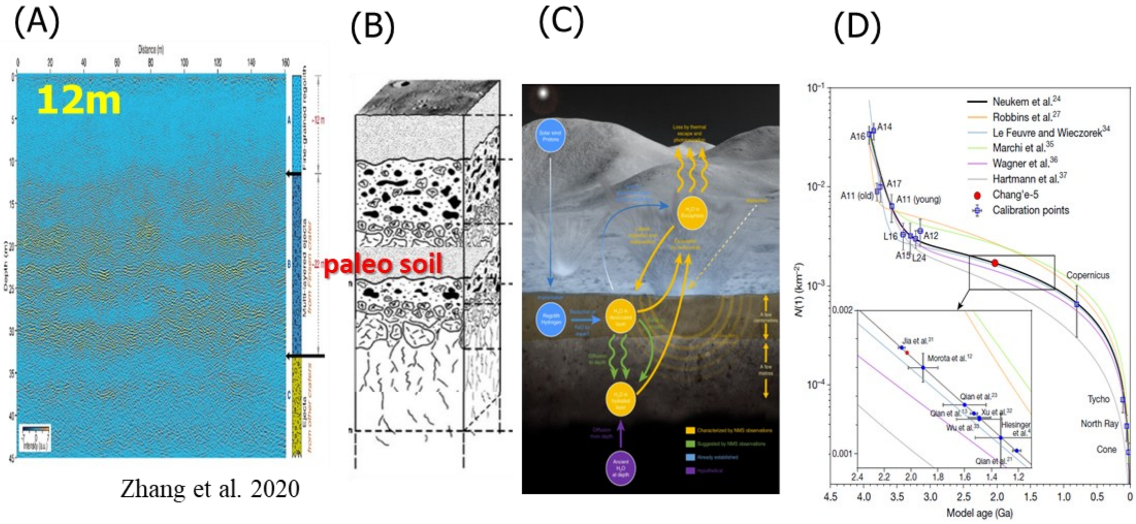


Figure 2. Exogenic evolution of the Earth-Moon system recorded on lunar surface. A) Lunar regolith and shallow structures detected by radar [*Zhang et al.*, 2020]; B) Schematic sketch of lunar regolith and shallow structures [*Heiken et al.*, 1991]; C) Cycles of solar wind implantation in lunar regolith [*Schörghofer et al.*, 2021]; D) Temporal variations of impact flux on the Moon [*Li et al.*, 2021].

Key scientific issues:

(1) Lunar regolith formation processes. Lunar regolith is formed by impact gardening and space weathering, as larger impacts episodically expose fresh blocks and distribute them across the surface. Substantial mixing of materials with different provenances has occurred during the formation of lunar regolith. Tracking the origin and protolith of lunar regolith has been a persistent difficulty in the study of lunar surface materials, which also hinders reliable interpretation for the radiation history of regolith at different depths. For example, what was the mixing process during the landing of distal

ejecta formed by young craters like Copernicus and Tycho? Unraveling lunar regolith formation processes, especially mixing of particles with various phases, provides the basis for inferring the historical records of lunar regolith cross-sections.

(2) Types of impactors in the Earth-Moon system and their variations over time. Unlike the eight planets in the Solar System, small objects have comparatively shorter orbital lifetimes and they might migrate away from the asteroid and/or Kuiper belt to become near-Earth objects, which may eventually cause impacts on other planetary bodies such as the Moon and Earth [*DeMeo and Carry*, 2014]. Dynamical simulations for orbits of Solar System objects suggested early migration of giant planets like Jupiter, injecting outer Solar System bodies inward while ejecting inner solar system objects outward [*Morbidelli et al.*, 2005; *Tsiganis et al.*, 2005; *Walsh et al.*, 2011]. This mechanism, with various versions of migration scenarios, has been used to explain the hypothesized Late Heavy Bombardment around ~ 3.9 Ga [*Gomes et al.*, 2005]. Impactor fragments in lunar regolith that has different exposing history and the formation history of lunar impact structures provide record on the history impact flux of various sources of impactors. These results shall provide a critical constraint on the possible history of orbital dynamics of Solar System bodies.

(3) Early solar radiation characteristics and their variations over time: Solar wind and energetic particles directly implant subjects into the lunar surface or interact with lunar surface substances. Therefore, lunar regolith has served as a unique solar sample collector and recorder. Analyses of samples from complete regolith cross-sections will inform possible changes in solar radiation intensity and composition over 4 billion years.

(4) Cosmic ray radiation history and high-energy astronomical events: Nuclear reactions of high-energy cosmic rays with lunar surface substances produce radioactive or stable isotopes. Nearby supernova explosions may eject neutron-rich nuclei into the solar system, getting deposited on the lunar surface. Thus, regolith cross-sections may have recorded the occurrence of high-energy astronomical events near the solar system over 4 billion years.

(5) Implantation of solar wind hydrogen and lunar surface water

migration/circulation: Solar wind implantation is an important source of lunar surface water (hydrogen in various forms). How do implanted H^+ ions of the solar wind interact with lunar regolith materials? Which form do the H^+ ions become and get fixed? What are the processes and dynamic mechanisms of hydrogen implantation and loss by heating? Has hydrogen migrated vertically into regolith cross-sections or laterally along with latitude?

Current state of researches: Thickness of lunar regolith generally exhibit a positive correlation with the surface exposure age. The landing site of Chang'e-4 is about 3.6 Ga old with a regolith thickness of about 12 meters [*Zhang et al.*, 2020]. The regolith drill cores (with a maximum length of 3.05 meters) acquired by Apollo missions represent a small portion of the regolith column. Analyses of the regolith drill cores showed enriching correlation relationship of various physical properties within the first one meter of depth, and the increased homogeneity at larger depths possibly reflects stronger early mixing processes. Quantitative model constraints that are consistent with sample analyses results are still lacking for studying substance migration and mixing of lunar regolith cross-sections.

Studies on lunar regolith have focused on two aspects: the composition of the Sun and space weathering effects. The findings of ^{16}O-rich oxygen isotopic composition in lunar regolith have overturned previous views about isotopic anomalies in the solar system [*Guo et al.*, 2022; *Hashizume and Chaussidon*, 2005; *McKeegan et al.*, 2011]. Space weathering has altered the visible to near-infrared spectral properties of lunar regolith through the formation of glass, metallic Fe nano-particles, ferrous iron, sulfides, and He bubbles on grain surfaces [*Gu et al.*, 2022; 2023; *Li et al.*, 2022]. Orbital spectroscopy shows H^+ implanted by solar wind may be the primary source of lunar surface water, and its abundance increases toward higher latitudes [*Li and Milliken*, 2017]. However, scientists are still unable to understand the migration and circulation mechanisms of water in vertical regolith cross-sections and between regions of different latitudes. Tracking with siderophile elements indicates the addition of about 1% asteroid substances [*Zong et al.*, 2022], but a very small number of actual asteroid remnants have been identified to date [*Li and Milliken*, 2017]. The understanding of cosmic ray interactions with lunar surface substances is still limited to cosmogenic radioisotopes and exposure ages and histories reflected by them.

Significance: Lunar regolith is the most ubiquitous and unique surface substances on the Moon. It is the direct subject for almost all lunar remote sensing activities so far (especially orbital probes). On the other hand, lunar regolith (drill cores) provides the most complete record of impacts by asteroids of all sizes (from hundreds of kilometers to sub-microns) and interactions of various radiative particles and the lunar surface over 4 billion years. These exogenic processes were not only important to the early evolution of the early Earth and terrestrial planets but also key factors determining the habitability and evolution of these planets. Moreover, lunar regolith is the primary subject for in situ resource utilization on the Moon. Studies of the key scientific issues mentioned earlier provide important support for the project's implementation.

2.1.3 Formation and effects of major impact basins

Impacts by small objects have been key processes in planetary evolution. About 74 impact basins larger than 200 km in diameter have been identified on the Moon [*Neumann et al.*, 2015], with the largest South Pole-Aitken (SPA) basin spanning 2,400 kilometers and reaching about 12 kilometers deep. Impacts have dramatically modified the topographical features and composition of the lunar surface. Basin-forming events have global effects, excavating and ejecting deep lunar substances [*Melosh et al.*, 2017]. Transient cavities caused by impacts could melt and mix lunar substances up to 400 kilometers in depth [*Melosh et al.*, 2017]. Impacts also relate to volcanic activities. Strong shock waves can affect tectonic activities in antipodal regions (Figure 3).

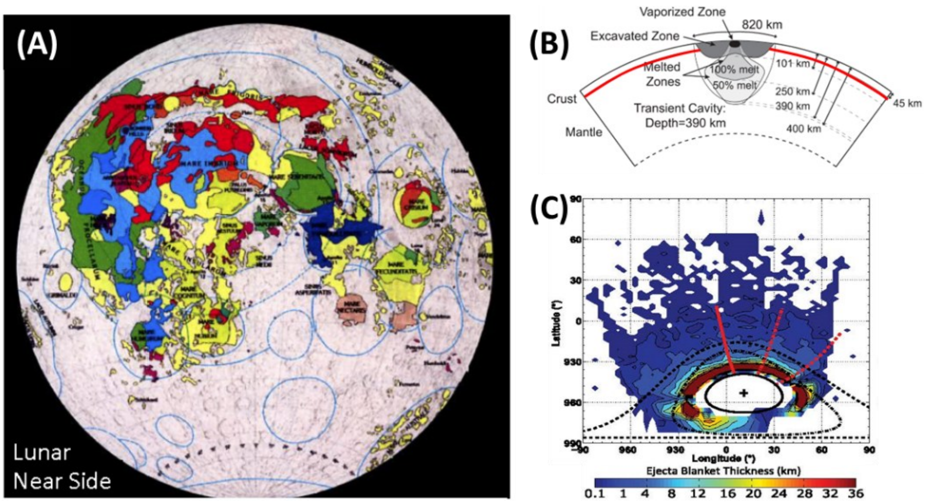


Figure 3. Formation and effects of major impact basins. A) Spatial relation between impact basins and basalt fillings of lunar maria [*Dhingra*, 2018]; B) Modification of the Moon's crustal and upper mantle compositions by major impacts [*Hurwitz and Kring*, 2014]; C) Substance migration and mixing due to excavation and ejecta by impacts [*Melosh et al.*, 2017].

Key scientific issues:

(1) Formation mechanisms of major impact basins: These involve 3D structures of impact basins and compositions and formation mechanisms of central peaks and peak rings; excavation depths of basins, rock compositions and structures of basin floors; basalt fillings and their relations to impact events; relations of gravity anomalies with structures of basins; spatial distributions and compositions of ejecta blankets and lunar rays.

(2) Effects of major impacts on early lunar evolution: These involve excavation, mixing and melting of the Moon's crustal and possibly mantle substances; distribution of Th-rich rings around the Imbrium basin and relation to events leading the Imbrium basin's formation; possible effects of heavy impacts in antipodal regions, especially possible relations of the SPA basin's formation with the Oceanus Procellarum's origin and the PKT's formation.

(3) Occurrence of Late Heavy Bombardment around 3.9 Ga: Many impact basins formed around 3.9 Ga, but the morphological features of many basins have become obscure due to overlapping and alteration caused by later impacts. It is important to identify all basins, if possible, then determine isotope ages for major ones, and quantify the earliest impact flux to evaluate evidence of Late Heavy Bombardment events.

Current state of researches: Human knowledge of major impact basins on the Moon has mainly come from orbital remote sensing of morphological features, compositions and distributions of substances, and the lunar gravity field. Major impacts may alter crustal porosity [*Huang et al.*, 2022], and the distribution of basins by size relates to the Moon's crustal thickness and temperature [*Miljković et al.*, 2013]. Major impacts may expose deep mantle substances, as olivine-rich substances distribute around some impact basins [*Miljković et al.*, 2015]. However, we are unable to conduct in situ validation of orbital probe data or acquire new insights from sample analyses as humans have not conducted cross-section surveys across impact basins or collected any samples for this purpose. For example, the origin and implications of mascons identified by GRAIL [*Melosh et al.*, 2013] are not understood. Central peaks and peak rings are hypothesized to form from deep material uplift after impact pressure release, but some models suggest they are possible remnants from the impacting objects [*Yue et al.*, 2013]. Moreover, most impact basins have not been dated with isotopic methods. More impact-melt samples have to be collected from the basins to precisely determine the ages.

Significance: The first crewed lunar exploration is expected to conduct the thorough investigation of major impact basins to obtain standard models for the basins' 3D structures. It will reveal the early effects of impact events on lunar volcanism and tectonics and establish mobilization and mixing models of lunar surface materials. Determining isotopic ages for basin formation will quantify the impact flux by the earliest small objects in the cislunar space, calibrate crater chronology models for dating ancient geologic units (older than 4 Ga), evaluate evidence for Late Heavy Bombardment events about 3.9 Ga, and provide key constraints for planetary orbital dynamical evolution in the solar system.

2.2 Lunar Endogenic Evolution

2.2.1 Spatiotemporal variations of lunar volcanism and long-term evolution of mantle source regions

Lunar mare basalt eruption represents the most significant volcanism on the Moon, with their scale reflecting the thermal state and evolution of the Moon. Meanwhile, basalts are products of partially melted mantle source regions, so they carry information on the mantle chemical composition, physical state, etc., serving as deep lunar probes (Figure 4).

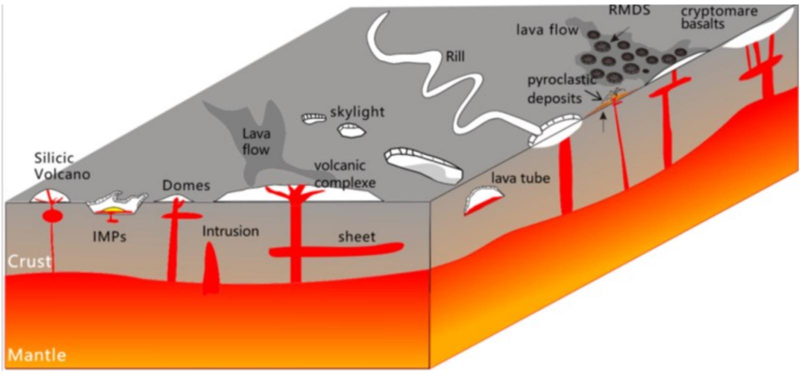


Figure 4 Lunar volcanic activities. Types of volcanic activities and associated structures. Magmas originate from partially melted mantle, carrying information from the deep mantle.

Apollo missions returned samples of basalts formed about 3.0 ~ 3.9 Ga. Chang'e-5 recently brought back the youngest basalt samples (about 2.03 Ga) from lunar maria available to date. Crater size-frequency distribution dating indicates massive volcanism on the Moon may persisted until about one billion years ago, with small eruptions possibly lasted to millions of years ago. All sample return missions landed at sites on the nearside of the Moon, but the Moon has a clear hemispheric dichotomy. That is, most of the nearside is covered by lunar maria basalts (94% of the total mare area), while the farside is mainly covered by highland anorthosites. Besides basalts, orbital probes have also revealed special volcanic products yet to be studied through in situ investigations and sample returns.

Key scientific issues:

(1) Crystallization and differentiation of basaltic magmas: Degassing and associated isotope fractionation of water and volatiles likely occurred during basalt magma eruption and cooling on the lunar surface, as well as differentiation and crystallization. However, basic issues about basalt magma eruption cannot be answered due to a lack of systematic investigation of the same magma flows and vertical cross-section sampling, and the

absence of observations and samples regarding the crystallization and differentiation of basalt magma, degassing of water and volatiles, etc.

(2) Origin and evolution of basaltic magmas: The intensity of mare basalt eruption weakened over time. Studies with Chang'e-5 samples have extended the period of eruption from 3.0 ~ 3.9 Ga to 2.03 Ga [*Li et al.*, 2021]. However, several outstanding questions remained. How old are the oldest and youngest lunar basalts? What are the origin depths and mechanisms for different types of basaltic magmas? How did associated processes like partial melting, differentiation, crystallization, eruption, and cooling occurred? What are the isotope fractionations during these processes? How did the types and sizes of basalt, along with their patterns and mechanisms of change over time?

(3) Formation mechanisms of special volcanic features: Irregular mare patches may represent extremely young small-scale volcanic activities (about 100 Ma) [*Braden et al.*, 2014] or collapse of Imbrian volatile-rich vents [*Qiao et al.*, 2019; *Stopar et al.*, 2019]. Other unique volcanic features include silicic domes, possibly existed granite intrusive, etc. What are the formation mechanisms and implications of silicic volcanic domes? Are there highly fractionated rocks like granites on the Moon [*Siegler et al.*, 2023]? Volcanic glass samples brought back by Apollo missions show their primary magma has high contents of water and volatiles [*Saal et al.*, 2008]. Orbital probes have found dark mantle deposits [*Head and Wilson*, 2017] in Rima Bode with possibly water-rich spectral signatures [*Milliken and Li*, 2017]. What are their compositional characteristics and formation mechanisms? How did the mechanisms for volcanic eruption modes changing over time in the same geologic unit? Can we find out the origins and formation depths of some shield volcanoes on the Moon [*Spudis et al.*, 2013]?

(4) Heterogeneous spatiotemporal distribution of lunar volcanism: One of the most striking features of the Moon is the significant difference between its near side and far side. But what causes this unevenness? Does it reflect variations in the internal structure and thermal history between the two sides, possibly related to the distribution of heat-producing radioactive elements?

(5) Compositions and spatiotemporal evolution of lunar mantle source regions:

Improved knowledge of the formation and evolution of basalt will enable better geochemical characterization of their mantle source regions. On this basis, investigations of basalts with diverse spatial and temporal distributions will then reveal the compositions and spatiotemporal evolution of the lunar mantle over time, including changes in the compositions of mantle source regions caused by the melting of basaltic magmas. Did mantle source regions experience degassing and dehydration processes? What are the heterogeneities and homogeneities between mantle materials in different regions and their origins?

Current state of researches: All current sampling missions have been concentrated in a very limited area on the near side of the moon. They have not involved the detection and sampling of basalt outcrops in their natural state, nor have they systematically explored and sampled along the flow direction of the same lava. This significantly limits our understanding of volcanic activity on the moon. In the lunar regolith samples returned by Chang'e-5, most (>90%) of the rock fragments came from the underlying basalts in the landing area, with different structures of the rock fragments representing different depths (e.g. different cooling rates) [*Tian et al.*, 2023]. They still cannot be used to reconstruct exact spatial relations of eruption sequences. Sampling a small area around the landing site makes it difficult to understand the multiple phases of volcanic activity in the same region, and it also fails to reveal the evolution of the mantle source within the same geological structural unit. Research based on Apollo and Chang'e lunar samples estimates that the water content in the lunar mantle source area varies by nearly two orders of magnitude. Moreover, no temporal and spatial variation pattern has been identified [*Hu et al.*, 2021]. Information on ancient basalts (cryptomare basalts), basalts on the farside, pyroclastics, irregular mare patches, and silicic rocks [*Nemchin et al.*, 2009] all are missing in in situ investigations and sampling.

Significance: Volcanic activity is a primary external manifestation of the Moon's internal dynamical evolution and serves as a crucial window for studying the composition and thermal evolution of the Moon's interior. The landing sites of the Apollo program were mainly located in the Procellarum KREEP Terrane (PKT) of the near side of the

Moon, in low-latitude areas, where the collected samples were mostly basalt, aged between 3 to 3.9 billion years. The Chang'e-5 mission collected 1.731 kg of lunar soil, within which the youngest basalt discovered to date, aged 2.03 billion years, was found, challenging previous understandings of young volcanic activity and KREEP rocks. Clearly, systematic and comprehensive exploration and sample return from key areas, such as Rima Bode, and a long-distance geological cross-section of the Moon will address a series of significant scientific questions related to lunar volcanic activity.

2.2.2 Formation of the Procellarum KREEP Terrane and its modification of the Moon

Based on Th distributions combined with the contents of FeO, TiO2, and other elements, Jolliff et al. [2000] identified three distinct geochemical provinces on the lunar surface: the Procellarum KREEP Terrane (PKT), the Feldspathic Highlands Terrane (FHT), and the South Pole–Aitken Terrane (SPA). The PKT, mainly consisting of Oceanus Procellarum and Mare Imbrium, hosts more than 60% of the mare basalts by area and appears to be the most Th-enriched region across the Moon's surface (Figure 5). The decay of high abundance of radioactive elements in PKT, such as U and Th, is generally thought to provide the thermal energy necessary for more recent lunar magmatism [*Borg et al.*, 2004]. However, this traditional model has been challenged by mare basalt samples returned by Chang'e-5 mission. The mantle source region of basalt unit where Chang'e-5 landed shows non-KREEP characteristic. Instead, the high concentrations of Th and other radioactive elements in magma reflect magmatic evolution processes [*Tian et al.*, 2021]. The origin of the extremely young basalts in the PKT remains a mystery [*Chen et al.*, 2023]. In addition, KREEP represents the enrichment of K, Rare Earth Elements (REE), P, and other large-ion lithophile incompatible elements, mainly occurring as geochemical characteristics in mare basalts and impact melt rocks. The Lunar Magma Ocean (LMO) model predicts the existence of KREEP rocks between the crust and mantle of the Moon, but so far, only some KREEP-like rock fragments and breccias were identified in Apollo 12 samples and lunar meteorite Sayh al Uhaymir (SaU) 169 [*Lin et al.*, 2012; *Liu et al.*, 2012].

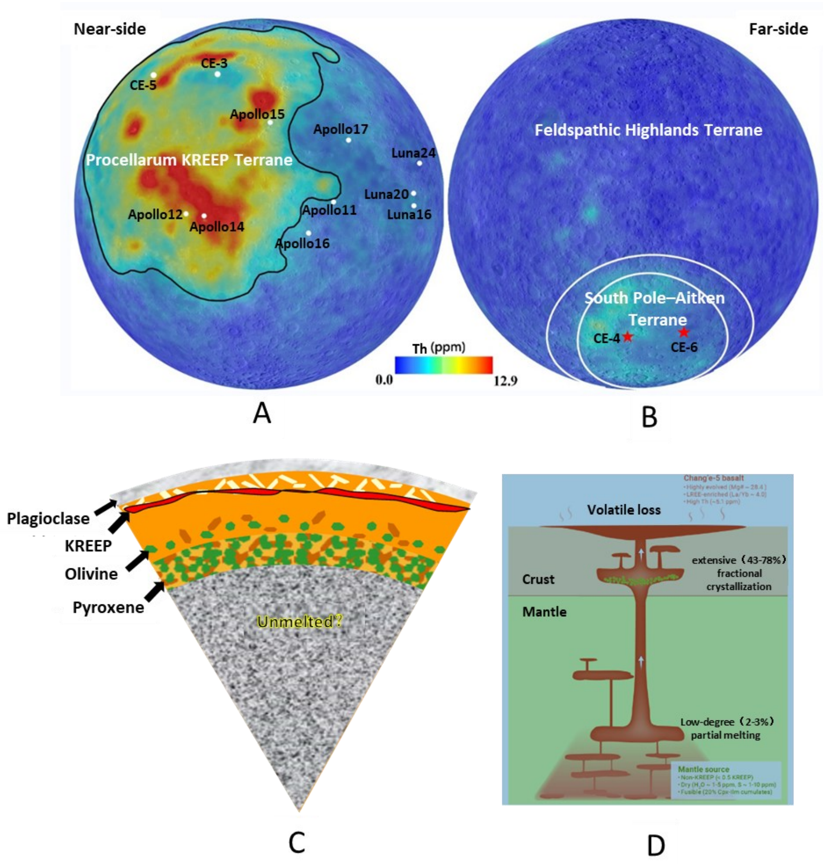


Figure 5. Formation and modification of the Procellarum KREEP Terrane. A-B) Thorium map of the Moon outlining the area of the PKT region. The significant difference between the nearside and farside of the Moon highlights the dichotomy of this earth's satellite; C) Schematic diagram of the Lunar Magma Ocean model illustrating the origin of KREEP components; D) KREEP-like geochemical characteristic generating from partial melting and fractional crystallization processes, modified from [*Chen et al.*, 2023].

Key scientific issues:

(1) Presence or absence of KREEP rocks: The LMO model suggests that the early Moon was covered by a global magma with the depth up to hundreds of kilometers [*Warren*, 1985]. The LMO differentiation formed mafic cumulate mantle and plagioclase-dominated crust, leaving the final residuum extremely enriched in incompatible elements including K, REE, and P (termed urKREEP) and crystallizing KREEP rocks between

them. The presence of pristine KREEP rocks could provide critical evidence for the LMO hypothesis.

(2) Origin of Oceanus Procellarum: Oceanus Procellarum constitutes a major part of the PKT, but its origin remains debatable. Did it form by once or multiple impacts [*Nemchin et al.*, 2009]? Or, was it the result of the antipodal effect from SPA basin-forming impact [*Zhang et al.*, 2022]? Mare basalts commonly occur in impact craters and basins. However, the topography and geomorphology of the entire Oceanus Procellarum region lacks features of large impact basins [*Andrews-Hanna et al.*, 2014].

(3) Spatial distribution and origin of the PKT: The Th-enrichment rings around Mare Imbrium have been explained to be the deposits of KREEP-rich materials excavated and ejected from the lunar interior, while the Th distribution in Oceanus Procellarum exhibits completely different characteristics [*Lawrence et al.*, 2000]. Studies with Chang'e-5 samples indicate high concentrations of Th and other incompatible elements could derived from high-degree differentiation of magma instead of KREEP components in the mantle. The PKT's origin thus warrants thorough re-investigation.

Research status: The proposal and definition of the PKT are based on the global Th distribution derived from remote-sensing data and Apollo samples' investigation. However, there was no concept of the PKT, even no exploration missions targeting it, during the Apollo program period. KREEP is still a hypothetical geochemical endmember that has not yet been discovered as actual lunar rocks. Studies with Chang'e-5 samples show that high degrees of magmatic differentiation can also produce chemical characteristics similarly to those of KREEP [*Tian et al.*, 2021]. Therefore, it is necessary to reexamine the geological structural significance of the spatial Th distribution, the LMO model, as well as the mineralogy, petrology, geochemistry, and origins of the PKT. In addition, the formation mechanism of Oceanus Procellarum is critically important for the formation and modification of the PKT, but its origin remains disputed. The GRAIL data has revealed that the gravity anomalies surrounding the PKT exhibit polygonal features [*Andrews-Hanna et al.*, 2014], contrary to the expected circular or elliptical shape of a giant impact basin.

Significance: Although the PKT is the most extensively and deeply studied region on the Moon, further research has given rise to even more questions, especially from studies with Chang'e-5 samples, which challenge the existence of KREEP rocks and lead to an urgent need to refine the spatial distribution of the PKT. Therefore, it is necessary to conduct systematic detection and sampling in key areas (such as Th-rich regions with high or low FeO contents) and large-scale lunar geological cross-sections to understand the geological structures as well as the spatial distributions of Th and other elements in the PKT. These efforts are expected to reveal the mechanisms for PKT formation and the origin of the Moon’s asymmetry, revise lunar solidification and differentiation processes, and achieve breakthroughs in lunar science.

2.2.3 Composition and modification of the Moon’s lower crust

The differentiation and crystallization of the Lunar Magma Ocean formed the crust-mantle stratification. The upper crust of the Moon is known to be highland anorthosite exposed on the lunar surface, but understanding of the lower crust is still very limited. Generally, plutonic rocks like Mg-suite are considered to represent the lower crust lithology, potentially recording early modification processes of the primordial crust. They are the key to understanding crustal formation and evolution and investigating the origin of the Moon’s dichotomy (Figure 6).

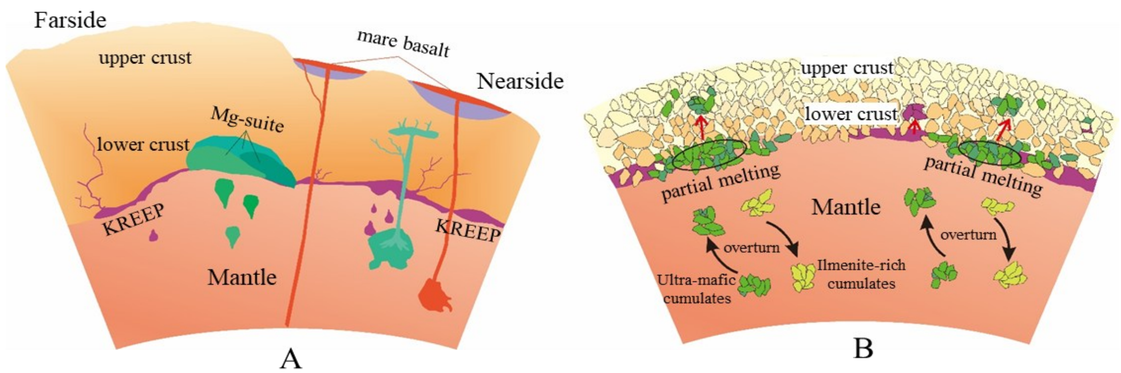


Figure 6. Composition and modification of the Moon's lower crust. A) the crustal structure and basalt formation resulting from the differentiation and crystallization of the Lunar Magma Ocean on the

Moon's nearside and farside. B) mantle overturning and associated partial melting modification of the lower crust [*Xu et al.*, 2020].

Key scientific issues:

(1) Compositional stratigraphy of the Moon's crust: The Moon's crust is about 50 kilometers in depth on average, possibly reaching 70 kilometers in lunar highlands and about 8 kilometers in lunar maria. The Lunar Magma Ocean hypothesis suggests a theoretical model for primordial crust composition, but it lacks evidence from precise seismic data of the Moon and systematic sampling of SPA basins. Therefore, the crust compositional model has yet to be validated.

(2) Origin of the Mg-suite: The Mg-suite formed at deep crustal levels, exhibiting high Mg# (>85) yet enriched in incompatible elements [*Shervais and McGee*, 1998]. These properties contradict traditional magmatic differentiation and crystallization and are considered to be possibly contaminated by the KREEP component [*Prissel Tabb et al.*, 2016; *Shearer and Papike*, 2005]. Its formation mechanisms include interstitial melts carried by uplifting plagioclase, mixing between KREEP and ultrabasic mantle melts [*Papike et al.*, 1997; *Shervais and McGee*, 1998], reaction between early mantle melts and primordial crust [*Nelson et al.*, 2021], etc. On the other hand, based on the Magma Ocean hypothesis, anorthositic crust formed earlier than the Mg-suite of the lower crust, but isotope dating shows similar ages for both types of rocks [*Borg et al.*, 2017; *Borg et al.*, 2015] with their initial εNd values falling in the same range. This contradicts the reaction models between the primordial crust and fluids/melts.

(3) Origin of olivine/magnesium spinel plutonic rocks: Remote sensing data reveals widespread distribution of olivine-rich and magnesium spinel-rich rocks [*Pieters et al.*, 2011; *Sun et al.*, 2017], generally considered to originate from the lunar mantle or associated with uplifting mantle melts [*Prissel Tabb et al.*, 2016]. However, these two rock types are rarely seen among returned samples and lunar meteorites. The origins of these two types of plutonic rocks remain highly controversial, with even extralunar origins being hypothesized [*Yue et al.*, 2013].

(4) Age of lunar crust formation: Lunar core-mantle differentiation occurred around

4.51 Ga [*Halliday and Kleine*, 2006], setting the upper limit for crust formation age. The Sm-Nd ages of olivine and pyroxene from ferroan anorthosite are 4.456 Ga [*Norman et al.*, 2003], while the most ancient lunar zircon age is 4.42 Ga [*Nemchin et al.*, 2009], representing the lower limit of crust formation age. However, ^{146}Sm-^{142}Nd extinct nuclide chronology estimates that the lunar crust formation age is 4.352 Ga [*Rankenburg et al.*, 2006], while the Sm-Nd and Rb-Sr ages of highland rocks mostly fall between 4.34-4.37 Ga [*Borg et al.*, 2015]. Thus, the age of lunar crust formation remains unsettled.

Current state of researches: Lunar plutonic rocks account for less than 5% of Apollo samples, mainly from the landing site of Apollo 16. Spectral data for the whole Moon reveals the distribution of Mg-suite and other plutonic rocks within central peaks of large craters and some impact basins as well as SPA basin floors [*Moriarty and Pieters*, 2018; *Wieczorek and Zuber*, 2001], but no samples of these rocks have been collected. Simulation experiments and calculations demonstrate that the primordial composition of the Moon, especially contents of water and volatiles, has significant effects on the crystallization processes of the Magma Ocean, thus changing crustal thickness and composition [*Lin et al.*, 2017]. Based on the constraints from crustal thickness, simulation results tend to suggest that the Magma Ocean had relatively low content of Al_2O_3 and shallow depth. Regarding composition, Mg# of mafic minerals in anorthosite from the Moon’s farside is, on average, 8% higher than that on the nearside, and heat-producing radioactive elements like Th are concentrated on the nearside. Existing models fail to explain current observational data.

Significance: The composition and modification of the Moon's lower crust remains a major unresolved scientific issue. Existing gaps in understanding are largely attributed to a lack of samples. Systematic investigations and sampling in areas with outcropping olivine-rich, spinel-rich and other plutonic rocks will reveal lower crustal composition, clarify modification processes of the lower crust, and demonstrate mechanisms for the Magma Ocean evolution and origin of the Moon's dichotomy.

Internal Structure of the Moon

2.2.4 Initiation and cessation of the lunar Magnetic Field dynamo and origin of lunar magnetic anomalies

Dipolar magnetic field associates planetary internal dynamics evolution with surface and space processes, manifest the state and motion of the planetary cores, are closely related to thermal evolution, and have been a focus of research in Earth and planetary sciences. On the other hand, intense impacts can also boost or weaken magnetic fields, being key factors of the Moon's surface space (Figure 7).

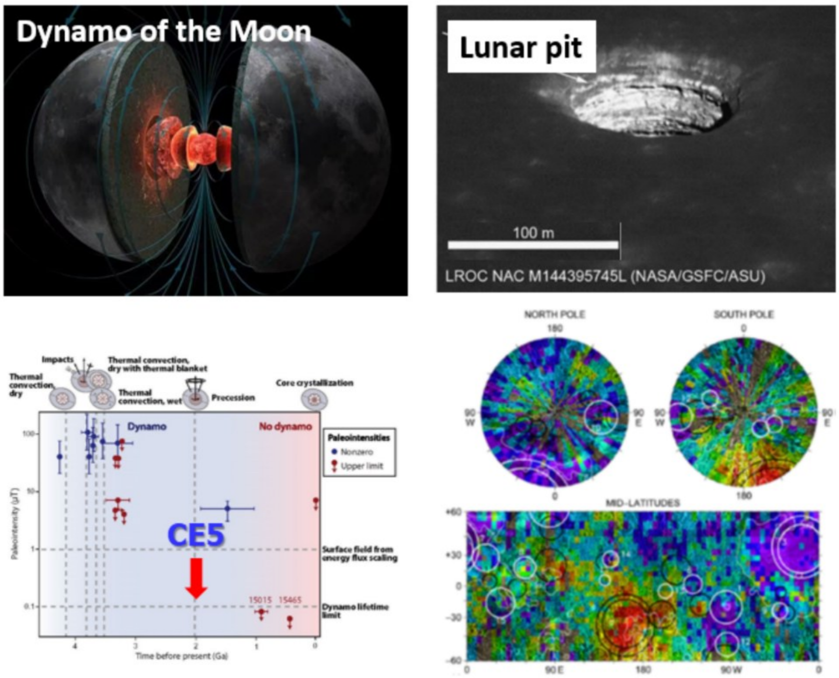


Figure 7. Initiation and cessation of the lunar magnetic field dynamo and origin of lunar magnetic anomalies. A) Lunar magnetic field dynamo model (Credit: Hernán Cañellas (provided by Benjamin Weiss); B) Outcrops with origin occurrences potentially recording 3D information of lunar magnetic fields; C) Remanence intensity of lunar rocks [*Mighani et al.*, 2020]; D) Magnetic anomalies and distribution of impact basins [*Mitchell et al.*, 2008].

Key scientific issues:

(1) Did the Moon once have a dipolar magnetic field? What was its orientation? The paleointensity preserved in Apollo samples suggests the early Moon likely had an internal dynamo generating a dipolar magnetic field analogous to that of the Earth. However,

magnetic paleointensity analyses can only provide information on the intensity of the ancient magnetic field without directional information. Strictly speaking, only by obtaining magnetic field vector information recorded at different locations for the same period can we establish the existence of a global dipolar magnetic field. The orientation of such an early lunar dipolar magnetic field is completely unknown.

(2) Was the ancient lunar magnetic field ever reversed? What is the frequency of magnetic field reversal? Geomagnetic reversals are an important characteristic of Earth's magnetic field. If the Moon also had a functioning internal dynamo in its early history, did it undergo magnetic field reversals? The frequency and causes of possible lunar magnetic field reversals remain key scientific issues.

(3) Time of initiation and cessation of the lunar dipolar magnetic field: The ages of Apollo basalts range from 3.0 to 3.9 Ga. Thus, their cooling processes record the magnetic field intensity for this period. Did the Moon have a dipole magnetic field earlier? When was the lunar dynamo started? How did the intensity of the lunar dipolar magnetic field vary with time? When did the lunar dynamo cease?

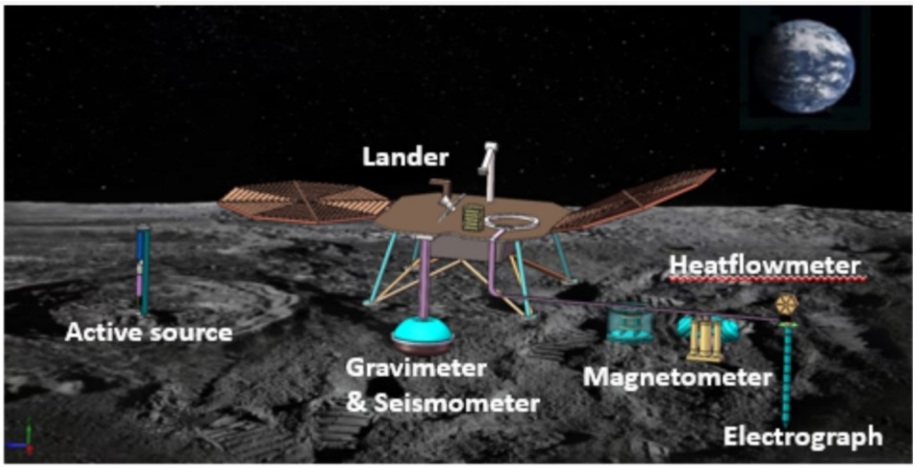
(4) Fine structures of magnetic anomaly regions: Lunar crustal magnetic anomalies are generally considered related to intense impacts [*Wieczorek et al.*, 2012]. High energy ions from impacts can induce magnetization, while high temperatures cause demagnetization [*Oran et al.*, 2020]. Due to the limited resolution of orbital probes (at altitudes >30 kilometers), the availability of fine 3D structures for magnetic anomalies restricts understanding of their formation mechanisms. Understanding the causal links between magnetic anomalies and major lunar swirls also relies on the measurement of fine structures of magnetic anomaly.

Current state of researches: Magnetic remanence analyses of Apollo samples indicate the Moon had a dipolar magnetic field at least between 4.0 and 3.56 Ga [*Oran et al.*, 2020; *Weiss and Tikoo*, 2014] and a liquid metallic core in motion. However, the drive of the magnetic field dynamo had different models [*Le Bars et al.*, 2011]. The ages of Apollo basalts range from 3.0 to 3.9 Ga, placing no constraints for more ancient or younger lunar magnetic fields. Therefore, it is impossible to determine the initiation and cessation times of the lunar dynamo. Although some impact melts could potentially record younger magnetic fields, the impact events themselves may have demagnetized or remagnetized the rock samples. On the other hand, all currently available lunar rocks are either relocated rocks or boulders without in situ investigations of in-place outcrops or 3D magnetic remanence measurement on targeted rock samples. The orientation of ancient lunar dipolar magnetic fields remains completely unknown, let alone the critical question of whether lunar fields underwent reversals. Orbiting probes have discovered magnetic anomalies in many regions [*Acuña et al.*, 1999; *Mitchell et al.*, 2008] but acquired no finer structures due to limitations caused by their orbital altitudes. Some lunar magnetic anomalies have a certain correlation with impact basins in terms of spatial distribution, but there are also cases lacking such a correlation [*Hood and Artemieva*, 2008]. The effects of impacts on magnetic fields still require further measurement and research.

Significance: Due to limitations in magnetic field measurement and returned samples, many issues remain concerning the lunar magnetic field, so crewed lunar exploration offers prospects for breakthroughs. For instance, investigation and returned samples of more ancient and younger basalts will finally delimit the onset and cessation time of the lunar magnetic field dynamo; magnetic measurement of in-place outcrops or collection of targeted rock samples will help determine the orientation of the lunar dipole field for the first time, providing definitive evidence for the operation of the lunar dynamo and potentially discovering lunar field reversal events.

2.2.5 Internal structure of the Moon constrained by multiple physical properties

The internal structure of the Moon is intricately linked to its formation process, significantly influencing and shaping its evolutionary history. It poses one of the most important questions in lunar science. The Lunar Magma Ocean hypothesis predicts the existence of primary KREEP rocks between the crust and mantle, and the mantle overturns arising from gravitational instability that produced lateral heterogeneity. Although the lunar surface exhibits pronounced dichotomy, it remains unclear whether deep interiors below the nearside and farside are also heterogeneous. Probing the Moon's internal structure is an important way to address these issues through the application of geophysical techniques encompassing gravitational, magnetic, electrical, seismic, and thermal properties. Among them, lunar seismic measurement is the most critical task (Figure 8) [*Briaud et al.*, 2023; *Chenet et al.*, 2006; *Garcia et al.*, 2019; *Khan et al.*, 2013; *Nakamura et al.*, 1973].



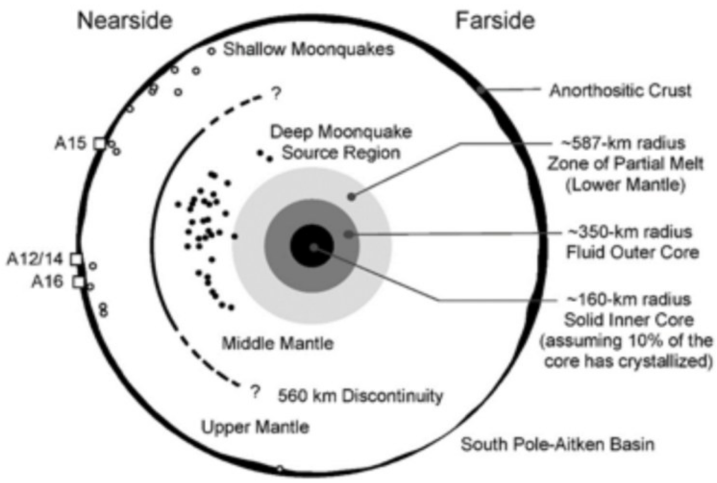


Figure 8. Internal structure of the Moon constrained by multiple physical properties. A) Deployment of gravitational, magnetic, electrical, seismic, and thermal sensors in future lunar exploration missions; B) Locations of seismic sensors of Apollo missions, locations of moonquakes, and a diagram of the Moon’s internal structure [*Wieczorek et al.*, 2006].

Key scientific issues:

(1) Crustal thickness and structure: GRAIL satellites have provided a global map of lunar crustal thickness, revealing deep structures, especially the polygonal gravity anomalies surrounding the PKT. However, these deep structures require additional constraints from new seismic data, while existing crustal thickness measurement is limited to the Moon's nearside.

(2) Mantle structure: Apart from the crust-mantle boundary, it is of particular interest to clarify whether a primary KREEP layer exists between the crust and mantle, whether mantle overturns took place, and whether mantle lateral heterogeneity produced. Apollo seismic data showed velocity changes around 500 kilometers deep for both P and S waves, which requires validation with more precise seismic measurements. What is the geological significance of such velocity changes? Do discontinuities exist? What are the mechanisms for deep moonquakes (>700 kilometers deep, peaking at 900 ~ 1,000 kilometers)?

(3) Size, state and composition of the lunar core: The Moon has a relatively small metallic core, but its accurate size, composition, state, and whether a molten outer core exists remain unclear. In addition, how do we further constrain the core's size and state based on lunar density, moment of inertia, and magnetic field disturbances when the Moon passes through the Earth's magnetotail?

Current state of researches: Probing the Moon's interior represents a weak link in understanding the Moon as it is challenging and available only in a limited number of missions. Due to the technical limits and number of units, the Apollo seismometers only detected some moonquake signals on the Moon's nearside and estimated crustal thickness to be 65 ~ 75 kilometers, later revised to be 45 kilometers and 30 ~ 38 kilometers. The GRAIL satellites conducted high-precision gravity field measurement, providing crustal thickness estimates around 35 ~ 43 kilometers [*Wieczorek et al.*, 2013] and discovering polygonal gravity anomalies surrounding the PKT [*Andrews-Hanna et al.*, 2014], ancient magmatic intrusions, and early expansion [*Andrews-Hanna et al.*, 2013]. Apollo missions also measured heat flows over landing sites with limited depth of investigation, and the result cannot exclude solar radiation effects. Magnetic field data mainly comes from orbit probes at very low spatial resolution. However, magnetic paleointensity analysis of Apollo samples discovered that the early Moon likely had an intrinsic magnetic field without information on its orientation.

Significance: Substantial mysteries remain concerning the Moon's internal structure, representing possible future breakthroughs for lunar science. Researches into the Moon's internal structure rely heavily on the deployment of geophysical instrument networks and long-term monitoring. Installation and adjustment by astronauts are one of the two major advantages of crewed lunar exploration. Three-dimensional probing of the lunar crust-mantle stratification will obtain critical evidence regarding the Lunar Magma Ocean hypothesis and deep extensions of the Moon's dichotomy. Deploying temperature sensors in the deep drilling core (≥12 meters, regolith thickness at the landing site of Chang'e-4) offers prospects of acquiring the most accurate heat flow data and critical parameters for lunar thermal evolution models. Moreover, the large-scale lunar geological cross-sections investigations will, for the first time, provide information on deep structures beneath key geological units.

2.3 Lunar Strata and Establishment of "Golden Spikes"

It is important to comprehensively study the key events in lunar formation and evolution, clarify their interrelationships in time and space, and determine their absolute ages through isotopic dating of samples representing major and global events. Major lunar events include basalt eruptions and the formation of impact basins and large craters. Basalt flow areas can exceed 100,000 square kilometers but are localized in distribution. In contrast, ejecta from impact basins and large craters can be found around the Moon. Therefore, ejecta from early impact basins and younger craters like Copernicus and Tycho are ideal stratigraphic markers, which could serve as "golden spikes" for lunar strata (Figure 9).

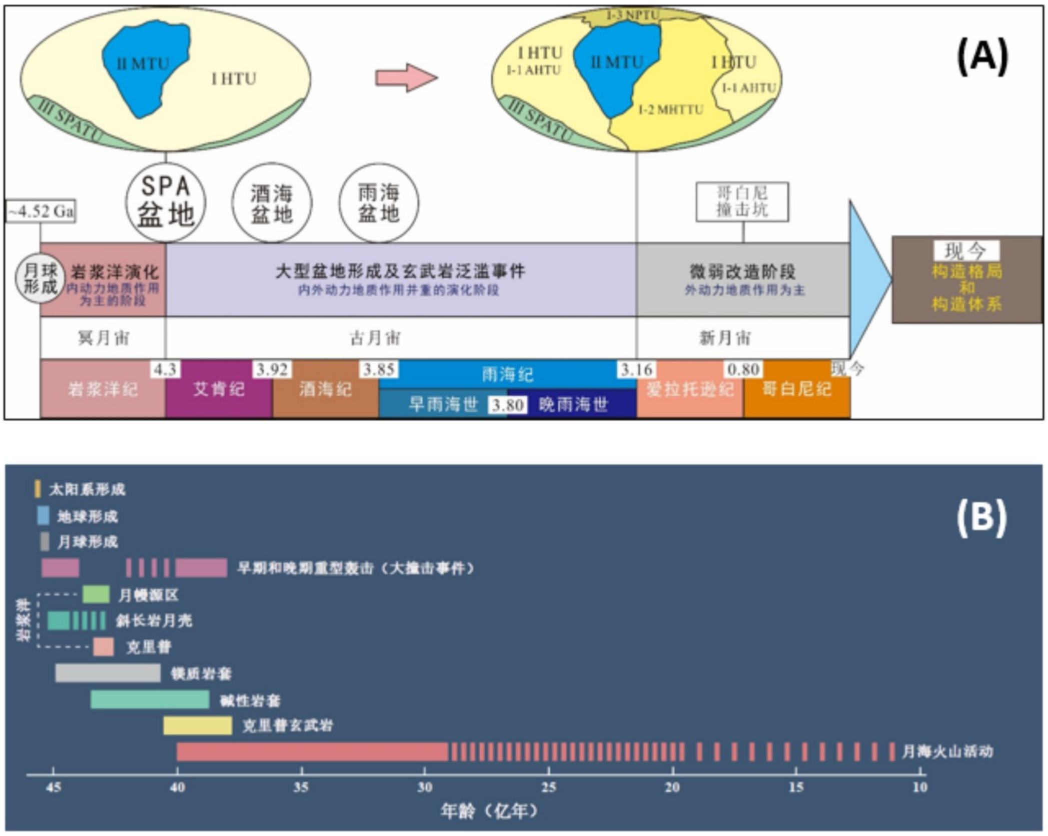


Figure 9. Lunar strata and establishment of "golden spikes." A) Major evolutionary stages and stratigraphic units of the Moon [*Lu et al.*, 2022]; B) Formation times of major rock types on the Moon [*Yang and Pan, 2023*].

Key scientific issues:

(1) Cross-sections reflecting the geologic and structural evolution of the Moon over 4 billion years: How do we identify major geological events and wide or even global distributions of ejecta from the same impact basin or large crater? How do we recognize geological events represented by cross-sections at depths in a region and reconstruct the geologic evolution for that region?

(2) Isotopic dating of “golden spikes”: How do we identify dating samples for each major event, especially rocks melted and re-crystallized in the events? How do we differentiate superimposing effects of later events? It is necessary to obtain isotopic ages for samples representing different types of events.

Current status of research: Based on research results of Apollo samples and the acquisition of high-resolution, high-precision orbital remote sensing data since the 1990s, the U.S. Geological Survey plotted a 1:5M geological map of the whole Moon. It constructed a lunar geologic evolution chronological table with the Mare Nectaris and Mare Imbrium basins, Copernicus crater and others as event boundaries. On this basis, Chinese researchers plotted a 1:2.5M geological map for the whole Moon, proposing the formation of the SPA basin as the most ancient event boundary. The most significant outstanding issue is determining the absolute ages for these major events, fundamentally due to controversies regarding the sources of samples for isotopic dating. Chang'e-6 is expected to land for the first time inside the Apollo crater of the SPA basin [*Zeng et al.*, 2023]. Inside the samples to be returned by Chang'e-6, identifying melts from the impact leading to the SPA basin's formation is the key for accurately dating the SPA basin.

Significance: Establishing lunar stratigraphic cross-sections will help clarify the temporal sequence of lunar geological and structural evolution, better reveal causality between different events, and improve understanding of the Moon's evolution. Comprehensive investigations of large-scale lunar geological cross-sections will reach major geological units and produce the most complete set of lunar stratigraphic cross-sections. We will also collect impact melt samples from key impact basins and large craters, conduct isotopic dating for these key impact basins and craters for the first time, and establish "golden spikes" onto lunar stratigraphic cross-sections as the chronometers of the Moon's evolution.

2.4 In Situ Resource Utilization on the Moon

In situ resource utilization on the Moon is a new research direction and serves as the foundation for constructing and operating lunar research stations. For the purpose of utilization, lunar resources encompass locations (especially locations with extremely limited area like rim highlands of impact craters in polar regions and lava tube windows), solar power (including temperature difference), substances (such as water and various forms of hydrogen, 3He, and ilmenite ore), as well as construction materials (Figure 10).

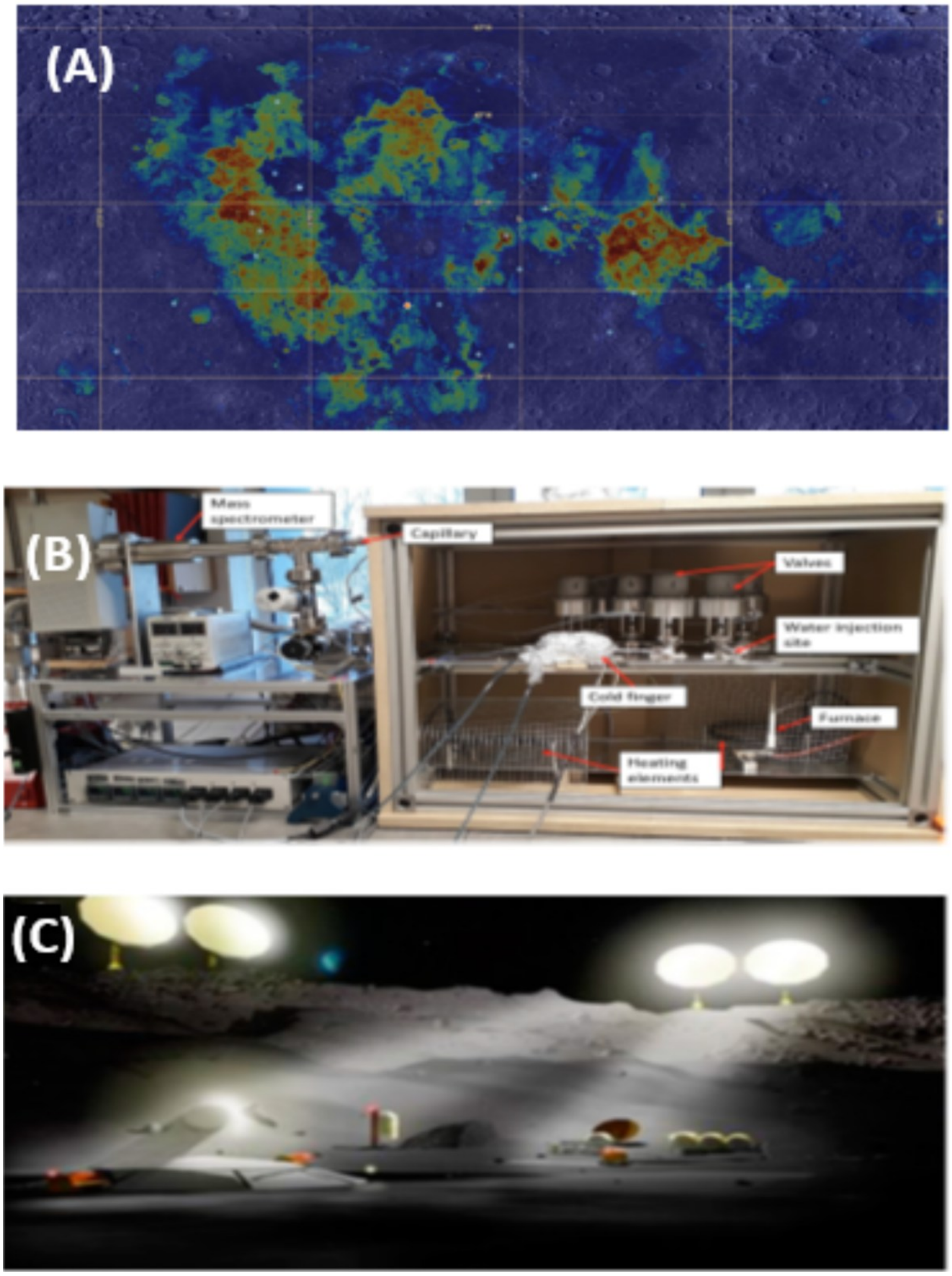


Figure 10. In situ resource utilization on the Moon. A) Spatial distribution of TiO_2 resources (https://quickmap.lroc.im-ldi.com/); B) Ground-based verification experiments on key technologies for lunar resource utilization; C) Schematic diagram showing mining of water ice deposits in permanently shadowed regions near lunar poles. B) and C) from [*Zhang et al.*, 2023a]

Key scientific issues and technologies:

(1) Potential in situ resources, their formation, spatial distribution and enrichment mechanisms: What utilizable resources exist on the Moon and what are their reserves,

formation mechanisms and spatial distributions? What mechanisms lead to the enrichment of substances in certain regions? For instance, the occurrence, contents, spatial distributions (depth and latitude), origins and formation mechanisms of water ice and water (including various types of hydrogen) in lunar regolith in the permanent shadow regions.

(2) Key technologies for in situ resource utilization: These include technologies for mining water ice in permanent shadow regions; extraction and separation of water, He and volatiles from lunar regolith; size and mineral (e.g., Ilmenite) sorting technologies for lunar regolith; hydrogen and oxygen production under the lunar surface environment; and lunar regolith solidification and construction technologies.

Current status of researches: Currently, no consensus exists regarding utilizable resources on the Moon. For in situ resource utilization, activities encompass the preparation of technical proposals and validation of key technologies, including engineering solutions for mining water ice in permanent shadow regions, molten basalt electrolysis for O_2 production and fiber preparation schemes, 3D printing experiments using lunar regolith, and more. In the development of key technologies, the validity and effectiveness of some verification experiments (such as extraction of solar wind implanted gases) cannot be conclusively proven due to the use of simulated lunar regolith.

Significance: In situ production of water on the lunar surface will provide a critical resource sustaining human presence and allow electrolysis to yield H_2 and O_2 gases as potential propellants for deep space exploration missions. ^3He from lunar regolith can serve as future nuclear fusion fuel and make possible cryocooling applications. Solidified lunar regolith may be used to produce fundamental construction materials for establishing lunar stations.

2.5 Utilization of Moon-Based Platforms

The Moon serves as an optimal platform for conducting global Earth observations as its nearside always faces the Earth. It can also enable unrivaled astronomical observation capabilities as well as new platforms and settings for basic physical experiments and life sciences studies due to unique environmental characteristics of the lunar surface, including high vacuum, low gravity and weak magnetic fields, nearly zero seismicity, and extremely low electromagnetic interference on the farside. The utilization of Moon-based platforms represents a key long-term goal for future lunar research stations through long-time phased implementation and complementing advances in space technologies. Current research priorities include leveraging the inherent advantages of potential Moon-based platforms and combining trends in scientific and technological developments as well as requirements for sustainable development for humanity on Earth, plotting developmental roadmaps, developing key technologies, and validating applications (Figure 11).

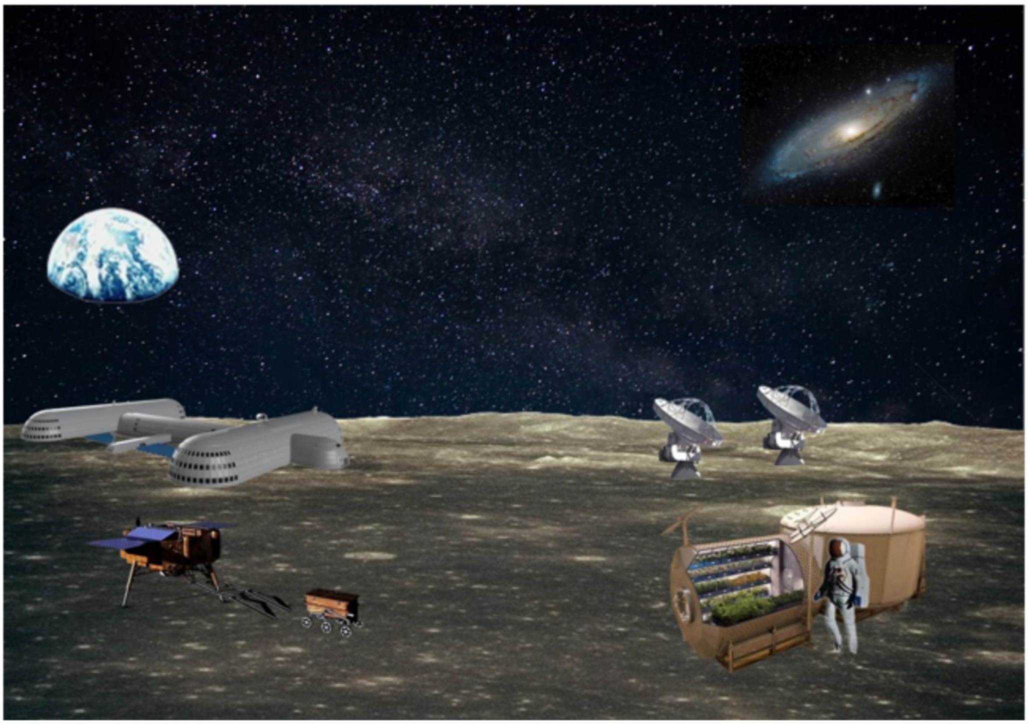


Figure 11. Utilization of Moon-based platforms. Based on the special environment of the Moon, we could carry out global Earth science observation, astronomical observation, life science and basic science experiments.

2.5.1 Moon-based monitoring of global phenomena on the Earth

(1) Energy budget balance and global climate change: Solar radiation and its interaction with Earth are key factors affecting global climate change. Compared to man-

made satellites and ground-based observations, long-term monitoring from Moon-based earth observing platform can provide global observations on the Earth's energy budget status temporal continuously and spatial consistently over extended periods and reveal its relationships with global climate change.

(2) Dynamics of the solid Earth: Including Earth tides, plate tectonics and continental deformation, glacier mass balance adjustments, and more. Moon-based observations can break through limitations currently hindering satellite remote sensing that can only retrieves regional-scale surface deformation and reveal spatiotemporal characteristics in the heterogeneity of global-scale solid Earth dynamics. Meanwhile, it is possible to figure out the mechanisms which driving solid Earth deformation globally considering the relative relationships between the Earth, Moon and Sun.

2.5.2 Moon-based astronomy

(1) Unknown ultra-long wavelength electromagnetic radiation from celestial bodies: Early cosmic evolution, origins and propagation of cosmic rays, and propagation processes of plasmas.

(2) Fine physical processes in solar/stellar magnetic activity: The essential nature of coronal heating, physical mechanisms of solar eruptive activity; evolution laws of interplanetary space weather in the solar system and impacts on life systems.

(3) Habitability of exoplanets: Variation laws in magnetic activity across different stellar types, characteristics of intense flaring radiation and stellar coronal mass ejections; impacts of electromagnetic radiation, particle radiation and mass ejections associated with intense magnetic activity of host stars on orbiting planets across different star and planetary systems.

(4) Unknown physical processes in the universe: Physical origins of gravitational wave sources and emissions, spectral radiation from special elements in the universe, supernova explosion mechanisms, and searching the evidence of dark matter annihilation.

(5) Origin of antimatter: Studies of electron-positron annihilation spectral line features in detection of pulsars and black hole binaries. Searches for a new class of MeV

gamma-ray pulsars and unprecedented polarization observations of gamma-ray pulsars.

2.5.3 Life sciences on lunar surface

(1) Lunar surface ecology: Lunar surface ecology deals with bioregenerative life support for long-term human residence on lunar surface. It involves in situ resource utilization, system balance regulation, species' adaptation mechanisms to the unique environment of lunar surface, plant cultivation and food production technologies.

(2) Space biological effects: Exploring influences of diverse lunar-surface environmental factors, including space radiation, low gravity, and low-intensity magnetic field on humans and mammals, so as to solve human health protection during long-term residence on lunar surface and extraterrestrial survival of terrestrial species.

(3) Technical basis for life sciences and human physiological studies: In situ monitoring, detection and data acquisition technologies, biological sample sustaining and preservation technologies, and micro-scale experimental systems as technological support for life sciences and human physiological studies on lunar surface.

2.5.4 Basic physical experiments on the lunar surface

(1) Ultracold atomic physics, quantum low-temperature states of matter and their special characteristics in the complex lunar environment.

(2) High precision time and frequency systems on the lunar surface for cutting-edge studies related to important physical constants and tests of general relativity theories.

(3) Three-dimensional material structures and dynamical processes in complex low-gravity plasmas; microscopic complex physical mechanisms and statistical laws.

3. Foundation and Conditions of Research in China and around the World

3.1 International Developments and Trends, and China's Position in the Domain

Lunar and deep space exploration has become as a frontier and hot field for the international community. The Artemis project of the United States aims to return astronauts to the Moon and make the Moon a stepping stone for future crewed missions to Mars. Besides scientific exploration, in situ resource utilization on the Moon has emerged as a new focal point as lunar exploration transitions from short-term investigations via intermittent missions towards establishing scientific research stations/bases for sustained, comprehensive, long-time observations.

The Chang'e project of China has gradually attained capabilities for landing and returning samples at any site on the lunar surface, especially the first-ever landing on the Moon's farside in human history. The accompanied researches kept achieving new discoveries, expanding scientific understanding of the Moon. The Chang'e-5 mission brought back samples of the Moon's youngest known basalts, revealing that lunar volcanic activity lasted 0.8 to 1 billion years longer than previously thought and rewriting human understanding of the Moon's volcanism and thermal history. The success of the mission significantly boosted China's capabilities in lunar exploration, strengthened our scientific prowess and significantly elevated China's international influence.

China has made remarkable strides in deep space exploration capabilities as well as lunar science research over the past 2 decades. However, China still falls behind the United States with substantial gaps [*Zhang et al.*, 2023b]. For instance, the number of papers in lunar science published by Chinese researchers has kept rising in recent years, with a total exceeding 3,000 papers, ranking second in the world. However, "three deficiencies" persist in lunar science research in China: (1) China publishes fewer high-impact research papers compared to the U.S., with only 0.9 per 100 publications compared to 4.0 of the U.S.; (2) China has a smaller number of top experts in lunar research compared to the U.S. All top ten most productive and influential authors in this field come from the U.S. In terms of the time of publication, three of the top ten authors started publishing related papers during the Apollo era (1969-1972), while 5 started publishing in the return-to-Moon phase (1991-1998). This indicates that lunar science critically relies on the actual execution of deep space exploration missions; (3) China lacks related academic journals. Eight of the top ten journals by papers published are based the U.S., and two based the U.K.

3.2 Inputs into Lunar Science in China and other Countries/Regions

The outputs of lunar science are closely related to inputs by countries and regions in this domain. Data shows that the U.S. spent USD 25.8 billion on the Apollo project between 1960 and 1973 (including USD 2.5 billion in lunar science research, around 10% of the total), equivalent to USD 257 billion in terms of 2020 purchasing power. By fiscal year 2025, the total costs for the Artemis project will reach USD 93 billion (with USD 2.96 billion for lunar science research).

During the initial stages of China's Chang'e project, no dedicated funds were allocated to scientific research, which impeded science outputs and the stable development of lunar science research teams. Recently, this situation has gradually improved. For instance, the State Administration of Science, Technology and Industry for China National Space Administration (CNSA) has worked with the Natural Science Foundation of China to deploy focused projects, which sponsored scientific research projects for Chang'e-4, Chang'e-5 and Tianwen-1 missions. The fourth phase of China's Lunar Exploration Project already has dedicated budgets for scientific research.

Regarding management, the Natural Science Foundation of China has established new discipline codes for planetary geology, planetary physics and planetary chemistry to enhance support for lunar and planetary sciences. Regarding talent cultivation, planetary science has been designated as a level-1 discipline, with some universities now recruiting undergraduates and offering more systematic curricula in planetary science. Regarding research platforms, China has built cutting-edge research platforms for compositional analysis but still requires further development of technologies and reference samples tailored for lunar and extraterrestrial samples.

3.3 China's Strengths and Weaknesses in Scientific Research in the Domain

China’s centralized system of governance facilitates coordinated advancement in deep space exploration. The sizable Earth science research community provides opportunities for expansion of the planetary science community. The existing cutting-edge research platforms for compositional analysis can provide technical support for studies with lunar samples.

However, due to China's late engagement into planetary science, the current research team can hardly address all scientific investigations required by the breadth of upcoming deep space missions. The synergistic interaction between Earth science and lunar science remains insufficient. This is also the case between lunar science research and deep space technology development. In addition, we still follow the research frameworks established by the U.S., which call for improved innovation capabilities in sciences and technologies.

4.Ideas and Policy Recommendations on China's Development in the Domain

4.1 Team Building

Unbalanced, inadequate and incomplete development in planetary science in China currently impedes China's ascent towards becoming a major power in deep space exploration. Compelling tasks in this regard include developing planetary science as a disciplinary system, cultivating top-notch planet scientists, and transforming China's natural sciences research landscape to facilitate the national strategy for deep space exploration.

Support should be prioritized for capable research institutes and universities with the necessary conditions and advantages to take the lead in constructing planetary science as a level-1 discipline, subsequently driving the collaborative establishment of a national planetary science talent cultivation framework and setting up research centers. Meanwhile, it is imperative to promote the expansion of Earth science towards planetary science, optimize the allocation of resources in the educational system, and broaden related majors across universities and research institutes. We should emphasize the cultivation of talents with compound knowledge in both sciences and engineering, attach importance to young spearheading scientists and research teams, and gradually construct echelons of high-level talents to take the lead in future deep space exploration projects, and drive China's becoming a powerhouse in planetary science and deep space exploration.

4.2 Platform and Capacity Building

Due to the late engagement of planetary science, China still lags substantially behind the U.S., Europe, and Japan in terms of foundational research platforms. Considering the characteristics and requirements in developing planetary science, it is recommended to enhance research platforms for planetary science by focusing on the following three aspects.

(1) Storage, processing, and preparation platforms of lunar samples. Storage and processing of extraterrestrial samples pose tremendous technical challenges. For instance, lunar and asteroidal samples coming from high vacuum environments are extremely susceptible to alteration by atmospheric water and oxygen on the Earth. Despite the currently available lunar sample facilities for the Chang'e project, they remain inadequate in terms of both scale and functionality to address demands in storing and analyzing the samples to be collected by future crewed lunar missions, considering their sheer quantity. To address this inadequacy, first, support research institutes with necessary conditions to establish extraterrestrial sample laboratories, preparing for studies with samples from future crewed lunar exploration missions, and second, develop key technologies related to storage, processing, and preparation of extraterrestrial samples, and enhance analytical capabilities and related scientific research.

(2) Lunar sample analysis platforms. Extraterrestrial samples may exhibit exceptionally complex composition with fine grain sizes, imposing extremely stringent requirements for analytical techniques. Laboratories are required to conduct micro-analyses with ultra-high spatial resolution as well as high precision ultramicro-analyses. Although Chinese research institutes and universities have established some analysis platforms, most of their analytical methods are established for terrestrial samples. Accordingly, it is recommended to construct dedicated analysis and experimental platforms for planetary samples through merging and procurement and develop analytical technologies for micro-analyses with ultra-high spatial resolution as well as high precision ultramicro-analyses.

(3) Lunar exploration payload development platforms. To meet the requirements for key scientific exploration missions, it is necessary to achieve breakthroughs in high-performance sensors, special materials, weak signal extraction and reconstruction, etc., realize domestic production of critical payloads, and propose and develop new types of payloads for lunar exploration.

4.3 International Cooperation Policies

Deepening globalization fuels a heated competition for international influence. Actively pursuing scientific and technological cooperation will help seize opportunities when the international order is reshaped and establish new-type relations in the international scientific and technological community. Against the backdrop of a shifting global economic balance where the East rises as the West declines, efforts should be strengthened towards fostering internationalized environments for scientific research, conducting multi-level, multi-player international cooperation, and encouraging engagement by non-governmental entities like civil organizations and private enterprises in international scientific and technological cooperation and exchanges. It is necessary to establish academic conferences and Internet forums, regularly convene high-level academic meetings, and facilitate domestic and international academic exchanges through both frequent small-scale specialized technical seminars and constant online panel discussions. While encouraging Chinese scientists to appear at overseas venues and participate in international organizations and missions, the government should also attract world-renowned foreign experts to contribute towards China's crewed lunar exploration project across the entire chain spanning from payload development/delivery to mission justification and sample and data analysis. Concurrently, as a major initiator and organizer of international deep space exploration mega-science projects, China should be present extensively in the development of international technical standards and protocols for deep space exploration to elevate China's influence and rule-making power in the international community.

4.4 System Development, Legalization and Environment Improvement

(1) Balancing top-level design and freedom in scientific research. As a national strategic initiative, crewed lunar exploration requires top-level planning and organization to ensure smooth execution. The academic and international influence of the project relies

upon the scientific outputs ultimately achieved. Hence, balanced considerations must be struck between the project's top-level design and freedom in scientific research to guarantee its success while maximizing science returns to enhance China's influence.

(2) Protecting intellectual property rights and promoting open discussions. The strategy for building China into a major power by developing intellectual property rights should be underlined and implemented firmly in the fields of planetary science and deep space exploration. It is recommended to establish a white paper system to protect original scientific ideas and intellectual properties while motivating scientists to extensively participate in the justification of crewed lunar exploration's scientific goals, preliminary research activities, ground-based experiments, data collection, payload development, etc.

(3) Evaluating missions with the realization of scientific goals as the key criterion. The ultimate goal of deep space exploration is to elevate human understanding of deep space and the universe. To achieve China's strategic transition from a major aerospace player towards an aerospace leader, it is necessary to gradually change the key criterion in mission evaluation from successful engineering implementation to realization of scientific goals.

(4) Refining assessment frameworks for technological and scientific contributions. It is important to develop comprehensive, diversified criteria for performance assessment in scientific research to apply differentiated assessment mechanisms by category to cater to different types of work. For instance, planetary science requires originality and innovation, so the formulation of assessment criteria should be guided by principles encouraging intrepid exploration while tolerating failures. They should be applied in a case-by-case manner to allow long assessment cycles to inspire persistent pursuit over decades. For deep space exploration missions, assessment criteria should be formulated in combination with the requirements for specific project deliverables and focused on breakthroughs in key technological innovations and accomplishments on major tasks as major assessment criteria.

4.5 Organizational Support

China's current lunar exploration project encompasses two primary components: the Chang'e project for uncrewed missions and later crewed missions. Uncrewed and crewed exploration each have inherent advantages. For instance, the former can access high-risk regions, while the latter (with astronauts' safety as the top priority) is ideal for sample collection and instrument installation and adjustment. Uncrewed and crewed exploration missions constitute two engineering pathways for China's lunar exploration. A national-level commission should be established with experts and leading agencies as members to develop roadmaps and engineering plans for lunar exploration and applied research in a unified manner.

References can be drawn from cooperative models found in the U.S. and EU, where stable specialized academic groups and committees comprise academicians and experts in respective domains. It is possible to rely on the Planetary Science Alliance to organize academic activities, such as the periodical release of discipline development guidelines, provision of guidance for key research projects, exchanges of insights on advancing disciplines, rallying of resources and support from stakeholders, and promotion of advanced results. Efforts also include long-term planning and justification in the selection of objectives and landing sites, sample/data analysis, science goal verification, and payload specification for upcoming planetary exploration missions. Tasks should be prioritized based on their scientific goals and budget requirements.

4.6 Effective Funding Mechanisms and Policy Recommendations

(1) Enhance support for original and innovative studies of planetary science, increase government funding for basic studies of planetary science, establish diverse funding mechanisms, drive and enhance inputs in science and technology from local governments and enterprises, and create a stable environment for the development of planetary science.

(2) Strengthen financial support for scientific research related to lunar exploration

missions, allocate appropriate proportions of research funds in future deep space exploration missions, and safeguard the execution of scientific research and the realization of research outcomes.

(3) Establish funds for justification and pre-research work to encourage more scientists to participate in preliminary and pre-research tasks prior to missions.

(4) Strengthen financial support for young talents in planetary science, give preference to young scientists in the selection of candidates for projects, and encourage young talents to participate in tasks for deep space exploration.

(5) Further optimize processes of authorities funding scientific research projects for unified acceptance of applications, peer review, and project assessment for planetary science projects. In a questionnaire covering 564 planetary and deep space scientists, around 99% of respondents believe the management of planetary science projects should be managed by a unified section, in which 71% of respondents believe a new first-level discipline should be established (40%) or it should be managed by the Earth science department (31%). Considering the fact that the planetary science research community is still small, it is more feasible to set up dedicated channels for accepting and funding planetary science projects by the Earth science department [*Yang et al.*, 2024].

References

Acuña, M. H., et al. (1999), Global Distribution of Crustal Magnetization Discovered by the Mars Global Surveyor MAG/ER Experiment, *Science*, *284*(5415), 790.

Andrews-Hanna, J. C., et al. (2013), Ancient Igneous Intrusions and Early Expansion of the Moon Revealed by GRAIL Gravity Gradiometry, *Science*, *339*(6120), 675-678.

Andrews-Hanna, J. C., et al. (2014), Structure and evolution of the lunar Procellarum region as revealed by GRAIL gravity data, *Nature*, *514*(7520), 68-71.

Borg, L. E., et al. (2017), Chronologic implications for slow cooling of troctolite 76535 and temporal relationships between the Mg-suite and the ferroan anorthosite suite, *Geochimica et Cosmochimica Acta*, *201*, 377-391.

Borg, L. E., et al. (2015), A review of lunar chronology revealing a preponderance of 4.34–4.37 Ga ages, *Meteoritics & Planetary Science*, *50*(4), 715-732.

Borg, L. E., et al. (2004), Prolonged KREEP magmatism on the Moon indicated by the youngest dated lunar igneous rock, *Nature*, *432*(7014), 209-211.

Braden, S. E., et al. (2014), Evidence for basaltic volcanism on the Moon within the past 100 million years, *Nature Geosci*, *7*(11), 787-791.

Briaud, A., et al. (2023), The lunar solid inner core and the mantle overturn, *Nature*, *617*(7962), 743-746.

Canup, R. M., and Asphaug, E. (2001), Origin of the Moon in a giant impact near the end of the Earth's formation, *Nature*, *412*, 708-712.

Chen, Y., et al. (2023), Chang’e-5 lunar samples shed new light on the Moon, *The Innovation Geoscience*, *1*(1), 100014.

Chenet, H., et al. (2006), Lateral variations of lunar crustal thickness from the Apollo seismic data set, *Earth and Planetary Science Letters*, *243*(1-2), 1-14.

Day, J. M. D., et al. (2007), Highly Siderophile Element Constraints on Accretion and Differentiation of the Earth-Moon System, *Science*, *315*(5809), 217-219.

DeMeo, F. E., and Carry, B. (2014), Solar System evolution from compositional mapping of the asteroid belt, *Nature*, *505*, 629.

Denevi, B., et al. (2016), The distribution and extent of lunar swirls, *Icarus*, *273*, 53-67.

Dhingra, D. (2018), The new Moon: Major advances in lunar science enabled by compositional remote sensing from recent missions, *Geosciences*, *8*(12), 498.

Dickey, J. O., et al. (1994), Lunar Laser Ranging: A Continuing Legacy of the Apollo Program, *Science*, *265*(5171), 482-490.

Garcia, R. F., et al. (2019), Lunar Seismology: An Update on Interior Structure Models, *Space Science Reviews*, *215*(8), 50.

Gomes, R., et al. (2005), Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets, *Nature*, *435*(7041), 466-469.

Gu, L., et al. (2022), Space Weathering of the Chang'e-5 Lunar Sample From a Mid-High Latitude Region on the Moon, *Geophysical Research Letters*, *49*(7), e2022GL097875.

Gu, L., et al. (2023), Measurement of ferric iron in Chang’e-5 impact glass beads, *Earth, Planets and Space*, *75*(1), 151.

Guo, Z., et al. (2022), Sub-microscopic magnetite and metallic iron particles formed by eutectic reaction in Chang'E-5 lunar soil, *Nature Communications*, *13*(1), 7177.

Halliday, A. N., and Kleine, T. (2006), Meteorites and the Timing, Mechanisms, and Conditions of Terrestrial Planet Accretion and Early Differentiation, in *Meteorites and the early solar system II*, edited, pp. 775-801.

Hashizume, K., and Chaussidon, M. (2005), A non-terrestrial ^{16}O-rich isotopic composition for the protosolar nebula, *Nature*, *434*(7033), 619-622.

Head, J. W., and Wilson, L. (2017), Generation, ascent and eruption of magma on the Moon: New insights into source depths, magma supply, intrusions and effusive/explosive eruptions (Part 2: Predicted emplacement processes and observations), *Icarus*, *283*, 176-223.

Heiken, G., et al. (1991), *Lunar sourcebook: A user's guide to the Moon*, Cup Archive.

Hemingway, D., and Garrick-Bethell, I. (2012), Magnetic field direction and lunar swirl morphology: Insights from Airy and Reiner Gamma, *Journal of Geophysical Research: Planets*, *117*(E10).

Hood, L., and Artemieva, N. (2008), Antipodal effects of lunar basin-forming impacts: Initial 3D simulations and comparisons with observations, *Icarus*, *193*(2), 485-502.

Horányi, M., et al. (2014), The Lunar Dust Experiment (LDEX) Onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) Mission, *Space Science Reviews*, *185*(1), 93-113.

Horányi, M., et al. (2015), A permanent, asymmetric dust cloud around the Moon, *Nature*, *522*(7556), 324-326.

Hu, S., et al. (2021), A dry lunar mantle reservoir for young mare basalts of Chang'E-5, *Nature*, *600*, 49-53.

Huang, Y. H., et al. (2022), Bombardment history of the Moon constrained by crustal porosity, *Nature Geoscience*, *15*(7), 531-535.

Hurwitz, D. M., and Kring, D. A. (2014), Differentiation of the South Pole–Aitken basin impact melt sheet: Implications for lunar exploration, *Journal of Geophysical Research: Planets*, *119*(6), 1110-1133.

Jacobson, S. A., et al. (2014), Highly siderophile elements in Earth/'s mantle as a clock for the Moon-forming impact, *Nature*, *508*(7494), 84-87.

Johnson, T. E., et al. (2022), Giant impacts and the origin and evolution of continents, *Nature*, *608*(7922), 330-335.

Jolliff, B. L., et al. (2000), Major lunar crustal terranes: Surface expressions and crust-mantle origins, *Journal Geophysical Research*, *105*, 4197-4216.

Khan, A., et al. (2013), The lunar moho and the internal structure of the Moon: A geophysical perspective, *Tectonophysics*, *609*, 331-352.

Lagos, M., et al. (2008), The Earth/'s missing lead may not be in the core, *Nature*, *456*(7218), 89-92.

Lawrence, D. J., et al. (2000), Thorium abundances on the lunar surface, *Journal of Geophysical Research: Planets*, *105*(E8), 20307-20331.

Le Bars, M., et al. (2011), An impact-driven dynamo for the early Moon, *Nature*, *479*(7372), 215-218.

Li, C., et al. (2022), Impact-driven disproportionation origin of nanophase iron particles in Chang'e-5 lunar soil sample, *Nature Astronomy*, *6*(10), 1156-1162.

Li, Q.-L., et al. (2021), Two billion-year-old volcanism on the Moon from Chang’E-5 basalts, *Nature*, *600*, 54-58.
Li, S., et al. (2020), Widespread hematite at high latitudes of the Moon, *Science Advances*, *6*(36), eaba1940.
Li, S., and Milliken, R. E. (2017), Water on the surface of the Moon as seen by the Moon Mineralogy Mapper: Distribution, abundance, and origins, *Science Advances*, *3*(9).
Lin, Y., et al. (2012), Very High-K KREEP-Rich Clasts in the Impact Melt Breccia of the Lunar Meteorite SaU 169: New Constraints on the Last Residue of the Lunar Magma Ocean, *Geochimica et Cosmochimica Acta*, *85*(10), 19-40.
Lin, Y., et al. (2017), Evidence for an early wet Moon from experimental crystallization of the lunar magma ocean, *Nature Geoscience*, *10*(1), 14-18.
Liu, D., et al. (2012), Comparative zircon U–Pb geochronology of impact melt breccias from Apollo 12 and lunar meteorite SaU 169, and implications for the age of the Imbrium impact, *Earth and Planetary Science Letters*, *319*, 277-286.
Lu, T., et al. (2022), The 1: 2,500,000-scale global tectonic map of the moon, *Science Bulletin*, *67*(19), 1962-1966.
McKeegan, K. D., et al. (2011), The Oxygen Isotopic Composition of the Sun Inferred from Captured Solar Wind, *Science*, *332*(6037), 1528-1532.
Melosh, H., et al. (2017), South Pole–Aitken basin ejecta reveal the Moon’s upper mantle, *Geology*, *45*(12), 1063-1066.
Melosh, H. J., et al. (2013), The Origin of Lunar Mascon Basins, *Science*, *340*(6140), 1552-1555.
Mighani, S., et al. (2020), The end of the lunar dynamo, *Science advances*, *6*(1), eaax0883.
Miljković, K., et al. (2013), Asymmetric Distribution of Lunar Impact Basins Caused by Variations in Target Properties, *Science*, *342*(6159), 724-726.
Miljković, K., et al. (2015), Excavation of the lunar mantle by basin-forming impact events on the Moon, *Earth and Planetary Science Letters*, *409*(0), 243-251.
Milliken, R. E., and Li, S. (2017), Remote detection of widespread indigenous water in lunar pyroclastic deposits, *Nature Geoscience*, *10*(8).
Mitchell, D. L., et al. (2008), Global mapping of lunar crustal magnetic fields by Lunar Prospector, *Icarus*, *194*(2), 401-409.
Monastersky, R. (2009), Shooting for the Moon, *Nature*, *460*(7253), 314-315.
Morbidelli, A., et al. (2005), Chaotic capture of Jupiter's Trojan asteroids in the early Solar System, *Nature*, *435*(7041), 462-465.
Moriarty Iii, D. P., and Pieters, C. M. (2018), The Character of South Pole-Aitken Basin: Patterns of Surface and Subsurface Composition, *Journal of Geophysical Research: Planets*, *123*(3), 729-747.
Nakamura, Y., et al. (1973), New Seismic Data on the State of the Deep Lunar Interior, *Science*, *181*(4094), 49-51.
Nelson, W. S., et al. (2021), Chemical heterogeneities reveal early rapid cooling of Apollo Troctolite 76535, *Nature Communications*, *12*(1), 7054.
Nemchin, A., et al. (2009), Timing of crystallization of the lunar magma ocean constrained by the oldest zircon, *Nature Geosci*, *2*(2), 133-136.
Neumann, G. A., et al. (2015), Lunar impact basins revealed by Gravity Recovery and

Interior Laboratory measurements, *Science Advances*, *1*(9), e1500852.
Norman, M. D., et al. (2003), Chronology, geochemistry, and petrology of a ferroan noritic anorthosite clast from Descartes breccia 67215: Clues to the age, origin, structure, and impact history of the lunar crust, *Meteoritics & Planetary Science*, *38*(4), 645-661.
Oran, R., et al. (2020), Was the moon magnetized by impact plasmas?, *Science Advances*, *6*(40), 11.
Ozima, M., et al. (2005), Terrestrial nitrogen and noble gases in lunar soils, *Nature*, *436*(7051), 655-659.
Papike, J. J., et al. (1997), Evolution of the lunar crust: SIMS study of plagioclase from ferroan anorthosites, *Geochimica et Cosmochimica Acta*, *61*(11), 2343-2350.
Pieters, C. M., et al. (2011), Mg-spinel lithology: A new rock type on the lunar farside, *Journal of Geophysical Research: Planets*, *116*(E6).
Prissel Tabb, C., et al. (2016), Formation of the lunar highlands Mg-suite as told by spinel, in *American Mineralogist*, edited, p. 1624.
Qiao, L., et al. (2019), Geological Characterization of the Ina Shield Volcano Summit Pit Crater on the Moon: Evidence for Extrusion of Waning-Stage Lava Lake Magmatic Foams and Anomalously Young Crater Retention Ages, *J. Geophys. Res.-Planets*, *124*(4), 1100-1140.
Rankenburg, K., et al. (2006), Neodymium Isotope Evidence for a Chondritic Composition of the Moon, *Science*, *312*(5778), 1369-1372.
ref-1 https://curator.jsc.nasa.gov/lunar/lunar10.cfm.
ref-2 NASA's Apollo technology has changed history.
Richmond, N. C., and Hood, L. L. (2008), A preliminary global map of the vector lunar crustal magnetic field based on Lunar Prospector magnetometer data, *Journal of Geophysical Research: Planets*, *113*(E2),.
Saal, A. E., et al. (2008), Volatile content of lunar volcanic glasses and the presence of water in the Moon/'s interior, *Nature*, *454*(7201), 192-195.
Schönbächler, M., et al. (2010), Heterogeneous Accretion and the Moderately Volatile Element Budget of Earth, *Science*, *328*(5980), 884-887.
Schörghofer, N., et al. (2021), Water Group Exospheres and Surface Interactions on the Moon, Mercury, and Ceres, *Space Science Reviews*, *217*(6).
Shearer, C. K., and Papike, J. J. (2005), Early crustal building processes on the moon: Models for the petrogenesis of the magnesian suite, *Geochimica et Cosmochimica Acta*, *69*(13), 3445-3461.
Shervais, J. W., and McGee, J. J. (1998), Ion and electron microprobe study of troctolites, norite, and anorthosites from Apollo 14: evidence for urKREEP assimilation during petrogenesis of Apollo 14 Mg-suite rocks, *Geochimica et Cosmochimica Acta*, *62*(17), 3009-3023.
Siegler, M. A., et al. (2023), Remote detection of a lunar granitic batholith at Compton–Belkovich, *Nature*, *620*(7972), 116-121.
Spudis, P. D., et al. (2013), Large shield volcanoes on the Moon, *Journal of Geophysical Research: Planets*, *118*(5), 1063-1081.
Stevenson, D. J. (1987), Origin of the moon - The collision hypothesis, *Annual review of*

earth and planetary sciences, *15*, 271-315.
Stopar, J. D., et al. (2019), Ina, Moon: Geologic setting, scientific rationale, and site characterization for a small planetary lander concept, *Planetary and Space Science*, *171*, 1-16.
Sun, Y., et al. (2017), Detection of Mg-spinel bearing central peaks using M^3 images: Implications for the petrogenesis of Mg-spinel, *Earth and Planetary Science Letters*, *465*, 48-58.
Tian, H.-C., et al. (2021), Non-KREEP origin for Chang'E-5 basalts in the Procellarum KREEP Terrane, *Nature*, *600*, 59-63.
Tian, H.-C., et al. (2023), Surges in volcanic activity on the Moon about two billion years ago, *Nature Communications*, *14*(1), 3734.
Tsiganis, K., et al. (2005), Origin of the orbital architecture of the giant planets of the Solar System, *Nature*, *435*(7041), 459-461.
Walsh, K. J., et al. (2011), A low mass for Mars from Jupiter's early gas-driven migration, *Nature*, *475*(7355), 206-209.
Warren, P. H. (1985), The magma ocean concept and lunar evolution, *Annual review of earth and planetary sciences*, *13*(1), 201-240.
Weiss, B. P., and Tikoo, S. M. (2014), The lunar dynamo, *Science*, *346*(6214).
Wiechert, U., et al. (2001), Oxygen Isotopes and the Moon-Forming Giant Impact, *Science*, *294*, 345-348.
Wieczorek, M. A., et al. (2006), The constitution and structure of the lunar interior, *Reviews in mineralogy and geochemistry*, *60*(1), 221-364.
Wieczorek, M. A., et al. (2013), The Crust of the Moon as Seen by GRAIL, *Science*, *339*(6120), 671-675.
Wieczorek, M. A., et al. (2012), An Impactor Origin for Lunar Magnetic Anomalies, *Science*, *335*(6073), 1212-1215.
Wieczorek, M. A., and Zuber, M. T. (2001), The composition and origin of the lunar crust: Constraints from central peaks and crustal thickness modeling, *Geophysical Research Letters*, *28*(21), 4023-4026.
Wood, B. J., and Halliday, A. N. (2005), Cooling of the Earth and core formation after the giant impact, *Nature*, *437*(7063), 1345-1348.
Xu, X., et al. (2020), Formation of lunar highlands anorthosites, *Earth and Planetary Science Letters*, *536*, 116138.
Yang, W. and Pan, Z. (2023), Lunar 'specialities': from Apollo 11 to Chang'e 5, *Bulletin of Mineralogy, Petrology and Geochemistry*, *42*(6), 1424-1438.
Yang, W. et al. (2024), Disciplinary policy research on science development strategies for crewed lunar exploration, *Bulletin of Chinese Academy of Sciences*, 39(11), 1931-1943.
Yuan, Q., et al. (2023), Moon-forming impactor as a source of Earth's basal mantle anomalies, *Nature*, *623*(7985), 95-99.
Yue, Z., et al. (2013), Projectile remnants in central peaks of lunar impact craters, *Nature Geosci*, *6*(6), 435-437.
Zeng, X., et al. (2023), Landing site of the Chang'e-6 lunar farside sample return mission from the Apollo basin, *Nature Astronomy*, 7(10), 1188-1197.

Zhang, J., et al. (2020), Lunar regolith and substructure at Chang'E-4 landing site in South Pole–Aitken basin, *Nature Astronomy*, *5*.
Zhang, N., et al. (2022), Lunar compositional asymmetry explained by mantle overturn following the South Pole–Aitken impact, *Nature Geoscience*, *15*(1), 37-41.
Zhang, P., et al. (2023a), Overview of the Lunar In Situ Resource Utilization Techniques for Future Lunar Missions, *Space: Science & Technology*, *3*, 0037.
Zhang, T., et al. (2023b), Frontiers in lunar science based on bibliometric analysis. Acta Petrologica Sinica, 39(10), 3169-3183.
Zong, K., et al. (2022), Bulk compositions of the Chang'E-5 lunar soil: Insights into chemical homogeneity, exotic addition, and origin of landing site basalts, *Geochimica et Cosmochimica Acta*, 335, 284-296.