POLICY FORUM

China's present and future lunar exploration program

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Since the beginning of the 21st century, the pace of lunar exploration has accelerated, with more than a dozen probes having undertaken scientific exploration of the Moon. Prominent among these have been the robotic "Chang'E" (CE) missions of the China Lunar Exploration Program (CLEP). We discuss technological and scientific goals and achievements for the four completed, and four planned, CE missions, and longer-term goals and plans of the CLEP beyond the CE missions. The exploration plan is flexible and iterative, with an emphasis on international cooperation.

On 3 January 2019, the first lunar farside in situ exploration mission, China's Chang'E-4 (CE-4), successfully landed in Von Kármán crater within the South Pole–Aitken (SPA) basin. Fifty years after U.S. astronaut Neil Armstrong took "one small step for [a] man, one giant leap for mankind" as the first human to set foot on the Moon, China's CE-4 lander and Yutu-2 rover left the footprints of humanity's first robotic visit to the surface of the far side of the Moon, opening a new chapter in lunar exploration. CE-4 is one of the missions of the China Lunar Exploration Program (CLEP). With China still in its infancy in this field, we discuss how the overall goal of CLEP is to undertake substantial scientific exploration by laying a robust engineering and technical foundation, with an emphasis on international cooperation.

The mysteries of the origin and evolution of the Moon are one of the most basic problems in natural science, continuing to attract the interest and excitement of scientists and engineers worldwide. Humanity has carried out more than 100 lunar exploration missions. Since the beginning of the 21st century, the pace has accelerated, with more than a dozen probes having undertaken scientific exploration of the Moon, including SMART-1 (ESA); SELENE Kaguya (Japan); Chandrayaan-1 (India); LCROSS; LRO; GRAIL; LADEE (United States); and CE-1, CE-2, CE-3, and CE-4 (China), resulting in many new discoveries and scientific achievements.

Science goals, technology development

In 2004, China formulated a robotic lunar exploration program, consisting of three phases—orbiting, landing, and returning—and named the program the "Chang'E Project," after the Chinese goddess of the Moon. In 2005, Ziyuan Ouyang, the first chief scientist of CLEP, raised 14 key questions and issues that have become the blueprint of China's developing strategy and planning for lunar exploration (Fig. 1), providing direction for China's scientific goals and payload allocation (*1*): (i) the composition, source, and evolution of the lunar atmosphere; (ii) the nature of the ionosphere of the Moon; (iii) the nature and origin of lunar topography and geomorphology; (iv) the nature of the space environment and the lunar surface environment; (v) the origin, material sources, distribution characteristics, and formation process of lunar soil (regolith); (vi) the main lunar rock types and their distribution and origin; (vii) the mystery of water ice on the Moon; (viii) the nature and history of tectonic deformation on the Moon; (ix) the internal structure of the Moon and the formation processes; (x) the heterogeneity of the distribution of material within the Moon; (xi) the origin and evolution of the lunar global intrinsic dipole magnetic field; (xii) the thermal evolution of the Moon; (xiii) the nature and timing of the major events in the evolution of the Moon; and (xiv) the origin of the Moon and the Earth-Moon system. In 2018, the NASA Advisory Council Lunar Exploration Analysis Group (LEAG) updated and improved 11 key scientific concepts for lunar exploration, as well as specific research proposals to address these 11 scientific concepts (*2*). These science questions are fundamental in lunar exploration missions, with individual missions focusing on addressing some of them.

The goals of CLEP from 2004 to 2020 are to gain a global and comprehensive understanding of the Moon through orbital spacecraft exploration; to conduct exploration and surveying of the lunar surface, through Earth-based monitoring, sky mapping, and lunar soft landing with landers and rovers; and to develop a more in-depth understanding of the Moon and its history through the sampling of lunar rocks and soils, and returning them to Earth. The missions are iterative and intertwined from the perspectives of science, engineering, and technology. The exploration plan is very flexible, depending on what is learned from these areas during each step in the program.

In the course of successfully executing the CE-1 to CE-4 missions (2007–2019), China has made considerable progress and development in many areas of space technology, such as orbit design, flight control, high-precision telemetry and telecommunication, lunar soft landing, and traverse exploration. For example, the CE-4 mission positioned a relay satellite in the Earth-Moon L2 halo orbit to establish communication between Earth and the far side of the Moon. In addition to laying solid technical foundations for subsequent lunar exploration missions, the CE missions have achieved important scientific results. For example, orbital exploration of the Moon from CE-1 and CE-2 provided a 7-m-resolution lunar global image and topographic maps (*3*), the first global analysis of the Moon's microwave radiation (*4*), and discovery of the acceleration of protons at the lunar day–night interface (*5*). The CE-3 lander and rover revealed a new type of lunar basaltic rock (*6*), and the characteristics of the subsurface structure of the landing area through radar probes (*7*, *8*). Using the lunar surface as a unique astronomical observation platform, CE-3 studied brightness changes of stars, as well as changes in Earth's plasmasphere in the ultraviolet band (*9*). The CE-4 spacecraft provided the first in situ measurements from the far side of the Moon. Visible and near-infrared spectra of impact ejecta excavated and delivered from the adjacent Finsen crater exhibit the petrographic features of the lunar deep interior materials (*10*). CE-4 is analyzing the electromagnetic environment of the far side of the Moon, assessing its potential as a site for low-frequency radio astronomy observations and research. CE-4 is also seeking to detect low-frequency radio waves (0.1 to 40 MHz) generated by solar activity and other sources (*11*).

The CE-5 mission, scheduled for early 2020, is designed to return samples to Earth from Mons Rümker, the northern part of Oceanus Procellarum. This site was chosen for having some of the youngest of the lunar volcanic mare basalt rocks, as yet unsampled. The scientific goals of CE-5 are to obtain a firm date for the end of lunar volcanism, to understand how the mineralogy and petrology of young volcanism differs from those of earlier times, and to provide a comprehensive view of lunar thermal and interior evolution.

In 2015, after the launch and successful execution of early phases of the CLEP orbiting, landing, and returning project, China proposed a follow-up plan to take place before 2030. This program consists of surveying the lunar environment and resources, constructing a long-term fundamental research platform, and verifying technology for exploiting available resources. The overall scientific objectives include (i) investigating the global distribution, content, and source of water and volatile components; (ii) investigating the composition and structure of the Moon's interior; (iii) measuring the age of the South Pole–Aitken Basin; and (iv) investigating the space physical environment above the lunar South Pole. The application objectives include (i) in situ lunar resource (water, helium, etc.) utilization experiments; (ii) Moon-based observation and research of Earth; and (iii) scientific experiments related to the lunar surface ecosystem, etc. On the basis of the overall scientific objectives, three missions were initially planned to be implemented by

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Flown missions 2004–2020						Missions in **development** 2020–2030			
CE-**1**	CE-**2**	CE-**3**	CE-**5T**	CE-**4**	CE-**5**	CE-**6**	CE-**7**	CE-**8**	
2007	2010	2013	2014	2018	2019	?	?	?	Robotic and manned exploration
Orbiter	Orbiter	Lander/rover	Orbiter/Earth returner	Relay/lander rover	Sampling return	Sampling return	Lander/station	Lander/station	
200-km-high orbit	100-/15-km high orbit	Mare Imbrium	Earth-Moon orbit	Von Kármán crater	Oceanus Procellarum	South Pole	South Pole	?	
Global survey	High-resolution global survey	Lunar surface survey	High-speed Earth return	Far-side surface survey	Lunar sample	Lunar polar samples	Lunar scientific research	Lunar scientific research	

Fig. 1. China's lunar exploration development strategy. Missions CE-1 to CE-5 before 2020 aim at successfully implementing the CLEP early three-phase "orbiting, landing, and sampling return" project. Follow-up missions CE-6 to CE-8 and possible further robotic and manned missions aim at "surveying, constructing, and exploiting" the Moon from 2020 to 2030.

2030, including CE-6, to sample return from the south polar area; CE-7, to survey the environment and resources in the south polar area; and CE-8, to verify key technologies such as "3D printing" construction on the Moon (*12*). Through these missions, a robotic scientific research station prototype will be built on the Moon. Exploration targets will shift focus from development of space technology, to space science and space applications. To achieve these goals, it is necessary to develop several key technologies, such as high-precision fixed-point landing, landing of large payloads, developing exploration capabilities in the permanently shadowed areas of impact craters, developing intelligent robot adaptation to the harsh environment of the polar regions, coordinated operation of intelligent robots, comprehensive operational control of a Lunar Scientific Research Station, and separation and extraction of rare gases. The Lunar Scientific Research Station, with the capability of long-duration operations and intelligent operational control, will be designed to carry out technical verification and validation of resource development and utilization technology, explore prospects for applications, enhance the ability of lunar science and resource application, and lay the foundation for the construction and operation of future Lunar Research Stations, as well as exploration of the Moon by humans.

After 2030, China's lunar exploration program will continue to develop capabilities in both robotic and human exploration. On the basis of factors such as technology development, launch vehicle selection, economic affordability, and cost-effectiveness ratios, robot exploration will remain the primary development direction of subsequent lunar exploration missions. By deepening lunar scientific exploration and verifying technology, such as resource development and utilization, bio-regeneration, and life support, the Lunar Research Station could be built into a long-duration lunar base that astronauts can visit for a short time, with the eventual goal of long-term stay of astronauts on the Moon.

Foundation of international cooperation

International cooperation is an important element in China's strategy of lunar and deep space exploration. For example, the CE-4 mission provided a host platform and opened its payload resources to the international community. The CE-4 lander, rover, and relay satellite carried experiments from Germany [Lunar Lander Neutrons & Dosimetry (LND)], Sweden [Advanced Small Analyzer for Neutrals (ASAN)], and the Netherlands [Netherlands-China Low Frequency Wavelength Explorer (NCLF)]. China cooperated with these countries in scientific instrument development, scientific exploration planning, exploration data research, and other aspects, and jointly completed the first soft landing mission on the far side of the Moon. In March 2019, the China National Space Administration (CNSA) and the Russian State Aerospace Corporation reached an agreement to jointly implement China's lunar polar exploration mission and Russia's Luna mission and collaborate on landing site survey capabilities, relay communication, scientific payload, and space experiments. In April 2019, the CNSA announced cooperation opportunities for China's CE-6 and its asteroid exploration mission (*13*) and signed lunar exploration cooperation agreements with the United Nations Office for Outer Space Affairs (UNOOSA), Turkey, Ethiopia, and Pakistan (*14*). China is also open to cooperation with NASA on lunar exploration; both sides can start cooperating on aspects such as exchange of scientific data and space situational awareness information (*15*). China also looks forward to exploring more opportunities to cooperate with NASA to preserve the space environment for generations to come. China has made policy adjustments to the sources of funding for future lunar and deep space exploration missions and has widely encouraged the participation of commercial and private enterprises in addition to governments. The CNSA is setting up general procedures for international collaboration and the mechanism to organize international teams. Extensive international cooperation and diverse sources of funding will inject additional vitality into the ongoing planning and development of lunar and deep space exploration.

Just as the Apollo program played a positive role in promoting the development of human society, China will work with countries around the world in its forward-looking lunar and deep space exploration projects to build a community and a shared future for humankind, promote the development of science, and jointly create a better future for humanity through space exploration and achievements in space science and technology.

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