

Latest Scientific Results of China's Lunar and Deep Space Exploration (2024–2026)*

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Abstract China's deep-space exploration program has entered a highly productive scientific stage, highlighted by the Chang'E-6 lunar farside sample return mission and continuous scientific exploitation of Tianwen-1 orbital and Zhurong rover datasets. This review summarizes the major scientific advances achieved between 2024 and 2026 in lunar and Martian explorations. The first returned samples from the lunar farside have provided unprecedented constraints on the formation of the South Pole-Aitken basin, early lunar crustal evolution, farside volcanism, mantle heterogeneity, volatile evolution, and space weathering processes. These studies reveal a complex evolutionary history involving long-lived magmatism, impact-driven crustal reworking, hemispheric differences in mantle composition, and distinctive regolith evolution. Meanwhile, recent Tianwen-1 investigations have significantly advanced our understanding of Martian surface composition, subsurface structure, geomorphological evolution, and the near-Mars space environment, providing new evidence for aqueous alteration, shallow ice-bearing materials, possible ancient shoreline deposits, and solar-wind-driven plasma processes. These achievements demonstrate the increasing scientific impact of China's planetary exploration program and provide important new perspectives on terrestrial planet evolution, volatile histories, impact processes, and surface-environment interactions across the inner Solar System.

Key words Lunar and deep space exploration of China, Chang'E-6 mission, Tianwen-1 mission

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1 Introduction

Over the past two decades, China has established a comprehensive deep-space exploration program that has significantly advanced planetary science. Through the successive Chang'E lunar exploration missions and the Tianwen planetary exploration program, China has achieved a series of major technological and scientific breakthroughs, including lunar orbiting, landing, roving, sample return, and independent exploration of Mars. These missions have not only provided unique datasets and returned samples, but have also enabled fundamental advances in understanding the origin and evolution of

the Moon, Mars, and other bodies in the Solar System.

The period from 2024 to 2026 marks a particularly important stage in China's deep-space exploration. The successful return of 1935.3 g of lunar samples by the Chang'E-6 (CE-6) mission represents the first sample return from the lunar farside, opening an entirely new window into the South Pole-Aitken (SPA) basin and enabling direct investigation of the lunar farside, one of the least understood regions of the Moon^[1]. At the same time, continued analyses of data acquired by the Tianwen-1 orbiter and the Zhurong rover have substantially improved our understanding of Martian surface processes, subsurface structure, aqueous history, and the near-

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Mars space environment. Together, these achievements have produced a large number of high-impact scientific results that reshape current views of planetary evolution.

This review summarizes the major scientific advances arising from China's lunar and deep-space exploration between 2024 and 2026, with particular emphasis on the CE-6 sample return mission and recent discoveries based on Tianwen-1 observations. For the Moon, we highlight new constraints on the formation of the SPA basin, early lunar evolution, farside volcanism, mantle evolution, volatile inventories, and space weathering processes. For Mars, we review recent progress in surface geology, subsurface structure, orbital remote sensing, and the Martian plasma environment. These results collectively demonstrate the growing scientific impact of China's planetary exploration program and provide important constraints on the evolution of terrestrial planets and other airless bodies in the Solar System.

2 Chang'E-6 Mission

The CE-6 mission represents the first successful sample return from the lunar farside, landing at the Apollo basin within the South Pole-Aitken (SPA) impact structure (41.625°S, 153.978°W) and returning 1935.3 g of lunar samples. As the oldest and deepest recognized impact basin on the Moon, SPA provides a unique geological window into the lunar interior and the early impact history of the inner Solar System. The CE-6 landing site is located on a complex basaltic plain within SPA, characterized by volcanic constructs, tectonic features, and impact structures, recording prolonged magmatic and impact reworking^[2]. Consequently, CE-6 samples preserve a mixed record of farside volcanism, SPA-related ejecta, and subsequent impact modification, offering an unprecedented opportunity to investigate lunar farside evolution.

2.1 Early Lunar Evolution and SPA Formation

CE-6 samples are dominated by basaltic fragments, impact melts, and minor highland lithologies^[1], recording intense impact mixing and long-term crustal reworking. Ancient anorthositic clasts and highland-derived fragments provide constraints on the primary lunar crust and magma ocean differentiation. Impact processes emerge as the dominant agents shaping the farside crust.

Widespread impact-melt rocks, breccias, and shock metamorphic minerals record high-temperature and high-pressure conditions and subsequent recrystallization, reflecting sustained modification of the SPA region over time. These observations provide critical constraints on early lunar crustal cycling and impact flux evolution.

Importantly, ancient norite clasts dated at ~4.25 Ga suggest excavation from deep SPA crust or melt-sheet-derived materials, providing a temporal constraint on early SPA evolution. Recent studies further identified a new suite of impact-derived noritic rocks (SPANs), which yield Pb-Pb ages of ~4.25 Ga and ~3.87 Ga. The older population is interpreted as crystallization products of SPA impact melt sheets, indicating that SPA likely formed at ~4.25 Ga^[3]. This provides a key anchor for lunar early bombardment chronology and suggests broadly similar early impact fluxes between the nearside and farside. In addition, CE-6 anorthositic clasts indicate that the farside primary crust is compositionally and temporally comparable to the nearside. A ~4.41 Ga KREEP-related thermal overprint further supports a Moon-wide magma ocean crystallization sequence and argues against asymmetric primary crystallization models^[4].

2.2 Farside Volcanism and Lunar Interior Evolution

CE-6 basaltic fragments provide the first direct chronological constraints on farside volcanism. The main basaltic unit yields an age of $\sim (2.807 \pm 0.003)$ Ga, demonstrating that farside volcanic activity persisted into the middle-late lunar history^[5,6]. This significantly extends the duration of lunar volcanism compared with nearside Apollo and CE-5 samples (~2.0 Ga)^[7,8]. A subordinate population of high-Al basalts with ages of ~4.2 Ga further indicates that farside magmatism was episodic and long-lived, spanning at least ~1.4 billion years^[6]. The persistence of volcanism into the late stages of lunar evolution raises fundamental questions regarding the heat sources capable of sustaining prolonged magmatic activity. Recent petrological and geochemical studies of CE-6 basalts identified two compositionally distinct volcanic suites, including ~2.9 Ga very-low-Ti basalts and ~2.8 Ga low-Ti basalts derived from mantle sources at different depths^[9]. Modeling suggests that

these source regions correspond to pyroxenitic lithologies formed during lunar magma ocean crystallization, including shallow Ilmenite-Bearing Cumulates (IBC). Because both CE-5 and CE-6 basalts originated from water-poor and KREEP-poor mantle sources, conventional models invoking mantle hydration or radiogenic enrichment are insufficient to explain these young volcanic episodes. Instead, thermal transfer from magmas ponded within the thickening lithosphere has been proposed as a mechanism capable of remobilizing shallow IBC-rich mantle reservoirs and sustaining late-stage volcanism. These observations suggest that ~ 3.0 Ga may represent a transition in lunar thermal evolution, after which shallow lithospheric heating became increasingly important for magma generation^[9]. Collectively, these results imply a prolonged thermal evolution of the lunar interior, with farside mantle sources evolving from early enriched to later depleted compositions.

Paleomagnetic and oxygen fugacity studies further refine this picture. CE-6 basalts record paleointensities of $\sim 5\text{--}21$ μT at ~ 2.8 Ga, suggesting that the lunar dynamo weakened after ~ 3.1 Ga but may have experienced a later rebound rather than a monotonic decay^[10]. Oxygen fugacity measurements indicate a more reduced farside mantle (Iron-Wüstite (IW) buffer, with $\Delta\text{IW} \approx -1.93$) compared to the nearside (≈ -0.8), providing the first direct evidence for redox heterogeneity between lunar hemispheres^[11]. This hemispherical contrast may reflect either asymmetric magma ocean crystallization or localized modification by SPA-forming impacts.

2.3 Volatiles and Mantle Heterogeneity of the Farside

Volatile studies of CE-6 samples provide the first direct constraints on farside mantle water content. Melt inclusions and apatite analyses indicate extremely low water abundances, with mantle source estimates of $\sim 1\text{--}1.5$ $\mu\text{g}\cdot\text{g}^{-1}$ ^[12], significantly lower than nearside estimates (~ 7.5 $\mu\text{g}\cdot\text{g}^{-1}$) derived from Apollo and CE-5 basalts^[13]. These results suggest a potential hemispherical dichotomy in lunar mantle hydration, with a “drier farside mantle” relative to the nearside. However, broader sample coverage is still required to confirm this global pattern. In addition, CE-6 impact glass beads demonstrate that solar-wind-derived hydrogen is efficiently implanted and stored in basaltic glasses but poorly retained in

anorthositic glasses^[14]. This compositional dependence indicates that regolith components play distinct roles in the lunar surface water cycle^[14]. Recent isotopic studies further suggest that this volatile depletion may be linked to the formation of the SPA basin itself. High-precision Fe and K isotope measurements of CE-6 basalts reveal unusually heavy K isotopic compositions that cannot be explained solely by magmatic differentiation processes. Instead, modeling indicates that volatile loss associated with the SPA-forming impact could account for the observed signatures, implying that the giant impact may have modified the volatile budget of the underlying mantle and contributed to the long-term suppression of volcanism on the lunar farside^[15].

2.4 Regolith Evolution and Space Weathering

CE-6 regolith provides the first in situ record of farside space weathering. The samples contain nanophase iron, impact melt products, and glassy materials formed by micrometeorite bombardment and solar wind irradiation, indicating coupled control by space weathering processes. Compared with nearside samples, CE-6 regolith shows differences in maturation degree, nanophase iron distribution, and amorphous rim development, reflecting variations in impact flux and geomagnetic shielding effects. Together with CE-5 and Apollo samples, these results suggest hemispherical asymmetry in space weathering intensity driven by both solar wind exposure and impactor population differences. Additional discoveries, including CaS minerals^[16], Fe-Cu-S system mobility^[17], Fe-oxide formation (including hematite)^[18], and metallic copper and iron assemblages^[17], reveal that impact-induced transient high-temperature and partially oxidizing environments can locally modify redox conditions on an otherwise reducing Moon.

Finally, nanoscale noble metal phases (*e.g.*, Ruthenium)^[19] and carbon nanostructures (including single-walled carbon nanotubes)^[20] highlight the Moon as a natural laboratory for extreme physicochemical processes, with implications for both regolith evolution and in situ resource utilization.

3 Tianwen-1 Mission

Tianwen-1 is China's first independently conducted Mars exploration mission. It was launched in July

2020 and was inserted into Martian orbit in February 2021. The Zhurong rover, carried by the Tianwen-1 spacecraft, landed in southern Utopia Planitia in May 2021 at 109.925°E and 25.066°N. During its surface operations, the rover worked for 347 Martian sols and travelled 1921 m, collecting images, spectra, radar profiles, meteorological measurements, and surface compositional data. From 2024 to 2026, studies based on data from the Tianwen-1 orbiter and the Zhurong rover continued to advance, covering Martian surface composition, weathering processes, subsurface structures, orbital remote-sensing observations, and the near-Mars space environment. These studies provide important constraints on the history of Martian aqueous activity, surface modification processes, and space-environment responses.

3.1 Martian Surface Composition and Properties

Recent work on the Zhurong landing site has substantially refined interpretations of hydrous materials in southern Utopia Planitia. Rather than treating the hydration signatures as isolated mineral absorptions, studies combining Multispectral Camera (MSCam) and Short-Wave Infrared (SWIR) observations emphasize their close relationship with dusty surfaces. The 1.9 μm feature, observed at both the Zhurong and Perseverance landing sites, is interpreted as a hydration signal that may be common in Martian dust. In contrast, the 2.2 μm band appears to be more locally characteristic of the Zhurong region and is consistent with hydrated silica in terms of spectral position and shape. These observations suggest that the hydrous components at the landing site may reflect a combination of aeolian deposits from nearby cones and local aqueous alteration products^[21].

Rock-surface observations further indicate that aqueous weathering affected some materials at the landing site. Some rocks bear dark patches that are regarded as dust-free surfaces; these patches exhibit near-infrared spectra with a concave-up blue slope. These spectral properties are interpreted as evidence for silica-enriched leached rinds on basaltic glass, implying that acidic fluids may once have modified rock surfaces at the landing site^[22]. Textural features on rock surfaces related to salt activity may have experienced dust deposition, surface adsorption, salt deliquescence, and modification by transient brine activity. Climate simulations indicate that, from late spring to summer, near-surface temperature

and relative humidity from nighttime to predawn may intermittently approach the deliquescence thresholds of some hygroscopic salts, resulting in cycles of brine formation and salt crystallization. This provides new observational evidence for short-lived brine activity in the modern near-surface environment of Mars^[23]. In addition, unmixing studies based on laboratory binary mixtures and SWIR spectra further quantified the abundance of hydrated minerals on the surface of the landing site, indicating short-term fluid-rock interactions involving ice and snow melt under cold climatic conditions and a low to moderate degree of water-limited alteration^[24,25].

Elemental measurements provide an additional perspective on these alteration processes. Studies based on Laser-Induced Breakdown Spectroscopy (LIBS) data indicate that sulfur is mainly associated with gypsum and other sulfates, whereas hydrogen may be hosted by hydrous mineral assemblages such as gypsum, hydrated silica, and ferrihydrite. These phases are consistent with acidic weathering processes at the landing site^[26]. Trace-element studies further show that Li, Sr, and Rb are mainly linked to igneous components in rocks and soils. The inferred secondary mineral assemblage is dominated by minor sulfates, whereas clay minerals appear to be absent or rare. This supports a scenario in which surface igneous materials were derived from relatively late Amazonian lava flows and subsequently experienced limited acidic alteration^[27].

Beyond composition, Zhurong data have also been used to characterize surface structure and photometric behavior. Navigation and Terrain Camera (NaTeCam) images, together with inertial measurement unit data, enabled the construction of spatially continuous 3D models and Digital Elevation Models (DEMs). These products allow degraded small-scale structures, directional degradation, and textured features in depressions to be recognized^[28]. Based on multi-phase-angle images acquired by the NaTeCam, together with the Discrete Ordinates Radiative Transfer (DISORT) model and the Hapke radiative transfer model, the photometric and microphysical properties of the soils were retrieved. The retrieved parameters indicate that soils at the landing site are dominated by backscattering, have relatively high particle porosity and/or heterogeneous grain-size distri-

butions, and show low macroscopic roughness. The observation of phase reddening, with a maximum near a phase angle of about 60° . These results provide important ground-truth information for quantitative spectral interpretation of the Zhurong landing site and surrounding regions^[29].

3.2 Subsurface Structure and Physical Properties

The Zhurong Rover Penetrating Radar (RoPeR) has provided key constraints on the subsurface structure and aqueous history of southern Utopia Planitia. RoPeR observations reveal northward-dipping reflectors at depths of 10–35 m along an approximately 1.3 km northward traverse. Their dip angles, geometry, thickness, and low-permittivity characteristics are comparable to terrestrial coastal deposits. This interpretation supports the presence of ancient prograding shoreline deposits and provides subsurface sedimentological evidence relevant to the ancient ocean hypothesis for the Martian northern lowlands^[30].

RoPeR analyses also highlight the heterogeneity of shallow to intermediate-depth materials. Frequency-domain studies identify an approximately 7 m thick low-loss layer whose dielectric properties are compatible with water ice. This layer may indicate ice-bearing material at depths of 15–57 m, and simulations suggest that dirty ice mixed with stones provides the closest match to the observations^[31]. For the uppermost approximately 4 m, attenuation analyses yield a loss tangent of about 0.0079, with lateral variations possibly related to changes in duricrust abundance^[32]. High-frequency quad-polarization radar observations further reveal complex subsurface structures, including three shallow subsurface layers, buried craters, and other features. These features are likely to have formed in aqueous environments during the middle to late Amazonian period, implying that water-related processes in Utopia Planitia may have persisted into relatively recent geological times^[33].

3.3 Mars Orbital Observations

The Tianwen-1 orbiter has advanced studies of Martian geomorphology and mineralogical mapping. Orbital observations from Tianwen-1 have provided new constraints on the origin of pitted cones in the Zhurong landing region. The High Resolution Imaging Camera (HiR-IC) topographic and imaging data suggest that these

cone-like landforms may be related to mud volcanism rather than representing a single simple volcanic or periglacial process. Their middle-to-late Amazonian ages, kilometer-scale inferred source depths, and preferred structural orientations indicate that subsurface material mobilization was likely controlled by regional tectonic and volcanic processes, including trough-related fracturing, basin subsidence, and activity associated with the Elysium volcanic province^[34]. Related flow features, including tongue-shaped lobes on cone flanks, apron-like deposits within pits or at cone bases, and adjacent rough units, provide additional evidence that these landforms may be connected to volcanic or volatile-driven processes^[35]. At a broader scale, orbital remote-sensing mapping identified geomorphological features in southern Utopia Planitia that are consistent with a nearshore zone, indicating the presence of different types of marine environments. Combined with Zhurong *in-situ* observations, these results suggest that the region may have experienced flooding from the Late Noachian to the Early Hesperian, followed by volatile loss during the Amazonian epoch^[36].

Tianwen-1 MMS (Mars Mineralogical Spectrometer) data have been used to map ferric oxides across Mars after systematic spectral processing. The results show that ferric oxides are widely distributed, with nanophase ferric oxides dominating bright terrains. The study also identified crystalline hematite in Meridiani Planum and Aram Chaos, including a newly reported red crystalline hematite deposit in southeastern Aram Chaos. These observations provide orbital mineralogical evidence for past aqueous and oxidative processes on Mars^[37].

In Aeolian geomorphology, AiTARs-Net was developed to automatically detect Transverse Aeolian Ridges (TARs) with arbitrary orientations, improving the efficiency of TARs mapping over large areas^[38]. Complementary orbital statistical analyses indicate that landform type, elevation, and slope all influence the distribution and dimensions of TARs around the Zhurong landing area^[39].

3.4 Near-Mars Space Environment and Interplanetary Space

The Tianwen-1 orbiter has provided valuable multi-spacecraft observations for understanding the response

of the Martian plasma environment to solar-wind variations. Joint measurements with Mars Atmosphere and Volatile Evolution (MAVEN) show that even relatively weak solar-wind disturbances can produce large-scale motions of the Martian bow shock, highlighting the importance of upstream plasma conditions, especially the magnetosonic Mach number, in controlling the location and variability of this boundary^[40]. During Interplanetary Coronal Mass Ejections (ICMEs) events, simultaneous observations by Tianwen-1 and MAVEN further demonstrate that the Martian bow shock responds differently to solar-wind dynamic pressure and interplanetary magnetic-field strength: enhanced dynamic pressure compresses the boundary planetward, whereas stronger magnetic fields can favor outward displacement^[41]. In addition, joint observations and hybrid simulations indicate that Mars can still sustain an induced magnetosphere under radial Interplanetary Magnetic Field (IMF) conditions, suggesting that magnetic-field draping and induced fields remain important even when the IMF is nearly aligned with the solar-wind flow^[42].

Beyond Mars itself, the Tianwen-1 orbiter has also extended its scientific role beyond Mars-focused observations. The HiRIC CMOS camera was used to observe the interstellar object 3 I/ATLAS from Mars orbit, demonstrating the potential of a Mars orbiter for small-body and interplanetary-object studies. Because the observations were obtained from a geometry different from Earth-based views, they provided useful constraints on the evolution of the object's coma and tail and helped interpret its dust activity^[43].

4 Summary

Recent advances from the CE-6 and Tianwen-1 missions demonstrate the growing importance of China's deep-space exploration program in addressing key questions in planetary science. For the Moon, CE-6 samples provide the first direct laboratory constraints from the lunar farside, refining our understanding of early lunar evolution and SPA formation, the duration and mechanisms of farside volcanism, the volatile and redox heterogeneity of the lunar mantle, and the evolution of farside regolith under space weathering. These findings show that the lunar farside preserves a distinctive record

of impact, thermal, volatile, and surface modification processes, rather than simply representing an extension of the nearside. For Mars, Tianwen-1 and Zhurong results have linked surface composition, subsurface radar sounding, orbital remote sensing, and plasma-environment observations into a more integrated view of the Zhurong landing region and the near-Mars environment. Evidence for hydrated minerals, limited acidic alteration, transient brine activity, possible coastal deposits, subsurface ice-bearing materials, and solar-wind-controlled plasma responses indicates that Mars has experienced both long-term aqueous modification and ongoing surface-atmosphere-space interactions. Overall, these studies highlight the value of combining sample analysis, in situ measurements, orbital observations, and multi-spacecraft monitoring to reconstruct planetary evolution. They also provide a strong scientific foundation for future Chinese missions to the lunar south pole, near-Earth asteroids, main-belt comets, and the outer solar system.

Conflict of Interests The authors declare that there is no conflict of interests

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