Progress of Space Sciences and Application Projects in China’s Manned Space Flight

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Abstract
Scientific results of Space sciences and application projects arranged in Tiangong-2 space laboratory and Tianzhou-1 cargo ship are described in details, covering research areas of the fundamental physics, space astronomy, microgravity fluid physics and materials science, space life science, and earth science. These experiments and researches will hopefully produce great scientific results and social benefits in several fields, including universe evolution, quantum communication, material development, global climate change and earth environment, etc.

Key words
Space sciences and application, Scientific results, Tiangong-2, Tianzhou-1, Space Laboratory, Microgravity

Over a dozen of space science and application projects are arranged in Tiangong-2(TG-2) space laboratory and Tianzhou-1 (TZ-1) cargo ship, covering research areas of fundamental physics, space astronomy, microgravity fluid physics and material science, space life science and Earth science. The projects are shown in Table 1.

Table 1  Space science and application projects onboard Tiangong-2 and Tianzhou-1

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1. Fundamental Physics

(1) Cold Atom Clock Experiment in Space

The space cold atom clock is the key instrument for next generation frequency standards and global time service. The aims of Cold Atom Clock Experiment in Space (CACES) in Tiangong-2 are to realize the operation of ultra-precision cold atom clock in microgravity at stability 10–16/day. The in-orbit operation of the CACES also includes laser cooling and manipulation of atoms, launching of cold atoms and estimation of CAES performance. In microgravity, a magneto-optic trap is used to cool and capture 87Rb atoms, which are further cooled by polarization gradient and adiabatic cooling during launching. The final temperature the cold atoms reach and the number of captured cold atoms are shown in Figure 1A and Figure 1B, respectively.

![Fig. 1](image1.png)

**Fig. 1** Results of laser cooling of atoms in CACES

The CACES uses the moving molasses technique to launch cold atoms. In microgravity, for the first time, the CACES Time Of Flight (TOF) signal is shown in Figure 2, which is a clear proof that CACES meets the operation requirement of a cold atom clock in microgravity.

![Fig. 2](image2.png)

**Fig. 2** In-orbit results of TOF signal of cold atoms

The CACES tested the operation principle in microgravity, for example, Ramsey fringes are tested at different launching velocity. At a velocity as low as 0.6 m/s, a 0.95 Hz (Figure 3A) line width of central Ramsey fringes is obtained (Figure 3A). The CACES has reached SNR=440 at 1.98Hz (Figure 3B), which corresponds to $2.1 \times 10^{-13} / \sqrt{T}$, according to the closed-loop operation of the CACES on the ground.

![Fig. 3](image3.png)

**Fig. 3** In-orbit Ramsey fringes of the CACES in microgravity

So far, the CACES has been working for more than 15 months in orbit. All units function well and operate in good condition. The results satisfy the goals of the CACES and the mission achieves a complete success.

(2) Quantum Key Distribution Experiment

The Quantum Key Distribution (QKD) system con-
consists of payload assembled on the TG-2 space lab and the ground optical stations. The space payload serves as the QKD transmitter and the ground optical station serves as the QKD receiver (see Figure 4). The experiment system also obtained the capability of space-to-ground laser communication. During a typical orbit pass, the transmitter establishes the quantum link between the space lab and the Nanshan ground station in Urumqi, Xinjiang province successfully. The transmission efficiency of the quantum keys is ~10 orders of magnitudes higher than that of terrestrial optical fiber channel at a distance of ~719 km. The final tracking and pointing precision is about 1–2 µrad. The timing accuracy of space-to-ground synchronization is better than 0.95 ns. The raw key rate is 1-5 kbps and the sifted key rate is 783 bps. The Quantum Bit Error Rate (QBER) is 1.8% and the final secure key rate is ~91 bps, which means the total keys can be as much as 13 kbits during one typical orbit pass. All the indicators meet the requirements of the mission index. At the same time, the first 1.6 Gbps laser-communication-based data transmission has also been realized (see Figure 5).

The program has realized the space-to-ground QKD experiment between a small-sized payload in the space lab and the ground station for the first time in the world. Together with the daylight QKD technology, the experiment paves the way for a satellite-constellation-based global quantum secure network with small-sized QKD payloads, lays the foundation for the establishment of an unconditional secure national quantum communication network and promotes the practical applications of QKD technology in the future.

2. Space Astronomy

The Gamma-Ray Burst Polarimeter-POLAR

The main scientific goal of the Gamma-Ray Burst polarimeter-POLAR is to measure the polarization of the prompt emissions of Gamma-Ray Bursts (GRBs)
with high precision. The polarization measurement and analysis results of GRBs detected by POLAR will be able to strongly constrain the current theoretical models of the prompt emission mechanisms of GRBs which will eventually lead to a better understanding of GRB physics and black hole formation [5].

The POLAR experiment is an international collaboration project between China and Europe, involving the Institute of High Energy Physics (IHEP) of Chinese Academy of Sciences (CAS) from China, the University of Geneva (UNIGE) and Paul Scherrer Institut (PSI) from Switzerland, as well as the National Center for Nuclear Research (NCBJ) from Poland.

POLAR makes use of the principle of Compton scattering to measure the polarization information of GRBs. Researchers can reconstruct the polarization information by calculating the azimuthal scattering angle of the Compton-scattered photons. POLAR is composed of the polarization detector (OBOX) and electric cabinet (IBOX), as shown in Figure 6. OBOX consists of 25 Detector Modular Units (DMUs) [6].

POLAR successfully detected 55 GRBs after launch, 49 of them have been announced as GCN circulars. The preliminary data analysis shows that POLAR has measured clear polarization information of GRBs. Researchers will review and verify all the analysis results in the next steps. Figure 7 shows the light curve of GRB 170206A measured by POLAR.

At the same time, POLAR has also detected the signals from the Crab pulsar which can be used for autonomous pulsar navigation research. The preliminary results have been published in the journal of SCIENTIA SINICA Physics, Mechanica, and Astronomica. Figure 8 shows the Crab pulse profile measured by POLAR in orbit.

Besides, POLAR also detected signals from the Solar Flares.

### 3. Microgravity Fluid Physics and Materials Science

#### (1) Thermo-capillary Convection in Liquid Bridge

This project aims to investigate the instability of thermocapillary convection in large Prandtl number liquid bridge and to discover the mechanism of the thermocapillary instability under space microgravity environment, expanding the recognition field of fluid mechanism [7–8]. It will provide scientific guidance for crystal growth in floating zone and obtain internationally advanced research results. This project will make a breakthrough on key technologies for space experiments, such as the establishment, the surface maintenance and the re-establishment of liquid bridge, which will further improve the space experiment capability and technical level of microgravity fluid science in China.

The thermocapillary convections of liquid bridges are investigated in the TG-2 space laboratory (see Figure 9). The aspect ratio effect and volume ratio effect on the
critical oscillation process in the thermocapillary convection are studied. Based on this, the secondary transition and other problems are discussed.

The thermocapillary convection experiment under different volume ratios and different aspect ratios was successfully completed. Up to now, more than 460 space experiments with different conditions have been completed. Compared with similar international experiments, our space experiments have obtained more abundant results about thermocapillary oscillations (see Figure 10).

This space experiment finds novel volume ratio effect which critical curves are two branches. This effect is extended to the study of aspect ratio, which expands and supplements the classic theory of volumetric effect. For the first time, the critical conditions and oscillations feature of the thermocapillary convection in the liquid bridge is obtained at different Aspect ratios ($A_r$) and different Volume ratios ($V_r$). The oscillation in the thin liquid bridge was found to be in low frequency mode, and the oscillation in the fat liquid bridge was high frequency mode. It is confirmed for the first time that the low-frequency oscillation mode transitions to the high-frequency oscillation mode through the mixed oscillation mode.

(2) Two-phase Fluid Experiment

The purpose of this project is to investigate the phase transition kinetics of liquid evaporation and condensation, gas-liquid-solid contact dynamics as well as two phase fluid transportation in microgravity, and demonstrate key technologies related to two-phase system experiment rack of CSS. It will provide theoretical foundation and data for fluid management of spacecraft, two-phase fluid heat transfer with high efficiency, and industrial applications on the ground [9]. The evolution of liquid film evaporation thermal patterns and heat flux measured at heating solid substrate on the ground is shown in Figure 12 [10].
(3) Multiple Sample Materials Processing
A Multiple sample Materials Processing Furnace (MMPF) with double zone resistance heater provides an opportunity for various material processing and formation mechanism study\cite{11-12}. The sample candidates include semiconductor, optoelectronics materials, metal alloys and metastable materials, functional single-crystal, nanometer and composite materials. The furnace is with ampoule number of 6 each batch, ampoule size of 16 mm × 260 mm, a temperature range of 500–950°C, the temperature gradient of 6–45°C·cm^{-1} and temperature stability of ± 0.5°C. The movement speed of material sample is 0.5–100 mm·h^{-1}. In the experiment, astronauts will replace the samples in orbit and send completed experimental samples back to Earth for analysis. The structure of MMPF is depicted in Figure 13.

4. Space Life Science

(1) Plant Flowering and Seed-setting in Space: Photoperiod Regulated Reproductive Development of Arabidopsis and Rice\cite{13-17}
Several previous attempts have been made to grow plants through a complete life cycle in space, but apparently, no published information exists concerning the flowering control of plants under microgravity in space. Arabidopsis thaliana and rice were used as plant materials in Chinese space lab TG-2 space experiment to investigate the effect of microgravity on seed germination, developmental phase transition and seeding under long-day and short-day photoperiod conditions, respectively. The Plant Growth Chamber (PGC) used in this experiment included two different boxes, a big main box and a small returning box (Figure 14a). The main box remained in-orbit and didn’t come background, while the returning box used for this experiment performed Arabidopsis plant grow on board TG-2 space lab and was brought back by SZ-10 astronauts (Figure 14b).

After 48 days, the returning box with Arabidopsis plants was recovered to earth for analyses. The plants in the main box remained in-orbit and finished from seeds to seeds under the Long-Day (LD) and the Short-Day (SD) conditions, respectively. Ground control experiments were carried out in parallel, but ten days later.

The seeds of Arabidopsis and rice successfully germinated, grew and developed under both the LD and the SD conditions, in space and the ground control condition. Arabidopsis completed a full life cycle in microgravity under the long-day condition and the short-day condition transferred to the long-day condition before flowering. As far as we know, this is the first time, FT gene expression was observed directly in orbit by the GFP image technique. The results demonstrate that: (1) microgravity significantly delayed the photoperiod controlling floral transition (Figure 15). (2) Downlinked images showed that expression of FT apparently up-regulated in response to microgravity in space (Figure 15). (3) Microgravity affected the photoperiod-controlling growth of rice seedlings could be related to the enhanced guttation in space (Figure 16). (4) To delineate the transcriptional response mechanisms, we also carried out whole-genome microarray analysis of Arabidopsis leaves. We identified a novel set of microgravity response genes, recognized mainly by quantitative differences. These included a transcriptome signature of more pronounced proline transport in developing leaves (Figure 17). The further analysis provides developmental stage specific molecular resolution of different age leaves and demonstrates that a new molecular plasticity in Arabidopsis leaves to adaptation to microgravity by adjusted genome status during flowering induction in space.

(2) Effect of Space Microgravity on Proliferation And Differentiation of Embryonic Stem Cells
Gravity is necessary to help maintain normal physiological processes in the human body on Earth. Microgravity may cause changes in cell spreading, migration, contraction, and division. Although much earth-bound simulated equipment (e.g., the High Aspect Ratio Vessel (HARV), the Rotating Wall Bioreactor (RWB), the
**Fig. 14** Culture chamber and the experiment equipment used in the TG-2/SZ-11 experiments. (A) plant growth chamber, which consists of the electric control box, the Orbit Growth Unit (OGU), which doesn’t come back and remains in orbit on the TG-2; the Recoverable Growth Unit (RGU), which returned with the SZ-11 spacecraft. (B) The detail mechanical set up for plant growth chamber in A. (C) Schematic diagram illustrating the experiment design for Arabidopsis and rice plants grown under the Long-Day (LD) and the Short-Day (SD) photoperiod conditions, onboard TG-2 Spacelab and the samples came back with the SZ-11 spacecraft. (D) Verification test of Arabidopsis and rice grown in the plant growth box.

**Fig. 15** Examples of images of Arabidopsis plants grown under MicroGravity (MG) onboard TG-2 (A-J) and the controls on the ground (1G) (K-T) under the long-day condition. (A-C) images took in flight 9, 50 and 77 days, respectively, after plant germination. (E-J) the green fluorescence of the GFP images of the TG-2 grown Arabidopsis plants. (E) An enlarged image of G. (N-T) the green fluorescence of the GFP images of the ground controls.
Fig. 16  Examples of rice plants grown in space (upper panel) or on the ground (lower panel) under the long-day condition at times from day 15 to day 24, showing guttation fluid on rice plants.

Fig. 17  Transcriptional responses of Arabidopsis to microgravity in space in comparison with their ground control. (A) Among 22746 genes presented on the GeneChip used in this analysis, 6195 genes exhibited changed expression in the MicroGravity (MG) grown plants (B) in comparison with their controls on ground (C). 1871 genes are found leaf specific response to microgravity, in which 1057 genes are related to leaf development and 46 genes could participate in plant adaptation to microgravity. (D) Number of Differentially Expressed Genes (DEGs) in response to microgravity of leaves of plants grown in space on the TG-2 in comparison with their controls on the ground. (E) Venn diagram of differential expression genes in response to microgravity in four selected leaves of the plants on the TG-2 in comparison with their controls on the ground. (F) Scatter plot of differential expression genes in response to microgravity in the indicated leaves. L1, L3, L5, and L7 are corresponding to leaf1, leaf3, leaf5 and leaf7.
Rotary Cell Culture System (RCCS), and the 3D clinostat) has been used to study the effect of microgravity on cell and tissue growth, spaceflight experiments offer a unique opportunity to assess the effect of real microgravity on cell and tissue function. Embryonic Stem Cells (ESCs) have the capability to self-renew and differentiate into all cell types. Due to their unique properties, ESCs provide a great model for studying stem cell responses to microgravity and hold great promise as a robust cell source of tissue engineering in microgravity. So far, studies on pluripotent ESCs under microgravity conditions are rare and controversial. In addition, despite a great number of studies analyzing the effects of microgravity on stem cell proliferation and differentiation, few of them has focused on what happens in such processes while the cells are in orbit. In this study, the real microgravity environment in the TZ-1 cargo spacecraft, the automatic cell culture equipment, and the live cell imaging techniques were utilized to examine the effects of microgravity on the morphology, proliferation, and differentiation of mouse Embryonic Stem Cells (mESCs).

The research objectives of this study are to get an initial understanding about whether the mechanical unloading effect on self-renewal of pluripotent stem cells in real microgravity; whether the real microgravity environment

This study possibly leads to a new understanding of the effect of space microgravity on the proliferation of pluripotent stem cells and initiation of their early differentiation and it may be critical in understanding the fundamental mechanisms of stem cell repair and regeneration and Earth-based degenerative conditions. Alterations to fundamental stem cell properties may have significant implications for the establishment of cell growth and tissue engineering in space.

In this study, Oct4-GFP mESCs were prepared and seeded in space cell culture chamber (Figure 18). The cell samples were seeded into each chamber and launched to space on April 20, 2017. 2 hrs after the spacecraft arrived in the orbit, the cell culture medium was changed automatically, and the images in space were proceeded synchronously. hundreds of high-resolution mESC photos growth in space were analyzed. It was found that mESCs exhibited features of 3D growth, survived longer, and retained greater stemness markers in the space microgravity environment (Figure 19). In addition, Brachyury-EB was also used to investigate the differentiation of stem cells in space, it was found that although EB could differentiate into mesendoderm lineage in the space environment, these differentiated cells maintained high expression of Brachyury after 15 days of culture (data not show).

Fig. 18 Pluripotence Oct4-GFP mESCs were used in this study, which expressed Oct4 and Nanog. Bar=50 μm

Fig. 19 Representative bright-field and fluorescence images of mESC culturing in space environment using the developed automated culture system. Bar= 100 μm

(3) Effects of Microgravity on Proliferation of Hepatic Stem Cell Lines

Liver stem cells is a kind of cells with multiple differentiation potential, which can be induced into hepatocytes and bile duct cells, and it is considered as ideal seed cells for cell therapy and artificial biological function. However, the premise of cell therapy is to get enough cells in vitro. In the liver parenchyma cells, only the liver stem cells are capable of amplification. The previously flat cultivation of liver stem cells may lead to
disappearing of some pivotal phenotype and function of cells, as well as the change of the cell biological characteristics and slower proliferation, thereby can’t meet the demand for liver stem cells. It has been reported that the simulated microgravity promotes liver stem cell proliferation, but the influence of the real microgravity in space on three-dimensional culture and proliferation of liver stem cells remains unknown. The objective of this study is to investigate the effect of microgravity on the proliferation of rat WB-F344 cells.

In this project, the liver stem-like cell line WB-F344 was carried on the Tianzhou-1 spacecraft and the effect of microgravity on the proliferation of WB-F344 was observed in space during the three-dimensional culture. Cells were attached to the micro-carrier surface for suspension culture. The changes in cell morphology and density were observed through space microphotography and image transmission technology. By comparing with the ground control images, researchers hope to explore the effect of microgravity on the proliferation of liver stem cells and provide a basis for the establishment of the expanded training system of liver stem cells in the future (Figure 20). Compared with the control group, the density of liver stem-like cells WB-F344 was significantly increased in space, suggesting that microgravity promotes the proliferation of liver stem cells (Figure 21).

(4) Microgravity in space Promotes Regeneration and Myocardial Differentiation of Induced Pluripotent Stem Cells

Space microgravity has wide impacts on human bodies, such as arrhythmia, cardiac atrophy, osteoporosis and muscle atrophy, which seriously threaten the health of astronauts.

The discovery of inducible Pluripotent Stem Cells (iPSCs) is a new milestone in the field of life science. Consideration of the superiority of multiple differentiation potential, free of ethical issues, ease of availability, iPSCs are ideal cells for studying the individualized cardiac development. The function of stem cells depends on their characteristics and the surrounding environment. Using the launch opportunity of the TZ-1 spacecraft, the effect of space microgravity on the regeneration and myocardium differentiation of iPSCs was studied.

Oct4 is a key protein to regulate the pluripotent activity of iPSCs. Expressed in cardiomyocytes, αMHC is one of the specific markers of cardiac development. Therefore, researchers constructed mouse OCT4-EGFP-iPSCs and αMHC-EGFP-iPSCs, which Enhanced Green Fluorescence Protein (EGFP) expressions were driven by Oct4 or αMHC gene promoter. This EGFP reporting system could selectively denote the myocardial differentiation status of iPSC.
OCT4-EGFP-iPSCs were loaded in 2 culture units of the bioreactor, which were filled with cell proliferation medium. Embryoid Bodies (EBs) derived from OCT4-EGFP-iPSCs and αMHC-EGFP-iPSCs were inoculated in 6 culture units and connected to cardiomyogenic differentiation culture medium. Then the bioreactors were integrated into the TZ-1 spacecraft. The ground control experiment was carried out under identical conditions to the spaceflight except for exposure to 1g ground gravity of earth.

In the microgravity (μG) group and the ground (1G) control group, the OCT4-EGFP-iPSCs clones were similar in size, compact with highly Oct4 expression before the launch of TZ-1. The size of cells clone in μG group increased rapidly in the day 1-3 after launch (DAL1-3). The clones gradually became loose and Oct4 decreased significantly. After DAL4, the clones grew in three-dimensional style and restored Oct4 expression. In the 1G experimental group, the Oct4 dribbled away and didn’t recover before DAL 10. These results showed that iPSCs regenerate well under the condition of spatial microgravity, and the spatial microgravity enhances the proliferation capacity of iPSCs (Figure 22).

At DAL1-4, the sizes of EBs from the two iPSCs lines increased slightly and then were relatively stable. EBs from OCT4-EGFP-iPSCs robustly expressed Oct4 before launch. Compared with the 1G control group, the Oct4 expression of EBs in the μG group dropped more dramatically at DAL1 and DAL2 (P < 0.01). Meanwhile, the EBs from αMHC-EGFP-iPSCs displayed green fluorescence before the emission. The αMHC expression was obtained at DAL4 (P < 0.05) and then reached to a relatively high level. The results of two iPSCs lines mutually confirmed the correct myocardium differentiation under the space microgravity, and the spatial microgravity accelerated the process (Figure 23).

Taken together, this study demonstrated for the first time that space microgravity promotes regeneration and myocardial differentiation of iPSCs. More space experiment should be performed to further confirm and unveil the underlying mechanisms of changed organization and function. This strategy also may be used in the fields of tissue engineering, drug screening, and disease predictions for boosting the health of humanity in the future.

(5) Effect of 3-hydroxybutyric Acid On Osteoporosis under Microgravity

The number and morphological changes of osteoblasts were observed under the condition of co-culture
containing or not containing 3-Hydroxybutyric acid (3HB)\textsuperscript{[18]}. Furthermore, the healthy growth of these cells in space was analyzed, and the therapeutic effect on osteoporosis was observed at the cellular level.

By comparing the images of different groups (the 3HB group and the control group) of cells, it is first found that 3HB could also promote fast growth of osteoblasts and keep the activity of cells under microgravity conditions in space (Figure 24 and Figure 25). And it is confirmed that 3HB has no significant interference with osteoblasts under microgravity conditions in space, which means that 3HB is also a potential anti-osteoporosis drug under microgravity conditions in space (Figure 26). Meanwhile, this study also found that the growth, apoptosis, and death speed of osteoblast in the flight testing are slightly faster than that in the ground test, which further confirmed that the apoptosis of osteoblast could be increased under microgravity conditions in space.

Therefore, this experiment confirmed 3HB has indeed promoted the growth of osteoblasts under zero-gravity conditions in space. 3HB could be a new potential medicine against osteoporosis for astronauts in space, and it could also be developed for the anti-osteoporosis drugs available for people on earth. 3HB has the academic significance as well as commercial value.

(6) Effect of Microgravity on the Function of Bone Cells

During long-term spaceflight, the microgravity-induced bone loss will threaten the astronauts’ health and hinder their performance efficiency. The previous studies demonstrated that the short or medium time exposure to microgravity has an adverse effect on the function of bone cells \textsuperscript{[19]}. For instance, the osteoblastic bone formation is inhibited and osteoclastic bone resorption is enhanced, which leads to destroy of skeleton homeostasis, deterioration of bone structure and decline of skeleton mechanical property. In this study,
researchers utilize the longtime space flight chance of the Chinese First Tianzhou-1 (TZ-1) cargo spacecraft and investigate the real-time changes of morphology and proliferation of osteocyte MLO-Y4 and osteoblast GFP-labelled MC3T3-E1 under the microgravity environment. In addition, the nodule formation of differentiation-induced osteoblast was also detected by in orbit alizarin red S staining procedure.

The results show that after 7 days flight, the morphology of osteocyte MLO-Y4 changed significantly from stellate to the spindle-like shape, but its proliferation rate was similar to the cells in the ground control group. For osteoblast, 7-day space flight led to the shrink of cell morphology, decrease at the proliferation rates and the attenuation of intracellular GFP fluorescent intensity. It was indicated that the microgravity suppressed the growth and activity of osteoblasts (Figure 27). Furthermore, after 14-day or 21-day spaceflight, the classical alizarin red S stained nodules in the differentiation-induced osteoblasts were hardly found. However, the GFP fluorescent intensity in the osteoblast under microgravity enhanced significantly compared with the ground control. It is suggested that during the long-term exposure to the microgravity environment, the confluent osteoblasts still maintain the tendency of three-dimensional growth. This research revealed the cellular mechanism of space bone loss and provided further evidence for the verification and evaluation of ground-based simulated microgravity experiment results of bone cells (Figure 28).

During 7 days space flight, the cells were photographed with the in-orbit bright field and fluorescence microscopy. The results showed that the growth rate of osteocyte MLO-Y4 was similar to the cells in the ground
control, and its morphology changed distinctly from stellate to the spindle-like shape. 7-day space flight led to the shrink of osteoblast morphology, decrease at the proliferation rates and the attenuation of intracellular GFP fluorescent intensity.

After 14-day or 21-day spaceflight, there were rarely classical alizarin red S stained nodules in the differentiation-induced osteoblasts. The GFP fluorescent intensity in the osteoblast under microgravity enhanced significantly in comparison with the ground control.

(7) Role of CKIP-1 in the Differentiation of Osteoblast in Space Microgravity Circumstance

The Casein Kinase 2 Interacting Protein-1 (CKIP-1) is previously identified as a negative regulator of osteoblast activity that could interact with the Smad ubiquitination regulatory factor 1 (Smurf1) to facilitate the ubiquitination and subsequent proteasomal degradation of the signal transducers in canonical BMP pathway. The research team further found that the aberrant elevated CKIP-1 expression in osteoblasts could directly inhibit bone formation to contribute to the bone formation reduction during aging as well as in the development of glucocorticoid-induced osteoporosis.

On the other hand, the microgravity in space could lead to bone formation reduction, which is one of the biggest challenges to the bone health of astronauts during space travel. However, the role of CKIP-1 in the microgravity-induced bone formation reduction maintains unknown. This project studied the effect of osteoblastic reduced CKIP-1 expression on the differentiation function in microgravity, which would not only uncover the regulatory mechanism on bone formation in microgravity circumstance but also provide a potential therapeutic strategy for protecting the astronauts from bone loss during space travel.

In aircraft flight test, carbon dioxide-independent MC3T3-E1 osteoblastic cells with stable low CKIP-1 expression were loaded and cultured in the bioreactor of the Tianzhou-1 aircraft. 20-fold microscopic images showed that the CKIP-1-silenced MC3T3-E1 osteoblastic cells maintained good state in microgravity for 21 days (Figure 29). Some mineralized nodules can be observed (Figure 29).

Fig. 28 Detection of nodule formation in the differentiation-induced osteoblast MC3T3-E1 under medium and longterm spaceflight or the ground environment

Fig. 29 20-fold microscopic images of CKIP-1-silenced MC3T3-E1 osteoblastic cells. (a) CKIP-1-silenced MC3T3-E1 osteoblastic cells loaded in a bioreactor for 5.5 hours before lunch. (b) CKIP-1-silenced MC3T3-E1 osteoblastic cells in microgravity for 1 day. (c) CKIP-1-silenced MC3T3-E1 osteoblastic cells in microgravity for 21 days, with mineralized nodules in red circles.
5. Earth Science

(1) Wide-band Imaging Spectrometer

The Push-broom Wideband Imaging Spectrometer (PWIS) is a seawater color remote sensing instrument mounted on Tian Gong-2 space lab. It’s designed to meet the next generation requirement of high performance monitoring on water color and water temperature of ocean/coastal zone.

The PWIS, which covers 14 programmable visible and near-infrared channels (range 0.40–1.40 μm), 2 shortwave infrared channels (1.232–1.252 μm and 1.63–1.654 μm) and 2 thermal infrared channels (8.125–8.825 μm and 8.925–9.275 μm), addresses the challenges of high sensitivity surveillance of ocean and coastal water color and temperature. The spatial resolutions at the nadir of the three bands are 100 m, 200 m and 400 m. The imaging spectrometer incorporates push-broom scan and multiple module FOV stitch technologies to achieve 300Km’s swath with 42° general FOV.

PWIS’s radiometric resolution in each channel is very high, SNR invisible wave main channels are larger than 500 at typical ocean radiance. The instrument’s average NEAT in thermal infrared channel T1 is less than 15 mK (300 K), which is the best among similar instruments in-orbit. On-board visible and shortwave infrared radiation calibration is done by a full FOV and aperture calibrator housed in the instrument with the internal reference radiation source. The calibration unit consists of pointing mirror, halogen lamp, and surface blackbody, and calibrates by rotating the mirror to point to the lamp and blackbody. Due to weight and size restriction, the in-orbit calibration is elaborately designed to achieve high application precision (Figure 30).

After the launch with Tian Gong-2 Space Lab, PWIS was turned on and worked fine. The Images captured are clear and rich in layers. Figure 31 is the first VNIR, SWIR and TIR spectrum images captured after reaching working orbit. In-orbit imaging and tests afterward carried out in-orbit spectral and radiances calibration tests for this instrument. Basic performance tests have been completed now and high quality seawater color and temperature images have been captured. It has been proved that the ground resolution, swath, dynamic MTF, radiance detection sensitivity and other characteristics fulfill project requirements.

Water color and temperature remote sensing inversion accuracy of the PWIS are evaluated using the typical spectral imaging data captured during in-orbit tests, after processing the data by radiance calibration, geometric locating and atmosphere correction. The relative error of water consistency of suspended substance and water chlorophyll concentration are all less than 40%, mean square root error of sea surface temperature is less than 1°C.

Test results proved that PWIS remote sensing products reached expected accuracy. PWIS has better spatial conformity and value compared to GOCI in detecting near coastal water consistency of suspended substance. With 100 m spatial resolution, PWIS can distinguish the spatial structure of the material much more clearly than instruments of 500 m resolution and can survey consistency of
suspended substance in rivers and medium or big lakes. With regard to continental and oceanic water body chlorophyll concentration detections, PWIS’ inversion calculation result is the same as MODIS and VIIRS and has finer distribution spatial structure and can distinguish small size vortex and frontal surface structure.

As a sea water color and temperature remote sensing instrument on TG-2 space lab, PWIS has the highest ground resolution among in-orbit sea water remote sensor in the world. In-orbit tests show that PWIS has good consistency and excellent water color detection ability compared to other instruments and is finer in spatial scale.

(2) Interferometry Imaging Radar Altimeter (InIRA)\cite{20–21}

Interferometric Imaging Radar Altimeter (InIRA) is a new type of microwave remote sensor for oceanography and sea surface height measurement. It adopts short baseline and small incident angle technology and robust height tracking algorithm to realize wide swath observations, representing a new generation of radar altimeter with wide swath, highly accurate sea surface height measurement and imaging capabilities. Compared with traditional SAR and InSAR, InIRA images have higher SNR and better coherence for water areas because of its small incident angle. Compared with traditional radar altimeters, InIRA has the advantages of the wide swath, imaging ability, and land-sea compatibility.

InIRA was launched with Tiangong-2 on 15 September 2016, which is designed by National Space Science Center (NSSC), Chinese Academy of Sciences. In on-orbit operation stage, InIRA conducted observations on the land/ocean calibration field to validate the performance of resolution, swath, and land/sea height measurement accuracy (Figure 32).

Fig. 32 Images taken by InIRA. (a) 2016.09.23 Rain cells observed in Philippines Sea. (b) 2017.03.14 Philippines Visayan sea image, many vessel wakes. (c) 2016.09.23 Obtained amplitude image (above) and DEM (bottom) of the Gibson desert, Australia. (d) 2016.09.23 Three-dimensional sea surface image in the Eastern Pacific Ocean
After nearly two years of in-orbit operation, InIRA has accumulated a large amount of land/ocean observation data and application results. (1) Obtained a large number of observations of typical ocean phenomenon, such as swell waves, internal waves, oil spill, ocean front, ocean eddy and rain cells; (2) Based on interferometric measurement principle, InIRA adopts symmetrical design to achieve high-precision interferometric phase measurement. The coherence of dual-channel interferometric phase is better than 0.02°; (3) Developed high resolution imaging algorithm, high precision location algorithm, and baseline correction method for InIRA to achieve 8.2 cm sea surface relative height measurement accuracy; (4) The first application of space-borne 300 W Ku-band long-life-time Solid State Power Amplifier (SSPA) in the world.

(3) Multi-band Ultraviolet Limb Imager[22–23]

This instrument will obtain ultraviolet and wider bandwidth spectrum emitted from Earth atmosphere by limb observation. There are two limb spectrum imagers, The Limb Imaging Spectrometer (LIS) and The Annular UV Imager (AUI), and they have been launched with TG-2 Space Laboratory (Figure 33).

These two payloads have a strong complementarity, the AUI provides the macrostructure of the multi-directional spatial distribution and dynamic of the atmospheric radiation, while the LIS provides a precise structure of the orientation. This is the first time in China to use the approach of limb UV sounding to carry out atmospheric detection, which can realize the atmospheric density and ozone and other atmospheric trace gas remote sensing at the same time. LIS can attain limb atmospheric height of 10–60 km with 290–1000 nm on its CCD detector (Fig.34), while AUI observes both 5° nadir sight and six limb azimuths with 10–80 km height in 3 UV bands (Figure 35). The detected limb radiation has been used for inverting the three-dimensional vertical distribution of O₃, NO₂, and SO₂.

The study will improve understanding of the interactions of different layers of the atmosphere, and the relationship between solar activity and atmosphere processes[24–25].

6. Validation of Key Technology

(1) Test of a Key Technique for Non-Newtonian Gravitation Force Detection in Space

The space-borne non-Newtonian gravitational force detection was proposed to test whether the gravity in micron-level distance is in accordance with Newton’s
Law using the space micro-gravity environment\textsuperscript{(26)}. This mission is of great significance in unifying all four fundamental interactions, the exploring for the new interaction and so on. The first step of the mission is in-orbit verification of the precision electrostatic suspension accelerometer, which is the key technique of the non-Newtonian gravitational force detection mission.

Since 2014, facing up to the space gravitational experiments requirement, the research group developed a precision electrostatic suspended accelerometer flight model (Figure 36) for the project TZ-1 cargo spaceship--the verification of the key technique for non-Newtonian gravitational force detection\textsuperscript{[27]} based on the previous 14 years space accelerometer study and research experiences\textsuperscript{(27)}.

![Fig. 36 Flight model for the verification of the key technique for non-Newtonian gravitational force detection](image)

TZ-1 cargo ship was launched to space on April 20, 2017; the accelerometer for “the verification of the key technique for non-Newtonian gravitational force detection” in the spaceship was switched on to start its work on April 29. During operation period, the accelerometer works well in orbit and all of its functions and performances are tested to be normal. In-orbit experimental results not only further verified the research mechanism but also enhanced the technological reliabilities of the accelerometer. The accelerometer measured the micro-gravity level of the spaceship in both the spaceship and TG-2 combination flight period and independent spaceship flight period. Especially in low frequency bandwidth, the micro-gravity measurement of the combined flight body achieved an unprecedented level, and its performance is the best in-orbit acceleration measurement level achieved in our country nowadays. It directly leads to the discovery of several new resonant modes, which could be useful for space station design. During this space test experiments, the accelerometer also jointed cooperation experiments with the active vibration isolation system, which was developed by the Technology and Engineering Center for Space Utilization of Chinese Academy of Sciences, and then obtained a series of significant results during the in-orbit experiments. The accelerometer not only measured and evaluated the performance of the vibration isolation system but also provided very important information for its further development. To sum it up, the experiment was a complete success, and all of the in-orbit experimental results of the accelerometer satisfied the key technique test requirement for the non-Newtonian gravitational force detection mission, which provides an important foundation for country's gravity field recovery missions and space gravitation experiments.

\textbf{(2) Validation of Microgravity Vibration Active Isolation System Technique}

Spacecraft is an ideal platform for microgravity science experiments. Since the microgravity environment is easily affected by vibrations on the spacecraft, the active isolation technology is used to realize better vibration isolation and achieve a higher microgravity level. Till now, the United States and Canada had developed and applied ARIS, STABLE, MIM systems in the International Space station, while MAIS (Microgravity vibration Isolation System) is developed by China at the first time. This technology needs to be validated in order to put forward the construction of the ultra-microgravity platform on Chinese Space Station in the future and serve for more and more micro-gravity science experiments, as well as some on-orbit serving payloads and precise optical instruments.

Firstly, the objective of this project is to validate the key technology of six degree-of-freedom electro-magnetic active vibration isolation and test the function and performance of the MAIS system. Secondly, it is to provide the long-term high-level microgravity environment for another payload in Tianzhou Cargo Ship named electrostatic suspension accelerometer\textsuperscript{(28)}.

The experiment device is separated into two parts named Main-body and Controller. The main body is composed with a stator and a floater and the payload is set up on the floater in the main body, and all of them are protected in a shielding case. The stator and floater are isolated by electromagnetic forces suspension control, so the floater is less affected by the vibrations on the spacecraft. The controller works on a closed-loop control procedure, which samples acceleration and relative position signals, calculates the feedback current to drive electromagnetic coils\textsuperscript{(29)}. 
MAIS works in Tianzhou Cargo Ship for 84 days, and the on-orbit experiment results show that the vibration-isolation capability is about 0–40 dB between 0.01 to 100 Hz. This performance is better than MIM and STABLE, and is equivalent to ARIS, which indicates that the performance of MAIS has been on the leading level in the world.

From the data of another payload of electro-static suspension accelerometer, the microgravity level can be up to the level of \(10^{-6}\) m/s\(^2\) when Tianzhou Ship is on the stationary phase, which exceeds previous expectation. The longest working time of MAIS is 9.5 days and during this time, MAIS is autonomously controlled and kept stable continuously even if the spacecraft carries out the big-angle attitude maneuver for many times.

Moreover, five control algorithms and more than 30 groups of parameters are tested on-orbit, and all these experimental algorithms are validated to be convergent and stable. The excitation control by reference input of different frequency, amplitude and direction are also tested, which validates the function for providing the excitation input for payload on MAIS (Figure 37). Four times of locking and unlocking is carried out on orbit, and it validates the function of autonomous capturing and locking function. All of above experiments on MAIS system are successful and lay a solid foundation for the further mission\(^{[30]}\).

(3) Space Experiments of Evaporation and Condensation—Technical tests for Two-phase System Research Rack in CSS onboard TZ-1 Spaceship-Cargo\(^{[31-34]}\)

Motivated by the further knowledge of the physical mechanisms in the two-phase fluids system and heat transfer behaviors in microgravity environment in space engineering, a dedicated space experimental facility applied in the two-phase research field was firstly manufactured to perform experimental investigations of phase change heat and mass transfer during evaporation and condensation process, technical tests of two-phase loop thermal control onboard Chinese TZ-1 Spaceship-Cargo (Figure 38). Experiments were performed successfully during the total 234 hours’ working time in orbit. (i) The comprehensive experimental investigations of phase change during evaporation and condensation were firstly performed, which is helpful to understand the influence of gravity effects on the heat and mass transfers during phase change process. (ii) In the framework of technical validation for development of the Two-Phase System Research Rack for CSS, thermal control techniques for the liquid-pump-driven two-phase fluid system, fluid management techniques for liquid storage in orbit, liquid injection and gas-liquid separation in space experiments, experimental techniques for combined conditions control and optical observations were successfully tested and supplied referenced technical data. In summary, the space task achieved a full success to obtain abundant scientific and technical test data.
coefficients. It was found that the gravity effect had a distinct influence on the phase change heat and mass transfer, with obvious different convective cells in the thermal fields (Figure 40).

The “Vapor Clouds” phenomenon was first investigated during evaporation in space, which was helpful to study the pure diffusion progress at the liquid-gas interface in the absence of buoyancy convection (Figure 41). The “Condensation evolution” was investigated in space; the onset of condensation was successfully recognized by thermal measurements and optical investigations (Figure 42). It was found that the heat transfer efficiency induced by condensation worsen than ground, owing to the condensation liquid film stabilized by surface tension in space (Figure 43).
The “Two-phase thermal control loop” was tested in space, it was found that the loop worked stably to satisfy the requirement for temperature control and heat dissipating in microgravity. Besides, the gas-liquid separator technique based on condensation was also tested to obtain a more than 67% separating efficiency (Figure 44).

References


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