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Progress of Planetary Science in China*

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Abstract The national and international progress in deep space exploration has greatly promoted the development of planetary science in China. Substantial progress in different areas of planetary science has been achieved in 2020–2022. In this report, we summarize the research achievements obtained in China in the last three years. The achievements include the research on geology, geochemistry, and space physics of the Moon, Mars, Mercury, Venus, giant planets, asteroids, and comets. The recent work on science objectives, mission payloads, and analytical capabilities that supports the lunar and deep space exploration program of China has also been introduced in this report. Finally, we report the progress on developments of discipline and research team of planetary science in China.

Key words Planetary science, Progress, Exploration, Mission, Solar system

Classified index P35, V476

1 Research Progress of Planetary Science

1.1 Moon

The Chang'E-5 (CE-5) landing site is in the northern Oceanus Procellarum. CE-5 lander landed on the continuous ejecta of the Xu Guangqi crater within the eastern Eratosthenian-aged Em4 mare unit[1–3]. The geological column of the CE-5 landing site was constructed through a synthesis of regional geology, the crater morphology technique to constrain regolith thickness, and the crater excavation technique to constrain mare flow thickness[1,4]. CE-5 directly landed on and sampled the top of the 4–6 m-thick regolith[1] at the landing site. The lunar regolith formed on the Em4 mare flow with a thickness of about 50 m[1]. There are no observable eruption fissures around the Em4 unit except for sinuous rilles. Detailed geomorphological investigations of the landing site yield four independent sinuous rilles in the northern Oceanus Procellarum, including Rima Sharp (1.9±0.3 Ga), Rima Mairan (1.4±0.2 Ga), Rima Louville, and Rima Harpalus[4]. The majority of Em4 unit was produced by the eruption of Rima Sharp, whereas the deposits of Rima Mairan are limited to the southeast of the Em4 unit. Rima Sharp eruption started from a sheet flow followed by centration of lava flow in the late stage of eruption in which thermal erosion happened and the sinuous rille channel formed[4]. Therefore, the returned CE-5 basaltic samples represent the lavas from Rima Sharp. Qiao *et al.*[5] performed an in-depth investigation into the geolo-

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gy of the specific CE-5 landing site and the nearby vicinity using high-resolution remote sensing datasets. Based on the geological characterizations around the landing site, a sequence of four geological events, including mare volcanism, tectonism, impact cratering and ejecta deposition, was identified. In particular, a northwest-southeast-direction and a northeast-southwest-direction secondary cratering features were identified across the CE-5 landing site, and their sources were traced back to Copernicus and Harpalus craters, respectively. The CE-5 mission may have collected materials ejected from these two Copernican-aged craters. Fu *et al.*[6] also identified four major compositional groups (feldspathic highland materials, Imbrium basin ejecta, Aristarchus ejecta, and mare basalts) and several subgroups around the CE-5 landing site. Xie *et al.*[7] quantitatively estimated the abundance of Distantly Sourced Particles (DSPs) in the regolith at the landing region using an updated ballistic sedimentation model. The results suggest that the total abundance of DSPs on the surface around the landing area varies from approximately 12% to 20%, and most of the DSPs on the surface are ejecta from the Pythagoras (about 5%) and/or Aristarchus (about 7%) craters.

The CE-5 lander carried four instruments including Landing Camera, Panoramic Camera (PCAM), Lunar Mineralogical Spectrometer (LMS), and Lunar Regolith Penetrating Radar to explore the landing region for supporting the sample collection and analysis. Bo *et al.*[8] developed a catalogue of small craters (<100 m in diameter) using the centimeter-resolution images measured by the CE-5 Landing Camera, and found that the mean depth-to-diameter ratio of 231 craters in the CE-5 landing area is about 0.055. The diameters of these craters range from 7.0 to 371.2 m and the depths of these craters range from 0.21 to 45.9 m. The results indicate that the craters in the catalogue have a slightly low depth-to-diameter ratio compared with other larger craters and the small craters in the CE-4 landing area. Lin *et al.*[9] analyzed the reflectance spectra acquired by the Lunar Mineralogical Spectrometer onboard the CE-5 lander on the lunar surface and estimated up to 120 parts per million (ppm) of water ($OH+H_2O$) in the lunar regolith, which is mostly attributed to solar wind implantation. A light-colored and surface-pitted rock was observed near the lander and its reflectance spectra suggest that it could be transported from an older basalt unit. This rock exhibits a stronger absorption, near 2.85 μm, than the surrounding regolith, with an estimation of about 180 ppm of water if the model to determine water content of regolith is applicable to rock samples, which may suggest additional water from the lunar interior. The low water content of the regolith suggests the degassing of mantle reservoir beneath the CE-5 landing site. Su *et al.*[10] constructed the hyperfine structures at the CE-5 landing site based on the Lunar Regolith Penetrating Radar data, suggesting that the top about 2.5 m of the landing site is dominated by fine grains with abundant rock fragments.

The lunar regolith samples returned by CE-5 mission have stimulated the research of lunar materials. Major contributions to lunar science have already resulted from the allocation of the first batch CE-5 regolith in the middle of 2021. The basic physical properties of bulk CE-5 regolith have been analyzed[11,12]. The median grain size obtained via laser diffraction analysis is 55.24±0.96 μm[11], whereas that determined using optical microscope image analysis is 52.54 μm[12]. The bulk chemical compositions of CE-5 soil measured using instrumental neutron activation analysis are consistent with that of mare basalt[12,13], which is also supported by the mineral compositions[11,12]. This basalt has been argued to be low-Ti/low-Al/low-K type with rare-earth-element contents lower than KREEP[12]. The basalt clasts in CE-5 soils analyzed so far have a uniform young age, 2030±4 Ma[14] and 1963±57 Ma[15] from two independent groups. This is the youngest crystallization age reported for lunar basalts by radiometric dating, confirming that lunar volcanic activity lasted at least until 2 Ga. The μ value of the CE-5 basalt mantle source indicates that the CE-5 basalts were produced by melting of a KREEP-poor source[14,15]. This is consistent with the petrogenesis of CE-5 basalts, which were produced by low-degree mantle partial melting and subsequent extensive fractional crystallization evidenced by major and trace elements, and strontium-neodymium isotopes[16]. Therefore, the CE-5 basalts were not generated by high concentrations of heat-producing element in the deep mantle of CE-5 landing site, in contrast to its location in the Procellarum KREEP Terrane[14–16]. Furthermore, the maximum water content of the parent magma of the CE-5 basalts was determined to be 283±22 ppm and that of the mantle source was calculated to be 1–5 ppm, which is at the low end of the range estimated from mare basalts of about 4.0 Ga to 2.8 Ga[17]. Therefore, this low water content could not drive the young volcanism, whereas the mantle source of the CE-5 basalts could be dehydrated by previous melt extraction from the Procellarum KREEP Terrane mantle during prolonged volcanic activity[17]. The apatites in CE-5 basaltic samples are F-dominated (0.91 wt%–3.93 wt%) with a Cl abundance range of 820 to 11989 ppm and a water abundance range of 134 to 6564 ppm[18]. Apatite chlorine isotopic compositions vary from 4.5‰ to 18.9‰, positively correlated with the Cl abundances, suggesting that magmatic degassing of Cl-bearing species at or near the lunar surface during volcanic eruption could have resulted in a large Cl isotope fractionation[18]. Olivine Ti contents of various basaltic clasts indicate that the CE-5 basalts originated from a low-Ti primary magma[19], consistent with the low Ti content of bulk soil[12]. On the other hand, a basaltic clast with extremely high ilmenite modal abundance has been suggested to be a high-Ti basalt with enriched REE contents[20]. Different valence states of iron were discovered in the CE-5 soil, pure metallic iron, ferrous iron in olivine crystals, and ferric iron in the amorphous matrix[21]. It has been demonstrated that the textures of the solar wind irradiation-damaged zone depend on the host mineral species, spherical nanophase Fe ($npFe^0$) particles in the amorphized zone of pyroxene, elongated $npFe^0$ in ilmenite, irregular $npFe^0$ on the jagged surface of iron sulfide, no $npFe^0$ found in Fe-poor merrillite, and vesicles found in the damaged zone of ilmenite and merrillite with different shapes[22]. The comparison with Apollo samples shows no significant altitude-dependent effects on the space weathering, which is important for decoding the reflectance spectra of the Moon[22]. On the other hand, a combined transmission electron microscopy and electron energy loss spectroscopy study reveals that the uppermost layer of soil grains exhibits the simultaneous coexistence of $npFe^0$ with Si-rich material overlying an Mg-rich layer, as well as numerous irregular vesicles containing oxygen-rich (SiO and O_2) components embedded in the $npFe^0$[23]. These microscopic features are consistent with subsolidus olivine decomposition during impact-induced fragmentation or local heating processes, which may alter the reflectance spectra of the Moon[23].

The diversified lunar meteorite studies in China have made important contributions to lunar science in the last couple of years. A new model has been proposed for the formation of lunar highlands anorthosites, which represent a feldspathic crust metasomatized by incompatible-element-rich KREEP melts and mantle-derived partial melts rather than solely a derivative from the lunar magma ocean[24]. This new proposed formation scenario is consistent with overlapping ranges of age and initial ε_{Nd} between lunar anorthosites and Mg-suite rocks, and with an overturn event of the cumulate mantle very early after primordial crust formation to produce the partial melts that metasomatized the crust[24]. Calcium isotopic compositions of different lunar meteorites have been analyzed[25], which are the first published lunar metal isotope data in China. The determined Ca isotopic compositions indicate a mean $\delta^{44/40}Ca$ value of 0.75±0.13‰ for lunar crust, a $\delta^{44/40}Ca$ range of 0.96‰–1.11‰ for the lunar mantle, and the Ca isotopic composition of the bulk silicate Moon similar to the bulk silicate Earth[25]. The oldest immiscible silica-rich melt observed in a zircon of NWA 10049 provides microscale evidence that evolved silica-rich melts were prevalent as early as about 4.38 Ga, implying a prolonged silicic magmatism on the Moon[26]. This implication is consistent with the identification of a 4.32 Ga granitic fragment in the Th- and TiO_2-poor lunar breccia NWA 10447 [27]. This newly-discovered granitic fragment suggests that silicic magmatism may occur outside of the PKT of the Moon[27]. Petrogeneses of two feldspathic meteorites NWA 11111[28] and NWA 11460[29], one mare basalt meteorite NWA 10597[30], and one olivine gabbro meteorite NWA 6950 [31] have been carried out by different groups in the last couple of years. The Cr-Zr-Ca armalcolite in lunar rocks has been demonstrated to be loveringite using EBSD analyses[32]. Several high-pressure phases have been discovered in the lunar regolith meteorites, including reidite in SaU 169 [33], tissintite and coesite in several feldspathic meteorites[34]. The stabilities of these newly discovered phases were used to constrain the pressure and temperature ranges of meteoritic impacts on the Moon that facilitated the formation and lithification of lunar regolith[33,34].

The Raman and FTIR spectra of plagioclase have also been used to investigate the shock history of lunar breccia meteorite NWA 4848, which is highly shocked with a pressure range of 20–48 GPa[35]. This spectroscopic method has been applied to olivine and plagioclase of lunar meteorite NWA 13120, which has revealed a pressure higher than 20 GPa during shock metamorphism of this breccia[36]. On the other hand, the mobility and deposition of sulfur- and phosphorous-poor fluid evidenced by the olivine veinlets observed in lunar breccia NWA 11273 may have an endogenic origin on the Moon[37].

The research on lunar space physics has shifted from macroscale to microscale in the last couple of years. Through detailed studies of satellite observations of plasma and electromagnetic fields near the Moon, the key evidence, manifestations and consequences of the interaction between the Moon and the solar wind were found and analyzed. Zhang *et al*.[38] studied the interaction of small-scale lunar remnant magnetic fields with the solar wind, and found low-frequency whistling fluctuations propagating along the magnetic field lines. Their results demonstrated that ions are not the source of the low-frequency fluctuations, and the diversion of the electron fluid around the remnant magnetic field is the source for these low-frequency whistle-waves. Zhang *et al*.[39] found that the magnetic field and plasma moments are periodically about every 2 lunar radii in lunar wake, and that the periodic increase in plasma temperature in the wake is direct evidence for the periodic intrusion of these reflected ions from remnant field. Using the magnetic field observations from the Lunar Prospector satellite, Zhang *et al*.[40] carried out an in-depth study of the magnetic field disturbance near the Moon, and found that the lunar surface magnetic field disturbance exhibits a completely new spatial distribution characteristic, and that near the lunar terminator, there is asymmetric distribution about the direction of the solar wind electric field, and revealed that the pickup of solar wind-reflected particles is a new mechanism for the enhancement of the near-lunar surface magnetic field. Wei *et al*.[41] proposed a hypothesis that the lunar soil on the farside could have recorded the evolution of Earth's dynamo process because the Earth's oxygen ions could be transported and implanted to the farside surface once the Earth's dynamo started. Wang *et al*.[42] used data from the Chandrayaan-1 spacecraft to map water at the Moon's poles and found water levels remain about the same all month, and do not change during the period when Earth shields the Moon from the solar wind, which indicate Earth's “wind” might serve as a bridge to the Moon, providing an additional source of water. Wang *et al*.[43] show that the Energetic Neutral Atom (ENA) cutoff energy and temperature are lower on the duskside than on the dawnside at the same solar wind energy using The Advanced Small Analyzer for Neutrals (ASAN) onboard the Yutu-2 rover. The observation difference of ENA and solar wind between the dawnside and duskside is possibly caused by solar wind deflection and deceleration on the duskside, which can be attributed to the interaction between solar wind and the lunar magnetic anomalies located nearby in the northwestern direction of the CE-4 landing site. Shang *et al*.[44] show that the magnetosphere can flap across the Moon much like a windsock, exposing it to hazardous solar wind particles. Previous simulations suggest that lunar satellites and astronauts on the surface could be considered safe during a full moon while they reside within the magnetosphere. However, the full moon may not be protected by Earth's magnetic field after all. They showed that the lunar exposure could occur even without a shockwave when the solar wind blows sideways, suggesting that the exposure could occur even more commonly than previously thought[44].

1.2 Mars

China's first Mars rover, Zhurong, landed on the southern Utopia Planitia successfully on May 15, 2021. Many studies have been conducted to characterize the geologic features around the landing site. The landing region is within the Late Hesperian Lowland (LHL) unit and its estimated surface age is around 3.1–3.4 Ga[45–47]. Vastitas Borealis Formation (VBF), likely oceanic deposits, covers most of LHL unit, including the landing site. Orbital imagery data show many geomorphic expressions such as pitted cones, mesa ridges, polygonal troughs, and various types of impact craters[45–48]. The presence of layered ejecta from impact craters strongly suggests that water/ice/volatile in the subsurface of landing site has changed through time[49]. The most prominent geomorphology is pitted cone that has various formations and pivotal implications, including volcanic origin (scoria cones, rootless cones, and tuff cones/rings), ice-related (pingos), and sedimentary origin (mud volcanos).

The regional evolutional history of the landing area was synthesized and outlined by Wu *et al.*[46], which provides an important framework to support *in-situ* investigation data analysis and interpretation on a broader scale. The Utopia basin formed during a huge impact event in the early Noachian. This basin has been modified and filled by sedimentary and volcanic materials. Subsequently, the northern lowlands were covered by Early Hesperian-aged volcanic plains which were then deformed by wrinkle ridges in the Middle Hesperian. Late Hesperian-aged outflow channels were emplaced, producing sedimentary deposits that obscured and modified the ridged plains. Loss of flooding effluents in a geologically short time resulted in the formation of VBF, which is considered as a residual sedimentary deposit. The giant polygons formed due to tectonic rebound after the removal of the water/ice load or volumetric compaction. Finally, Amazonian-aged lava flows and lahars emanating from the Elysium Mons draped the southeastern portion of the basin.

Ye *et al.*[47] mapped the distribution of geologic features around the landing site of the Zhurong rover closely. Strikingly, troughs and pitted cones are located in the northeast and southwest of the landing site respectively. This geomorphology transition boundary is not a straight line along the latitude but follows the topographic change of the basin. The troughs may have been formed by tectonic uplift and extension of the utopian basin resulting from sublimation of ice-rich basement or volume compaction. The spatial correlation between the troughs and pitted cones could partly be explained by the latitude-dependent water-ice abundance, thickness or possibility of melting. The topography has an important influence on the distribution of landforms, and sediment and ice may be the driving forces of landform development. By comparing the height/basal aspect ratios between the pitted cones around the landing site to terrestrial mud volcanoes, Ye *et al.*[47] found similar relationships. Furthermore, these cones are also similar in scale to other putative mud volcanoes on Mars. Therefore, they thought pitted cones are likely mud volcanoes, which have important implications for climate and astrobiology of early Mars. A conceptual model was proposed: the magma chamber which fed these dike swarms could have been a heat source for maintaining the mobility of the mud reservoir and groundwater system. The rapid burial of aqueous sediments after water activities could have also fed an enormous mud reservoir around the Utopia basin and provided favorable conditions for sediment upwelling and methane releasing.

On a smaller scale, Zhao *et al.*[48] outlined the key questions associated with the evolution of the northern lowlands through high resolution geologic mapping. They suggested that several questions could be addressed by the Zhurong rover, including (i) origin of pitted cones, (ii) origin of graben-like troughs, (iii) evidence for ancient oceans, (iv) evidence for mudflows, (v) origin of surface/near surface rocks, (vi) nature of the Amazonian climate record, (vii) impact crater stratigraphy, (viii) nature/origin/age of aeolian features, and (ix) stratigraphic sequence. A possible scenario of geological evolution was proposed for the landing region of the Zhurong rover. Basaltic lava was emplaced on the underlying Noachian cratered basement during the Early Hesperian, followed by the water/ice containing VBF materials. Amazonian lava flows or mudflows appear to have been emplaced on top of the VBF materials around about 757 Ma. Water ice and/or carbon dioxide ice are interpreted to have been deposited into the relatively loose materials due to changes in eccentricity and obliquity that altered the climatic conditions. Relatively light-toned aeolian bedforms developed and were subsequently covered by airfall dust.

The research progress on the Martian meteorites in the last three years focused on the petrogeneses[50,51], hydrothermal activities[52–57], dating[50,55], and shock metamorphism[58,59]. Mars could have a long duration (about 1.6 Ga to 150 Ma) of hydrothermal activities evidenced by the petrography, mineral chemistry, water abundance, hydrogen and chlorine isotopes, rare earth elements, U-Pb and Sm-Nd dating of regolith breccia (NWA 7034 and its pair), olivine phyric shergottite NWA 6162, basaltic shergottite NWA 8656, and many other shergottites[52–55,57]. Most Martian meteorites have experienced strong shock metamorphism which resulted in the formation of high-pressure phases of coesite, ringwoodite, and widespread of maskelynite[58,59]. Asteroid impacts on

Mars could have supplied adequate energy to melt the underground ice to create a temporary hydrothermal system, facilitating the water-rock interaction on Mars[53]. The petrogenesis studies on the basaltic shergottite NWA 8653 and nakhlite NWA 5790 indicated that the Martian mantle is chemically heterogeneous[50,51].

The climate of Mars has changed from a wet and hot environment to a dry and cold condition evidenced by the presence of phyllosilicates in old terrain (>3.0 Ga) and evaporate salts in young terrain (<3.0 Ga). The alteration products on Mars' surface have carried key records of how Mars has evolved into current state. Systematic laboratory simulations on the formation of salts and their derivatives (chloride, perchlorate, brines, akaganeite, and manganese oxides) have been carried out to study the formation conditions of these secondary phases and the environmental clues for understanding the climate evolution of Mars[60–64]. Atmospheric escape played an essential role in Mars's water history and climate evolution. The Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft carried out remote sensing measurements of the Mars upper atmosphere using an Imaging UltraViolet Spectrograph (IUVS) onboard. Using these remote sensing measurements, Qin[65,66] reported comprehensive quantifications of the atmospheric state and escape rate associated with the O and H atoms in Mars' upper atmosphere. The solar cycle, seasonal, diurnal, and dust-storm-driven variations have been documented. A long-standing discrepancy between the Mars upper atmospheric temperatures derived from different methods has also been resolved[66], showing that the daytime Martian exobase temperature varies typically in the range of about 150–280 K.

Mars has patches of localized intense remnant crustal fields, particularly in the southern hemisphere, in contrast to the induced magnetosphere of Venus and the intrinsic magnetosphere of Earth. These crustal fields contribute to solar wind interactions, complicating the Martian space environment. NASA's MAVEN spacecraft carried both magnetometer and plasma instruments enabling us to study the space environment of Mars. Using the scientific data measured by MAVEN, our Chinese team has made fruitful findings on Martian space environment. Using the plasma data and magnetic field data of MAVEN, Liu *et al.*[67] statistically surveyed the distribution of solar wind parameters in the upstream of a bow shock, and revealed the radial profile of solar wind parameters between Earth-Mars and evaluated its variation with solar activity level. Liu *et al.*[68] statistically surveyed the occurrence of Proton Cyclotron Wave (PCW), and found that the amplitude and occurrence frequency of PCW is higher when the orientation of IMF is closer to the Sun-Mars line. Wang *et al.*[69] developed an automatic algorithm to identify the crossing of PEB by MAVEN based on the electron spectrum, which could be applied further to the dataset of MEX to study the long-term variation of Martian ionosphere. Zhang *et al.*[70] studied an event of periodical plasma cloud at low altitude, and suggested that the cloud was trigged by reconnection driven by solar wind and crustal field, and that the cloud could carry planetary ions to escape significantly. Fan *et al.*[71] statistically studied the interaction of solar wind with Marian crustal field, and noticed that the solar wind flow can be deflected by the crustal field. Previous crustal field models were established based on the MGS data at the altitude of about 400 km, and the MAVEN's data collected down to the altitude of 120 km provides an opportunity to establish a more accurate model. Based on both datasets of MGS and MAVEN, Gao *et al.*[72] developed a new Martian crustal field model which has the least fitting error than the previous models. To clarify the scientific objectives of the Lander of China's Mars mission, Li *et al.*[73] developed a regional high-resolution crustal field model based on both datasets of MGS and MAVEN, and inferred the magnetic field distribution on the Mars surface. Zhang *et al.*[74] statistically studied the 3-D magnetic field configuration around Mars, and found that the field structure in Martian magnetotail has an evident hemispheric asymmetry along the direction of solar wind electric field. Using the data from ASPERA-3 and MARSIS onboard Mars Express, Qin *et al.*[75] found double-peaked Total Electron Content structures in the Martian crustal magnetic cusp regions and analyzed the possible links between this new phenomenon in the Martian nightside ionosphere with the patterns of precipitating electrons. The upper atmosphere and ionosphere of Mars is a region full of variations and frequently affected by the factors from above (solar radiation, solar wind, *etc*.) and below (dust storms, gravity waves, *etc*). Qin *et al.*[76] compared the observed neutral densities and MCD simulated neutral densities and found that in some cases MCD simulation results largely underestimated neutral densities. Recently, China's Mars mission team released the original plasma data sampled by Tianwen-1 spacecraft en route for Mars. Zhang *et al*.[77] and Fan *et al*.[78] processed the data and found that the plasma instrument works well in measuring the solar wind. More work will be carried out in the near future to investigate the data from plasma instrument of "Tianwen-1".

1.3 Mercury

Mercury, the closest planet to the Sun, is the only terrestrial planet other than Earth owning a global dipolar magnetic field in the solar system. Mercury's dipole moment, however, is only about 4/10000 of Earth's dipole moment. Furthermore, Mercury has no atmosphere but possesses a tenuous surface-bounded exosphere. As the closest planet to the Sun, Mercury encounters a much stronger impingement of solar wind, whose density and dynamic pressure are an order of magnitude higher than those at Earth, and thus, Mercury has a much smaller, weaker and more dynamic magnetosphere than Earth. Using the scientific data measured by MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) orbiting Mercury from March 2011 to April 2015, our Chinese team has made fruitful findings about Mercury's magnetosphere, which enriches the knowledge and understanding of Mercury's space environment. Zhong *et al*.[79] found that the direction of Interplanetary Magnetic Field (IMF) can modulate the scale of magnetopause that the magnetopause is inflated when IMF is quasi-parallel to solar wind, and shrunken when IMF is quasi-perpendicular to the solar wind. In addition to the large-scale magnetospheric field structures, many transient or dynamic processes were surveyed. Using the state-of-the-art technique, Zhang *et al*.[80] studied the oscillation of magnetic field in magnetotail and argued that the oscillation with a period of about ten seconds can be propagated as kink-like waves from one tail flank to the opposite flank. Zhong *et al*.[81,82] studied an event of crossing the diffusion region of reconnection in magnetotail and found evidence of giant flux rope/plasmoid in tail plasma sheet, suggesting that the Mercury magnetotail is highly spatial-temporal dynamic under the "strong-driven" by solar wind. With the data-based magnetic field model, Jang *et al*.[83] applied a series of test particle simulations to study the charged particle dynamics around the polar cusp and found that the polar cusp is capable of trapping energetic ions. Zhao *et al*.[84] investigated the proton properties in Mercury's magnetotail plasma sheet, and the results reveal the non-adiabatic nature of proton in the central plasma sheet. It has been much debated whether Mercury's dipolar magnetic field could trap an ensemble of charged particles that, analogous to the Earth's ring current, drift as a westward current around the planet. Based on the analyses of plasma data and particle tests, Zhao *et al*.[85] recently argued that Mercury has a westward ring current in the nightside inner tail, but becomes bifurcated when moving to the dayside high-latitude cusps. The existence of Mercury's ring current also indicates the magnetic storm at Mercury. Zong *et al*.[86] derived the Disturbance storm time (Dst) index at Mercury based on a spacecraft-based Dst algorithm, and caught an Earth-like magnetic storm event just before the end of the MESSENGER mission. Nonetheless, the analysis of magnetic field by Shi *et al*.[87] demonstrated that there is no significant Earth-like ring current flowing westward around Mercury, but found, for the first time, an eastward current encircling the planet near the night side equator with an altitude of about 500–1000 km. The eastward current is closed with the dayside magnetopause current and could be driven by the gradient of plasma pressure as a diamagnetic current.

1.4 Venus

Venus, the closest planet to Earth, has neither a global dipole field nor an intrinsic remnant field. Venus only relies on its ionosphere as an obstacle to solar wind, and the interaction with solar wind results in an induced magnetosphere. The Venusian magnetosphere was previously surveyed by Pioneer Venus Orbiter (PVO, 1978–1992), but the covered region is restricted to the distant downstream tail (8–12 Venusian radii). The ESA's mission, Venus Express (2006–2014), with state-of-the-art instruments, can cover the near tail (0–3 Venusian radii). Using the scientific data measured by Venus Express, our Chinese team has made fruitful findings about Venusian space environment. The bow shock is the outermost boundary of Venusian space environment. Combining the dataset of PVO and Venus Express, Han *et al*.[88] investigated the variation of the boundary, called ionopause, between ionosphere and the solar wind, and found that the altitude of ionopause increases with the solar EUV radiation. Based on the data analyses of

Venus Express, Gao *et al.*[89] reported the evidence of crossing the ion diffusion region of magnetic reconnection in Venusian plasma sheet, which demonstrated that the Venusian plasma sheet is highly dynamic and favors the triggering of magnetic reconnection.

1.5 Giant Planets

Literally, magnetic dipolarization describes the process when a magnetic field line change from a stretched configuration to a dipole shape. Magnetic dipolarization is expected as a consequence of substorm current wedge formation, during which the cross-tail currents are diverted into the ionosphere via field-aligned currents. The direction connection between dipolarization and auroral intensification was not yet made until the Juno era. Using coordinated observations from Juno and the Hubble Space Telescope, Yao *et al.*[90] reveal that the auroral injection is associated with dipolarization injection, which is known to cause hot plasma injection in the magnetosphere. Moreover, their results show that the auroral dawn storm is likely associated with magnetic reconnection, which continually produces plasma injections in the dawn-side magnetosphere, leading to multiple auroral injection structures when rotating to larger local times. Their proposed picture is consistent with that the poleward initiating auroral signature is likely a signature of magnetic reconnection. Using the joint measurements from Juno and the Hubble Space Telescope, Guo *et al.*[91] showed the evolution of a double-auroral arc on the dawnside from observations by the Hubble Space Telescope, together with simultaneous in situ observations from the Juno spacecraft provide direct evidence of magnetic reconnection and magnetic dipolarization. Their results indicate that the evolution of the double-arc structure is likely a consequence of the non-steady progress of magnetic reconnection.

Besides the reconnection and dipolarization processes, plasma waves are known to play key roles in driving auroral emissions, while the observation evidence is mostly for the terrestrial environment. Using the large datasets from the Hubble Space Telescope and Juno since 2016, Pan *et al.*[92] showed coherence between auroral emissions and Alfvenic plasma wave, which provide direct evidence for the wave driving aurora at Jupiter. Moreover, the low frequency compressional Alfvenic wave is found to modulate electromagnetic ion cyclotron waves that could efficiently scatter heavy ions to produce the energetic soft X-ray auroral emission[93].

Research done with a newly developed global magnetohydrodynamic model of Jupiter's magnetosphere provides evidence in support of a previously controversial and criticized idea that Jupiter's polar cap is threaded in part with closed magnetic field lines rather than entirely with open magnetic field lines, as is the case with most other planets in our solar system[94]. The results finally solved why Jupiter's polar cap emission is not as expected in the textbook used in past decades.

Besides Jupiter, good progress is made in the global picture of Saturn using the Cassini large dataset. The distributions of magnetic reconnection and the associated structures, such as plasmoids are established by several groups in China[95–97]. The distribution of low-frequency waves and the associated connection to solar activities are systematically analyzed[98]. In the past years, several Chinese groups have also made significant progress in Saturn and Jupiter on the radiation belt[99–103] and radio emissions[104,105]. Guo *et al.*[91] found that the formation of the double-arc structure on the main aurora was related to the magnetic reconnection process in the magnetosphere. By comparing observations on Saturn, Jupiter and Earth, Hao *et al.*[99] found that the global convection electric field could accelerate radiation belt electrons on giant planets more efficiently than on Earth. This process is essential on giant planets due to their fast rotation and southward intrinsic magnetic field. The properties of the global convection electric field have also been systematically studied[102]. Sun *et al.*[101] revealed the impact of such convection on ions.

Deep dielectric charging/discharging is a serious space environmental effect on spacecraft in Jovian planets' orbits. Yu *et al.*[106] used GEANT4, a Monte Carlo toolkit, and Radiation-Induced Conductivity (RIC) to calculate deep dielectric charging effects for Jovian planets. The results were compared with the criteria for preventing deep dielectric charging effects in Earth orbit. The findings show that effective criteria used in Earth orbit are not always appropriate for preventing deep dielectric charging effects in Jovian orbits. Generally, Io, Europa, Saturn, Uranus, and Ganymede missions should have a thicker shield or higher dielectric conductivity, whereas Neptune and Callisto missions can have a thinner shield thickness or a lower dielectric conductivity. Moreover, dielectrics grounded with double metal layers and thinner dielectrics can also decrease the likelihood of discharges.

1.6 Asteroids

A quantitative two-endmember mixing model of the Noncarbonaceous (NC) bodies has been developed using the isotopic anomalies of different elements (Ca, Ti, Cr, Fe, Ni, Mo, and Ru) with different cosmochemical behaviors[107]. Therefore, the isotopic anomalies of NC bodies for all the considered isotopes, including the isotopic anomalies that are difficult to measure or have been altered by spallation processes, can be calculated using this mixing model, as well as the mixing proportion between the two endmembers in each NC body and the feeding zones of the NC bodies[107]. The estimated feeding zones of NC bodies indicate a large population of interlopers in the main asteroid belt and an indigenous origin of Vesta, and that the orbits of Jupiter and Saturn during the formation of terrestrial planets were likely to be more circular than their current ones[107].

Detailed physical, petrographic, and isotopic systematic studies on Ca-Al-rich Inclusions (CAIs), the first condensation solids from solar nebula, and Al-rich chondrules, have been conducted on Kainsaz (CO3), Ningqiang, Allende (CV3), and NWA 3118 (CV3) in the last three years[108–114]. These studies indicate that the CAIs could have experienced post-formation alteration evidenced by triple oxygen isotope compositions probably on the parent bodies[108, 109, 111, 112]. The petrology, mineralogy, bulk compositions, rare Earth element abundances, and in situ oxygen isotopic compositions of Aluminum-Rich Chondrules (ARCs) from various carbonaceous chondrites revealed that the ARCs formed by melting of mixtures of diverse refractory components with FerroMagnesian Chondrules (FMC) in the FMC-forming region[113]. The potassium isotope measurements on chondritic components in meteorite Allende display that the nominally K-free refractory minerals are enriched in heavy K isotopes with δ^{41}K variation of –0.30‰ to –0.25‰ and the chondrules have lighter δ^{41}K values (–0.87‰ to –0.24‰)[110]. The correlation of K isotope with the components indicates that most of the Allende chondritic components experienced aqueous alteration and their K isotopic compositions are the ramification of Allende parent-body processing instead of primary nebular signatures[110].

Many studies on the chondrites and achondrites have been carried out in the last three years. Olivine in diogenite NWA 8321 has been partly replaced by orthopyroxene, troilite, and minor metal, indicating a sulfur-involved metasomatism in the interior of Vesta[115]. Sulfurization was also identified in monomict eucrite NWA 11591 [116]. A new occurrence of corundum was identified in eucrite NWA 8647, occurring as a mineral inclusion in a highly deformed pyroxene fragment[117]. The disproportionation of iron in eucrite NWA 11592 reflects that the strong shock metamorphism took place on its parent body[118]. Some metallic-Cu-bearing mineral assemblages have been identified in type-3 ordinary and CO type chondrites[119]. The parent body of ungrouped achondrite NWA 7325 could have had sulfur-rich magmatism[120]. Two unusual fragments dominated by Ca, Fe-rich olivine with various amounts of Al, Ti-rich augite, anorthite, oxide minerals, Ca-phosphate mineral, FeNi metal, enstatite, and less Al, Ti-rich augite, have been identified in CH3 carbonaceous chondrite SaU 290, revealing a new basaltic planetesimal[121]. The U-Pb dating of phosphates in silicate inclusions of IIE iron meteorites[122] could constrain the formation time of their parent bodies and the following strong asteroid impact events. Noble gases of meteorites have been measured to constrain their exposure histories[123,124]. The discovery of nanophase iron particles in shock-induced melt veins and pockets in ordinary chondrite supports the decomposition of host silicates under high temperature and pressure conditions[125].

1.7 Comets

Sungrazing comet C/2011 W3 (Lovejoy) shows a distorted and unconventional tail shape near the perihelion (1.2 Rs). Hou *et al.*[126] simulated the dynamics of charged particles (ions and dust particles) released from the comet based on the modeling results of corona and inner heliosphere. They found that dust particles near the sun are affected by strong magnetic Lorentz forces, unlike dust particles farther away from the sun, which are mainly affected by the Sun's gravity and radiation pressure. Based on their simulations, they proposed that the magnetic mirror effect, which bounces charged dust particles back from the sun, is considered one of the key causes of dust-free zones[126]. They further found that the ions moved mainly along magnetic field lines, at an acute angle to the direction of the comet's movement. The direction of movement of the comet's ions is determined by the comet's speed and coronal magnetic field, which is responsible for the distinctive tail shape of C/2011 W 3 near the perihelion. In addition, ion particles undergo vertical drift motions, dominated mainly by electric field drift, which is similar to and can be used to approximate the lateral velocity of the solar wind in its source region.

The Parker Solar Probe (PSP) aims to explore new solar winds near the sun. The PSP is also expected to encounter small objects such as comets and asteroids. He *et al.*[127] surveyed ephemeris for recent encounters and then modeled the interaction between the released dusty plasma and the solar wind plasma. On 2 September 2019, a comet-like object 322 P just passed its perihelion, approaching the heliocentric distance of 0.12 AU, swept by the PSP at a relative distance of 0.025 AU. He *et al.*[127] showed the dynamics of dust particles emitted from 322 P, forming a curved dust tail. The plasma and magnetic field states were sampled and illustrated along the path of the PSP in the simulated inner heliosphere, and the simulated magnetic field sequences were directly compared with the in-situ measurements of PSP. By comparison, they concluded that 322 P may be at a low activity level, emitting limited dust plasma during the evolution of becoming a "rock comet" [127]. They also showed images of solar wind streamers recorded by the Wide Field Imager (WISPR), showing signs of dust bombardment superimposed on images with messy tracks. They found 322 P's transition from dark to relatively bright streamer during perihelion passage from the Large Angle and Spectral Coronagraph (LASCO), and performed a simulation to confirm 322 P's flight from relatively fast to slower solar currents, thus altering the state of local plasma flows[127].

1.8 Meteoritic Impacts on Earth

A large number of meteorites have been recovered from Gobi desert in northern and western China in the last decade[128,129]. At least 42 dense meteorite collection areas have been discovered, mainly in northern and western China. Most of the approved meteorites recovered in China are ordinary chondrites and iron meteorites with a few CO3 chondrite, diogenite, ureilite, brachinite, and eucrite[129,130]. The ongoing collection tour will supply more extraterrestrial materials to the planetary science community in the near future.

A new impact crater has been identified in Heilongjiang province and named as Yilan, which is supported by the presence of planar deformation features in quartz from the unmelted granite in drillcore samples[131]. Detailed studies of high-pressure polymorphs of silica and feldspar have been carried out in samples from Xiuyan crater[132,133]. The first natural redite was identified in terrestrial samples, which are from Chicxulub impact crater[134]. A systematical search of Australasian microtektites in the Chinese Loess Plateau showed that no confirmed microtektites were discovered in the 19 loess sections, indicating that Australasian microtektites are not a widespread stratigraphic marker in the Chinese Loess Plateau[135].

2 Mission Support to the Lunar and Deep Space Exploration

2.1 Science Goals and Mission Objectives

CE-4 mission has three main science objectives: (i) low-frequency radio astronomical observation, (ii) geomorphology, mineral compositions, shallow subsurface structure of and near the landing area, and (iii) lunar environment at farside of the Moon[136,137]. To achieve these objectives, different payloads were installed on the lander, rover or relay satellite to detect the solar low frequency radio radiation (0.1–40 MHz) and the low frequency radio radiation from other celestial bodies in solar system and galaxy (0.1–80 MHz), analyze the chemical composition (element content and distribution), mineral compositions (mineralogical content and distribution), regolith thickness and shallow subsurface structure in situ, and measure the electrically neutral component, neutrons, γ-rays, fast neutron flux, and thermal neutrons flux, neutral atom, and cation on the farside of the Moon[136].

There are two scientific objectives for CE-5 mission: (i) to carry out in situ exploration in sample collection area, collect the samples with the scientific support from the in situ analyses and establish the connection between the data acquired on the Moon and those analyzed in the laboratory, and (ii) to systematically study about the lunar regolith samples in the laboratory, analyze the structure, physical properties, and mineralogical, chemical and isotopic compositions of lunar samples and investigate the origin and evolution history of the Moon[137].

The scientific objectives of Tianwen-1 mission include: (i) map the morphology and geological structure, (ii) investigate the surface soil characteristics and water-ice distribution, (iii) analyze the surface material composition, (iv) measure the ionosphere and the characteristics of the Martian climate and environment at the surface, and (v) perceive the physical fields (electromagnetic, gravitational) and internal structure of Mars[138–140]. To achieve these objectives, a scientific payload system, including those on the orbiter, the lander, and the rover, was developed to carry out these specific tasks: (i) to analyze the Martian ionosphere and survey the interplanetary environment, (ii) to detect Martian surface and subsurface water ice, (iii) to survey the characteristics of soil and structures of Mars, (iv) to survey the characteristics of topography and geomorphology of Mars, and (v) to analyze the composition of the Martian surface material for the obiter; and (i) to study topography and geological structure of the roving area, (ii) to survey the soil structure (profile) of the roving area and to search for water ice, (iii) to survey elements, minerals and rock types of the roving area, and (iv) to survey the atmosphere physical characteristics and the surface environment of roving area for the rover[140].

2.2 Science Payloads in China's Missions

CE-4 mission has six scientific payloads[136]: three on the lander, including the Landing CAMera (LCAM), the Terrain CAMera (TCAM), and the Low Frequency Spectrometer (LFS); and three on the rover, including the Panoramic CAMera (PCAM), the Lunar Penetrating Radar (LPR), and the Visible and Near-Infrared Imaging Spectrometer (VNIS). The LFS is newly developed for CE-4 and the others are inherited from CE-3. Besides, there are also three international joint collaboration payloads: the Lunar Lander Neutrons and Dosimetry (LND) on the lander with Germany, the Advanced Small Analyzer for Neutrals (ASAN) on the rover with Sweden, and the Netherlands-China Low-frequency Explorer (NCLE) on the relay satellite with the Netherlands.

Tianwen-1 mission has thirteen scientific payloads[138,140]: seven onboard the orbiter, including two cameras, the Mars-Orbiting Subsurface Exploration Radar, Mars Mineralogy Spectrometer, Mars Magnetometer, Mars Ion and Neutral Particle Analyzer, and Mars Energetic Particle Analyzer; and six on the lander and rover, including Multispectral Camera, Terrain Camera, Mars-Rover Subsurface Exploration Radar, Mars Surface Composition Detector, Mars Magnetic Field Detector, and Mars Meteorology Monitor.

CE-7 plans to be equipped with two science payloads on the relay satellite, five on the orbiter, seven on the lander, four on the rover, and one on the mini-flying probe[141]. The two science payloads on the relay satellite are a Grid-based Energetic Neural Atom Imager and a lunar orbit Very Long Baseline Interferometry system. The orbiter would carry High Resolution Stereo Mapping Camera, Miniature Synthetic Aperture Radar, Wide Band Infrared Spectrum Mineral Imaging Analyzer, Lunar Neutron Gamma Spectrometer, and Lunar Orbit Magnetometer. The lander would carry Landing Camera, Topography Camera, In-situ Measuring System of Volatiles and Isotopes on Lunar Surface, Lunar Soil Section Thermal Current Measuring, Lunar Surface Thermometer, Extreme Ultraviolet Camera, and Lunar Seismograph. The rover would carry Panoramic Camera, Rover Magnetometer, Lunar Penetrating Radar, and Lunar Raman Spectrometer. The Mini-Flying flight would carry Water Molecule and Hydrogen Isotope Analyzer.

2.3 Analytical Procedures and Methods for Planetary Materials

A series of in situ and high precisions analytical protocols and techniques have been established in the last several years, including water abundance measurements in olivine and pyroxene[142], high spatial resolution measurements of volatile elements[53], high-resolution U-Pb dating in zircon[143], elemental mapping technique[144], FIB-SEM technique for manipulating micrometer-sized particles[145], and high precision measurements of Nd[146] and Cr[147] isotopic compositions. Different facilities for the curation of CE-5 lunar regolith have been constructed, which have supported a series of scientific research on these precious samples.

3 Developments of Discipline and Research Team of Planetary Science

About twenty years ago, China did not have its own spacecraft mission to study space physics exclusively, let alone the missions to the Moon and to Mars. Who could have imagined that China has successfully implemented the “Double Star” mission to explore Earth’s magnetosphere, the series of lunar missions of “CE-1, -2, -3, -4, -5”, and the first Mars mission of “Tianwen-1” over the past twenty years. These successful missions have undoubtedly driven the rapid development of China’s planetary science. This is because more and more planetary scientists are needed to become involved in analyzing the scientific data returned by spacecraft, and more scientific requirements are presented to regulate the mission as well as the scientific payloads onboard spacecraft.

In such circumstances, different branches of planetary science and their respective communities have developed gradually in China, such as planetary space physics, planetary atmosphere, planetary geology, planetary geochemistry, planetary interior dynamics, exoplanets, terrestrial small body, astrobiology, *etc*. Meanwhile, a few universities, represented by the University of Chinese Academy of Sciences (UCAS), have started to provide the related courses to educate students in planetary science. The academic consortiums and organizations of planetary science have also been established, like the China University Planetary Science Alliance, the Lunar Science and Comparative Planetology Committee of Chinese Space Science Society, the Planetary Committee of Chinese Astronomical Society, and the Planetary Physics committee of Chinese Geophysical Society. Moreover, to advertise the original studies of China’s planetary science, the first international peer-reviewed journal of planetary science of China, named “Earth and Planetary Physics” (EPP), was issued in 2017. In summary, planetary science as a field of study has bloomed within China over the past 20 years.

In contrast to the booming development of China’s planetary science, China, however, had not yet held its own national planetary conference. Due to this, many Chinese scientists have previously had to attend international conferences, such as the Lunar and Planetary Science Conference (LPSC) and the EuroPlanet Science Congress (EPSC) to seek academic communications. Given the rapid global development of planetary science and the current state of the COVID-19 overseas, Chinese scientists are more eager than ever to attend a nationally held conference. The time seemed ripe to hold a comprehensive planetary conference for the wide communities of planetary science in China.

The conference, the first Chinese Planetary Science Conference (CPSC), organized by the Planetary Physics committee of Chinese Geophysical Society, took place on 18–21 June 2021 in Suzhou, Jiangsu province of China, which will also serve as the base of the aerospace industry in China[148]. CPSC received about 500 abstracts covering a wide range of disciplines within planetary science, including planetary space environment, planetary atmosphere, planetary geology, planetary interior dynamics, asteroids, comets, exoplanets, biology, future missions to space, and probing techniques, *etc*. It is also astounding to note that the conference attracted 1020 attendees together from 106 affiliates, including the attendees from the universities of Macao and Hong Kong. The size is comparable to that of the EPSC (regularly around 1000 attendees each year), and about half that of LPSC (regularly around 1800 attendees each year). It is regretful that CPSC was not open to the world yet due to COVID-19 restrictions on travel, but some non-Chinese scientists who have lived for a long time in China were able to attend this conference, and were also able to speak English in the sessions they attended. The sheer number of attendees demonstrates that planetary science within China has developed rapidly in recent years and the number of planetary scientists has already grown to a massive scale.

Overall, some clear conclusions about the current status of China’s planetary science can be drawn from this conference.

(1) Half of the attendees were students, and female scientists occupied nearly a quarter of the total attendees. Thus, the current community of China’s planetary scientists is very youthful, and female scientists play an important role in this community.

(2) About half of the attendees were from the institutes of Chinese Academy and Sciences (CAS), which

means that the main force to conduct planetary science in China is led by CAS.

(3) The abstracts received by the conference covered various aspects of planetary science, which implies that planetary science is being treated as a system science, and the interdisciplinary nature of planetary science in China is maturing.

(4) The abstracts of planetary space environment and planetary geology dominated the abstracts received by the conference, which suggests that the communities of planetary space and planetary geology are of particular importance to the current study of planetary science in China. The reasons are understandable, because, on one hand, conventional Earth space scientists can easily change to study planetary space science, and on the other hand, the series of China's Chang'E missions and the Mars mission of "Tianwen-1" brought about the rapid development of planetary geology.

(5) To encourage and facilitate comprehensive discussions, most presentations, including the presentations of graduate students, were delivered as oral presentations, which strengthens the training and education of young scientists, in particular. In contrast, both EPSC and LPSC assigned oral presentations only for a small number of attendees.

Several striking takeaways from the plenary lectures of this conference demonstrated that: (i) China will launch an optical telescope with 2 m-aperture, named China Space Station Telescope (CSST) around 2024, to detect celestial bodies within the solar system and cosmos. (ii) China is planning to launch a spacecraft around 2024, which is aiming to fly to 100 AU and beyond till approximately 2049, allowing it to explore the boundary of the solar system or heliopause. (iii) The future of China's lunar missions will gradually shift to a study of the Moon's interior, as China will look to establish research stations on the lunar surface with international collaborations. (iv) China is actively developing its discipline of modern planetary science, and the Chinese universities, represented by UCAS, have already made significant progress in facilitating the growth of the education system around planetary science.

All the attendees were eager to gather again for the next conference. As a response, the conference committee held an interim discussion with regards to the conference period and reached a consensus that being parallel to EPSC and LPSC, CPSC should be held consistently be held annually, and must open up to international planetary researchers. Moreover, we expect that more and more international planetary scientists will participate in this conference and become a part of the global collaboration with China to explore the mysteries of planets, for the common benefit of all humankind.

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