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The Management Mode and Scientific Achievements of International Cooperative Payloads on the Chang`E-4 Mission

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Abstract: Chang`E-4 mission is the first probe which had achieved soft landing on the far side of the Moon. The four international cooperative payloads are: the Lunar Lander Neutron & Dosimetry (LND) developed by Kiel University in Germany; the Advanced Small Analyzer for Neutrals (ASAN) developed by the Swedish Institute of Space Physics; the Netherlands-China Low Frequency Explorer Instrument (NCLE) developed by the University of Nijmegen in the Netherlands; and the Lunar Small Optical Camera (KLCP) developed by King Abdul-Aziz City for Science and Technology (KACST), Saudi Arabia. They were all successfully powered on and obtained scientific exploration data. This is the first substantial international cooperation in the field of the lunar and deep space exploration in China, which opens a new chapter of international cooperation on several aspects such as application of international cooperative payloads, organizational management model, responsibilities and division of labor. This paper reviews the mode of international cooperative payloads of Chang`E-4 mission, summarizes the work principle, mission goals, technical indicators and preliminary scientific achievements obtained by the four international cooperative payloads, analyzes the problems and risks in the management of international cooperative payloads, proposes a solution and makes suggestions for a wider international cooperation in the field of lunar and deep space exploration in the future.

Keywords: Chang`E-4, International Cooperation, Scientific Payloads, Scientific Achievement, Suggestions and Prospects

1. Introduction

Space exploration goals, such as the Moon and Mars, involving the common interests of all mankind have become hot spots of concern for governments and the scientific community. However, deep space exploration missions are technically difficult and require huge human resources and financial investment, therefore, only a few major spacefaring countries have the foundation for mission implementation in the field of deep space, which include high thrust launch vehicles, highly reliable spacecraft, ground-based deep space telemetry, tracking, and command (TT & C) networks, etc. [1] For scientists who explore the mysteries of the universe, every opportunity for deep-space probe to conduct scientific exploration of unknown regions is very precious. The deep space exploration programs of the United States and Europe usually carry payloads from other countries. For example, the Cassini probe of the United States involved as many as 27 countries. Internationalization has become one of the important features of the current space science exploration field. [2]

During the demonstration process of Chang`E-4 mission, the China National Space Administration (CNSA) proposed the first international cooperation in the field of deep space exploration and issued Announcements of opportunities for Scientific Payloads to other national space agencies. After several rounds of communication and demonstration, the international payload configuration were determined as below: the Lunar Lander Neutron & Dosimetry (LND) equipped on the lander, developed by Kiel University in Germany; the Advanced Small Analyzer for Neutrals (ASAN) equipped on the rover, developed by the Swedish Institute of Space Physics; the Netherlands-China Low Frequency Explorer Instrument (NCLE) equipped on the relay communication satellite, developed by the University of Nijmegen in the Netherlands; and the Lunar Small Optical Camera (KLCP) equipped on the "Longjiang II" microsatellite, developed by King Abdul-Aziz City for Science and Technology (KACST), Saudi Arabia [3].

The Chang`E-4 mission implemented two launch missions: the "Queqiao" relay satellite was launched on May 21, 2018; the combination of the Yutu-2 rover and the lander was lifted off from the Xichang Satellite Launch Center on December 8, 2018, and successful landed on the preselected region—Von Karman impact crater on Jan 3, 2019. The scientific exploration tasks involving several countries and international organizations have been performed one after another [3].

2. The International Cooperative Payloads on Chang`E-4 Mission

2.1. The Netherlands-China Low Frequency Explorer Instrument (NCLE)

The Netherlands-China Low Frequency Explorer Instrument (NCLE) is mounted on the Chang'E-4 relay communication satellite platform. It consists of three Strip monopole antennas that can be extended to a maximum length of 5 meters, a low-noise amplifier, an electronics box and attached connection cables [6]. China and the Netherlands jointly proposed and completed the conceptual design, and the University of Nijmegen, the Netherlands, the Radio Astronomy Institute ASTRON and ISIS jointly completed the detailed design and processing of the equipment, worked with the Chinese team on delivery testing and satellite integration. NCLE can work in the range of 80 kHz ~ 80 MHz, and its basic scientific detection tasks are to detect the low-frequency radio radiation signal of the universe, including: to map the radio radiation flux in the 2~3 bands between 1~60 MHz; to detect and study the terrestrial kilometric radiation burst and Jupiter's radio burst; and to detect radiation of solar II, III and IV radio burst [4, 6]. The main technical indicators of NCLE are shown in Table 1.

Table 1. *Main technical indicators for the Low Frequency Radio Spectrograph for Relay Satellite.*

Parameter	value
Work frequency	0.1MHz~80MHz
Receiver Sensitivity	~100Jy@10 MHz (10kHz bandwidth)
Dynamic Range	~84DB
Frequency Resolution	0.1~2.0MHz: 1KHz 1.0~10 MHz: 10KHz 10 ~80 MHz: 100KHz
Maximum data rate	1~2Mbps
Power	≤50W
Weight	≤10kg

2.2. The Advanced Small Analyzer for Neutrals (ASAN)

The Advanced Small Analyzer for Neutrals (ASAN), an international scientific payload equipped on the Yutu-2 rover of the Chang`E-4 mission, was jointly developed by the Swedish Institute of Space Physics and the National Space Science Center of the Chinese Academy of Sciences. It consists of a probe and cable assemblies [6]. Its scientific objectives are: to detect energy-neutral atom and positive ion at the lunar surface about information on energy, composition, and flux; and to determine the distribution function of energy-neutral atoms and positive ions and the relationship between this distribution function and the topography and local time of the lunar surface [4, 6]. The main technical indicators of ASAN are shown in Table 2.

Table 2. *Main technical indicators for the Advanced Small Analyzer for Neutrals.*

Parameter	value
Measures	ENAs, positive ions
Energy Range	10eV-10keV (ENA, i)
Mass Resolution	Ions: m/q grounds: 1, 2, 4, 8, 16, 32 ENA: H, heavy
Energy Resolution	7%
Time Resolution	10s

2.3. The Lunar Lander Neutron & Dosimetry (LND)

The Lunar Lander Neutron & Dosimetry (LND) is mounted on the lander and was jointly developed by the University of Kiel, Germany and the National Space Science Center, Chinese Academy of Sciences. It consists of a probe and mount, an electronics box, and cable assemblies [6]. The scientific objectives are: to provide comprehensive measurements of integrated lunar surface particle radiation and its dynamics by monitoring on the integrated dose rate of neutral and charged particles, LET spectrum, and particle radiation on the lunar surface, and to study the heliospheric science [4, 6]. The main technical indicators are shown in Table 3.

Table 3. *The main technical indicators for LND.*

Parameter	value
Fast neutron spectrum	2-20MeV
Thermal neutron flux	10-104 units/min
proton spectrum	10-30MeV
electron spectroscopy	100-500keV
α Particle spectrum	10-20MeV/n
heavy particles spectrum	20-100MeV/n
range of LET spectrum	0.1-430keV/µm

Table 4. *The main technical indicators for KCLP.*

Parameter	value
Imaging mode	Plane Array, Bayer RGB
Equivalent focal length	70 mm
Pixel pitch	5.5 μm
Angle of field of view	9.2°×4.9°
Pixel resolution	2048×1088
Ground resolution	30 m (orbit altitude 300 km)
size	100 mm×110 mm×120 mm
Communication Interface	RS-422
power	<5 W
weight	630 g

2.4. The Lunar Small Optical Camera KCLP

"Longjiang-2", the lunar ultra-long-wave astronomical observation microsatellite, which was launched together with "Queqiao"relay communication satellite, carries a Lunar Small Optical Camera (KCLP) which was developed by King Abdulaziz City for Science and Technology, Saudi Arabia. Its working modes include lunar fixed point imaging, earth fixed point imaging, and inertial directional imaging. The working modes can be set according to different shooting targets and attitude control modes [5]. The main technical indicators are shown in Table 4, and the physical diagram of the flight piece is shown in Figure 1.

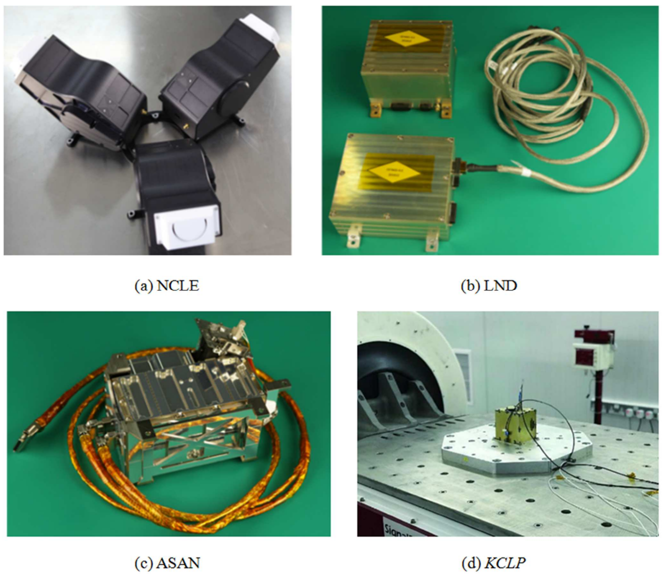

Figure 1. *(a): NCLE; (b): LND; (c): ASAN; (d): KCLP. [5, 6]*

3. The Management of International Cooperative Payloads on Chang`E-4 Mission

3.1. The Application of International Cooperative Payloads

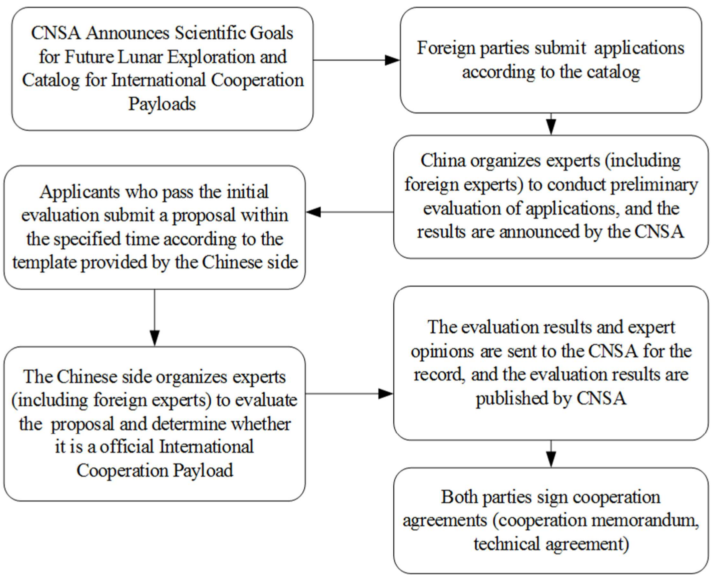

Figure 2. *Application Process for international cooperative payloads.*

To standardize the application work of international cooperative payloads, an application process has been formulated for Chang`E-4 international cooperative payloads, and the international cooperative payload bidding work had been done according to this process.

In 2015, the China National Space Administration (CNSA) collected experimental payloads carried on Chang'E-4 mission from several relevant countries. Under the leadership of the management department of the CLEP, scientific payloads subsystem organized all relevant domestic units to demonstrate and evaluate over 20 feasibility of proposals on experimental payloads from 10 countries. Finally, four international cooperative payloads were confirmed to be finally equipped on Chang'E-4 mission. [7]

3.2. International Cooperative Payload Management Mode

3.2.1. General Principles

The international cooperative payloads are not included in the main task assessment of Chang`E-4 mission, and they cannot affect the safety of the probe or the satellite platform in any working mode, while the foreign parties must ensure that they are delivered to the Chinese side before the scheduled time node and cannot affect the mainline planning process. [8]

Each international cooperative payload sets up a Chinese development team, which is responsible for the technical coordination between the foreign party and probe system, ground application system and scientific payload subsystem. They should complete the calibration and testing of the international cooperative payload with the foreign party, analyze and process the in-orbit scientific data together, and share the scientific achievement with the foreign party. [9]

The technical cooperation agreement is a programmatic document for the management of the international cooperative payloads. The contracting parties need to follow the terms of the cooperation agreement and specifically formulate detailed management methods or measures to ensure that the matters of the cooperation agreement are implemented. [9]

3.2.2 Job Assignment and Responsibilities

Learning from the management mode of lunar exploration project, principal scientist of international cooperative payload is set up. The Chinese and foreign sides both have a principal scientist for the payload, who shall be responsible for jointly proposing the scientific objectives, scientific exploration tasks, overall design scheme and main technical indicators of the payload, and evaluating the ability to achieve the scientific objectives of the payload. After obtaining the scientific data in orbit, the principle scientists lead to carry out analysis and research, and quickly obtain the research results. However, the data sharing and release still need to comply with regulations of the Chinese side.

The Chinese and foreign teams jointly work as a technology cooperation team (TCT). The Chinese team includes the principle scientist and the person in charge of engineering development, as well as the persons in overall department, probe system, ground application system and scientific payload subsystem. TCT jointly formulate the technical process and planning process of international cooperative payload, define the standard and application scope of product assurance, guide engineers to complete the development and production of international cooperative payload and take the responsibility of testing and debugging, calibration, environmental test and a series of work. [9]

The international cooperative payload belongs to the scientific payload subsystem. The responsibilities of the scientific payload subsystem include: to organize the signing of the technical cooperation agreement between China and foreign countries and the technical requirements of each international cooperative payload; to be responsible for determining the project implementation overall plan and quality requirements; to be responsible for international cooperative payload product acceptance and subsystem pre-integration test; to be responsible for the technical coordination between the payload and probe system; to be responsible for the design, development and test, and request for the review at key nodes.

The probe system is responsible for confirmation and system level verification of international cooperative payloads interface status.

The ground application system is responsible for managing the on-orbit operation and data application of international cooperative payloads.

The office of CLEP is responsible for organizing the ground application system to demonstrate, evaluate and approve the scientific objectives proposed by the principle scientist of the international cooperative payloads; participating in the thematic study and experimental verification of the realizability of scientific objectives of the international cooperative payloads; managing the scientific data according to the regulations and approving the data release; organizing the probe system to demonstrate the engineering feasibility of the international cooperative payload and coordinating the acceptance, testing and launch implementation and other related matters. [9]

4. Scientific Achievement of the International Cooperative Payloads

4.1. Detection and Study on Lunar Surface Particle Radiation Environment

LND is the first time to detect the particle radiation environment at the lunar surface. LND can comprehensively measure total radiation dose of lunar surface particle, radiation dose of neutral particles, LET spectrum, neutrons and charged particles (protons, electrons and heavy ions). The measured results show that the particle radiation dose rate at the lunar surface is 13.2 uGy/h(si), of which the radiation dose rate of neutral particles (neutrons and gamma rays) is 3.1 uGy/h(si), about 23% of the total, with a quality factor of 4.3 and a particle radiation dose equivalent of about 60 uSv/h. The dose equivalent at the lunar surface is twice as high as on the surface of Mars and inside the space station, 5 to 10 times higher on once flight and 300 times higher on the Earth's surface (Beijing) [10].

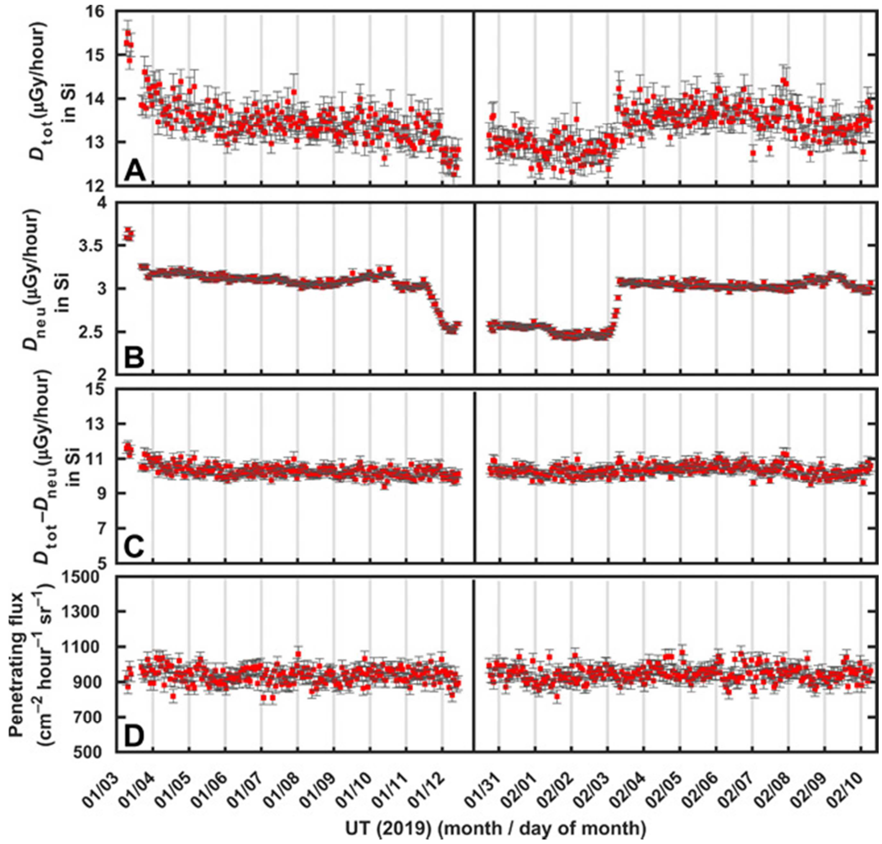

Figure 3. *Lunar surface radiation dose measured by the LND instrument (horizontal axis is UTC, vertical axis is: a. total radiation dose rate in silicon (μGy/hour), b. radiation dose rate of neutral particles in silicon (μGy/hour), c. radiation dose rate of charged particles in silicon (μGy/hour), d. cosmic ray penetrating particle flux (pcs/cm^2- hour-radian)).*

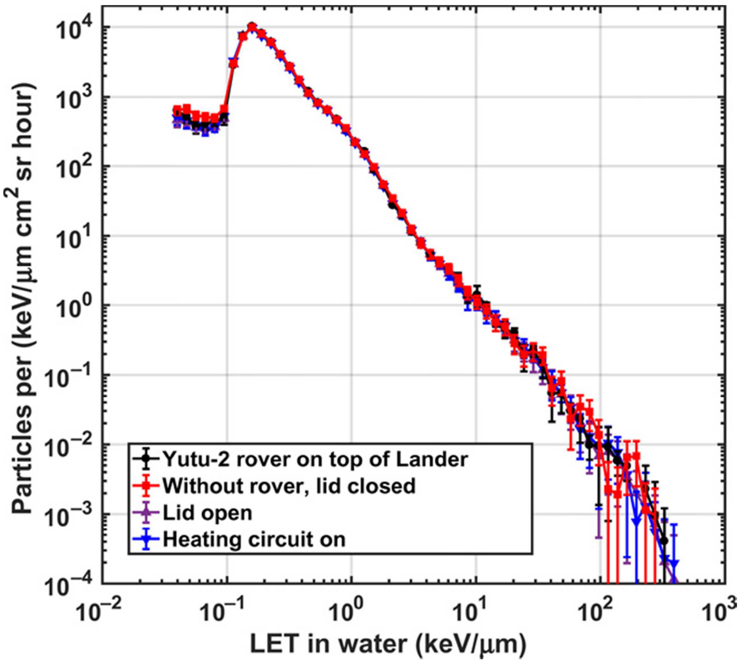

Figure 4. *LET spectrum of particle radiation at the lunar surface (water) measured by LND (the horizontal coordinate is the linear energy loss of the particle equivalent in water (keV/μm) and the vertical axis is the flux of particles (pcs/(keV/μm)-cm^2-radians-hr)) [10].*

LND has achieved the first in-situ detection on the lunar surface, and the results of its field measurements will provide an important reference of radiation environment parameters for China's subsequent Chang'E program, especially the implementation of the manned lunar landing. It also differentiates the radiation dose of charged particles and neutral particles so as to provide more accurate radiation physical quantities, which can serve the astronaut's radiation protection.

The research was published in “Science Advance”, a sub journal of Science. [10]

4.2. Lunar Surface Neutral Atom in-situ Detection Data for Solar Wind-lunar Surface Interaction Studies

The Moon does not have a dense atmosphere and a global-scale magnetic field, and the most solar wind ions can hit the lunar surface directly then they can be scattered by the lunar surface or sputtered against the lunar surface material to form energy neutral atoms (ENA). The parametric characteristics of the lunar surface neutral atoms are very important to study the microscopic interactions between the solar wind and the lunar surface, and the role of lunar surface sputtering in the formation and maintenance of the lunar escape layer.

The study based on the detection data of ASAN found that the flux of neutral atoms on the lunar surface with energy below 0.1 Esw (the energy of incident solar wind ions) is significantly higher than previous results of remote sensing observations. This finding can enable scientists to further reveal the interaction between the solar wind and the lunar surface. The research team analyzed that remote sensing and long-range large-area averaging surveys were carried out on Chandrayaan-1 and IBEX, and their results reflected the macroscopic scale characteristics. While in-situ and local area surveys of the lunar surface were carried out by ASAN, and its results reflected the 1-meter scale microscopic characteristics, which gives a new scale and direction for the study of the microscopic interaction mechanism between the solar wind and the lunar surface. It is also the first time for human to conduct in-situ detection of neutral atomic parameters on the lunar surface [11].

The research was published in PSS.

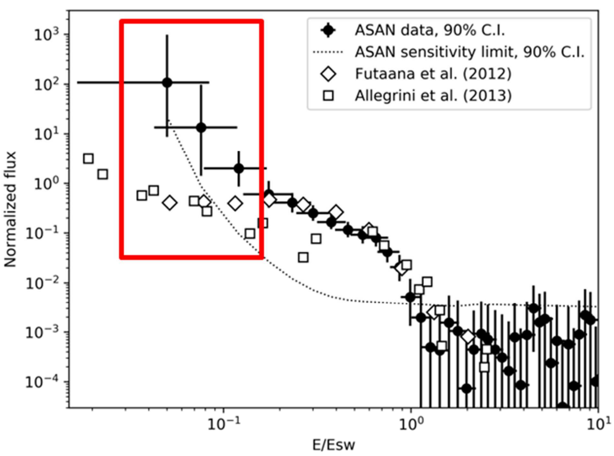

Figure 5. *Comparison of the ENA energy spectrum structure of Chang'E-4 (●) with Chandrayaan-1 (◇) and IBEX (□) [11].*

4.3. Saudi Camera KCLP

Saudi camera KCLP was powered on for the first time on May 28, 2018. The first valid lunar surface image was obtained on May 30, and the Earth and Moon in the same image was obtained on June 4 [5]. While the satellite is on orbit, it obtained several scientific exploration images, which has strong repercussions in the Middle East region, further deepened Sino-Arab cooperation in the space field, and became another landmark achievement in the cooperation between China and countries along the "Belt and Road" in the space field [12-14].

Figure 6. *Earth and Moon in the same image taken by Saudi camera KCLP. [5]*

Earth and Moon in the same image taken by Saudi camera KCLP (Figure 6) was taken on June 8, 2018 at 13:29 Beijing time, at the satellite orbital altitude of about 728.1 km, and the satellite point of 149°1'W, 22°28'N on the lunar surface. The camera is pointing at the center of the Earth. The image was taken near Crater Petropavlovskiy M in the northern hemisphere of the lunar surface, and the areas of the Persian Gulf, Red Sea, Mediterranean Sea, and Arabian Peninsula can be clearly distinguished. [5, 13, 14]

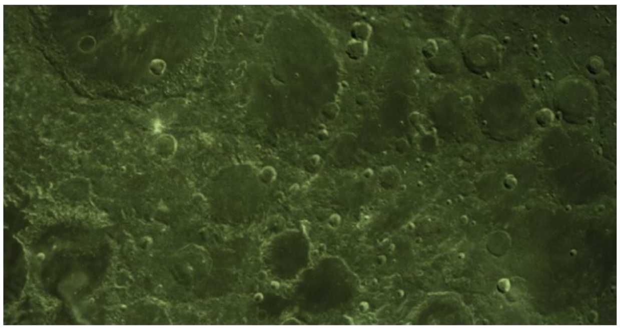

Figure 7. *Local image of the South Pole-Aitken Basin on the lunar surface taken by Saudi Camera KCLP. [5]*

Local image of the South Pole-Aitken Basin on the lunar surface (figure 7) [5], was taken on August 15, 2018 at 00:06 Beijing time, at the satellite orbits altitude of about 4773 km and the satellite point of 175°45' E, 36°32' S. The center of the image is 175°54' E, 44°48' N, and the features of the lunar surface such as the Von Karman impact crater and the central peak "Tarzan" can be clearly distinguished. [5]

5. Experience in International Cooperation in Lunar and Deep Space Exploration

Most of Chang'E-4 international cooperative payloads are developed in accordance with ESA or similar ESA product assurance specifications, while there are certain differences between ESA and Chinese side in the specific content of product assurance specifications, which are reflected in many aspects such as component and subassembly selection requirements, environmental test requirements, software development requirements, and so on. It could bring certain difficulties to the assessment of product quality, reliability and safety, so the Chinese team is required to set up mandatory inspection points at various levels and links, such as interface safety, environmental test verification, calibration and system-level testing, to ensure the interface compatibility, system compatibility and operational reliability of the products developed by foreign team. [15]

Considering the foreign party's protection of its own intellectual property rights, it is hard for the Chinese team to obtain all the technical documents and technical information of the payloads, and it is difficult to perform comprehensive manage and control the quality and schedule compared with the domestic development teams. Therefore, they are effective and concrete measures for risk control by determining reasonable and multi-party-accepted assessment guidelines for international cooperative loads, developing corresponding operable management methods, and fully utilizing the role of the Chinese team in international cooperation projects.

If payloads developed by foreign team with insufficient technical maturity cannot meet the requirements of the Chinese planning process or quality problems occurred, it will have a relatively large impact on the overall progress of the probe or satellite, even may cause concern at the diplomatic level. Therefore, risk control measures need to be developed in advance, and the delivery conditions and nodes of foreign teams can be appropriately relaxed under the premise of ensuring the interface and overall safety.

6. Future Prospects

Deep space exploration has always been a competition and cooperation activity. International space in the new situation requires a multi-channel and multi-level cooperation approach between countries.

We can Promote communications between the deep space detection and foreign scientific, engineering and tech fields by bilateral and multilateral cooperation. We can carry out research on international cooperation policies and strategic layout, innovate international cooperation modes, optimize international cooperation rules, promote international cooperation at mission level and system level in deep space exploration, jointly carry out research on scientific data and extraterrestrial samples, carry out joint demonstration of major scientific problems in the field of deep space exploration with interested countries and research to determine scientific objectives.

Around international lunar research stations and other missions, Carry out multilateral or bilateral joint mission design, planning and demonstration. We can carry out joint development and mutual carriage of scientific payloads with relevant countries, develop internationally leading and pioneering scientific payloads, promote the level of scientific payload development, and promote scientific output. We also focus on scientific data and extraterrestrial samples to expand cooperation targets and deepen cooperation contents.

The mode of future lunar exploration has changed from single-point short-term exploration to long-term exploration by building lunar surface infrastructure. Since 2016, China has begun to promote the lunar research station during the talks with other countries` space agencies, and now China is actively carrying out the joint construction of the international lunar research station, which has become one of the international large science project cultivation projects. China will jointly carry out scientific objectives research, engineering feasibility demonstration and joint implementation program design with Russia and other countries. According to the idea of "planning docking, joint design, collaborative implementation and result sharing", the international lunar research station will be built together. [16] Aiming at the key problems of lunar science, we will gather global superior scientific and technological resources to jointly realize major original scientific discoveries and drive China a great-leap-forward promotion in the fields of space science, space technology and space applications.

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