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Recent advances in China's planetary science research

Yongxin PAN[1*], Wei LIN[1] & Liping QIN[2]

[1] *Key Laboratory of Planetary Science and Frontier Technology, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China*
[2] *State Key Laboratory of Lithospheric and Environmental Coevolution, University of Science and Technology of China, Hefei 230026, China*

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Abstract Planetary science is an emerging interdisciplinary field that explores the origin and evolution of planets, moons, small celestial bodies, and exoplanets, along with their multisphere processes and interactions, potential habitability, and resource utilization. Since the early 21st century, China has launched a series of lunar and planetary missions and made numerous research progresses in the planetary science. This article summarizes key insights from the 150th "Planetary Science" Frontier Forum hosted by the Chinese Academy of Sciences, reviews new progress in lunar, Martian, small body, and exoplanetary research in China, and highlights major scientific questions and future directions for China's planetary science endeavors.

Keywords Planetary science, Earth science, Mars, Moon, Habitability

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1. Introduction

Planetary science represents an interdisciplinary field dedicated to investigating the fundamental characteristics, internal structures, compositional evolution, and potential habitability of planets, moons, and small celestial bodies. This emerging discipline integrates Earth science and Astronomy to develop comprehensive theoretical frameworks for understanding planetary formation, evolution, and resource potential, and thus plays a central role in driving deep space exploration (Pan and Wang, 2021; Wang et al., 2022). Planetary science encompasses multiple research fields, including planetary geology, planetary geochemistry, planetary geophysics, planetary atmospheric science, and astrobiology, collectively advancing our understanding of planetary systems and their origin and evolution.

China's planetary science, although established relatively recently, has made remarkable progress. The implementation of lunar and planetary exploration programs has propelled China's planetary science into a phase of rapid development. Notably, the Chang'e lunar exploration program and the Tianwen-1 mission have yielded transformative discoveries in lunar and Martian research. The Chang'e missions have achieved significant breakthroughs in lunar exploration and scientific investigation, while the Tianwen-1 mission successfully executed both orbital and surface exploration of Mars, establishing China as the second nation to conduct successfully *in situ* scientific exploration of the Red Planet. National institutions, including the China National Space Administration (CNSA), Chinese Academy of Sciences (CAS), and the National Natural Science Foundation of China (NSFC), have launched planetary science research initiatives. These efforts have significantly accelerated the development of relevant scientific research, fostering interdisciplinary collaboration and technological innovation in planetary exploration.

In the last century, Chinese researchers made substantial advancements in laboratory analyses of extraterrestrial ma-

* Corresponding author (email: yxpan@mail.iggcas.ac.cn)

terials, primarily focusing on meteorite samples. These efforts led to breakthroughs in micro-analytical techniques for extraterrestrial materials and initiated foundational studies of the Earth-Moon system through analyses of Apollo lunar samples. In 2004, China launched the Chang'e program, which established research teams dedicated to lunar remote sensing, lunar geology and lunar geophysics. This initiative facilitated both technological development and scientific investigation. The accomplishment of the Chang'e-5 lunar sample return mission in 2020, coupled with the China's first Mars exploration Tianwen-1 mission, marked a new era in China's deep-space exploration and planetary science endeavors. These missions enabled Chinese scientists to study firsthand scientific data and returned lunar samples, marking the transition of China's planetary science research from follow-up studies relying on international data to original investigations based on Chinese mission data and samples. This paradigm shift has led to a series of significant scientific achievements. In 2021, planetary science was formally established as a first-level academic discipline in China. The field is currently progressing toward enhanced disciplinary structure, institutional development, and systematic organization. Current efforts focus on key scientific questions regarding planetary habitability and evolution, while simultaneously developing interdisciplinary, full-chain, and integrated research platforms. These initiatives, along with the construction of large-scale scientific infrastructure, are establishing the foundation for a dual-drive approach where both engineering technology and scientific research propel deep-space exploration forward.

To advance planetary science in China and address the scientific requirements of China's deep-space exploration initiatives, the Chinese Academy of Sciences convened the 150th Frontier Forum on Science and Technology of "Planetary Science" in Beijing on October 28–29, 2023. This interdisciplinary forum discussed critical scientific questions, including lunar formation and evolutionary processes, Martian habitability and climate evolution, asteroid and comet research, and exoplanetary habitability assessments. This review synthesizes the key progresses and expert perspectives of the forum and outlines strategic priorities for advancing China's planetary science research.

2. Progress in lunar scientific research

The Moon, Earth's sole natural satellite, represents a unique celestial body whose origin and evolution are intrinsically linked to Earth's history. As the most extensively studied extraterrestrial object, the Moon has been the focus of human exploration efforts ranging from early telescopic observations to sophisticated robotic and crewed missions. The Apollo missions significantly advanced our understanding of lunar formation and evolution, providing profound insights into the Earth-Moon system. Since the 1990s, the United States, Europe, Japan, and India have successively conducted high-precision lunar exploration missions. Notably, China's Chang'e program has made substantial progress in lunar exploration. The Chang'e-5 mission's successful return of 1,731 g of lunar samples in 2020 has opened new avenues for investigating lunar geology, volatile evolution, and thermal history, reshaping our understanding of the Moon's past and present (Wang C et al., 2023; He H et al., 2024).

2.1 Lunar regolith and volatiles

The lunar surface is covered by regolith which ranges from several meters to tens of meters in thickness. The lunar regolith is formed through space weathering of the lunar crust, primarily composed of weathered basalt and anorthosite resulting from long-term meteorite and micrometeorite impacts, as well as exposure to solar wind and cosmic rays (Crawford et al., 2012). Serving as a significant repository of lunar evolutionary history, lunar regolith consists of a heterogeneous mixture of locally weathered materials and impact ejecta, including lithic clasts, mineral fragments, breccias, glasses, and agglutinates. Additionally, it preserves hydrogen and helium implanted by solar wind, along with remnants of meteorite impacts (Heiken et al., 1991). Unlike terrestrial soil, lunar regolith lacks liquid water, organic matter, and biotic material.

The Chang'e-5 (CE-5) mission successfully collected 1,731 grams of lunar regolith from the Mons Rümker region in December 2020. Systematic investigations of the CE-5 samples have revealed that lunar soil particles are predominantly smaller than 500 μm (Li et al., 2022b). The agglutinates are irregular in shape, composed of glassy fragments formed by impact, adjacent rock fragments, and mineral fragments, with a volume fraction of glassy fragments ranging from 10% to 25%. Spherical glass beads are usually brown to black, while irregular glass fragments are generally lighter in color, containing mineral inclusions such as pyroxene, olivine, plagioclase, ilmenite, and minor amounts of quartz and apatite. The CE-5 lunar soil is primarily composed of local basaltic materials (>90%), mixed with a small amount of ejecta from other lunar regions and meteorite residues (Wu et al., 2024). Analysis of the bulk CE-5 mare basalts revealed a negative europium anomaly. These basalts are rich in iron (more than 20 wt%) and depleted in magnesium, with a magnesium index (Mg# = Mg/(Mg+Fe)×100 in molar ratio) of 26–32 (Tian et al., 2021; Lu et al., 2023). Based on the titanium content, these basalts were proposed to have originated from low-degree partial melting of the lunar mantle and extensive magmatic differentiation (Tian et al., 2021; Luo et al., 2023).

One of the most significant scientific achievements of the

Apollo era was the discovery that the water content of the moon is extremely low (<1 ppb, 1 ppb=1 μg kg^{-1}) (Taylor et al., 2006), which supported the Giant Impact Hypothesis of the Moon's origin (Hartmann and Davis, 1975). Advances in microanalytical techniques enabled the first detection of trace water in lunar volcanic glasses, exhibiting degassing signatures, which indicates that the water content in lunar magma may be as high as 745 ppm (1 ppm=1 mg kg^{-1}) (Saal et al., 2008). This discovery has triggered extensive research on lunar mantle water. Subsequent studies measured water concentrations and hydrogen isotopes in diverse lunar samples, including apatite, melt inclusions, and nominally anhydrous minerals (Boyce et al., 2010; Hauri et al., 2011; Hui et al., 2013), leading to the hypothesis of a potential "wet" Moon. Initial water content in some lunar magma could be as high as 1,400 ppm, reigniting debates over the Moon's water abundance versus depletion (Sharp et al., 2010). Recent analysis of CE-5 mare basalts estimated a mantle source water content of 1–5 ppm (Hu et al., 2021), lower than that of Apollo sample, which may indicate a temporary depletion of the Moon. Overall, the water content in the mantle sources of lunar basalts is <20 ppm, with exception of certain volcanic glasses, which are considered to be derived from the mantle sources with water content comparable to those of the Earth's upper mantle (McCubbin et al., 2023).

Geochemical studies on the CE-5 lunar samples have revealed multiple formation mechanisms for nano-Fe phases in the lunar regolith, including disproportionation, impact-induced thermal decomposition, and eutectoid reactions (Li et al., 2020; Li et al., 2022a). These studies suggest that magnetite and digenite may have formed during impact events. The distribution and origin of surface water and other volatiles gases such as H_2S, H_2, CO_2, N_2, CH_4, NH_3, and noble gases remain key topics in lunar research, with significant implications for future in-situ resource utilization. The CE-5 landing site, located in a mid-latitude region, provides an ideal opportunity to investigate water distribution and sources on the Moon. Recent studies have demonstrated that the surfaces of lunar soil particles and impact glass beads from CE-5 contain substantial concentrations of solar wind-derived water (Xu Y et al., 2022; Zhou et al., 2022; He H et al., 2023). The water content in impact glass beads exhibits a gradual decrease from >1500 ppm at the outer edges to markedly lower concentrations in the interior, likely attributed to the inward diffusion of solar-wind-implanted hydrogen.

Considerable uncertainties persist regarding the origin, distribution, and abundance of lunar water. Spectral data from the Moon Mineralogy Mapper (M^3) indicate that water content in the permanently shadowed regions (PSRs) of the lunar south pole reaches approximately 0.07% (Honniball et al., 2020). In contrast, near-infrared to ultraviolet spectra obtained from the Lunar Crater Observation and Sensing Satellite (LCROSS) impact into Cabeus crater revealed an average water content of 5.6 wt% at the LCROSS impact site, along with other volatile compounds including H_2S, NH_3, C_2H_2, CO_2, and CH_3OH (Colaprete et al., 2010). The PSRs at the lunar poles have been suggested to be enriched in water and other volatiles. However, several key aspects remain unresolved. The content of these volatiles exhibits considerable variation, their distribution appears highly heterogeneous, and their origin remains poorly constrained. While solar wind-derived water has been supported by remote sensing and sample analyses, contributions from asteroidal and cometary impacts, as well as inherited water and other volatiles from early magmatic activity, require further analysis. Accurate measurements of lunar surface volatiles are thus essential. The Chang'e-7 (CE-7) mission will target the lunar south pole, conducting systematic measurements of volatiles and their isotopes using a water molecule analyzer and a volatile composition analyzer (Wang et al., 2024). The key payload of the CE-7 lunar exploration mission, the *in situ* volatile analyzer, is aimed at detecting volatiles and water ice at the lunar south pole.

2.2 Impact history of the Moon and crater chronology

Impact is a fundamental geological process in the formation and early evolution of the Moon. The impact flux governs the surface modification rate of celestial bodies, while also serving as the basis for estimating the model ages of extraterrestrial surfaces. Due to its relatively weak magmatic activity, the lunar surface preserves a nearly complete record of the Solar System's impact history. Given that inner Solar System bodies may have experienced similar impact processes, the Moon serves as a critical reference for calibrating crater statistical model ages and the impact histories of other inner Solar System bodies (Yue et al., 2021, 2022).

The prevailing hypothesis suggests that the Moon experienced a high-frequency bombardment in its early formation stage, followed by a relatively low and stable impact frequency over the subsequent more than 3 billion years and more. The uncertainties in crater size-frequency distribution dating primarily arise from the estimation of lunar impact flux and the ambiguous origins of impact ejecta, including but not limited to ballistic ejecta, impact melt, and impact glasses, which exhibit multiple potential sources (Xiao et al., 2021, 2022). Additionally, insufficient predictive models of depositional patterns and significant controversies surrounding sample properties further contribute to dating uncertainties. Another source of error stems from background secondary crater contamination, as well as the heterogeneous distribution of impact ejecta fragments, leading to notable discrepancies in secondary crater densities and equivalent model ages (Chang et al., 2021). Moreover, differential degradation of impact crater topography introduces complications, given that the degradation rate of crater morphology is size-dependent. Different computational models yield substantial variations in the initial crater production rate and model age estimations (Xie et al., 2017, 2019).

The South Pole-Aitken (SPA) basin is the largest, deepest, and oldest confirmed impact basin on the Moon, covering approximately 10% of the lunar surface with a diameter of 2,500 km and an excavation depth of up to 100 km (Garrick-Bethell and Zuber, 2009). Based on crater chronology, it is inferred to have formed ~4.2 billion years ago through an oblique impact from the south to the north (Fernandes et al., 2013). This impact event profoundly influenced the Moon's geological evolution by excavating and ejecting material from deep within the mantle (Yamamoto et al., 2012), ultimately shaping the Moon's three primary terranes: the SPA Basin Terrane, the Procellarum KREEP Terrane, and the Feldspathic Highlands Terrane. The impact may have directly or indirectly contributed to the formation of lunar dichotomies (Zhang N et al., 2022), and triggered asymmetric thermal evolution, as evidenced by the uneven distribution of mare basalts (Wilson and Head, 2017; Zhao J et al., 2023). The SPA basin is a key region for exploring several major scientific questions, including the structure of the lunar crust-mantle system, mantle heterogeneity, the formation of early Solar System giant impact basins, and the Late Heavy Bombardment (LHB) event.

2.3 Lunar formation and early evolution

The most widely accepted theory regarding the formation of the Moon is the Giant Impact Hypothesis, which posits that approximately 4.52 billion to 4.42 billion years ago, a Mars-sized celestial body collided with the proto-Earth. The ejected material subsequently accreted to form the Moon, ultimately creating the current Earth-Moon system (Hartmann and Davis, 1975). This violent impact could have produced a magma ocean on the Moon's surface. As the magma ocean crystallized and differentiated, the lunar mantle and crust gradually formed, creating a unique layer between the lunar crust and the mantle—the potential urKREEP layer (rich in heat-generating elements). The solidification of the magma ocean is estimated to have occurred between 4.4 and 4.2 billion years ago, constituting the fundamental model for lunar crust-mantle differentiation. Around 3.9 billion years ago, the Moon possibly underwent an episode of intensive bombardment, known as the LHB event, which created several large basins, including those underlying the present lunar maria. The LHB event may have also exerted significant influence on other terrestrial planets in the Solar System. Notably, during almost the same period, Earth witnessed the formation of continental crust and the emergence of the earliest life. A potential correlation between the LHB event and these geological processes and biological developments on Earth cannot be ruled out (Chen et al., 2023; Wu et al., 2024).

Traditionally, it was believed that due to the small size of the Moon, it cooled very quickly. Based on dating analyses of Apollo returned samples and lunar meteorites, the ages of lunar mare basalts generally range between 3.9 and 3.0 billion years, with the youngest lunar meteorites dating back to ~2.8 billion years ago (Borg et al., 2004). However, crater chronology studies suggest that magmatic activity in some regions of the Moon, particularly within the Oceanus Procellarum KREEP terrane on the lunar nearside, may have continued until as recently as ~1 billion years ago. The CE-5 mission landed in the northern Oceanus Procellarum, a higher-latitude region compared to the landing sites of the Apollo and Luna missions. High-precision radiochronological analyses of the CE-5 returned basalt samples show that the basalt samples have an age of 2 billion years (Che et al., 2021; Li Q L et al., 2021). This discovery extends the duration of lunar magmatic activity by approximately 800 million years, reshaping our understanding of mid-to-late-stage lunar thermal evolution and volcanic history.

The CE-5 basalts may have been produced by low-degree partial melting of a mantle source that lacks radioactive heat-generating elements (e.g., K, Rb, U, Th) and KREEP components, followed by high-degree fractional crystallization of the basaltic magma (Tian et al., 2021). This indicates that the mantle melting was not caused by radiogenic heating. The addition of water and volatiles can significantly reduce the solidus temperature, thereby facilitating mantle melting. However, the CE-5 basaltic mantle source was extremely water-poor 2 billion years ago, which may be dehydrated due to continuous partial melting of mantle (Hu et al., 2021). Moreover, the abundances of volatiles such as F, Cl, and S were also relatively low (Liu X et al., 2022; Ji et al., 2022). Therefore, the mid-stage lunar mantle melting might have originated from other mechanisms. Compared to the Apollo samples, the primary magma of CE-5 basalts exhibits higher calcium and titanium contents (Su et al., 2022), indicating that their mantle source was relatively enriched in these elements. Calcium is primarily found in clinopyroxene, and titanium is mainly in ilmenite, both of which likely crystallized during the late stage of the lunar magma ocean (LMO). When the mantle source contained substantial late-stage LMO cumulates (clinopyroxene-ilmenite assemblages), the melting temperature (or solidus) was lowered, promoting the formation of younger volcanic activity. However, the Sr-Nd-Hf radiogenic isotope systematics of CE-5 basalts does not support significant contributions from such late-stage LMO cumulates (Shen et al., 2025). The reason behind the Moon's unusually slow cooling rate remains an enigma worthy of further exploration.

3. Advances in Mars scientific research

On 23 July 2020, China successfully launched the Tianwen-1 mission, its first Mars exploration endeavor. The probe entered Mars orbit on 10 February 2021 and landed in southern Utopia Planitia on 15 May 2021, deploying the Zhurong rover. This mission marked the first instance of a single endeavor that accomplished orbiting, landing, and roving on Mars, establishing China as the second nation, after the United States of America, to conduct *in situ* exploration on the Martian surface. The Tianwen-1 mission, comprising the Zhurong rover and an orbiter, carries 13 scientific payloads designed to systematically investigate Mars' morphology and geological structure, surface material composition, soil characteristics, water ice distribution, ionosphere and space environment, and geophysical fields and internal structure (Wan et al., 2020; Li C et al., 2021; Pan et al., 2021; Zhang, 2021).

3.1 Aqueous activities on Mars

The ancient terrain of Utopia Planitia preserves landforms associated with fluvial, lacustrine basins, and possibly even marine environments (Liu Z et al., 2021), indicating that liquid water may have flowed on the Martian surface around 4 billion years ago. Despite substantial geological evidence, the climate conditions that sustained surface liquid water over a long term remain enigmatic. Low solar radiation flux during the first few hundred million years of Mars, combined with limited greenhouse effects from carbon dioxide and other gases, implies that the early climate was predominantly cold (Liu Z et al., 2021). However, the widespread distribution of phyllosilicate minerals in the Noachian highlands suggests episodic warm and wet conditions during the Noachian period (Mustard, 2019). Transient warming events likely triggered snow and ice melt, leading to temporarily active hydrological cycles that formed valley networks and other fluvial erosion features. Nevertheless, the driving mechanisms behind such warming episodes remain unclear. During the Amazonian period, liquid water activity was sporadic, with prominent glacial processes and extensive aeolian landforms. However, globally distributed seasonal features, such as recurring slope lineae, suggest ongoing freeze-thaw cycles of brines or sand-flow surface modification. The high-resolution stereo images from the Tianwen-1 HiRIC and NaTeCam instruments have been utilized to reconstruct and map the landing-site topography, identifying landforms including concave cones, boulders, dunes, polygonal impact craters, and grooves (Liu J et al., 2021, 2023a; Ye et al., 2021; Zhao et al., 2021; Wu et al., 2022). The Zhurong rover has discovered multiple lines of evidence for Late Amazonian aqueous activity (Li et al., 2022c; Liu Y et al., 2022; Qin et al., 2023; Zhao Y Y S et al., 2023), suggesting that the recent Martian climate may have been less arid than traditionally assumed. However, some key aspects—such as the nature, intensity, and duration of Amazonian hydrological processes—still require further investigation.

Martian meteorites provide crucial insights into the water activity on Mars. To date, over 390 Martian meteorites have been confirmed and officially named, with the majority discovered in deserts and Antarctica. Chinese researchers have recovered two basaltic Martian meteorites in the Grove Mountains of Antarctica, dated at 177±5 and 192±10 Ma, respectively (Jiang and Hsu, 2012). Geochemical analyses indicate that their parental magmas originated from moderately depleted and enriched source regions, respectively, leading to the proposal of a two-stage fractional crystallization model (Lin et al., 2005, 2013). Further analyses of water content and hydrogen isotopes in Martian meteorites suggest that magmatic intrusion into subglacial/permafrost ice could have formed groundwater systems. The hydrogen isotopic composition of this groundwater was calculated as δD=6034‰±72‰, while the water content of the Martian mantle source region was found to be relatively low, ranging from 38 to 75 ppm (Hu et al., 2014; Usui et al., 2015). Additionally, studies of the Tissint Martian meteorite revealed that organic carbon on Mars exhibits a light carbon isotopic signature (Lin et al., 2014).

The development of the hydrological system on early Mars suggests the existence of widespread water bodies in the northern plains during the late Noachian and Hesperian periods, forming the Vastitas Borealis Formation (VBF) sedimentary strata widely distributed in the Chryse Planitia and Utopia Planitia region (Head et al., 2002). Due to the lack of in-situ exploration of the VBF in previous missions, interpretations of its lithology remain highly uncertain and controversial. Recent studies on scientific data from the Zhurong rover have identified water-related minerals within the duricrust at the landing site, suggesting potential groundwater activity in the past (Liu Y et al., 2022). Morphological features observed along the rover traverse, such as desiccation cracks and cloddy structures, indicate episodic liquid water activity, with the possibility of briny water movement even under current environmental conditions (Liu J et al., 2023b; Qin et al., 2023). Analyses of the Zhurong rover data further revealed the potential presence of hydrated mineral phases in the landing area (Lin H et al., 2023). These minerals may include hydrous sulfates/hydrated silica, as well as allophane, and imogolite/opal formed through the alteration of volcaniclastic soil. These findings confirm the occurrence of water-rock interactions in Utopia Planitia, implying that aqueous activity in the northern Martian plains during the Amazonian may have been more extensive than previously assumed (Liu C et al., 2022).

Analysis of high-resolution image data acquired by the Zhurong rover shows that the exposed surface rocks have typical marine sedimentary stratification structures, supporting the hypothesis that an ancient ocean existed during this period (Xiao et al., 2023). By extracting the physical properties of the strata through dielectric constant inversion of Zhurong radar data, it was found that the southern Utopia Planitia experienced multiple phases of surface modification events since the Late Hesperian (3.5–3.2 Ga), with water-related geological processes potentially persisting until the Middle to Late Amazonian (approximately 1.6 Ga). No obvious evidence of a liquid water layer has been found within the uppermost 80 m of the shallow subsurface along the traverse of Zhurong rover in this region, though the presence of a certain amount of saline water/ice cannot be ruled out. This study indicates that the sedimentary deposits of northern lowlands underwent significant aqueous activity during the Late Hesperian, which later evolved into the current relatively dry conditions with minimal liquid water activity (Li et al., 2022c).

3.2 Composition of Martian surface materials and environmental changes

In April 2023, China released the first global color image of Mars obtained by the Tianwen-1 mission, with a resolution of less than 100 m.

Dunes, boulders, and crust layers have been observed along the Zhurong rover traverse (Liu J et al., 2021; Ding et al., 2022). *In-situ* compositional analysis revealed that these materials were primarily formed through the weathering of basaltic rocks in a cold, water-deficient environment. By systematically analyzing over 2,000 dunes in southern Utopia Planitia using high-resolution images from the Tianwen-1 orbiter, researchers identified a 70° shift in paleowind directions, represented by bright and dark dunes. This shift indicates significant changes in the ancient Martian environment and climate (Liu J et al., 2023a). Integrating previous studies on Mars polar ice deposits, this transition is inferred to be associated with variations in Mars' axial tilt. Crater-based dating suggests that the paleowind direction shift occurred approximately 400 ka ago (Liu J et al., 2023a). Additionally, comparative analysis of the Zhurong landing site using high-resolution orbiter imagery confirmed the volcanic dome origin of small hills, providing evidence of localized magmatic activity on Mars (Lin Y et al., 2023).

The redox conditions and evolution of the Martian surface environment are key clues to the evolution of Martian climate, geology, and potential life. They also hold significant implications for the search for extraterrestrial life and the understanding of organic matter/potential biosignature generation and preservation. The geologic record of Mars contains abundant evidence reflective of aqueous and environmental redox conditions, including mineral assemblages, elemental distributions, and organic compounds. However, research progress in areas such as iron-manganese oxidation, oxyanion cycling, and atmospheric composition evolution has also sparked debates regarding paleoenvironmental interpretations (Hurowitz et al., 2007; Zhao et al., 2018; Deng et al., 2020; Qu et al., 2022; Mitra et al., 2023; Wen et al., 2023). Future Mars sample-return missions are expected to provide breakthroughs in unraveling the Martian paleoenvironment and even biosignatures.

3.3 Martian ionosphere and atmosphere

The Tianwen-1 probe has uncovered the structure of Mars' atmosphere and ionosphere, as well as their variations with solar wind dynamics (Hu et al., 2022; Zhang A B et al., 2022). Atmospheric escape is recognized as a key driver of Mars' transition from an early warm and wet environment to its current cold and dry state. The escape of volatiles such as carbon, nitrogen, oxygen, and hydrogen has significantly influenced the evolution of Martian habitability. While current international research on Martian atmospheric escape predominantly focuses on the present-day state, the evolution of habitability on Mars is more fundamentally determined by atmospheric changes over its entire 4.5-billion-year history (Dong et al., 2018). High-resolution observations from the Tianwen-1 magnetometer (MOMAG), along with NASA MAVEN's magnetometer and ion analyzers, have uncovered the real-time rapid response of bow shocks to minute-scale solar wind perturbations. These observations demonstrate rapid oscillations of the Martian bow shock induced by variations in solar wind dynamic pressure, interplanetary magnetic field rotations, and typical solar wind irregular disturbances (Wang Y M et al., 2023; Cheng et al., 2024). Early Mars possessed a much denser atmosphere, raising critical questions about the role of escape in its atmospheric evolution, particularly regarding how much of its early atmosphere was lost through condensation versus escape, how the faint young Sun and the varying magnetic conditions in the solar wind influenced atmospheric depletion, and whether planetesimal impacts enhanced or diminished the atmosphere. These key questions remain at the forefront of Martian scientific research. Understanding the mechanisms of atmospheric escape and evolution on Mars extends beyond the traditional domains of atmospheric and space physics, requiring an interdisciplinary integration of astronomy, geology, geophysics, and fundamental physics and chemistry to achieve a comprehensive understanding.

Martian dust storms represent a significant atmospheric phenomenon on Mars, profoundly affecting the Martian atmospheric environment, surface morphology, space environment, and the safety of exploration missions. These storms are characterized by high frequency, wide spatiotemporal scales, extensive distribution, and challenges in prediction, making them a cutting-edge research focus in Martian science. To support future Mars exploration programs, Chinese scientists have conducted comprehensive reviews of current dust storm research (Wang Y et al., 2023; Zhou X et al., 2024), detailed analyses of the spatiotemporal distribution of dust storms in the Tianwen-1 landing zone, and dust activity trends (Wei et al., 2022). Furthermore, scientific recommendations for the landing site selection of the future Tianwen-3 mission have been proposed (He F et al., 2024; Tian et al., 2024). Additionally, conceptual frameworks and detection strategies for future satellite-based monitoring of Martian dust storms have been outlined (He F et al., 2023; Rong et al., 2023). A significant progress has also been made in Martian atmospheric modeling and dust storm simulations with domestic-developed models demonstrating the capability to simulate the dynamics of Martian dust storms (Wu et al., 2022; Dong et al., 2024; Zhou X et al., 2024).

3.4 Martian physical fields and internal structure

Currently, Mars no longer has an intrinsic magnetic field, with crustal magnetization widely distributed in the southern hemisphere but largely absent in the northern hemisphere. An improved signal extraction method based on in-orbit calibration of Zhurong's onboard magnetometer (RoMAG) has been developed, which revealed the presence of an extremely weak magnetic field along the rover traverse, with an average intensity of approximately 10 nT (Du et al., 2023). These findings provide critical data for further discussions on the magnetization history of Utopia Planitia and the evolution of Mars' intrinsic magnetic field and dynamo.

The early understanding of Martian internal structure primarily relied on geochemical data from Martian meteorites and orbital geophysical data. The analysis of seismic data from the NASA's InSight mission has confirmed the existence of a layered crust-mantle-core structure on Mars. Comparative seismic studies have recently revealed evidence for possible persistent magma activity in the upper mantle (Sun and Tkalčić, 2022).

Using low-frequency radar data collected by the onboard ground penetrating radar of Zhurong rover (RoPeR), the Zhurong radar team conducted high-resolution analysis and imaging to obtain, for the first time, a precise subsurface structural profile (depth <80 m) along a 1,171-m transect in the southern Utopia Planitia. The study identified two upward-thinning sedimentary sequences beneath the approximately several-meter-thick regolith, located at depths of ~10–30 m and 30–80 m (Li et al., 2022c). Additionally, radar signals detected further subsurface structures, revealing polygonal terrain likely formed by aqueous activity during the Amazonian period (Zhang et al., 2024).

4. Advances in the study of small bodies and exoplanets

Small bodies in the Solar System, including asteroids, comets, dwarf planets, and natural satellites, preserve key information about the formation and evolutionary stages of the Solar System. China's newly launched Tianwen-2 and upcoming Tianwen-4 missions aim to explore near-Earth asteroids, main-belt comets, and the Jovian system, addressing key questions about the origin of interstellar organic molecules and the potential for extraterrestrial habitable environments. Additionally, these studies will provide essential data for major scientific and engineering endeavors, including the space resource utilization and planetary defense (Li et al., 2019).

4.1 Asteroids

Asteroids are celestial bodies that orbit the Sun, with sizes and masses smaller than those of dwarf planets, and negligible gas and dust released. They typically range in diameter from 0.01 to 1,000 km. To date, over 1.3 million asteroids have been confirmed, with more than 90% concentrated in the asteroid belt between the orbits of Mars and Jupiter. The rest of the asteroids are distributed near Earth's orbit, Jupiter's orbit, the region between Jupiter and Neptune, and the trans-Neptunian space. The classification system of asteroids is primarily based on spectral characteristics, which reveal their chemical compositions. They are categorized into siliceous (S-type), carbonaceous (C-type), X-type, and other groups (Xu and Zhao, 2005).

Understanding the composition of asteroids primarily relies on studies of meteorite samples. Advances in high-precision metal isotope analysis have provided new constraints on the material sources of terrestrial planets (Qin et al., 2010, 2011). Distinct types of asteroids exhibit characteristic isotopic anomalies, reflecting nucleosynthetic variations, which are signals passed down from various pre-solar stars, heterogeneously distributed in the protoplanetary disk. Samples that share the same origin often show similar isotopic anomalies, aiding in tracing the origins of unknown meteoritic materials. For instance, using a coupled ^{54}Cr anomalies and oxygen isotope compositions confirmed that the NWA 8321 meteorite is originated from Vesta, and subsequent mineralogical study found evidence of sulfide metasomatism in its interior (Zhang et al., 2020). Similarly, the eucrite NWA 15118 was identified as a Vesta sample, further supporting the existence of a magma ocean on Vesta (Li et al., 2024). Short-lived radionuclide (SLR) chronometry provides temporal constraints for early Solar System events. By integrating SLR dating with isotopic anomaly data, the spatiotemporal distribution of Solar System material reservoirs can be reconstructed. Joint investigations of the Mn-Cr SLR system and Cr isotopic anomalies in primitive chondrites and iron meteorites indicate rapid mixing of materials in the inner Solar System, whereas heterogeneity was better preserved in the outer Solar System (Zhu et al., 2019).

Asteroid sample return missions have become a promising focus of deep space exploration in recent years. China's Tianwen-2 mission aims to return samples from the near-Earth asteroid 2016 HO3. Preliminary investigations into the asteroid's orbital dynamics, solar wind interactions, spectral classification, formation mechanisms, and evolutionary processes have been conducted (Feng et al., 2022; Hu et al., 2023; Li et al., 2023), providing insights into the complexity of orbital and chemical evolution in near-Earth asteroids. Additionally, it is planned to deploy an impactor for planetary defense test targeting 2019 VL5, another near-Earth asteroid, to analyze its composition and study the momentum transfer efficiency during impact (Wang K D et al., 2023).

4.2 Comets

Comets are small celestial bodies capable of releasing ejected gas and dust. They typically consist of a nucleus, a coma, and a tail, and are comparable in size to asteroids. Most comets are found in the Kuiper Belt beyond Neptune, though some are also distributed within the main asteroid belt. They are primarily composed of water ice, gases, volatile substances, loose regolith, and dust particles. After completing its mission to detect and sample the asteroid 2016 HO3, the orbiter of Tianwen-2 is scheduled to proceed toward Comet 311P/PANSTARRS (hereafter 311P). This comet belongs to the category of main-belt comets but exhibits orbital characteristics similar to those of asteroids, leading to its classification as an active asteroid. Current knowledge about 311P remains limited. Preliminary research has investigated its peculiar multiple tail features, contributing to an improved understanding of the mechanisms behind its activity (Liu B et al., 2023). However, its actual structure, as well as the chemical composition of its nucleus and tail, remains to be clarified through data obtained during the upcoming flyby mission.

4.3 Icy moons

Both Jupiter and Saturn have numerous icy moons, some of which possess subsurface oceans, making them prime targets for extraterrestrial life exploration. Among Jupiter's moons, Europa is characterized by an ice-dominated surface and an extensive subsurface ocean. Ganymede, the largest moon in the Solar System, exhibits a global magnetic field. Depending on salinity variations and depth-related pressure differences, its subsurface environment may consist of stratified layers of water and ice (Mueller and McKinnon, 1988). The surfaces of Ganymede and Callisto are older than that of Europa, suggesting less pronounced surface-interior material exchange (Mueller and McKinnon, 1988). Building on current understanding of Jupiter's representative icy moons, China's Tianwen-4 mission plans to investigate Callisto. This mission, together with other international Jovian system exploration missions, will deepen insights into the chemical composition and evolutionary history of Jupiter's icy moons.

4.4 Exoplanets

Exoplanets represent an important focus in humanity's search for habitable environments beyond our Solar System and for understanding the formation and evolution of planetary systems. Since the first exoplanet discovery in the 1990s, the pace of exoplanet detection has accelerated significantly, with nearly 6,000 confirmed exoplanets documented to date. The primary methods currently employed in exoplanet detection include transit method, radial velocity measurements, microlensing, direct imaging, and astrometry (Zhou J L et al., 2024). Due to their vast distances, observations and studies of exoplanets predominantly focus on atmospheric spectroscopic analysis. To date, eight space telescopes have been successfully deployed in near-Earth orbit, including the Hubble Space Telescope, Spitzer, CoRoT, Kepler, Gaia, TESS, CHEOPS, and the James Webb Space Telescope.

China's exoplanet exploration program has made rapid progress in recent years. Utilizing observation facilities at the Xinglong Observatory, China's Antarctic astronomical stations, multiple exoplanets and over a hundred new exoplanet candidates have been successfully identified (Liu et al., 2009; Zhang et al., 2019). Recently, China has initiated the development of key instrumentation for the Chinese Space Station Telescope (CSST) program. A primary objective of this project involves designing an advanced exoplanet-imaging coronagraph system, specifically optimized for studying cold exoplanets (Zhu et al., 2021). Future missions will focus on detecting Earth 2.0 analogues, investigating exoplanetary atmospheric evolution, and searching for potential biosignatures (Zhang, 2020; Ge et al., 2022).

5. Perspectives

Planetary science in China is undergoing rapid development. To stimulate scientific breakthroughs in cutting-edge research and strengthen its role in future China's deep space exploration missions, we propose the following strategic priorities.

5.1 Scientific research frontiers

The Chang'e-5 mission has achieved transformative insights through the study of returned lunar samples, sparking a new wave of lunar research. Building on this success, the Chang'e-6 mission has collected the first samples from the far side of the moon, providing unprecedented opportunities to explore the key scientific questions regarding lunar geological characteristics and evolutionary history. Before 2030, the Chang'e-7 and Chang'e-8 missions will land near the lunar south pole, deploying advanced scientific instruments such as seismometers to explore the lunar interior structure, magnetometers to detect crustal magnetic field, and so forth. Lunar thermal simulation research will further elucidate the evolution of the lunar mantle and thermal history, focusing on the cooling rate of the lunar mantle and the mechanism triggering young volcanic activity. The study of lunar water and other volatiles remains a critical direction. The upcoming missions will detect volatile materials at the lunar south pole, exploring their migration mechanisms and predicting their distribution. Additionally, understanding the characteristics of lunar regolith requires the strengthening of laboratory simulations and extensive deep drilling to characterize its macro- and micro-scale features and evolution processes. These endeavors will support the planning and implementation of future robotic and crewed missions, while promoting key parameter analysis and process mineralogy breakthroughs to advance lunar in-situ resources utilization. In parallel, systematic and in-depth studies of returned samples from the Chang'e-5 and Chang'e-6 missions must remain a priority in the coming years.

The scientific data from China's first Mars exploration mission, Tianwen-1, necessitate further analysis. Key research areas include: (1) Comprehensive geological research on southern Utopia Planitia. Investigate the geological tectonic evolution and paleoenvironmental and climatic changes in southern Utopia Planitia from the late Hesperian to the Amazonian periods using data from the Zhurong rover. (2) Global Mars exploration. Utilize orbiter-mounted cameras for long-term observations of polar sediments to study paleoenvironmental evolution and employ coordinated observations by multiple orbiters to understand Martian space environment, atmospheric conditions, and magnetic field changes, supporting the landing site selection for the Tianwen-3 Mars exploration mission. (3) Mars gravity, magnetic, and seismic studies. Investigate Mars' internal structure through future geophysical exploration and explore internal processes controlling habitability. (4) Atmospheric evolution investigation. Deepen understanding of Martian atmospheric circulations using advanced remote sensing observations and simulations. (5) Supporting the Tianwen-3 Mars sample return mission (Hou et al., 2024). This will mark a new milestone in Mars exploration, laying the foundation for unprecedented studies of Martian environmental evolution and the search for potential signs of life on Mars.

China's current and future missions, include asteroid sampling and return missions (Tianwen-2 mission), Jupiter system exploration (Tianwen-4 mission), and the search for habitable exoplanets, will deepen our understanding of the characteristics and evolution of various celestial bodies in the Solar System. Exploring extraterrestrial habitable environments and biosignatures is a pivotal scientific goal of planetary science and deep space exploration, as well as a key area of astrobiology research (Lin et al., 2022). Astrobiology research in China is currently entering a phase of rapid development and must align with the national deep space exploration strategy, address cutting-edge scientific questions, and establish a research framework. Future directions may focus on several key aspects. (1) The origin of life on Earth and its environmental constraints. This involves studying the transition from chemical processes to biological processes during the early stages of life and exploring the environmental conditions that influenced this evolution. (2) Microorganisms and their adaptation mechanisms under extreme environments. Research will focus on the survival and adaptive strategies of life in extreme environments that resemble certain extraterrestrial conditions, with particular emphasis on biological features that could be used to detect extraterrestrial life. (3) Detection of habitable environments and biosignatures within the Solar System. This includes studying the environmental evolution of Mars, icy moons, and Venus, evaluating their potential for habitability, and developing advanced detection technologies and payloads. (4) Detection of habitable exoplanets. This entails assessing the habitability of exoplanets and searching for potential biosignatures.

5.2 Integrated development of scientific research and engineering technology

The advancement of planetary science thrives on interdisciplinary integration and the synergy between scientific research and engineering innovation. By integrating knowledge from multiple disciplines such as earth science, astronomy, space science, physics, chemistry, biology, and AI and computer science, planetary science offers a comprehensive understanding of planetary structure, evolution, environment, and resources, thereby revealing the complexity of planets within and outside the Solar System, and stands in the forefront of science, technology, and engineering. Accelerating technological innovation in detection capability, data processing and analysis, intelligent systems, and autonomous control is crucial for refining and accomplishing the scientific goals of future missions, guiding the development of innovative payloads, and enhancing the application of big scientific data.

5.3 International cooperation

To advance planetary science in China, strengthening bilateral and multilateral beneficial international cooperation is essential. Collaborations with scientists, technicians, engineers, and research institutions worldwide will facilitate resource sharing, knowledge exchange, and collective problem-solving of major challenges. These international partnerships promote interdisciplinary interactions that stimulate innovation and address critical issues in space exploration. Through international collaboration, especially in a modern, fast-changing world, we need to work together to enhance scientific collaborations and to achieve long-term and broader scientific goals in future deep-space explorations.

5.4 Talent development system

The advancement of planetary science relies on the development of a comprehensive talent cultivation system. By establishing strong linkages between industry, academic institutions, universities, and research organizations, aligned with mission objectives, we can strengthen the entire educational continuum from theoretical foundations to practical applications. This integrated approach facilitates knowledge dissemination while simultaneously enhancing student engagement, scientific literacy, and innovative capabilities. Moreover, it provides the essential human resources needed to drive scientific advancement in planetary science. Establishing a multi-level educational framework spanning undergraduate through graduate levels is crucial for developing planetary science professionals with both global perspectives and innovative capacities. Planetary science research not only expands the knowledge frontiers of our understanding of the universe but also offers novel approaches for continuously, comprehensively understanding the origin and evolution of our home planet Earth and life.

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