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Recent Progress in Space Science and Applications of China's Space Station in 2020–2022

GAO Ming ZHAO Guangheng GU Yidong

(*Technology and Engineering Center for Space Utilization*, *Chinese Academy of Sciences*, *Beijing* 100094)

Abstract China scheduled to complete the assembly of the T-shaped Tiangong Space Station in 2022, and will enter a new stage of utilization. There are more than 20 experiment racks inside the modules, and more than 50 external onboard payloads mounting spaces, which will support large-scale science and technology experiments during the operation. The development of internal experiment racks and external research accommodations approved during the construction has been completed, of which 4 racks in Tianhe core module, including High Microgravity Level research Rack (HMLR) and Container-less Materials Processing Rack (CMPR), have finished on-orbit tests; while other racks in Wentian and Mengtian experiment modules are under comprehensive ground tests. The Chinese Space Survey Telescope (CSST) has advanced much in the last two years with 24 pre-launch research projects funded and 4 joint science center built in preparation for CSST's future scientific observations and operations. The systematic research planning for China's Space Station (CSS) during 2022–2032 is updated with the researches classified into four important areas: space life sciences and human research, microgravity physical sciences, space astronomy and Earth science, and new space technologies and applications. According to the planning, more than 1000 experiments are expected to perform in CSS during the operating period. Overall, the CSS utilization missions are proceeding as planned, which will contribute to the major scientific or application output and have a positive impact on the quality of life on Earth.

Key words China's Space Station (CSS), Space utilization, Experiment racks, Chinese Space Survey Telescope (CSST), Research planning

Classified index V476, P35

1 Recent Progress of the CSS

China launched the CSS's core module Tianhe on 29 April 2021 at Wenchang Satellite Launch Center, kicking off the construction of CSS. It is expected to complete the three-module space station with six related missions in 2022, totaling eleven missions for the assembly of CSS. Two new space station modules, named Wentian and Mengtian, are prepared to be launched in the coming months, docking with the Tianhe core module and formally completing the T-shaped space station by the end of the year.

One major objective of the space station is to build a national space laboratory at an internationally advanced level, carrying out large-scale multi-disciplinary scientific experiments or key technological tests, serving educational purposes and obtaining research results of great scientific value or promising application. In addition, the CSS will contribute to the peaceful development and utilization of space resources for mankind through international or regional cooperation[1-3]. At present, 21 internal experiment racks and more than 50 external payloads mounting spaces are provided by the CSS[1], which will meet the requirements of large-scale

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E-mail: mgao@csu.ac.cn

multidisciplinary space experiments. Research aboard the CSS has unique advantages such as astronaut's participation in the experiments, maintainable and upgradeable experiment equipments, returnable experiment samples, and information transmission between the CSS and Earth. The space station is expected to operate in orbit for more than 10 years, with sufficient experimental resources, which provides a historic opportunity for multidisciplinary and serialized long-term space research.

2 Space Science and Application Missions of the CSS

The scientific experiments and application research will use the internal experiment racks, external experiment platforms or the accompanying CSST. The experiment racks consisting of numerous technical hardware are installed in the pressurized module and play a key role in supporting scientific experiments of various disciplines. The extravehicular experiment platforms are deployed on the exterior of the CSS, to which payload adapters or large payload hanging sites are installed to provide standard mechanical, thermal, electrical, and data interfaces for exposed payloads. Until now, three external facilities for sciences and applications were approved and developed. The CSST is a major science project of China Manned Space Program (CMSP), which will fly independently in the same orbit as the CSS while keeping a large distance apart.

2.1 Brief Introduction of Internal Racks and External Facilities

The internal experiment racks can be categorized into disciplinary racks or supporting racks in accordance with their uses. The disciplinary racks provide special research conditions for disciplines such as life sciences and biotechnology, and microgravity physics, while the supporting racks support the routine operations such as sample storage, high microgravity experiments, variable gravity experiment comparison, payload adjustment and detection[4]. 21 experiment racks including 12 disciplinary racks, 4 supporting racks and 5 general payload installation racks have been deployed inside the Tiangong Space Station modules. A brief introduction of the main components and prime functions of the racks are shown in Table 1[1].

Three external facilities are arranged outside of the

Table 1 Overview of experiment racks' chief components and prime functions

No.	Classification	Name	Main components	Prime functions
1	Disciplinary racks	Human System research Rack	Medical sample microscopic observation and recording apparatus Medical sample preparation unit Weightlessness physiological effect research unit Cardiovascular research unit Space Raman spectrometer Basic cognitive ability measuring unit Motion characteristic measuring unit	Supporting research on human physiological effects and human abilities in long-term space environment and experiments aiming at developing new protection technologies
2		Medical Sample Analysis Rack	Space centrifuge Space medical sample refrigerator	Support samples centrifuged and refrigerated (4℃)
3		Life and Ecology research Rack (LER)	Common creature cultivation unit Small centrifuge experiment unit Microbe detection unit Small controlled life ecological experiment unit Small common creature cultivation unit	Gravity biology and radiation biology research using biological individuals (plants, insects, small mammals, aquatic organisms, microorganisms, *etc*.), cells, tissues, microbes, *etc*.; Research on the foundation and application of biological regeneration life support system
4		Biotechnology experiment Rack (BTR)	Cell and tissue experiment unit Cell and tissue detection and regulation unit Crystallization and analysis of protein	Microgravity cell and tissue cultivation, protein crystallization, biomolecule construction, biomechanical research and biotechnology transformation research
5		Fluid Physics research Rack (FPR)	Fluid dynamics unit Complex fluid unit	Hydrodynamics research, experiments of various transparent systems (model alloy, protein crystallization, solution crystal growth, supercritical fluid); particle experiment, colloid and other complex fluid (soft matter) research

(continued)

No.	Classification	Name	Main components	Prime functions
6	Disciplinary racks	Two-Phase System research Rack (TPSR)	Optical observation platform Gas management unit Small-flow liquid supply unit Large-flow liquid supply unit	Evaporation and condensation phase changes with interface, phase changes enhanced by heat transfer, two-phase heat transfer and fluid management, two-phase loop system dynamics
7		Combustion Science research Rack (CSR)	Exhaust purification and collection subsystem Oxidant and diluent subsystem Combustion chamber and experimental plug-in	Research on microgravity combustion process and dynamics of solid, liquid and gas, experiment of aerospace propulsion combustion, fire prevention experiment of manned mission materials
8		High-Temperature Materials research Rack (HTMR)	Batch sample management unit High-temperature furnace unit X-ray real-time observation unit	Scientific experiments on crystal growth, solution growth and solidification of metal alloy, semiconductor, inorganic multifunctional materials encapsulated by ampoule structure
9		Container-less Materials Processing Rack (CMPR)	Container-free experimental platform Vacuum and pressure unit	Solidification mechanism of metallic and nonmetallic material, deep supercooling research, accurate measurement of thermophysical property of high-temperature melt, preparation of new materials, *etc*.
10		Cold Atom Physics research Rack (CAPR)	Physical subsystem Rubidium potassium laser Optical trap laser Complementary magneto-optical plug laser Optical lattice laser Polarized molecular laser	Quantum properties of the critical point at ultra-low temperature for large scale and long-life-time Bose and Fermi quantum degenerate gas
11		High-Precision Time-Frequency System (HPTFS)	Optical atomic clock Active hydrogen maser Cold atomic microwave clock Precision orbit determination unit	Fundamental physics and applied research with the frequency stability and uncertainty of a few parts in 10^{-17}
12		Aerospace Basic Test Rack	Payload installation unit	Carry out experiments aiming at verifying the basic and key technologies of space in microgravity and other space environments
13	Supporting racks	Glovebox and Cold Storage Rack (GCSR)	Scientific glove box Cryogenic storage apparatus	The scientific glove box provides the enclosed and clean environment for the operation of life science and other scientific experiments, *e.g.* samples preparation. The cryogenic storage device provides preservation of biological or other samples at –80℃, –20℃ and 4℃
14		Variable Gravity research Rack (VGR)	Centrifuge	Normal gravity, low gravity and supergravity experiments in the range of 0.01–2 g for the experiments of fluid, life and materials sciences
15		High Microgravity Level research Rack (HMLR)	Suspension test bench	Support fundamental physical experiments and other scientific experiments that need high microgravity level
16		On-orbit Maintenance and Manipulation Workbench (MMW)	Mobile maintenance platform Diagnostic unit	Preparation, cleaning, welding, lubrication, assembly, testing, fault diagnosis and maintenance of payload module or unit; on-orbit experiment of independent payloads
17		Universal Payload Installation Rack	Payload integrated management unit Thermal control unit	Provides information and power supply interfaces, heat dissipation environments and nitrogen, vacuum, and exhaust gas interfaces for individual payload

modules occupying three payload adapters to support the exposure research of biological samples, materials and components. The prime functions of external facilities are shown in Table 2 [1].

In the construction of Tiangong space station, the chief aim is to complete the assembly and conduct on-orbit test of the scientific experiment racks, create favorable experimental conditions for the subsequent large-scale and systematic scientific research, and explore effective space experimental methods and approaches in

Table 2 Prime functions of external facilities

No.	Name	Prime functions
1	Space biology exposure experiment device	Research on the animal model (nematodes), plants and plant seeds, microbes, and biological tissues, *etc*. in the extravehicular cosmic radiation environment
2	Extravehicular materials exposure experiment device	Space damage and service performance study of applied materials (lubrication, thermal control, film coating, shape memory, functional coating, polymer, composite material, *etc*.); Study of tribology
3	Universal extravehicular device for components	Support on-orbit tests of components and subassembly, *e.g.* obtaining on-orbit operation parameters and reliability test data

the space station. More than 100 experimental projects have been approved using the various onboard scientific experiment racks and are expected to make progress in the frontier of scientific research such as the multi-level influence study of comprehensive environment (*e.g.* microgravity) on living bodies, the breakthrough of space high-strength/high-efficiency heat exchange technology of spacecraft power system, the space preparation mechanism of important strategic or new high-performance materials, the test of equivalent principle and the measurement of gravitational redshift.

2.2 Advancement of the CSST

The 2 m-aperture CSST is a major science project of China Manned Space (CMS)[5–6]. It is expected to start science operations in 2024 and has a nominal mission lifetime of 10 years or more.

During normal observations, the CSST will fly independently in the same orbit as China’s Tiangong space station but keep a large distance apart. It can dock with the space station for refueling and servicing as scheduled or as needed. With a cook-type three-mirror anastigmat design, the CSST can achieve superior image quality within a large Field of View (FoV), which gives it an advantage for survey observations. Being an off-axis telescope without obstruction, its Point Spread Function (PSF) does not have diffraction spikes from mirror support structures and is thus helpful for precision photometry, position, and shape measurements when properly sampled. The radius encircling 80% energy of the PSF within the CSST’s central 1.1 square degrees of FoV is specified to be no more than 0.15″, including all wavefront errors in the optics and instruments and dynamical effects such as the telescope’s attitude control and vibration.

The CSST will be launched with 5 instruments including a Survey Camera, a Terahertz Receiver, a Multichannel Imager, an Integral Field Spectrograph, and a Cool Planet Imaging Coronagraph. The primary task of the CSST is to carry out a high-resolution large-area multiband imaging and spectroscopy survey of the median-to-high galactic latitude and median-to-high ecliptic latitude. The Survey Camera will image roughly 17500 square degrees of the sky and take spectroscopy of the same sky in 3 bands over 10 years of orbital time. In addition, a number of deep fields will be selected for further observation to reach at least one magnitude deeper than the wide-area survey. The Multichannel Imager plans to observe five ultra-deep fields of 300 square minutes in total to 30th magnitude in the visible band.

To fully explore the CSST’s potential and to prepare for its science and operations, CMS funded 24 prelaunch research projects that were selected by the CSST Science Committee. These projects cover a wide range of research fields, including Cosmology, galaxies and active galactic nuclei, Milky Way science, stellar science, astrometry, transients, exoplanets, and the solar system. In addition, there is a project aiming to optimize the survey plan and observation strategy for the overall science return. The projects are managed by the CSST joint science center (hosted at National Astronomical Observatories, NAOC) and coordinated at Peking University Science Center, NAOC Science Center, Yangtze River Delta Region Science Center (hosted at Shanghai Astronomical Observatory), and Guangdong-Hong Kong-Macao Greater Bay Area Science Center (hosted at Sun Yat-sen University). In total, about 400 researchers from more than 30 institutes are involved.

The research projects are classified into two categories: (i) research areas that are expected to be competitive or necessary and that require large, coordinated efforts to prepare in advance (12 projects); (ii) Exploratory studies, feasibility studies, and planning of research programs (12 projects).

Several category 1 projects also serve as much needed extensions to the scientific data reduction (sub) system and will deliver high-level science data pipelines and/or simulations for the broader CSST community. Such projects include Error analysis and optimization of photometry measurements, Redshift survey with slitless spectroscopy, Numerical simulation methods and emulators for cosmology, High-level tool pack for galaxy image analyses, High-level tool pack for galaxy spectrum analyses, and Fundamentals and methods of astrometry.

Although the CSST main survey will miss much of the galactic plane and the ecliptic plane, its data will still be invaluable for studies of the Milky Way and its neighbors, stellar science, and high-inclination solar system objects. Patchy observations in the galactic plane, in or near the budge, and in the ecliptic plane are under consideration to enhance CSST science. Because the main survey takes only two or four exposures per filter (grating) at each pointing direction, it is not well suited for regular time-domain studies. Nevertheless, a huge number of transients will be caught by the CSST Survey Camera. Methods to identify (and even classify) them need to be developed. Small dedicated programs can also be implemented or combined with deep fields to achieve better time resolution.

Unlike the Survey Camera, the other four instruments all have a small FoV. They enable unique capabilities for detailed studies of individual objects or small fields. The Terahertz Receiver will be used to carry out spectral line surveys or mapping of star-forming regions of the Milky Way, nearby galaxies, late-type stars, and solar system objects. The Multichannel Imager can observe the same field in three bands simultaneously, capable of obtaining instantaneous color of fast varying objects such as fast transients, comets, and spinning asteroids. The Integral Field Spectrograph splits its 6″× 6″ FoV into 32×32 units and obtains 1024 spectra of these units. It can provide both two-dimensional spatial information and spectral information of the target, particularly helpful for investigations of the co-evolution of supermassive black holes and galaxies and star formation in the nearby universe. The Cool-Planet Imaging Coronagraph aims to realize 10^{-8} high-contrast direct imaging of exoplanets in the visible. It plans to follow up exoplanets discovered by radial velocity observations, study planet formation and evolution, and probe protoplanet disks.

The combined advantage of its aperture, angular resolution, wavelength coverage, and versatile instruments makes the CSST highly competitive, and, at the same time, its observations will also be highly complementary with other large projects of its time, such as the Vera Rubin Observatory, the James Webb Space Telescope, the Euclid mission, and the Roman Space Telescope. The 24 pre-launch research projects comprise a crucial step in the preparation of both Chinese astronomers and the CSST science program for exciting opportunities of studies from the solar system to cosmology and beyond in the near future.

2.3 Progress of On-orbit Test of Scientific Experiment Racks

On-orbit testing has been implemented on the experiment racks that were already installed in the Tianhe core module, which was launched in 2021, and these racks will be used for container-free material science and high microgravity experiments. With regard to other experiment racks in Wentian and Mengtian experiment modules, the development work has been finished and the ground testing has begun, as it is shown in Fig.1. On-orbit testing progress for HMLR and CMPR is shown as follows.

(1) HMLR. The HMLR adopts the internationally advanced technology "magnetic levitation & jet suspension" as double-layer vibration isolation scheme. Specifically, the magnetic levitation vibration isolation is realized by wireless energy transmission and wireless com-

Fig. 1 Part of science experiment racks in Wentian and Mengtian are being tested on the ground

munication technology without umbilical cord in the inner layer, and the jet suspension vibration isolation is realized by binocular vision measurement and jet propulsion technology without umbilical cord in the outer layer, which meets the requirements of different microgravity environments. At present, the HMLR has completed the on-orbit function test and fine adjustment of parameters, and carried out the verification work of jet suspension, magnetic levitation control test, and double-layer suspension test. The test results in Fig.2 showed that the microgravity level has been achieved in the order of 10^{-6}–10^{-7} g at $f \leqslant 0.1$ Hz, and the best microgravity level at some frequency points is better than 10^{-7} g. Further optimization of the control system and longer time of high microgravity verification will be conducted lately.

(2) CMPR. The CMPR is an electrostatic levitation facility developed to study the solidification mechanism and thermophysical property under ultra-high temperature for metal, ceramics and glass using container-less process in microgravity environment. The main performances of the container-less experimental device included: (i) a coupling laser heating system with semiconductor laser with an output power of 300 W and carbon dioxide laser, which can heat melt metals and non-metals up to 3000℃; (ii) a molecular pump vacuum system and argon pressurization unit are installed in the rack to adjust experiment environment of the container-less process from 10^{-4} Pa to 3 atm; (iii) a serials of optical devices are mounted on a polyhedron chamber with 38 faces for position controlling of the sample with an accuracy of ±0.1 mm, for the thermophysical property measurement of density, viscosity, surface tension, specific heat and spectral emissivity, and also providing a triggering nucleation function to realize phase selective solidification under different supercooling degrees.The on-orbit functional verification of the rack and electrostatic levitation facility has been completed. In the future, the container-less scientific experiments will be conducted on superalloys and functional materials.

2.4 Progress of the International Cooperation Projects

CSS attaches great importance to the organization and development of international cooperation projects. Through the joint project solicitation released with the United Nations Office for Outer Space Affairs, a total of 9 projects from 17 countries and 23 entities were selected[7], which will be conducted in the LER, CSR, TPSR and extravehicular payload adapter. Through a joint call between Chinese Manned Space Agency (CMSA) and European Space Agency (ESA), 10 China-Europe cooperation projects were selected, mainly using onboard experiment racks such as BTR, LER, TPSR, FPR, HTMR and CFPR. To date, all international cooperation projects are advancing as planned, and it is expected that most of them will be implemented on-orbit between 2023 and 2025.

CSS will continue to expand cooperation with European countries and countries of the "the belt and road initiative", further strengthening the cooperation with relevant international organizations and countries in the field of space science and application; actively participating in international science projects; continually improving the comprehensive application benefits of CSS and the influence of national science and technology.

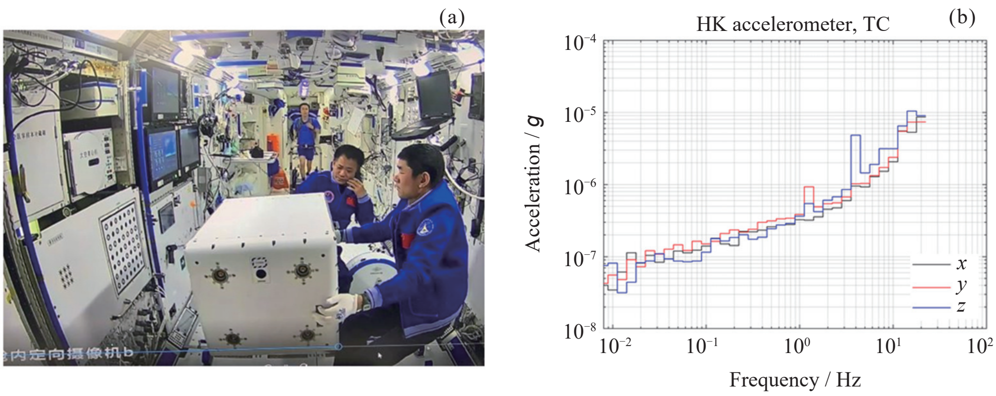

Fig. 2 (a) Astronauts are conducting the test, (b) microgravity level of the suspension test

During the operation, the CSS will solicit and select international cooperation projects on a regular basis.

3 CSS Utilization Planning for 2022–2032

CSS completed a long-term and systematic planning for space utilization in 2021. The planning could be categorized into four main areas [8–10]: space life sciences and human research, microgravity physical sciences, space astronomy and Earth science, and new space technologies and applications. Within these four areas, new devices will be developed and more than 1000 experiments will be performed during the operation period of 2022–2032. The primary research of these areas is described as follows.

The space life sciences and human research are dedicated to solving the scientific problems faced by human long-term space survival, through constantly improving the experiment supporting abilities of related facilities, and systematically carrying out fundamental and exploratory space experiments. In terms of research on the influence and mechanism of various factors of space environment on life from molecules to tissues and organs, the laws of space growth and breeding of cognitive living bodies will be explored, and the main health issues faced by long-term survival of human beings in space will be studies. In terms of research on the closed-loop ecosystem, the system development and evolution law of multi-generation replacement of organisms will be revealed. With respect to research on the origin of life, the formation mechanism, the occurrence and evolution conditions of primitive cells in special space environment will be explored. In addition, to promote the national economic development and people's medical and health services, the special space environment will be used to develop high-tech products *e.g.* stem cells, regenerative medicine, targeted drugs and synthetic biomanufacturing.

The main goal of microgravity physics is to investigate the law of matter movement and its influence on the law of movement when the effect of gravity almost disappears, including fluid physics and thermo-physics, combustion science, materials science as well as the fundamental physics. Fluid physics and thermo-physics are to study new phenomena and new laws of fluid motion and thermal (mass) transportation, to obtain a systematic understanding of turbulent flow transfer processes, multiphase flow thermal mass transport, soft matter self-organization phenomenon far from equilibrium state, *etc*., and serving space applications in aerospace thermal and propellant management. The study of combustion science is to decouple the effect of gravity field on flame, reveal the essence and law of traditional and new fuel combustion, develop spacecraft fire prevention and fire extinguishing technology, and promote technological progress in the energy technology. The study of materials science is to reveal the processing and preparation laws of various types of materials in space environments, grow new materials that have important application backgrounds, study the laws of service performance of space application materials in the outer space environment, and provide a scientific basis for the research and development of advanced materials for aerospace. The study of fundamental physics includes experiments of ultra-cold atomic physics under extreme conditions, low-temperature quantum phase transition, general relativity testing, developing and using advanced high-precision time-frequency technology, and developing microgravity complex plasma research, to promote the understanding of fundamental physics.

The space astronomy and Earth science is a comprehensive interdisciplinary subject that uses spacecraft to observe and study cosmic objects and all spheres of the Earth system (the atmosphere, hydrosphere, lithosphere and biosphere, extending to the Earth ionosphere, magnetosphere and solar-terrestrial space). Space astronomy plays an important role in the scientific research of the space station: through the CSST, large-scale multi-color photometry and spectral survey for more than 10 years is expected to make major breakthroughs in the fundamental problems of cosmology, the formation and evolution of active galactic nuclei and supermassive black holes, the formation and evolution of galaxies and stars, temporary source/source change and sudden astronomical events, *etc*. Furthermore, a cosmic High-Energy Radiation Detection facility (HERD) is scheduled to explore the extreme physics of the universe[11]. In addition, some other gamma-ray and soft X-ray polarization detection, Milky Way thermal baryon measurement, and ultraviolet astronomy facilities are also planned to ensure accurate measurement of multiple astrophysical quantities. Geoscience focuses on space environment monitoring, studying the coupling relationship between ionosphere and magnetosphere, and building a more refined space weather and space environment prediction model. In addition, new Earth observation technologies applied in the fields of global climate change, natural resources survey and natural disaster early warnings are encouraged.

The new space technologies and applications area keeps keen eyes on the frontier of new space application technology, and makes systematic layout for future manned lunar exploration and deep space exploration. The on-orbit manufacturing and construction technology verification is planned, including the test verification of on-orbit assembly and construction of large components and space payloads, high-precision on-orbit additive manufacturing, *etc*. Space robots and intelligent control technologies are planned to reduce astronauts' on-orbit work. Other technologies such as new technologies for autonomous navigation of spacecraft in Earth-Moon space, new space energy and propulsion technology, environmental control and life support system technology and other basic technologies are also planned to serve space exploration and discovery purposes and support the sustainable development of space utilization.

4 Conclusions

China aims to have the CSS fully assembled by the end of 2022, and large-scale space science and application tasks will be conducted thereafter, providing a historic opportunity for the leap-forward development of space science and applications. With the CSS starting its regular operation, in the follow-up, the solicitation of experimental projects will be carried out regularly to ensure sufficient project reserves. In addition, the new generation of payloads will be approved and launched to meet the requirements of on-orbit experiments and to continuously improve the on-orbit scientific experiment supporting and sample analysis abilities.

The CSS is completely open to the world, and provides opportunities for countries around the world to use the space station to carry out scientific experiments, which is a concrete embodiment of China's concept of building a community with a shared future for mankind and building a new type of international cooperation in the "new region" of outer space. Regular international projects solicitation will be released, and scientists from all over the world can submit project requirements through China Manned Space Agency, the United Nations Office for Outer Space Affairs, or national space agencies under bilateral cooperation agreements. Chinese scientists are actively encouraged to initiate extensive cross-regional or transnational cooperation to improve the human science and technologies.

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