

GU Yidong, GAO Ming, ZHAO Guangheng, WANG Qiang, LYU Congmin, ZHONG Hongen, LIU Guoning. Recent Progress in Space Science and Applications on Chinese Space Station in 2022–2024. *Chinese Journal of Space Science*, 2024, **44**(4): 607–621. DOI:10.11728/cjss2024.04.2024-yg09

# Recent Progress in Space Science and Applications on Chinese Space Station in 2022–2024

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**Abstract** Chinese Space Station (CSS) has been fully deployed by the end of 2022, and the facility has entered into the application and development phase. It has conducted scientific research projects in various fields, such as space life science and biotechnology, space materials science, microgravity fundamental physics, fluid physics, combustion science, space new technologies, and applications. In this review, we introduce the progress of CSS development and provide an overview of the research conducted in Chinese Space Station and the recent scientific findings in several typical research fields. Such compelling findings mainly concern the rapid solidification of ultra-high temperature alloy melts, dynamics of fluid transport in space, gravity scaling law of boiling heat transfer, vibration fluidization phenomenon of particulate matter, cold atom interferometer technology under high microgravity and related equivalence principle testing, the full life cycle of rice under microgravity and so forth. Furthermore, the planned scientific research and corresponding prospects of Chinese space station in the next few years are presented.

**Key words** Chinese Space Station (CSS), Space material science, Micro-gravity fluid physics, Fundamental physics, Space life sciences and biotechnology

**Classified index** P35, V47

## 1 Construction and Operation of CSS during 2022–2024

With the successful launches of the Wen Tian experiment module in July 2022 and the Meng Tian experiment module in October 2022, the three modules configuration of the Chinese Space Station has been completed in orbit and entered a stage of application and development lasting more than ten years. In the past two years, four Tianzhou cargo spaceships (TZ-4, 5, 6, 7) have been launched and 5 Shenzhou manned spaceships (SZ-14, 15, 16, 17, 18), fifteen astronauts have entered

the space station, completing four short-term missions with six people on board, and conducted Tian gong Classes<sup>[1]</sup>.

Chinese Space Station (CSS), known as the National Space Laboratory, with the most comprehensive support capabilities, and unique advantages such as human participation and spaceship transportation. It has the capability to conduct large-scale space science research based on a variety of advanced scientific research and technology experimental facilities<sup>[2]</sup>. In order to explore the frontier of space science, promote space applications, and develop space technology, CMS has carried out in-

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depth discussions and demonstrations, with over 1000 scientists from various fields and more than 200 research institutes participating, and has formulated forward-looking scientific and application mission plans for the next ten years<sup>[3]</sup>. In 2023, CMS released project guidelines to the whole society, openly called for science and application proposals<sup>[4]</sup>, which received positive responses from all sectors of China and provided strong support for future achievements.

So far, the scientific experiment racks and payloads are operating well. More than 100 scientific and applied projects have been carried out, achieving outstanding progress and results in space life science and biotechnology, microgravity fluid and thermophysics, combustion science, space materials, microgravity fundamental physics, and new space application technologies. Overall, the Chinese Space Station has achieved normalized project collections, experimental materials delivery, in-orbit scientific experiments, ground analysis, and preliminary application benefits.

## 2 Recent Scientific Research in Space

### 2.1 Space Materials Science

Material scientific researches on Chinese Space Station are mainly carried out in containerless material experimental rack and high-temperature material experimental rack. Some typical progresses have been made, for instance, the rapid solidification of ultra-high temperature alloy melts has been investigated, getting precise measurements of supercooled liquid alloys so as to promote

the understanding of large undercooling behavior, solidification process along with crystal growth in space; effective control of the solidification process and structure of monotectic alloy was realized, samples with the multi-layer structure were obtained; the preparation method of space InAsSb ternary semiconductor crystals has been studied, presenting the growth of high-quality InAsSb crystals in space for the first time, which is difficult to prepare on the ground. The performance of the transistor made of the crystal material is greatly improved, improving the development of ultra-fast electronic and optoelectronic devices. Some noteworthy results are presented in detail as follows.

#### 2.1.1 Accurate Measurement of Liquid Properties of Refractory Alloys

The thermophysical properties of supercooled liquid alloys are crucial to condensed matter physics and solidification theory. Related research in outer space in a containerless environment has unique advantages because Electrostatically Levitated (ESL) droplets on the ground are bound to be affected by gravity, resulting in a change in droplet shape and buoyancy-driven convection. Fortunately, this disadvantage can be solved well in a microgravity environment. As one of the most significant materials for aerospace, Nb-Si refractory alloy has an excellent strength-to-density ratio and high-temperature performance but still lacks the understanding of the alloy in liquid. Nb-Si has been chosen as the near-eutectic alloy for the space-based ESL experiments. The schematic of the ESL furnace on CSS is shown in Figure 1, which mainly consists of three pairs of high-voltage electrodes

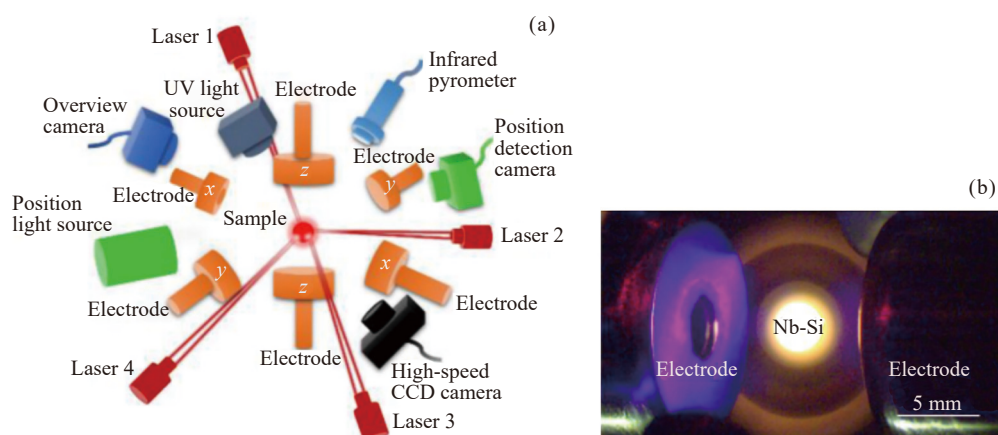


Fig. 1 Electrostatic levitation facility and experimental conditions on board the Chinese Space Station. (a) Schematic of the ESL system. (b) Image of a levitated NbSi alloy droplet<sup>[5]</sup>

with a feedback loop, four semiconductor lasers with the tetrahedral configuration, a position detection camera, and so forth.

Aiming to determine the thermophysical properties of liquid Nb-Si refractory alloys over a broad temperature range along with the atomic structures of high-temperature liquids, the scientists from Northwestern Polytechnical University in China attempted to develop a path to get large undercooling of liquid refractory alloys with high activity, to achieve the fine sphericity of liquid alloys and to find the reliable thermophysical properties and the characteristics of atomic cluster in the undercooled Nb-Si alloy melts. The team successfully experimented with a series of operations under microgravity *via* heating, melting, cooling, undercooling, solidification, and the thermal physical properties measuring for the refractory alloys. The experimental samples were re-

turned to the ground aboard the Shenzhou manned spacecraft, as shown in Figure 2.

The team found that under this microgravity condition, the levitated alloy melt will appear perfectly spherical under the action of surface tension, deviating from the ideal sphericity by only about 0.5%, showing extremely high sphericity, see Figure 3(a).

### 2.1.2 Alloy Surface Nucleation and Structure Control

The researchers successfully achieved ultra-high temperatures of 2338 K and extreme metastable states of 1752 K by heating and melting the refractory alloy in a containerless rack onboard. They obtained an extreme metastable alloy melt with an undercooling degree of 437 K, reaching the theoretical limit of  $0.2 T_e$  for uniform nucleation, see Figure 3(b). The evolution of the Nb-Si alloy liquid structure was determined with the

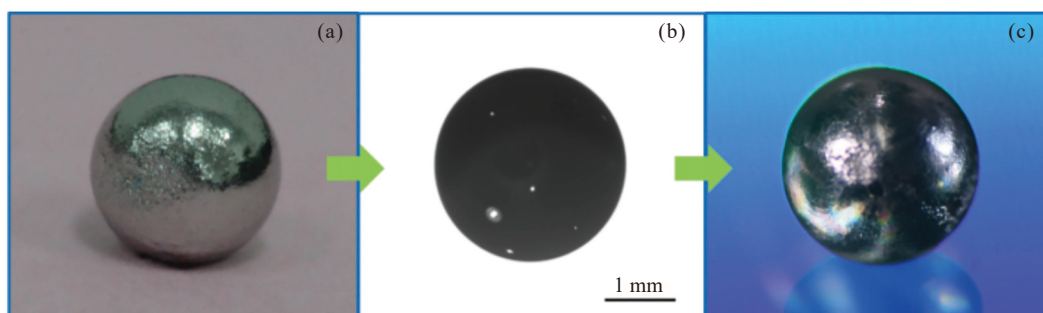


Fig. 2 Refractory alloy space station experiment samples. (a) Refractory alloy on the ground was carried into the core module of the Chinese Space Station by Tianzhou-3 cargo spacecraft. (b) Projection of the 2200 K ultra-high temperature alloy melt in the space station experiment. (c) Alloy pellets prepared by solidification on the space station were returned to the ground laboratory on board the Shenzhou 14 manned spacecraft [6]

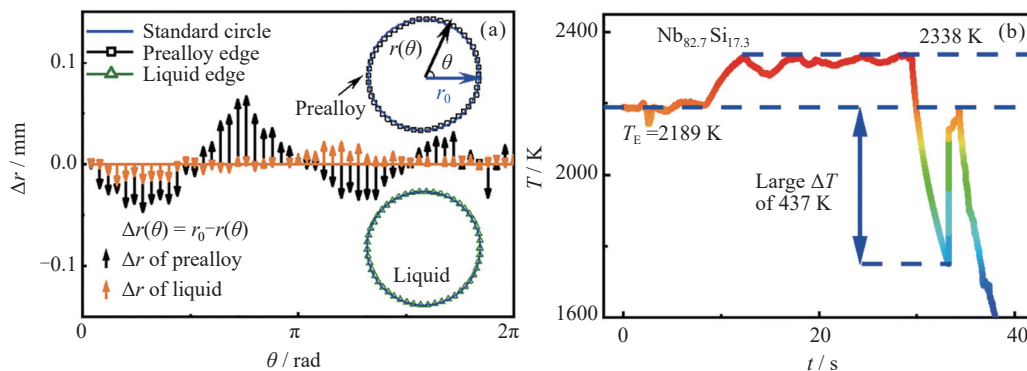


Fig. 3 (a) Circular deviation of floating prealloy surface is notably pronounced, but after undergoing heating and melting, the circular deviation of the floating droplet surface becomes comparatively minimal. (b) Nb-Si alloy reaches an ultrahigh temperature of 2338 K and experiences deep undercooling of 437 K [6]

Voronoi Polyhedron (VP) method (see Figure 4).

The surface microstructure consists of the primary solid solution (Nb) and the surrounding (Nb) /Nb<sub>3</sub>Si eutectic phase, as shown in Figure 5.

This discovery is confirmed to realize the dual regulation of “macro form and micro-texture”. Under the microgravity condition, the natural convection disappears, and the weak Marangoni convection effect appears, which can cause peculiar changes in the flow field distribution of alloy melt. These abundant microscopic flows contribute to the formation of specific structures

and structures during the process of eutectic solidification, which becomes a new way to regulate the surface microstructure<sup>[7]</sup>.

The weak Marangoni convection effect appears, which can cause new changes in the flow field of alloy melt. Such microscopic flows play a critical role in the formation of distinct structures during eutectic solidification. For example, the application of an electrostatic field can induce perturbations in the alloy melt, resulting in the emergence of surface periodic ripple structures and vortex, presenting a novel method for controlling surface microstructure<sup>[6,8]</sup> (see Figure 6).

### 2.1.3 “Decoupled” Growth of Eutectic Alloys

A decoupling effect was found being induced by the microgravity and containerless states aboard the space station, which led to the independent dendrite growth of two eutectic phases within an extremely undercooled liquid Nb-Si refractory alloy. The confronting fluid flow pattern driven by polar heterogeneous nucleation was found to stimulate the elongated surface deformation of alloy droplets at a high dendrite growth velocity. The direct observation of the solidification process provides comprehensive insights into dendritic growth velocity, formation of shrinkage cavity, and other phenomena under microgravity. In experiments, the alloy spheres were melted at eutectic temperature and reached a maximum temperature, multiple smooth eutectic cells can be distinguished on the surface, indicating the presence of multiple nucleation sites during solidification<sup>[9]</sup> (see Figure 7).

Rapid solidification kinetics within undercooled Nb-Si alloy leads to the macroscopic surface deformation of the solidified droplets and decoupled growth of eutectic phases under microgravity and containerless states. It is regarded to be related to the reduction in convection and the decoupling effect caused by rapid solidification kinetics<sup>[10]</sup>.

These researches advanced our understanding of large undercooling behavior, solidification process as well as crystal growth in space. Knowledge serves to generate new regulatory methods for material preparation.

### 2.1.4 Immiscible Alloy Solidified in Space

The solidification process of the alloy with a miscible gap in the liquid-liquid phase diagram is known as liquid-liquid decomposition, which holds significant potential for the development of high-performance *in-situ*

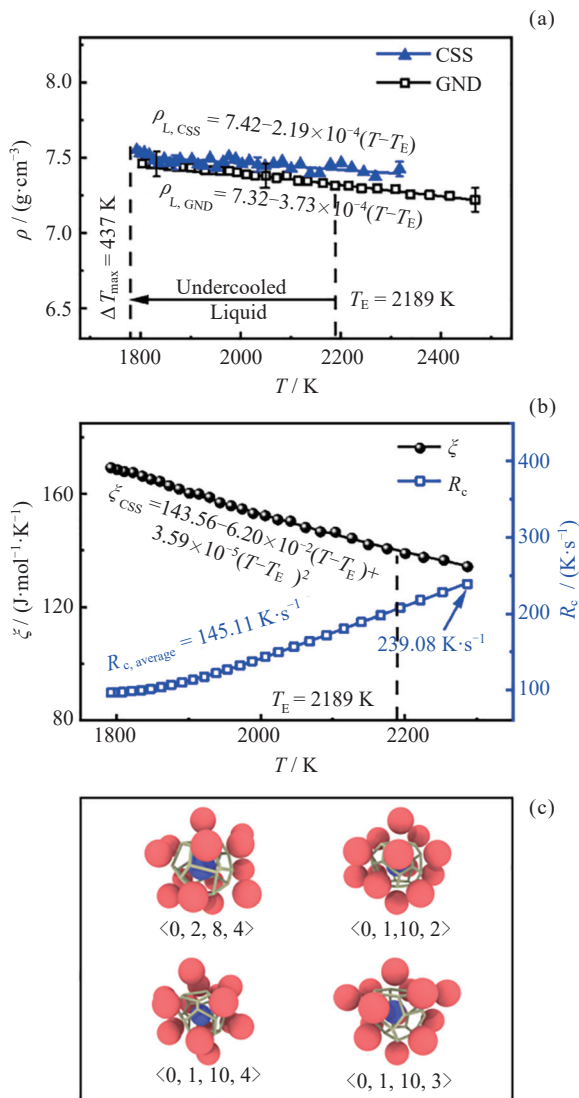


Fig. 4 Properties and structure of liquid Nb-Si alloy obtained by space station experiment: (a) liquid density, (b) liquid heat radiance ratio, (c) the predominant Voronoi polyhedral structure in liquid alloys<sup>[6]</sup>

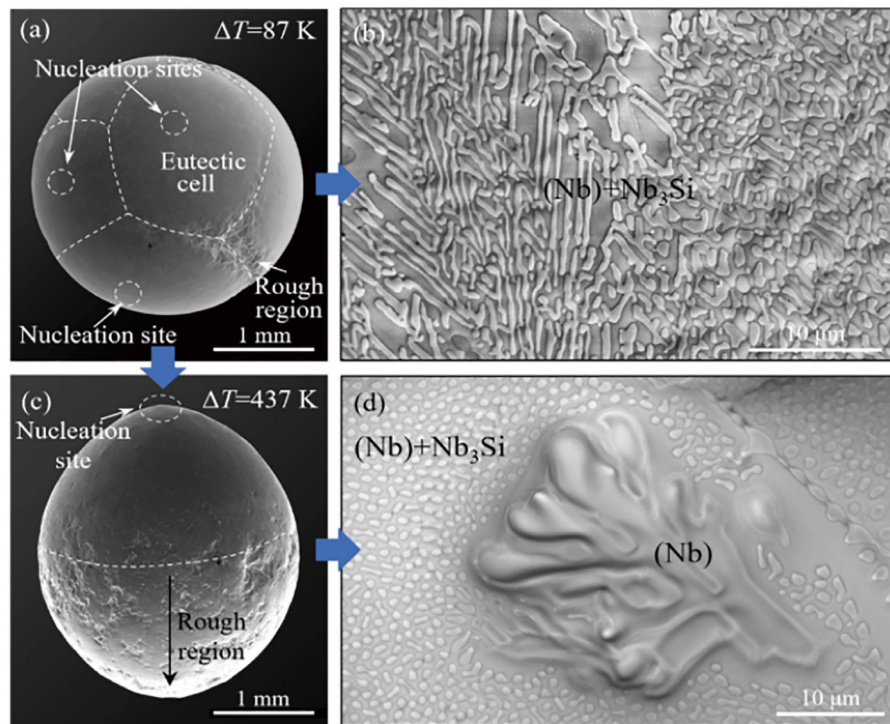


Fig. 5 Spherical and olive alloy samples prepared in the space station experiment were: (a) photos of small subcooled spherical samples, (b) typical growth microstructure of small undercooling spherical samples, (c) photos of large undercooling olive samples, (d) large undercooling olive-shaped samples (Nb) lead eutectic growth in microstructure<sup>[6]</sup>

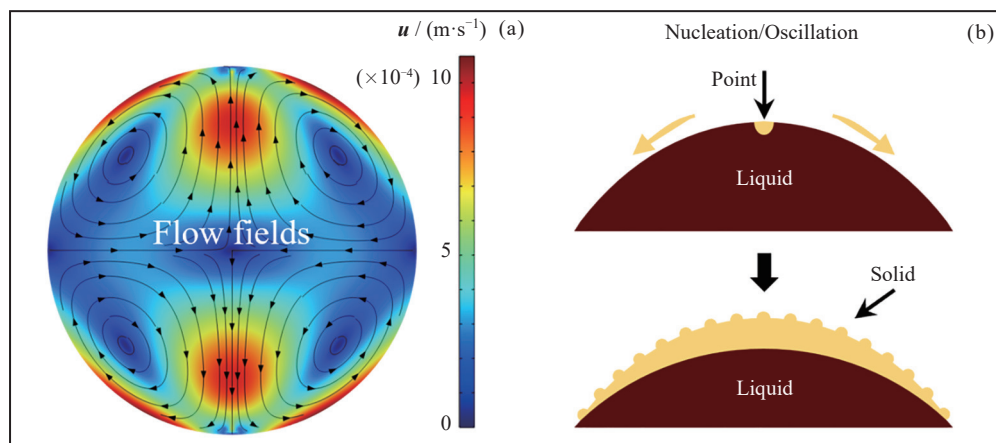


Fig. 6 Flow behavior and surface wave formation of space station alloy melt: (a) flow field distribution in alloy melt under microgravity, (b) schematic diagram of alloy surface wave structure formation<sup>[6]</sup>

particle composites and core/shell structure composites. Due to the phase segregation effect during ground solidification, it is important to conduct solidification experiments under microgravity conditions. The microstructure of most composite materials fails to get the expected effect due to the influence of the cooling rate and surface contamination of the crucible. To address this issue,

a research team from the Institute of Metal Research of the Chinese Academy of Sciences conducted containerless solidification experiments on Chinese space station to achieve fast cooling rates and avoid contamination<sup>[11]</sup>. The Ti-Go-Gd immiscible ball experienced a cooling, as shown in Figure 8.

The differences between the microstructures of the

two samples, studied respectively on the ground and in space, are caused by the gravity-related convective flow of the melt and the Stokes motion of the Gd-rich droplets. When solidifying the alloy on the ground, the Gd-rich droplets sink in the matrix melt and the natural convection occurs in the matrix melt. It is the Stokes motion of the Gd-rich droplets together with the natural convection that promotes the collisions and coagulations between the Gd-rich droplets and leads to a rapid coarsening of the droplets, causing the formation of a phase-segregated microstructure, as shown in Figure 9.

In space, the Marangoni migration of droplets together with the diffusional transfer of solute Gd causes the formation of the Gd-poor region next to the Gd-rich phase shell. Enhancing the cooling rate promotes the formation of a well-dispersed microstructure.

## 2.2 Fundamental Physics

The ultracold atomic science rack and the cold atom interferometer provide opportunities for fundamental physics research on the space station. The former is a highly integrated experimental platform based on the principle of full optical trap evaporation cooling for

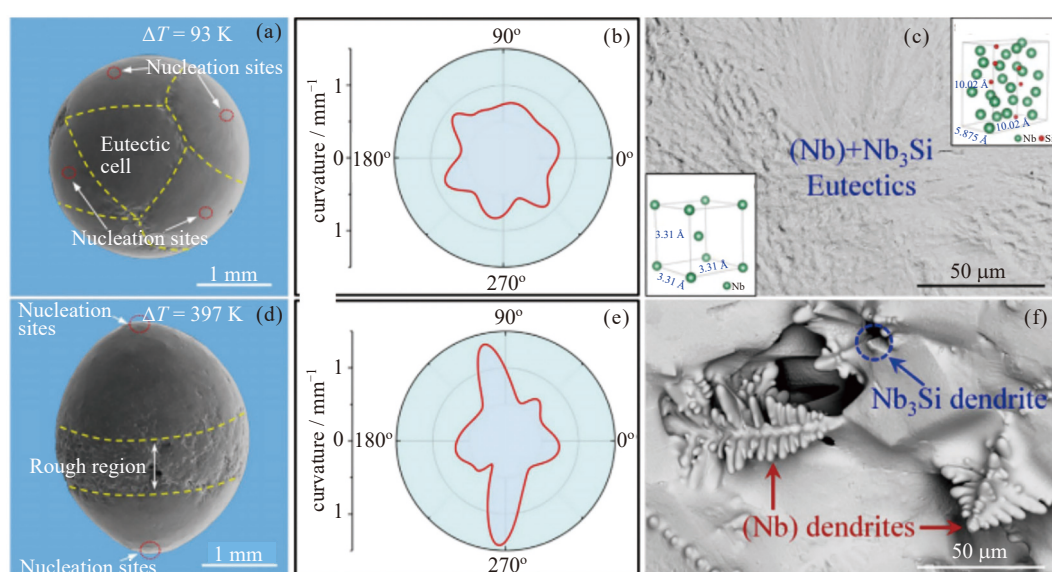


Fig. 7 Macroscopic shapes of eutectic Nb-Si alloy droplets solidified with different undercoolings aboard CSS<sup>[9]</sup>

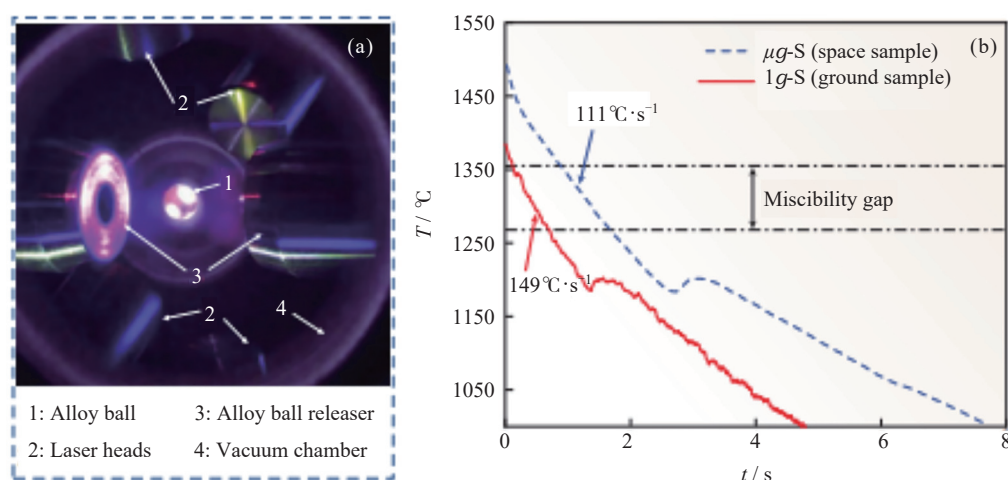


Fig. 8 Solidification microstructure formation of Ti-Co-Gd alloy. (a) Electrostatic levitation device. (b) Cooling curves of samples<sup>[11]</sup>

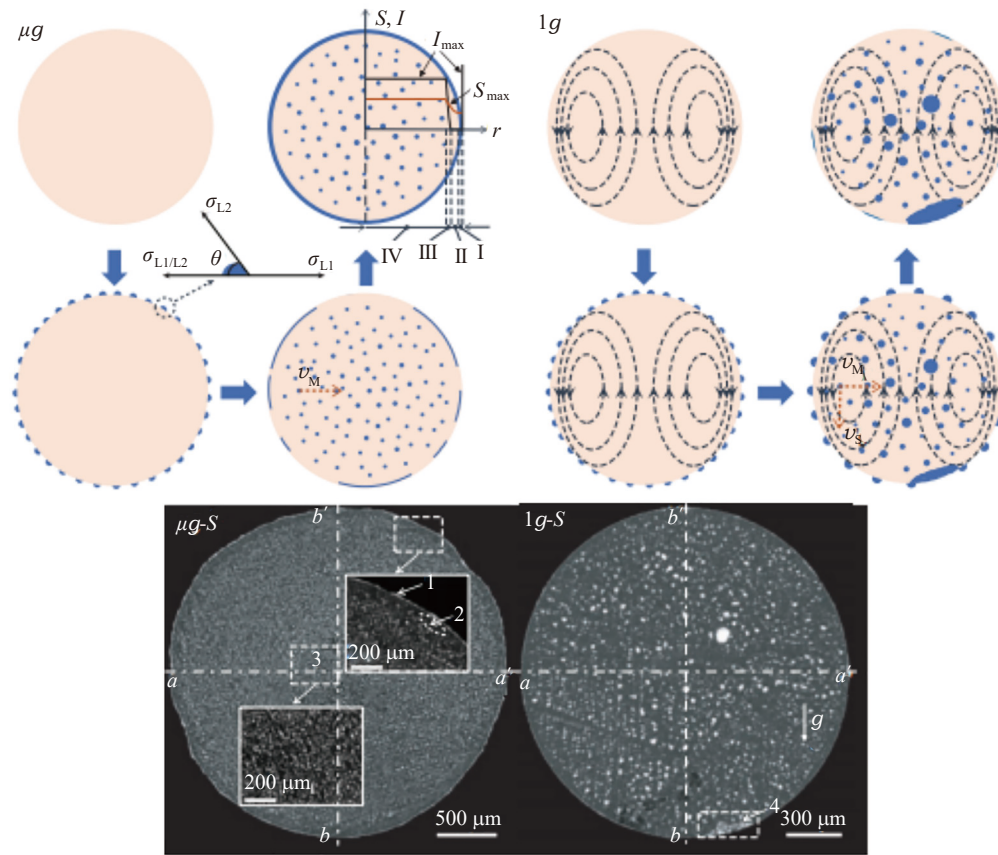


Fig. 9 Schematics of the microstructure formation during liquid-liquid decomposition in space and on the ground<sup>[11]</sup>

ultracold atomic physics experiments. It can serve quantum simulation experiments based on optical lattice modulation of ultracold atoms. It will be expected to achieve the Bose-Einstein condensate. Thereafter, quantum simulation experiments on singular quantum states and dynamics will be conducted. The latter is a dual-species cold rubidium atom interferometer, installed in the microgravity scientific rack in Chinese space station to carry out such experiments with high-precision measurement as the weak equivalence principle test and so forth.

### 2.2.1 Testing the Equivalence Principle Based on the Space Cold Atom Interferometer

Atom interferometers offer a method for testing the Weak Equivalence Principle (WEP) at the microscopic level using atoms. Achieving high-precision WEP measurements involves measuring the differential acceleration of two atomic clouds with two types of atom interferometers. The atomic interferometer is an  $^{85}\text{Rb}$ - $^{87}\text{Rb}$  dual-type atomic interferometer developed by the Institute of Precision Measurement Science and Technology

Innovation of the Chinese Academy of Sciences. It works in the microgravity science laboratory cabinet of the Chinese Space Station, and its scientific goal is to conduct in-orbit experiments on atom interferometry measurements. The use of an atomic interferometer for testing WEP not only enhances the accuracy of the test but also broadens its scope. Scientists have proposed a three-dimensional (3D) velocity selection method to efficiently lower the atomic ensemble temperature. Depending on the cooling process, the atomic cloud is allowed to expand freely, and the velocity of the atomic cloud in or perpendicular to the direction of the Raman laser is chosen<sup>[12]</sup>. The experimental scheme of the velocity selection method is shown in Figure 10.

The physical system contains a vacuum chamber, its accessories, the supporting structures, the optical components, and a magnetic shield, as shown in Figure 11.

To test WEP with high accuracy, the experimental process includes laser cooling, atom interference, and fluorescence detection stages. In the laser cooling exper-

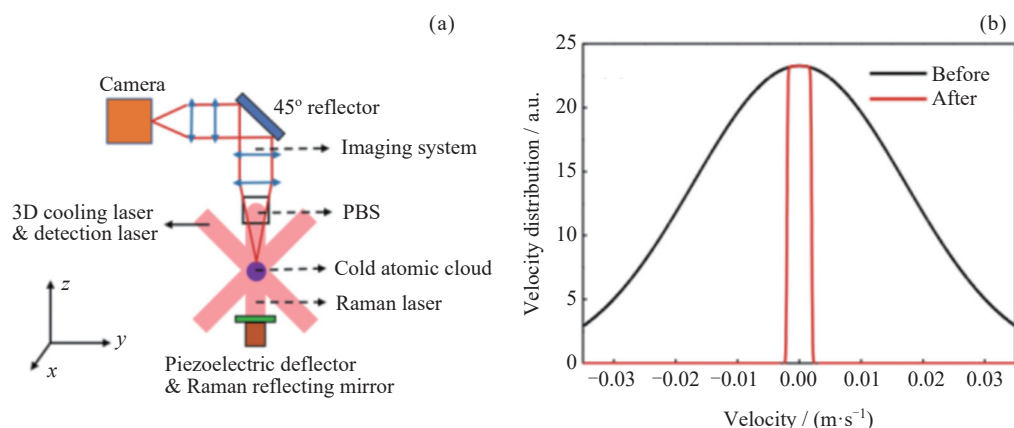


Fig. 10 Scheme of the velocity selection and velocity distribution. (a) 3D velocity selection. (b) Velocity distribution of the atomic cloud before and after velocity selection<sup>[12]</sup>

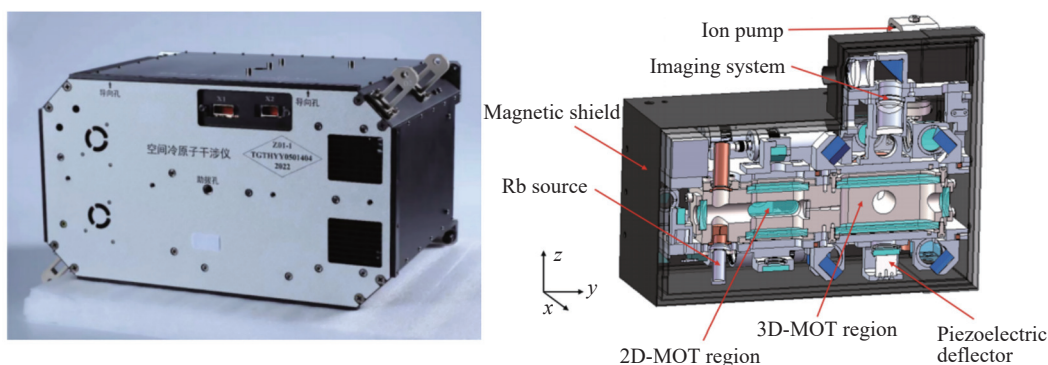


Fig. 11 Space cold atom interferometer payload<sup>[12]</sup>

iment, images of the cold <sup>85</sup>Rb atomic cloud in the 3D-MOT and time-of-flight images of the atomic clouds after the polarization gradient cooling process are shown in Figure 12. The number of the atoms was calculated to be more than  $2 \times 10^8$  and the calculated atomic temperature was about 4  $\mu$ K in one dimension.

To date, the atomic interference fringes of point source are realized up to 200 ms, and the on-orbit acceleration and rotation measurements are detected through the interference fringes. At the same time, by measuring the period of the point source interference fringe, the on-orbit Raman laser mirror angle coefficient calibration is obtained, and the systematic error evaluation of the rotation measurement value is carried out. The first measurement of on-orbit atomic interference rotation in the world is achieved with an accuracy of  $1.71 \times 10^{-5} \text{ rad} \cdot \text{s}^{-1}$ . The instrument is carrying out the in-orbit equivalence principle test experiment, and the dual component syn-

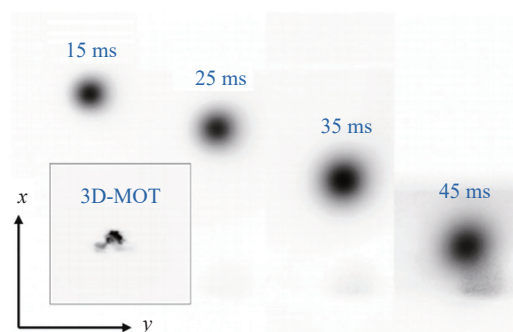


Fig. 12 TOF fluorescence images of the <sup>85</sup>Rb atomic cloud with different falling time<sup>[12]</sup>

chronous atomic interference of <sup>87</sup>Ru and <sup>85</sup>Ru in orbit has been accomplished.

## 2.2.2 High Precision Gyroscopes in Space

High-precision space gyroscope is of great significance for complex scientific experiments and deep space navigation. Microgravity in space provides an ideal condi-

tion for the operation of cold atom gyroscopes. The researchers implemented a cold atom gyroscope by using the atom interferometer whose evaluated rotation measurement is  $(-115.64 \pm 1.71) \times 10^{-5} \text{ rad} \cdot \text{s}^{-1}$  in space, and acceleration measurement resolution is  $1.03 \times 10^{-6} \text{ m} \cdot \text{s}^{-2}$  for a single image. This project is the first gyroscope based on the atom interferometer in space and paves the path for future related space-based experiments<sup>[13]</sup>.

The gravity of the Earth is a major disadvantage that limits the interference interrogation time and thus the resolution of the gyroscope. As the preliminary conditions, the cooling, state preparation, and fluorescence detection processes for the Chinese space station atom interferometer have been optimized, and the Mach-Zenden type interferometer for the  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  atoms has been constructed<sup>[13]</sup> (see Figure 13).

The measurement data suggested that the angular velocity in orbit with an accuracy of  $1.71 \times 10^{-5} \text{ rad} \cdot \text{s}^{-1}$  can be obtained. The results are compared with the rotation values measured by the space station platform, and a good agreement is obtained. At the same time, the resolution of acceleration measurement is  $1.03 \times 10^{-6} \text{ m} \cdot \text{s}^{-2}$ .

### 2.3 Micro-gravity Fluid Physics

The research on fluid physics under micro-gravity on Chinese space station involves fluid dynamics, multiphase flow, and heat transfer, together with soft matter physics. The experiments of fluid storage and transportation in spherical and capsule tanks were carried out onboard. A theoretical model of bubbles in the tank was established, successfully verifying the fluid management performance of the tank, and supporting the development of novel plate tanks for spacecraft. Convection, evaporation, and phase transition heat transfer of the

droplet and liquid layer were studied, finding the law of complex interface flow with heat and mass transfer. The glassy transition and rheology of the colloidal system were investigated, implying that the structure evolution of the three-dimensional colloid system was coherent across scales in length. The gravity scaling law of heat transfer and bubble thermodynamic behavior in pool boiling is being studied, preliminary results demonstrate that boiling heat transfer performance rises instead of decreasing with the shrink of gravity, which seems intuitive and is expected to reveal the mechanism of gravity action in boiling phenomenon<sup>[14]</sup>. It provides direct instruction to fluid thermal management in multi-gravity environments for space exploration missions. The 3D trajectories of specific magnetic particles embedded in dense particles under various gravity conditions were measured precisely with Hall effect sensors, finding that the movement direction of particles with different sizes and density can be effectively controlled by the boundary geometry and motion conditions, and the abnormal “Brazil nut” effect has been observed. This discovery is expected to improve the ability of space missions to manipulate particles under different gravity conditions and to benefit particle mixing and separation engineering in pharmaceutical, food, chemical, and other industries.

#### 2.3.1 Research on Fluid Storage, Transport and Interface Behavior in Space

For spacecraft, to ensure the safety of the propellant management device, the tank that stores the propellant on the satellite usually has a central column. It is of great significance for fluid management under microgravity to explore the morphological characteristics of the bubbles in a tank with a central column and to study the various factors affecting them. However, the static shape and motion of bubbles under microgravity conditions have not been studied. The influence of geometry and liquid contact angle on the annular bubble profile is not clear. The research group of the Institute of Mechanics of the Chinese Academy of Sciences has carried out a spherical tank model filling experiment on the Chinese Space Station. The liquid is pumped into the tank by an air pump.

An annular bubble surrounding the central column is formed inside the tank, see Figure 14. This kind of bubble under microgravity is observed for the first time,

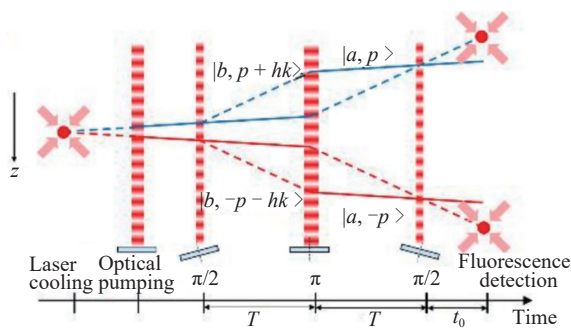


Fig. 13 Principle of the double single diffraction scheme for Rb atom<sup>[13]</sup>

which will have important significance for the on-orbit liquid management and residual gauging. Annular bubbles are also observed in both experimental and numerical results. It can be seen in Figure 15 that the speed of liquid climbing along the guide vanes is faster than that in other areas; thus, a concave liquid surface is formed on the model wall, which is in good agreement with the experimental results in the CSS<sup>[15,16]</sup>.

Different from the phenomena during the filling process, under this circumstance, the liquid is still spreading on the central column, forming another kind of bubble. Figure 16 shows the results, there is an obvious large annular bubble in the middle of the tank model, the liquid distribution on the surface of the central column is clear to see, and the bulge is in the middle region of the central column.

In this experiment, the complete characteristics of the flow driven by surface tension in the fully managed or semi-managed structure of the tank fluid were obtained, and the dynamical evolution roadmap of the bubble merging in the space large-scale structure was achieved. Based on the results, the theoretical model of

an annular bubble contour in the tank is found. The law of bubble-shaped deformation and flow were revealed, and the fluid management performance of the tank in microgravity was confirmed. The liquid drainage rate of the semi-managed tank model exceeds 99%, which is a useful exploration for the in-orbit supply of spacecraft.

### 2.3.2 Vibration Fluidization Characteristics of Granular Materials under Variable Gravity Conditions

In various industrial processes and natural phenomena, particle segregation occurs when different shapes or sizes of particles are subjected to external vibrations or disturbances. Understanding and controlling this phenomenon is of significant importance in industries such as pharmaceuticals, where achieving a homogeneous distribution of components in powders is crucial, as well as in geological disasters such as earthquakes and landslides. Besides, granular systems provide valuable insights into nonequilibrium phenomena and are extensively studied in fundamental physics research.

Based on the centrifuge deployed on the Chinese Space Station, the scientists from the Institute of Physics, Chinese Academy of Sciences carried out experimental investigations on vibration fluidization of granular materials. Nevertheless, granular segregation faces challenges, particularly in three-dimensional systems. Traditional high-speed imaging techniques are limited to two-dimensional systems. In the experiment, a novel 3D particle tracking technique is utilized, *i.e.* the Hall-effect magnetic sensing technique, for high-precision trajectory tracking of a single magnetic sphere with varying densities within a granular bed<sup>[17]</sup> (see Figure 17).

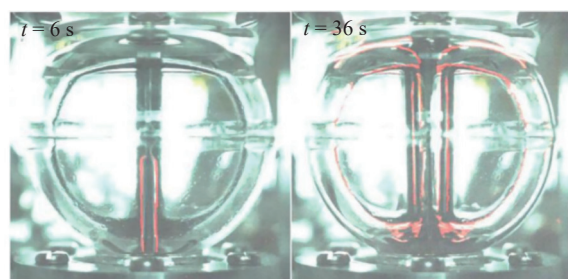


Fig. 14 Liquid distribution versus time when filling tank<sup>[15]</sup>

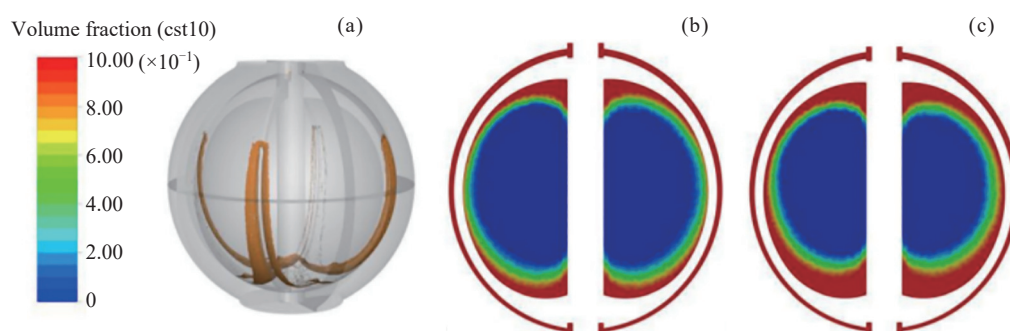


Fig. 15 Liquid-gas interfaces when filling TA (a). Liquid distribution in the cross section when the liquid seal just forms (b), and liquid distribution in the cross section after further filling (c). Red region represents liquid and the blue region represents the gas<sup>[16]</sup>

A single large sphere acted as an intruder model system. The microscopic measuring of the dynamics of the intruder within the granular bed is obtained<sup>[18]</sup> (see Figure 18).

They hunt for the relationship between the equilibrium position of the intruder and the vibration acceleration and density. The experiment reveals that the primary mechanism driving the upward motion of the intruder is the void-filling mechanism, while the effect of convection may play a limited role according to the observed phenomena since the intruder also exhibits upward motion near the container wall, confirming the Brazil nut effect, which is regarded as a critical conclusion for the dynamics of granular material<sup>[19]</sup>.

Another extended experiment was carried out on the test bench to investigate the three-dimensional convection mode of fluidized particle materials through vibration in cube and cylindrical containers, which explains that convection mainly controls the motion dynamics of quasi-static shear particle media in cuboid containers, while its effect is less pronounced in cylindrical containers. These findings highlight the importance of vessel geometry in inducing periodic helical

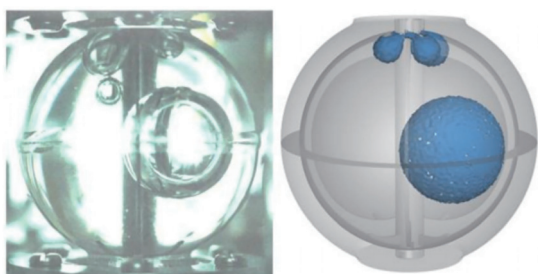
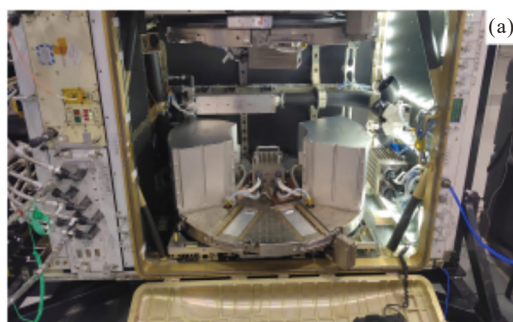


Fig. 16 Comparison between experimental and numerical results<sup>[15]</sup>



oscillatory motion, which needs to be considered in the engineering design of systems involving mixed particles.

## 2.4 Space Life Sciences and Biotechnology

Space stations provide suitable opportunities to carry out astrobiology experiments to explore the possibility of life beyond the Earth and enable us to better understand the limits and requirements of life in different environments. Based on Chinese Space Station exo-ecosystem space experiment conducted onboard, the microorganisms will be exposed to space conditions, including microgravity, vacuum, UV radiation, and extreme temperatures.

### 2.4.1 Astroecology Experiment in Tiangong Space Station

The researchers set to examine whether methane-producing microorganism can survive in the environments inside and outside the space station at the first stage, validating methanogenic bacteria's adaptability to simulated environments (gravity, radiation) can provide indirect evidence for the process of generating methane on the planets such as Mars or Enceladus, which will help us understand whether the detected methane gas on these worlds may be a biological feature. Extraterrestrial exposure experiments will be conducted on standard sample cassettes equipped with UV filters provided on the external platform of the space station (see Figure 19)<sup>[20]</sup>.

### 2.4.2 Human Embryonic Stem Cells into Hematopoietic Stem/Progenitor Cell

The inaugural in vitro study of human embryonic stem cell hematopoietic differentiation has been conducted aboard the Chinese Space Station. Microscopic images of cells collected and downlinked from orbit revealed that these human embryonic stem cells were successfully induced to differentiate into cobblestone-like Hema-

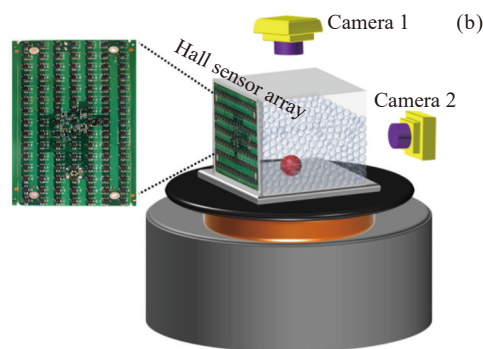


Fig. 17 Assembly of test bed in centrifuge<sup>[17,18]</sup>

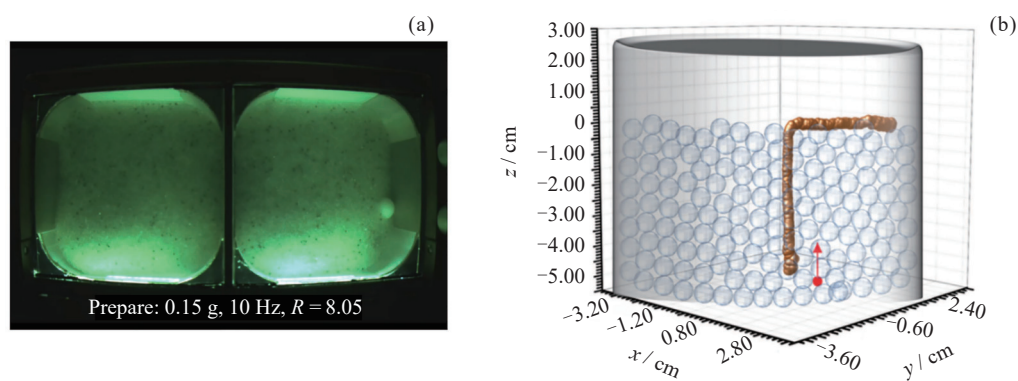


Fig. 18 3D trajectory plot illustrating the path followed by the intruder throughout the experiment<sup>[18]</sup>

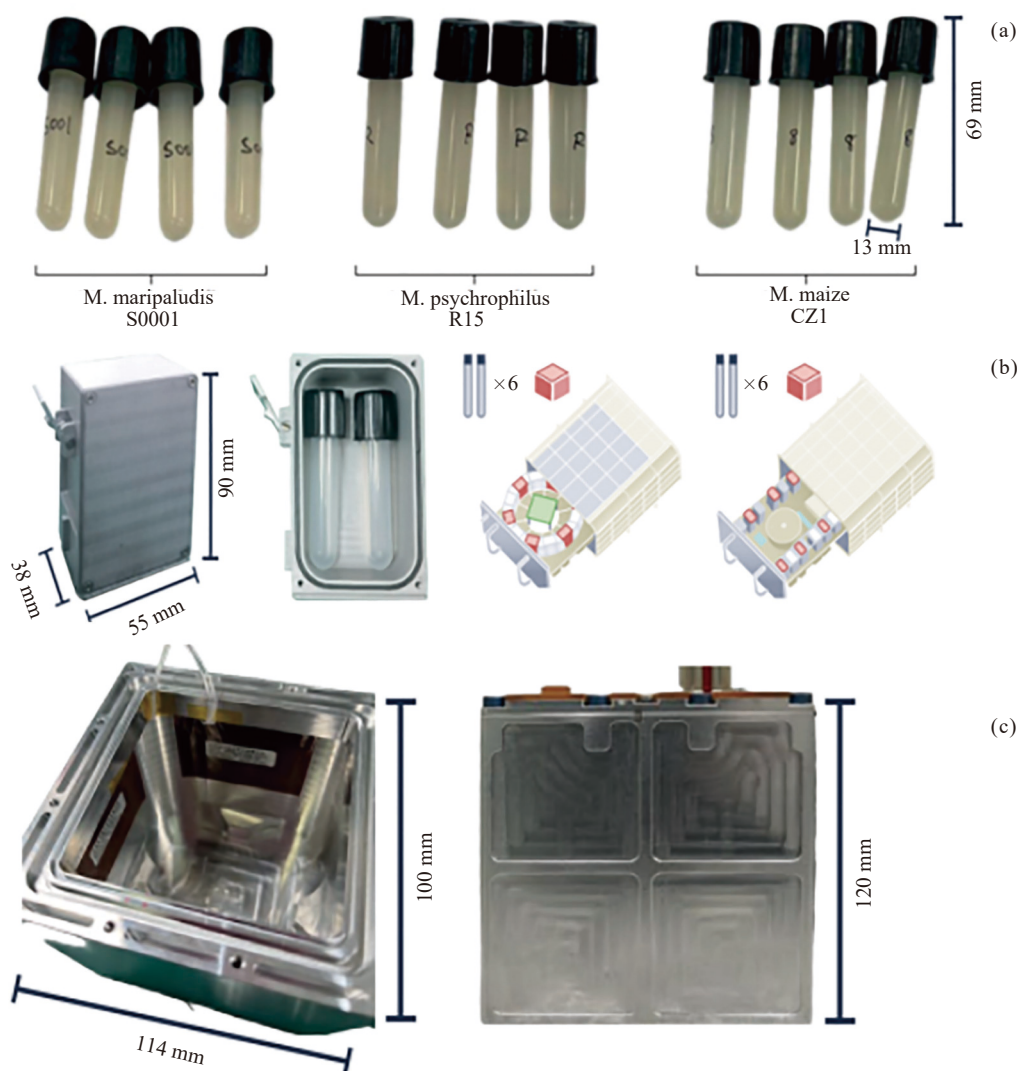


Fig. 19 Schematic view of exo-ecosystem space experiment. (a) Space samples. (b) Units for the simulated gravity experiments conducted in the Wentian module of Chinese space station. (c) Units for radiation experiments conducted at the exposure platform in the Mengtian module<sup>[20]</sup>

topoietic Progenitor Cells (HPCs). As development and differentiation progressed, these HPCs proliferated and formed grape-like clusters of hematopoietic cells. Subsequent analyses will involve the identification of the fixed samples returned from orbit, comparative analyses between space and Earth samples, and multi-omics studies. This mission establishes a foundation for future studies on early-stage hematopoiesis of stem cells in space and is anticipated to elucidate the mechanisms by which microgravity influences the differentiation of human pluripotent stem cells into early-stage hematopoietic cells.

### 2.4.3 Effects of Microgravity on Plant

#### Growth and Development

The long-term cultivation of higher plants in space plays a substantial role in investigating the effects of microgravity on plant growth and development, acquiring valuable insights for developing a self-sustaining Biological Life-Supporting System (BLSS). In the studies on board, the researchers from the Center for Excellence in Molecular Plant Sciences, Chinese Academy of Sciences continued to conduct long-term plant research in space. Based on the so-called Biological Culture Module (GBCM), which was installed in the Wentian experimental Module of the CSS, was constructed to grow *Arabidopsis thaliana* and rice (*Oryza sativa*) plants a full life cycle in space. Dry seeds of *Arabidopsis* and rice were watered and germinated within a duration of 120 days. To this end, both *Arabidopsis* and rice plants completed a full life cycle in microgravity on the CSS. To date, this is the first space experiment achieving rice's complete life cycle from seed to seed in space. Some of these seeds have been used in a subsequent experiment to successfully produce a second generation after returning to Earth. Germination rates for space-produced seeds were about 90%, indicating that mature seeds developed in microgravity were healthy and viable. This result demonstrates the possibility of cultivating the important food crop rice throughout its entire life cycle under the spaceflight environment.

### 2.4.4 Microgravity Impairs Bone Formation by Inducing Gene Misregulation

Microgravity-related bone loss is affecting astronauts with long-term space travel due to decreased osteoblastic bone formation and increased osteoclastic bone re-

sorption. A team from Zhejiang University, focuses on the impact of microgravity on osteogenesis at the cellular and molecular levels. Transcriptomic, proteomic, and genome-wide DNA methylation analysis was performed on pre-osteoblasts and osteoblasts derived from human Mesenchymal Stem Cells (hMSCs) cultured in space station or on Earth. The results showed that microgravity impairs osteoblast differentiation and drives adipogenesis from hMSCs by disrupting disease genes of “osteoporosis” and “osteoarthritis”, as well as pathways related to glucose metabolism and extracellular matrix organization. The study also identified several potential extreme-microenvironment-sensitive molecules that could be targeted for improving osteogenesis<sup>[21]</sup>(see Figure 20).

### 2.4.5 Space Radiation Biology Research

To study the molecular mechanisms of space radiation damage and genetic mutations, a systematic biological analysis is needed for model organisms exposed to space for long periods. However, because the individual sample in the long-term space exposure receives different high-energy heavy ions, traditional big data analysis methods cannot meet the big data analysis needs of space experiment samples. According to the necessities. A scientific group from Dalian Maritime University has successfully developed Space radiation metrology and biological damage assessment technology which overcomes key technologies such as microchannel structure

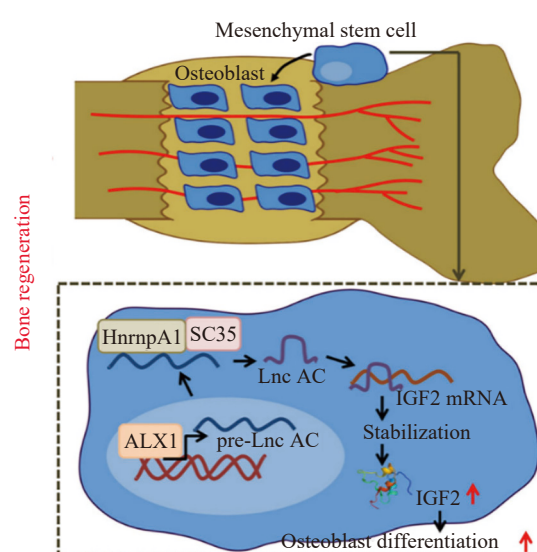


Fig. 20 AC132217.4 promotes osteogenesis and bone healing

design, fluid control, and biological matching. For the first time in the world, the automatic monitoring model of animal nematode individual horizontal growth, movement, tissue fluorescence protein labeling imaging was realized in orbit, and the whole-life tracking of various nematode species individuals was realized in situ. The results of the in-orbit analysis show that an animal experimental model of the biological effects of radiation and microgravity in orbit has been established. This work provides an experimental model for in-situ individual lifetime automatic analysis for space medicine and protection research in manned deep space exploration projects.

#### 2.4.6 Survival Limits in Space of Microorganisms from Extreme Environments

The study on the tolerance and mechanism of microorganisms to space environments aims to explore the survival limits and interstellar transmission potential of microorganisms in space, to provide a basis for research on the origin of life and exploration of extraterrestrial life and data support for planetary protection technology research, and to evaluate the ability of pioneer microorganisms to expand into outer space. The tested/testing samples included 3 types of lithic microbial samples and 8 lichens collected from cold or arid regions from Northwestern China, 10 radiation-resistant strains isolated from deserts, glacial moraines, and 2 *Bacillus* strains, isolated from the spacecraft AIT environments, with different protection conditions by different spacecraft materials. The first batch of samples was returned at the end of October 2023, and the results indicated that most of the microbial samples could survive the extravehicular environment of the Mengtian module for three months.

### 3 Research Planning and Outlooks

To make critical scientific discoveries persistently, and transfer some of the achievements into applications in the next few years. It is planned to conduct innovative research in various fields of space science.

For instance, for bioscience, space breeding of mammals is going to be realized for the first time in the world, obtaining important new targets for aging and pathology, and making breakthroughs in stem cells, promoting pharmacological research and development.

For the physical science, many highlight studies will be carried out, for instance, high-quality semiconductor crystals, rare Earth permanent magnet materials, biological and nanomaterials, *etc.* will be prepared in space and applied to the research and development of infrared detectors, scintillation crystals or other devices. Studies on space cold atom physics and their applications will become more in-depth and extensive, in particular, the research on quantum simulation and atom interferometer applications, *e.g.* ultra-cold temperature quantum gas preparation, exploring quantum decoherence mechanisms, topological quantum states studies, and expanding the in-orbit cold-atom interferometer applications on Earth science and fundamental physics testing.

The peculiar hydrodynamics under microgravity will be still of great importance to nonlinear mechanics investigation and engineering. The dynamics, especially for the evolution behavior of particulate matter in turbulence, the special flow of fluid caused by the thermal capillary phenomenon, and the rheological properties of non-Newtonian fluids will be deeply explored in the absence of gravity or low gravity conditions. In addition, the scientists who are interested in soft matter physics will have the opportunity to pursue the myths in three-dimensional collective behaviors of active matters (such as artificial active colloids, bacteria, *etc.*), investigating colloid and polymer self-assembly behavior and the other problems of statistical physics far from equilibrium. Moreover, more studies on fluid phase transition (*e.g.* evaporation, condensation, and boiling) and enhanced heat transfer mechanisms are planned, which directly strengthen the efficiency of fluid as well as thermal management in a large number of engineering fields, from ground-based applications to deep space exploration.

The studies of space combustion science will focus on basic combustion processes in the energy or power systems, such as ignition, flame propagation, flame stabilization, quenching, *etc.*, committing to solving the key problems such as efficient and low-carbon combustion or performance improvement.

These interdisciplinary studies conducted on the experimental platform of Chinese Space Station, are greatly helpful to humanity's comprehension of the open scientific principles, driving the advancement of cutting-edge technologies, expanding the scope of human activi-

ties in space, and presenting substantial benefits from these endeavors.

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