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Latest Scientific Results of China's Lunar and Deep Space Exploration (2022–2024)

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Abstract China has successfully launched six lunar probes so far. From Chang'E-1 to Chang'E-4, they completed the circling, landing and roving exploration, of which Chang'E-4 was the first landing on the far side of the Moon in human history. Chang' E-5 was launched in December 2020, bringing back 1731 g of lunar soil samples. Through the detailed analysis of the samples, the scientists understand the history of late lunar volcanism, specifically extending lunar volcanism by about 800 million to 1 billion years, and proposed possible mechanisms. In addition, there are many new understandings of space weathering such as meteorite impacts and solar wind radiation on the Moon. China's first Mars exploration mission Tianwen-1 was successfully launched in July 2021. Through the study of scientific data, a number of important scientific achievements have been made in the topography, water environment and shallow surface structure of Mars. This paper introduces the main scientific achievements of Chang'E-4, Chang'E-5 and Tianwen-1 in the past two years, excluding technical and engineering contents. Due to the large number of articles involved, this paper only introduces part of the results.

Key words Lunar and deep space exploration of China, Chang'E-4 mission, Chang'E-5 mission, Tianwen-1 mission

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1 Introduction

This year marks the 20th anniversary of China's Lunar Exploration Project, from the launch of the first lunar exploration satellite by Chang'E-1 in 2007 to the launch of Chang'E-6 in 2024 and the successful return of lunar samples, so far six lunar exploration missions have been successfully launched.

Chang'E-4 performs the first soft landing and exploration on the far side of the Moon, obtaining data on the surface morphology, material composition, shallow structure, and the near-lunar space environment.

Launched in December 2020, Chang'E-5 brought back 1731 g of lunar soil samples from the Moon, which is the first time humans have obtained samples of young volcanic regions on the lunar surface. Over the past three years, the China National Space Administration has distributed more than 80 grams of lunar samples seven

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times to more than 100 scientific teams in China. At present, more than 100 scientific and technological papers have been published, which delayed the end of lunar volcanic activity by about 800 million to 1 billion years through geological dating of samples, innovatively discovered the formation mechanism of solar wind, and also discovered the sixth new mineral on the Moon "Chang'E stone" and other scientific achievements.

On 24 April 2020, the China National Space Administration announced that China's planetary exploration mission would be named as Tianwen, and China's first Mars exploration mission would be named "Tianwen-1". Tianwan-1 would be launched in July 2020 and land on the Utopia Plain of Mars at 5°–30° north latitude in May 2021 for landing and roving exploration. As the first mission of China's planetary exploration project, Tianwen-1 has achieved three goals of orbiting, landing and touring Mars through a single launch, which is unprecedented in the history of Mars exploration in the world. At present, the goal of China's first Mars exploration mission has been successfully accomplished. Through the study of scientific data, the scientific research team has achieved a number of scientific achievements in the topography, water environment, atmosphere and material composition, and shallow subsurface structure of Mars.

2 Chang'E-4 Mission

2.1 Lunar Topography and Geomorphology

The lunar regolith morphology is mainly acquired by imaging equipment including the Landing CAMera (LCAM) of Chang'E-4 lander, the ground Terrain CAMera (TCAM) image and the DEM of the Yutu-2 Panoramic CAMera (PCAM) validate the crater degradation levels from a qualitative and quantitative perspective, *etc*., which are suitable for acquiring images of centimeter-scale craters, rocks and ejecta to measure their shape, size, color, reflectance, roughness *etc*.[1]. Some of the craters contain high-reflectance materials at the bottom, suggesting secondary impact events, which hint at notable differences in the impact frequency between the lunar farside and nearside[2].

2.2 Characteristics and Composition of Lunar Regolith

Visible and Near-infrared Imaging Spectrometer (VNIS) is critical in constraining the accurate mineral proportions and composition of the lunar regolith[3]. Based on the mineral abundances retrieved from the VNIS data, the average plagioclase abundance (60.4 vol.%) is beyond the high-plagioclase end of the mineralogical range of SPA impact melt differentiation products and would require an additional contribution from potential ejecta[4]. VNIS also found iron-rich and magnesium-rich components, such as Finsen and Leibniz crater sputtering, requiring additional contributions from the lunar crust[5,6]; Rocks rich in low-Ca pyroxene and deficient in Mg-olivine have also been found, such as four special rocks encountered along the way, indicating that they were crystallized at a high temperature (980–1300℃) and a rapid-cooling magmatic system produced by impact melt differentiation or volcanic resurfacing events[5,7]. These newly discovered compositional features combined with lunar rock minerals provide new insights into the origins of SPA.

The results show that the particle size of the lunar regolith at the Chang'E-4 landing site is similar to 15 μm on average over depth, which indicates an immature regolith below the surface[8], and the viscosity of the lunar regolith on the far side of the Moon is higher than that on the near side[9].

2.3 Sub-surface Structure

The layered structure of the upper 300 m of the lunar surface in the South Pole-Aitken Basin was discovered by using the measurements from the Lunar Penetrating Radar (LPR) onboard the Chang'E-4 rover Yutu-2[10]. The high-frequency radar observed a buried lens structure similar to 27 m below the lunar surface, interpreted as paleo regolith by previous studies[11]. Below the depth of 90 m, with thicknesses ranging from 20 m to larger than 70 m[12]. At least three strata basalt flows were speculated, while the shallowest stratum is composed of multiple thin lava flows[12]. Both the dielectric properties and the ilmenite content suggest a shallow sequence of basaltic layers overlaying a low-ilmenite ejecta blanket[13]. The LPR also found a series of buried impact craters[14]. The smaller the impact craters are, the more likely they are to degenerate. The smaller the impact crater yield is, the closer it is to the removal rate, the more difficult it is to reach the equilibrium state[1]. The maximum penetrating depth of the low-frequency channel reaches 450 m, revealing multi-episode eruptions[15].

2.4 Lunar Space Environment

The Moon represents an airless body, whose surface can directly interact with ambient space particles, bringing a space weathering effect. Some solar wind protons can be scattered as Energetic Neutral Atoms (ENAs) from the surface, which carries rich information of the solar wind-surface interaction. Sometimes, the interaction can be hindered by a magnetic anomaly, where a Lunar Mini-Magnetosphere (LMM) is formed. Due to the lack of in situ measurements on the lunar surface, people still know little about the ENA truth as well as the internal structure of LMM on the surface. The Chang'E-4 mission is the first mission soft-landed on the lunar far side near strong magnetic anomalies. Moreover, the Advanced Small Analyzer for Neutrals (ASAN) instrument onboard the rover of Chang'E-4 can measure the backscattered ENAs from the surface. With the ENA data from Chang'E-4 mission and the solar wind data from ARTEMIS spacecraft, Xie *et al.*[16] reported a unique multi-point observation of the LMM, and found that there was no shock but just a boundary layer near the magnetic anomalies and the shock could only appear downstream from the magnetic anomalies known as the trailing shock. Zhong *et al.*[17] found that the ENA energy measured by Chang'E-4 showing a good relation with the solar wind energy, and the loss rate of ENA energy favored a higher solar wind energy and a lower solar zenith angle. Wieser *et al.*[18]presented a semi-empirical model to describe the energy spectra of the neutral emitted atoms, and found that the ENAs emitted from the lunar surface consist of two components: one is reflected and neutralized solar wind protons and the other is particles sputtered ENAs from the lunar regolith.

Apart from low-energy solar wind particles (with an energy of about 1 keV), there are also some high-energy space particles (with energies higher than several MeV), such as Solar Energetic Particles (SEPs) and Galactic Cosmic Rays (GCRs), which can directly bombard the lunar surface. The Lunar Lander Neutron and Dosimetry (LND) Experiment aboard the Chang'E-4 Lander can measure energetic charged and neutral particles and monitor the corresponding radiation levels. It is found that GCRs are the dominating component of charged particles on the lunar surface during solar quiet times. Moreover, the interaction of GCRs with the lunar regolith also results in upward-directed albedo protons which are measured by the LND[19]. Combined with the Radiation Environment and Dose at the Moon (RED-Moon) mode, Xu *et al.*[19] have also provided the ratio of albedo protons to primary protons for measurements in the energy range of 64.7–76.7 MeV. In addition, Luo *et al.*[20] reported the first measurements of the low-energy (about 10 to 100 MeV/nuc) cosmic ray spectra on the lunar surface around the solar minimum 24/25, and found that the proton, helium, CNO, and heavy-ion groups, the ratios (ratio errors) of the Chang'E-4 fluxes to those from the near-Earth spacecraft are 1.05 (0.15), 1.30 (0.18), 1.08 (0.16), and 1.24 (0.21), respectively. Moreover, a notable enhancement of $^3He/^4He$ ratio was observed at about 12 MeV/nuc, and the cosmic ray dawn-dusk symmetry was confirmed[20]. These results provide valuable insights into the cosmic rays on the lunar farside surface and will benefit future lunar exploration.

3 Chang'E-5 Mission

Unlike the Apollo and Luna samples, the Chang'E-5 lunar samples were collected at mid-to-high latitudes and are the youngest lunar basalts to date (2.030 ± 0.004 Ga) and have higher FeO contents, with moderate TiO_2 and Al_2O_3[21–26]. There is evidence that Chang'E-5 lunar soils are mainly derived from spallation from the Xu Guangqi crater to the north-west of the landing site and have a higher lunar soil maturity, a feature probably due to the predominance of micrometeoroid impacts processes[27,28]. The study of the Chang'E-5 lunar samples by various analytical methods, including the newly developed Raman spectroscopy analysis, showed that the average particle size of the Chang'E-5 lunar soils was about 50 μm, with relatively low glass content, and that the basaltic fragments were mainly composed of clinopyroxene, plagioclase, olivine and ilmenite, with obvious textures diversity, including porphyritic, ophitic/subophitic, poikilitic[22,23,26,27,29,30]. It is noteworthy that previous petrological analyses of late-stage basalts based on remote sensing data have shown abundant olivine, but laboratory spectral analyses of the Chang'E-5 samples revealed iron-rich high-Ca pyroxene rather than olivine[31]. To present, the detailed chemical composition distribution of the lunar surface has been constrained[32].

3.1 Impact Glasses

Chang'E-5 glasses come in a wide variety of multitype and origins. The finding of indigenous ultra-elongated glass fibers and widely distributed ultra-thin amorphous layers without np-Fe^0 indicates the relatively moderate impact environment in the Chang'E-5 landing site[33]. The composition of the impact glass from the Chang'E-5 samples suggests a predominantly local origin, limiting transport distances to less than about 150 km, and U-Pb isotopic dates of the impact glasses indicate that the regional impact glass formed between a few million and two billion years ago, younger than the Chang'E-5 basalts[34]. Impact glass enriched in large KREEP material (>20 vol%) was found in the uniquely weathered lunar breccia returned by Chang'E-5 mission, suggesting a possible origin from a mixed region between the P58/Em4 mare unit and its contiguous eastern highlands[35].

The impact glasses in lunar breccias are enriched in a large KREEP material (>20 vol.%), suggesting a possible origin from a mixture of the Lunar Sea Unit and the Eastern Highlands[35].

3.2 Space Weathering

Chang'E-5 samples offer valuable insights into the study of space weathering processes. According to the research, space weathering in iron-rich basalts leads to a faster generation rate of np-Fe^0 and saturated aggregation to form larger particle sizes[28]. The discovery of np-Fe^0 caused by in situ thermal decomposition in the amorphous layer rims on the surface of fayalitic olivine provides new evidence for the mechanism of the formation of np-Fe^0[36]. Li *et al.*[37] found np-Fe^0 and Fe^{3+} in the amorphous mixture at the bottom of the microcraters on the surface of olivine, where high temperatures and pressures during the impact process drove the disproportionation reaction of Fe^{2+}, and the contribution of solar wind injection was very weak[37]. Lunar agglutinate glass formed and widely distributed by micrometeoroid impacts in the Chang'E-5 lunar samples contains a large amount of np-Fe^0 and Fe^{3+} produced by disproportionation reactions, and the content of Fe^{3+} increases continuously with the continuous micrometeoroid impacts[38].

In addition, a study reported for the first time the discovery of iron meteorite fragments in the lunar soil of Chang'E-5, the meteorite fragments are Ni- and P-rich, S-poor, and are classified as IID-group based on their mineral chemistry and overall composition. As this meteorite fragment experienced only limited partial melting followed by rapid cooling, suggesting formation by a low-velocity impact[39]. In addition, the natural nanophase new minerals trigonal Ti_2O and triclinic Ti_2O were found in micrometeorite impact craters on the surface of Chang'E-5 glass bead, as well as the seventh and eighth newly discovered minerals in lunar samples. This discovery not only acquires the response of Ti-oxides such as ilmenite to the micrometeorite impacts modification process and its effects, but also complements the understanding of the new products of space weathering, and suggests a new idea that space weathering can alter the photocatalytic properties of lunar regolith[40]. Nonetheless, the prolonged and persistent impact events resulted in extensive, uneven and complex thermal modification events in the Chang'E-5 landing site[41].

3.3 Sulfides

Although sulfides are less than 1% in the Chang'E-5 lunar samples, they still show abundant weathering modification features[23]. Guo *et al.*[42] discovered sub-microscopic magnetite particles and np-Fe^0 with impact-induced formation by eutectoid reaction for the first time in Chang'E-5 lunar soil, Magnetite and np-Fe^0 particles embedded in oxygen-dissolved iron-sulfide particles from Chang'E-5 samples, representing large impact events on the lunar surface[42]. Furthermore, digenite mineral with characteristics of impact-induced evaporative deposition was reported for the first time in a lunar sample[43].

3.4 Solar Wind-derived Water

The Chang'E-5 lander performed in situ spectral measurements while collecting samples, and these observations revealed the presence of water on the lunar surface[44, 45]. Solar wind-derived water is one of the major sources of lunar surface water, and recent studies have reported the presence of high levels of solar wind-derived water (OH/H_2O) in the surface mineral layer, with the Chang'E-5 samples containing more than 170 ppm (1 ppm=10^{-6}) of water, consistent with lunar in situ spectroscopic measurements[44–46]. Moreover, the impact glasses from Chang'E-5 lunar soil are the major source of molecular H_2O in the lunar soil, with a content of up to 15 to 25 ppm. Due to the complexity of their formation mechanisms, impact glasses can preserve and record large sources of OH and molecular H_2O associated with the solar wind and a variety of other sources, including water derived from solar wind, deposited by water-bearing meteorites/micrometeorites, and inherited from lunar indigenous water[47]. Solar wind-derived water is preserved by diffusion into the impact glass beads, along with the ability to sustain the lunar surface water cycle. The abundance of solar wind-derived water in the impact glass beads can be as high as about 2000 ppm, with an average of about 500 ppm[48].

3.5 Petrogenesis and Volcanic Activity

The results of a comprehensive multi-method study of basaltic clasts in the Chang'E-5 lunar samples, including quantitative structural analysis, diffusion chronometry, clinopyroxene geothermobarometers, and crystallization simulations, show that the Chang'E-5 basalts originated in the olivine-bearing pyroxenite mantle source and that the source region has a pressure of $(1.0–1.3)\times10^3$ MPa and a temperature of about 1350 ± 50℃. It is similar to the Apollo 12 low-Ti basalts[30]. Research suggests that the Moon is still magmatic at least 2 billion years ago and the presence of additional and yet-unrecognized lunar volcanic eruptions[49].

A study of the Chang'E-5 basalts revealed that most olivine grains have very short cooling timescales. Thermal modeling suggests that the minimum thickness of the lava flow bounded by most basalt grains is between 10–30 m, and the flat topography of the Chang'E-5 landing site suggests that large-scale magmatic eruptions continued into the late lunar period. Although lunar volcanism has generally declined over time, its late indirect eruptions still exhibit higher than average eruptive fluxes[26,50]. The Moon's youngest volcanism was not driven by abundant water in its mantle source[51], and further research is needed to clarify the causal mechanisms.

It has been reported that late-stage lunar magma ocean easily-melted cumulates in the lunar mantle source region lowered the melting point of the lunar mantle and triggered young volcanism on the Moon, with Chang'E-5 source magma having higher calcium and titanium dioxide contents than the Apollo counterparts[52]. The rapid cooling crystallization exhibited by the basalt debris and the smaller volume of vesicles observed in the Chang'E-5 samples indicate that the Chang'E-5 basalts have a lower degree of degassing compared to the Apollo basalts, and less volatile substances escape[53]. Two young basaltic lunar meteorites discovered in the Chang'E-5 lunar samples have similar source regions and formation mechanisms with Chang'E-5 basalts, suggesting that lunar volcanism shifted from KREEP-like dominance to non-KREEP dominance about 3 billion years ago[54].

4 Tianwen-1 Mission

4.1 Martian Aeolian Landforms

The Zhurong rover conducted observations of Aeolian landforms in the southern Utopia Planitia on Mars, revealing the dynamic changes in Martian Transverse Aeolian Ridges (TARs) and dunes. Studies indicate that these landforms were initially formed by northern winds and later re-worked by northeastern winds, showing significant aeolian reworking and climate change[55]. The analysis of Martian dunes suggests that wind direction changes coincided with the end of the recent "ice age" (roughly 0.4–2.1 million years ago), leading to the transformation of barchan dunes into longitudinal dunes, reflecting a major climatic transition from glacial to interglacial periods. This wind direction shift and the corresponding changes in dune morphology provide crucial evidence of Mars' dynamic climate history[56]. The transverse aeolian ridges are also analyzed[57], the presence of cones indicates a potential mud volcano origin[58], and the three-dimensional morphological features of rocks are analyzed[59,60].

4.2 Ancient and Modern Environments in Southern Utopia

MultiSpectral Camera (MSCam) onboard the Zhurong rover with its calibration target used to monitor dust deposition, providing a new ground observation, showing a low deposition rate in the first 110 sols, indicating clear weather, followed by an accumulation of dust[61]. Meteorological data show that wind speed and direction also exhibit significant seasonal characteristics, especially strong southern winds in the northern spring and summer mornings, indicating that wind speed is likely a key factor controlling the dust deposition rate—the higher the wind speed, the faster the deposition[62].

The surface temperature analysis showed that thermal inertia and dust have the greatest impact on temperature. Fluctuations in atmospheric pressure and temperature affect the performance of surface thermal inertia, with increased dust storm activity thickening the dust cover and stabilizing surface temperature[63], consistent with the observed daily and seasonal temperature fluctuations in meteorological data[62]. Modeling the impact of daily and seasonal temperature variations on surface temperature suggested that the likelihood of shallow subsurface water ice is low[64]. This is corroborated by the radar data from the Mars Rover Penetrating Radar (RoPeR) of the Zhurong rover, which studied the dielectric properties of the Martian regolith, indicating that the regolith at the landing site likely consists of volcanic rocks and possible hydrated minerals or sediments[65].

4.3 Water Environment on Mars

The combination of radar and thermal simulation results suggests that liquid water, sulfate or carbonate brines are difficult to stabilize above 100 m above the shallow surface. However, since the dielectric constant of sulfate or carbonate salt ice (2.5–8) is comparable to that of rocky materials, the presence of salty ice at shallow depths shows a possibility[66]. The Mars Climate Station (MCS) can record local wind speeds, temperatures, and barometric pressures, found that the meteorological conditions at the landing site were largely controlled by the seasonal variations on Mars. It was also found that water here frosts every morning and quickly sublimates and disappears after sunrise, and a brief period of liquid water may exist on the surface of the landing site around the summer solstice each year. The dissolution of salts in the soil can allow salt water to remain on the surface for a period of time. All these evidences suggest the existence of an active water vapor cycle at the soil-atmosphere interface in the landing site[67]. At the same time, using different cameras including the Navigation and Topography Cameras (NaTeCam), an in-depth study of the micro-morphological features and material composition characteristics of the surface of the dunes in the area, it found that the surface of the dunes shows crusts, cracks, agglomerations, polygonal ridges, banded watermarks and other surface features. Through spectral data analysis, it is revealed that the dune's surface is rich in water-containing sulfate, opal, water-containing iron oxide and other substances, it was determined that these surface features are associated with frost or snowfall on the surface of saline dunes during cooling. This finding fills a gap in ground-based observational evidence for liquid water at low Martian latitudes, revealing that modern Martian climates can occur in wetter environments at low latitudes where surface temperatures are relatively warm and favorable[68].

The main rocks and soils in the landing site are basalts, and their chemical weathering index (CIA) is extremely low, revealing that the degree of aqueous alteration is low and that they may have been formed mainly by a mixture of widespread Martian dust and localized materials rich in calcium and poor in magnesium. The amorphous minerals found in Blessing may have been formed by the alteration of volcanic detrital material under conditions of low temperature, weak acidity, and low water-rock ratios, and it is estimated that the amount of water involved in water-rock interactions may have been low or short-lived[69]. Based on the spectroscopic studies, it can be inferred that the presence of a variety of water-bearing minerals in the landing site, such as polyhydric sulfates, gypsum, and water-bearing silicates, suggests that there was once water activity in the northern lowlands of Mars, which is consistent with speculation of the presence of subsurface glaciers or permafrost in the region, indicated by geomorphic features such as walled impact craters, pancake impact craters, and concave cones found in the Utopia Platinum. Based on the identification of sulfate minerals combined with dating results, it is suggested that groundwater or even surface water may have existed in the landing site 3.5 billion years ago[70]. The bright-colored rocks of the dunes found in the landing site are interpreted as locally developed crust layers, which require large amounts of liquid water to form and cannot be formed by atmospheric water vapor alone, and exclude the possibility of large-scale water activity on the surface before. The study deduces that these sulfate-rich crust layers may have been formed by the intermittent overflowing of groundwater, or by capillary action of evaporation and crystallization of salts crystallized minerals cemented to Martian soil The crusts were formed by petrogenesis, followed by erosive loss of the topsoil overlying the crusts, which ultimately exposed the crusts. It also found signs of water activity in landing sites of younger geologic age, suggesting that the Martian hydrosphere during the Amazonian period may have been more active than previously thought[71]. Analysis of the chemical composition and water content of the rocky crust using the Laser Induced Breakdown Spectrometer (LIBS) corroborated the hydrogen-rich signals found in Zhurong's short-wave infrared, and further confirmed the presence of groundwater activity in the Martian Amazonian over the vast area of the landing site. LIBS analysis of three other types of relatively loose material (dunes, soils and colluvium) found that the colluvium had similar elemental trends to the soils and dunes, indicating a similar material origin to the local soils and dunes. While its water content ordering indicated the presence of water-bearing magnesium salts. By analyzing the correspondence between water and other metal ions, it is also possible to determine that in these looser materials, water can be present in two forms, evaporated salts containing crystalline water (*e.g.*, hydrated magnesium sulfate) and adsorbed water molecules[67]. From the point of view of surface morphology, the possible causes of the polygonal fissures on the dunes: the exchange of water vapor between the surface and the atmosphere led to the formation of a hardened sandy crust layer on the surface, which broke up to form the polygonal fissures. The chronological characterization of the dunes suggests, they may be indicative of recent water activity and surface-atmosphere water exchange processes on Mars, thus providing clues to the study of the water cycle on Mars under the current cold and arid climatic conditions[72].

4.4 Subsurface Structure and Physical Properties

Li *et al*.[66], using low-frequency radar data from the Zhurong rover, conducted detailed analyses and imaging to obtain the first high-resolution subsurface stratigraphy (<80 m) of a 1171 m profile in the southern Utopia Planitia, They identified two fining-upward sedimentary sequences beneath a few meters of regolith, at depths of approximately 10–30 meters and 30–80 meters. These findings suggest multiple episodes of resurfacing events in southern Utopia Planitia since the late Hesperian period (3.5–3.2 billion years ago), with potential water-related geological processes persisting into the mid-to-late Amazonian period (around 1.6 billion years ago). Further, Zhang *et al.*[73] utilized high-resolution time-frequency analysis methods to discover alternating high- and low-frequency bands in the radar profile. This indicates significant changes in water activity and/or thermal conditions from the late Hesperian to early Amazonian periods, implying intense paleoclimate variations in the mid-to-low latitudes (about 25°N), potentially related to ancient Martian obliquity shifts. Chen *et al*.[74] conducted fine-scale investigations of the subsurface regolith structure up to 5 meters deep using high-frequency radar data from Zhurong rover. They did not find distinct stratification but identified residual impact craters and lenses, revealing the influences of Mars' thin atmosphere and other surface geological processes, such as wind erosion, on regolith layer formation and the degradation rate of small impact craters. In the southern Utopia region where Zhurong operates, Du *et al.*[75] detected extremely weak magnetic fields, with an average vector field strength of about 10 nT and spatial variation on the scale of hundreds of meters. These observations provide critical evidence on the cessation of Mars' magnetic dynamo: the weak magnetic field indicates complete demagnetization of the Utopia basin during its formation, supporting the idea that Mars' early dynamo ceased around 4.0 Ga. The absence of remagnetization in the subsequent early Hesperian lava flows suggests the dynamo might have stopped working between 3.6 and 3.7 Ga. Guo *et al*.[76] explored the potential of improving Phobos' gravity field estimates using Doppler tracking data from Tianwen-1 and Mars Express flybys. Their study examined different internal structure models for Phobos, indicating that incorporating more flyby data, especially under optimal conditions, could achieve a fifth-degree gravity field estimate.

4.5 Verification of in-situ Payload Performance of the Orbiter

Zhang *et al*.[77] and Fan *et al*.[78] utilized effective data on Tianwen-1's transfer orbit to Mars to confirm that MINPA's performance is reliable and stable. Wang *et al*.[79] found that 0.48% of ion observations at Mars were UV contaminated. A removal algorithm was proposed to reduce contamination while preserving valid signals, effectively improving data quality. Chi *et al*.[80] compared the magnetic field measurements from Tianwen-1/MOMAG and MAVEN/MAG during the ICME and

SIR interval and found a generally good consistency between them.

4.6 Interplanetary and Near Mars Space Environment

Fu *et al*.[81] reported the first MEPA measurements of the widespread SEP event when Tianwen-1 was in transit to Mars. Moreover, the decay phases of the time-intensity profiles at Mars and Earth clearly show the reservoir effect. The double-power-law spectrum is likely generated at the acceleration site, and a small but finite cross-field diffusion is crucial to understanding the formation of the SEP reservoir phenomenon. Wang *et al*.[82] combined the upstream solar wind observations measured by MAVEN, ACE) and DSCOVR, successfully predicted the upstream solar wind conditions up to Mars. Zhong *et al*.[83] presented an accurate prediction for the arrival time and in-situ parameters of Corotating Interaction Regions (CIRs) when Earth and Mars have large longitudinal separations. Wang *et al*.[79] explored the Differential One-way Ranging (DOR) signals of Tianwen-1, observed by the China VLBI Network (CVN), to study the solar wind. The data catch the impact of the CME on the DOR signals when a CME passed across the ray paths of the telescope beams. The analysis indicates that multifrequency DOR signals observed by VLBI stations have great application in characterizing the density variations and propagation of the solar wind.

4.7 Impact of the Upstream Solar Wind on the Martian Space Environment

Cheng *et al*.[84] presented direct evidence of solar wind effects on the bow shock by analyzing Tianwen-1 and MAVEN data. The results indicate that the bow shock is rapidly compressed and then expanded during the dynamic pressure pulse in the solar wind, and is also oscillated during the IMF rotation. The superposition of variations in multiple solar wind parameters leads to more intensive bow shock oscillation. Protons in solar wind exchange electrons through collisions with neutral particles in the exosphere to produce Hydrogen Energetic Neutral Atoms (H-ENAs). Zhang *et al.*[85] developed an algorithm to invert the solar wind parameters from the H-ENAs measured in near-Mars space, suggesting the solar wind parameters inversed from H-ENA observation could be an important supplement to the dataset supporting studies on the Martian space environment.

Using Tianwen-1 and MAVEN, Su *et al*.[86] presented the first observation of significant modifications by a solar wind stream interaction region to the Martian foreshock waves. After the stream interface hit Mars, an unusual band of foreshock waves emerged, with a central frequency of about 0.4 Hz and a frequency width of about 0.2 Hz. These waves exhibited highly distorted waveforms and were approximately elliptically polarized, propagating highly obliquely to the background magnetic field. These waves differed greatly from the commonly known Martian foreshock 30 s waves and 1 Hz waves, but resembled, to some extent, the less frequently occurring terrestrial foreshock 3 s waves. From observations from the MINPA, Jin *et al*.[87] found the dominance of the field-aligned distribution type over the energy range from 188 to 6232 eV. Maps of the occurrence rate show the preferential presence of a trapped-like distribution at the lower altitudes of the surveyed nightside region. Chi *et al*.[88] presented two multipoint ICMEs detected by the Tianwen-1 and MAVEN at Mars and the BepiColombo upstream of Mercury. These findings highlight the importance of background solar wind in determining the interplanetary evolution and global morphology of ICMEs up to Mars distance. Yu *et al*.[89] utilized the simultaneous spacecraft observations from Tianwen-1/MOMAG in the solar wind and multiple instruments onboard the MAVEN in the Martian upper atmosphere, to study the response of Mars to an ICME. During this event, the altitude of the Martian ionopause location was lowered. The depletion of the plasma density in the topside Martian ionosphere on the night side reveals the presence of substantial ion and electron escape to space. The column abundance of plasma dramatically decreased, with 34% e^-, 61% O_2^+, and 73% O^+ reduced.

Planetary heavy ions in the ionosphere are picked up by the solar wind, forming an important Martian ion escape channel known as a "plume". Ma *et al*.[90] took advantage of the joint observations of Tianwen-1 and MAVEN to study oxygen ion plumes, confirming the convection electric field acceleration as the energization mechanism of plume ions (up to >15 keV). Qiao *et al*.[91] delved into a Pick - Up Ion (PUI) event captured by the MINPA, revealing a faster acceleration than expected by the presence of an electric field region within the magnetosheath. The peak of the electric field strength is located at the upper edge or within the Magnetic Pileup Boundary. Hu *et al*.[92] conducted the Tianwen-1 radio-occultation experiment on 5 August 2021, retrieved excess Doppler frequency, bending angle, refractivity, electron density, neutral mass density, pressure and temperature profiles, exhibiting the ionosphere M1 (M2) layer peak, planetary boundary layer, troposphere and a stratosphere. The inversion system[93] developed for Tianwen-1 radio occultation observations enabled the derivation of neutral atmospheric density, pressure, temperature, and electron density profiles of Mars. Importantly, these inversion results from Tianwen-1 maintained consistency with results from the Mars Express and the Chapman theory.

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