National Aeronautics and Space Administration

2025 INTERNATIONAL SPACE STATION

Annual Highlights of Results

Annual Highlights of Results from the International Space Station

Oct. 1, 2024 – Sep. 30, 2025

A product produced for the International Space Station Program Science Forum

The Program Science Forum (PSF) includes members from participating agencies:
- ASI (Italian Space Agency)
- CSA (Canadian Space Agency)
- ESA (European Space Agency)
- JAXA (Japan Aerospace Exploration Agency)
- NASA (National Aeronautics and Space Administration)
- State Space Corporation "Roscosmos"

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Visit the **Space Station Research Results** webpage to access all past and current editions of the *Annual Highlights of Results from the International Space Station*.

LETTER FROM THE PROGRAM SCIENCE FORUM

On Nov. 2, 2025, humanity marked a cosmic milestone: 25 years of continuous human presence on the International Space Station. This achievement is a testament to international collaboration, human ingenuity, and dedication to the mission of our laboratory in low Earth orbit.

Those 25 years have seen a variety of scientific breakthroughs, exemplifying the station's enduring impact on science, technology, and exploration. The space station is a proving ground to develop new systems and technologies for missions beyond Earth that will enable our future explorers to thrive, such as testing new methods for deep space navigation and laser communication, exploring novel nutrition sources, and discovering 3D printing innovations with materials from simulated lunar regolith to human tissue. The space station has also contributed to improving critical life support systems and validating countermeasures to maintain astronaut health. Research aboard the space station not only pushes humanity farther into the universe but has also refined advanced materials such as semiconductor crystallization and investigated complex human health issues on the ground. Space station research has provided new insights into treatments for diseases like cancer, Alzheimer's, Parkinson's, and heart disease, and enabled the growth of high-quality stem cells to develop new regenerative therapies.

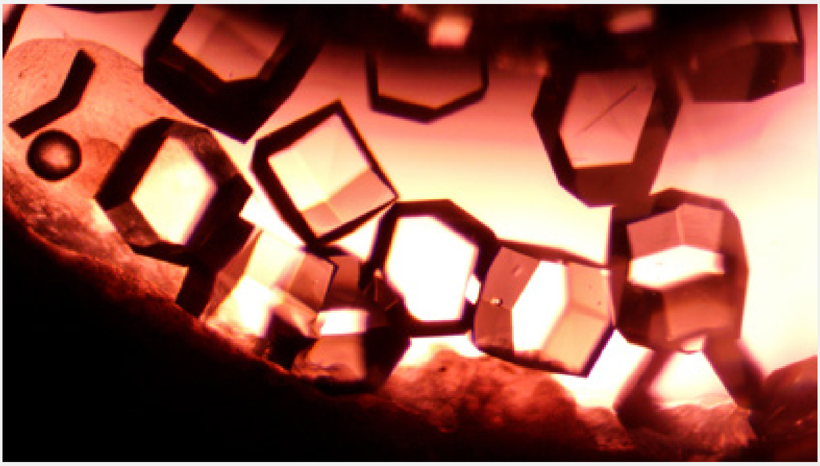
In 2025 alone, more than 750 experiments supported exploration missions, improved life on Earth, and opened commercial opportunities in low Earth orbit. This year saw us deepening our understanding of our Sun, exploring medical implants to support nerve regeneration, and the U.S. Food & Drug Administration approval of an injectable medication used to treat several types of early-stage cancers that was informed by research aboard the space station.

The 2025 Annual Highlights of Results includes a small subset of the scientific achievements across the space station partnership, showcasing the exceptional and diverse research capabilities of the orbiting laboratory and the global teams working around the clock to support its mission. The space station continues to drive innovation by enabling human exploration of the Moon and Mars, transforming medical research, deepening our understanding of the universe, and spurring a robust commercial economy in low Earth orbit.

We are excited for the future of the International Space Station, for new innovative ideas and the continuation of successful research as we continue into our third decade of science.

KEY TAKEAWAYS

- A total of 508 publications were collected in Fiscal Year (FY) 2025. These include peer-reviewed scientific articles as well as other forms of literature, such as books and patents. Approximately 80% of the publications collected in FY25 were associated with NASA research.
- In FY25, approximately 63% of the publications reported results in Earth and Space research, primarily from investigations associated with NASA and JAXA.
- Approximately 60% of the publications collected in FY25 were Derived Results, indicating a strong return on investment. Derived results are primarily generated from studies that use openly available data to make new discoveries. This represents a 19% increase compared to the previous fiscal year.



ADSEP-PIL-02 *lysozyme crystals grown in Redwire's Pharmaceutical In-space Laboratory. Lysozyme plays a critical role in innate immunity, helping protect against bacteria, viruses, and fungi. NASA ID: jsc2024e038397.*

- A total of 4,943 publications have been screened and archived since the station began operations, representing the breadth and impact of research conducted onboard.
- From 2014 to 2024, the publication rate grew by approximately 7.4% per year. Publication growth rates differ by space agency.
- A total of 935 publications, approximately 20% of station results, have been published in top-tier journals. Nearly 85% of top-tier research has been published since 2018.
- Over 100,000 total citations were identified, underscoring the widespread dissemination and utilization of station-generated knowledge.
- Between 2002 and 2024, international research collaborations between countries grew at a faster rate (20% per year) compared with domestic collaborations within individual countries (8.9% per year). While international collaborations for station research are associated with higher citation impact, this effect may vary by research discipline.
- Partner agencies sustain extensive collaborations across multiple sectors, including academia, industry, and medical institutions. Academic research serves as a primary driver of investigations in Biology and Biotechnology, Earth and Space Science, and Physical Science.
- Across all partner agencies, the number of investigations consistently exceeds the number of facilities, demonstrating that research productivity on the station goes far beyond the development of infrastructure.

INTRODUCTION

Orbiting 250 miles above Earth, the International Space Station has served as a home, laboratory, and testbed for new technologies for more than 25 years. During this time, 290 astronauts have carried out thousands of cutting-edge experiments in space. To date, over 4,000 investigations aimed at improving life on Earth have been conducted aboard the station. These studies span a wide range of disciplines, including biology and biotechnology, physical science, Earth and space science, technology development, and human research. The breadth of this work is reflected in science results published across more than 1,800 sources – including peer-reviewed journals, conference proceedings, books, and patents – and its impact is demonstrated by more than 100,000 scientific citations worldwide.

The space station offers a unique research environment of sustained microgravity, unlike Earth-based methods such as parabolic flights or drop towers that offer only brief periods of reduced gravity. This continuous exposure to microgravity allows researchers to study fundamental physical and biological processes under conditions where key variables – such as sedimentation, buoyancy, convection, hydrostatic pressure gradients, mechanical loading, and shear forces – are significantly reduced. Combined with elevated levels of space radiation, these persistent changes make the station an unparalleled laboratory for investigating how this altered physical environment affects processes such as protein crystallization, cell growth and differentiation, material behavior, and fluid dynamics.

Thanks to the coordinated operation of a vast and complex system – including hundreds of crewed and cargo flights and more than 1,500 facilities that provide the infrastructure and equipment necessary for research – scientists aboard the station have made groundbreaking discoveries in human body adaptation, plant growth, cosmic events, material science, tissue regeneration, in-space manufacturing and much more. In turn, this research informs agricultural monitoring, drug development, and life-support systems to improve life on Earth and help pave the way for NASA's Moon to Mars missions and commercial space activities in low Earth orbit.

What began as a dream has grown into the world's largest international partnership, where science serves as the common language. This collaboration has brought together numerous academic institutions, corporations, and funding agencies around the globe to produce high-quality, impactful research. Fields that once seemed distant and disconnected have become emerging disciplines, inspiring new generations of students, researchers, and organizations to seek solutions and drive innovation.

The research highlighted in this report is just a small sample of the work conducted on the station in the past 12 months. Many more groundbreaking results were reported in FY25, including:

- An anti-COVID drug complex remained chemically stable and without signs of degradation during spaceflight (**ICE Cubes Experiment Cube #6 – Kirara**).
- Spaceflight suppresses innate immune signaling in the brain's immune cells of mice, which may influence inflammation-related conditions in astronauts (**Rodent Research-1 CASIS**).
- Artificial gravity can help protect the eyes of crew members in space (**Joint Partial-gravity Rodent Research/Mouse Habitat Unit-Fuller**).
- Accurate satellite calibration requires accounting for the Sun's illumination angle at ground reference sites (**DESIS**).

On the station, scientists conduct both fundamental and applied research, and each drives progress in the other. Studies that explore basic questions about physics, biology, and human health often lead to real-world innovations that improve life on Earth and help humans thrive in space. For example, research on fluid behavior informs the design of spacecraft fuel systems and medical devices, while cell biology studies guide new treatments and health countermeasures for astronauts. Together, these efforts show how science on the station is transforming our future through global collaboration, curiosity, and ingenuity.

Information on space station investigations, facilities, and publications is publicly available on the **Space Station Research Explorer (SSRE)** website.

BIBLIOMETRIC ANALYSES: MEASURING SPACE STATION IMPACTS

Literature related to space station research results – including scientific journal articles, books, patents, and more – is collected, curated, and linked to individual investigations. The content from these publications is classified according to how the results are obtained. The current classifications are:

- **Flight Preparation Results** - Publications reporting development work performed for an investigation or facility prior to its operation on the space station.
- **Station Results** - Publications reporting the performance and outcomes of an investigation or facility during its operation on the station or aboard a vehicle bound for the station.
- **Derived Results** - Publications that use open data from an investigation conducted on the station. Access to raw data by new researchers helps expand global knowledge and maximize scientific benefits.
- **Related** - Publications that indirectly contributed to the development of an investigation or facility. To date, over 2,400 publications have been identified as Related. These publications are not included in the analyses presented in this report.

Projects taking place on station (facilities or investigations) are assigned to one of six science disciplines:

- **Biology and Biotechnology**: Includes plant, animal, cellular biology, habitats, macromolecular crystal growth, and microbiology.
- **Earth and Space Science**: Includes astrophysics, remote sensing, near-Earth space environment, astrobiology, and heliophysics.
- **Educational and Cultural Activities**: Includes student-developed investigations and competitions.
- **Human Research**: Includes crew healthcare systems, all human-body systems, nutrition, sleep, and exercise.
- **Physical Science**: Includes combustion, materials, fluid, and fundamental physics.
- **Technology Development and Demonstration**: Includes air, water, surface, and radiation monitoring, robotics, small satellites and control technologies, and spacecraft materials.

Bibliometric analyses, which examine publications and their citations across different categories, provide insight into research productivity, quality, collaboration, and impact. These measurements help our organization identify trends in research growth and better plan and support new scientific initiatives. The analyses presented in this report focus on both fiscal year data and cumulative publication data, promoting research accountability, integrity, and the advancement of knowledge for the benefit of humanity.

Station Research in FY 2025

Between Oct. 1, 2024, and Sept. 30, 2025, a total of **508** publications associated with space station research were collected. **Figure 1A** presents this publication count by research discipline and space agency, while **Figure 1B** breaks it down by publication type and space agency. Derived Results, which are new scientific studies generated from shared open-source data, represent an additional return on the investment in the station. In FY25, the return on investment climbed to 58%, reflecting a 19% gain from the previous fiscal year. Note: NASA publications include articles related to experiments conducted by the Italian Space Agency under the ASI-NASA agreement.

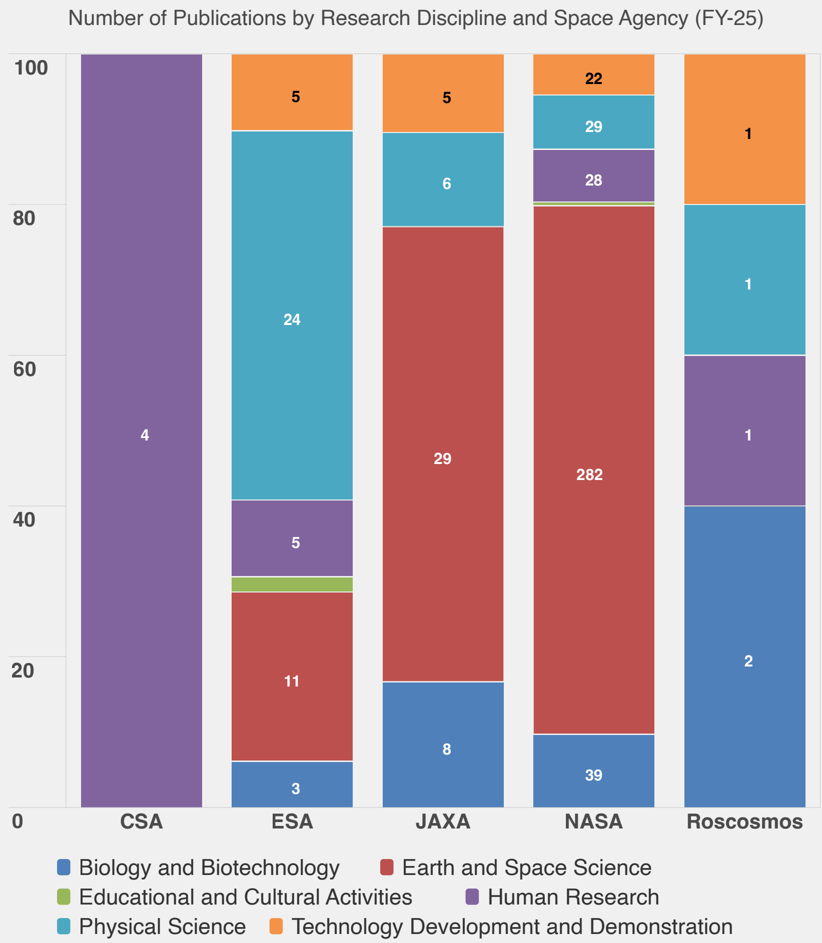


Figure 1A. Publication count by research discipline and space agency. *A total of 508 publications were collected in FY25. Approximately 63% reported results in Earth and Space research, primarily from investigations associated with NASA and JAXA.*

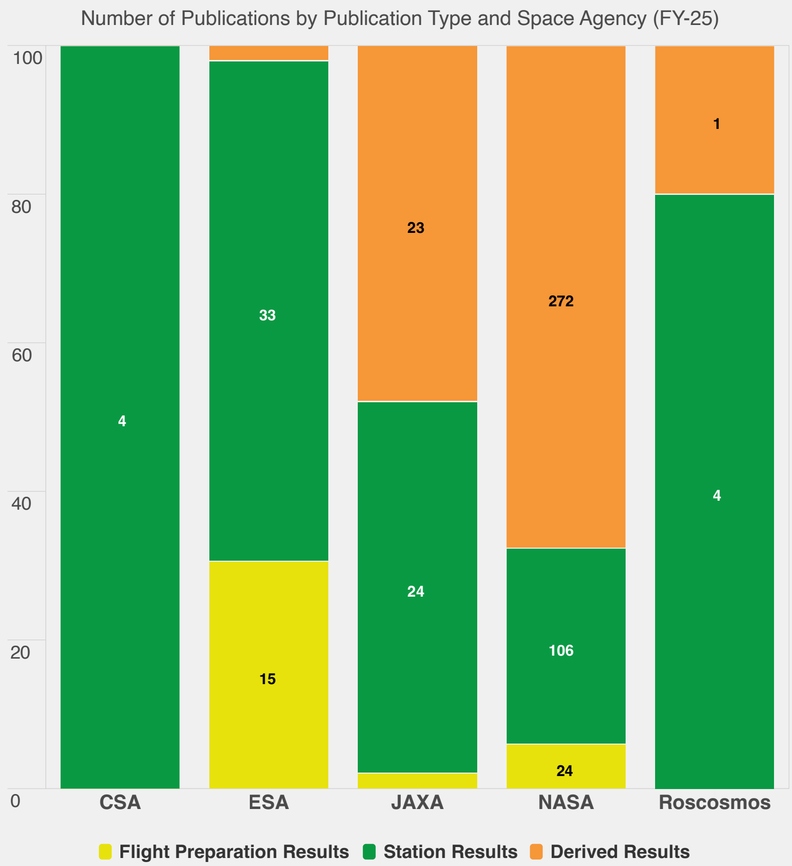


Figure 1B. Publication count by publication type and space agency.
During FY25, 508 publications were documented, about 80% of which were linked to NASA research. Derived Results reflect a 58% return on investment – a 19% increase from FY24.

Growth, Quality, Impact, and Diversity of station research

Growth: A total of 4,943 publications have been collected since the station began operations. Individual publications can be accessed through the station's program database, **Space Station Research Explorer**. **Figure 2A** illustrates publication growth by partner agency over time. All partners show sustained impact and steady increases in output, particularly during the years of active station utilization after 2010. Data indicate that between 2014 to 2024, the publication rate grew by approximately 7.4% per year.

Quality: A total of 935 publications, approximately 20% of station results, have been published in top-tier journals. Top-tier journals publish peer-reviewed studies and are ranked in the top 100 according to Clarivate™ (Web of Science™)[1], a global database that uses readership and citation metrics to calculate a journal's Eigenfactor Score[2] and ranking. **Figure 2B** shows the growth of these top-tier publications by station science discipline. This chart indicates that about 85% of top-tier research has been published since 2018.

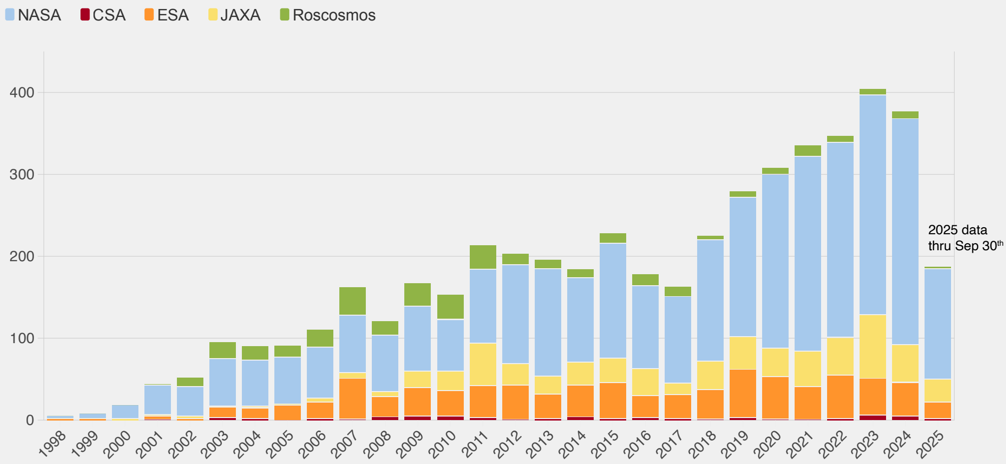


Figure 2A. Publication growth by partner agency. *From 2014 to 2024 (n= 4,943), the publication rate grew by approximately 7.4% per year.*

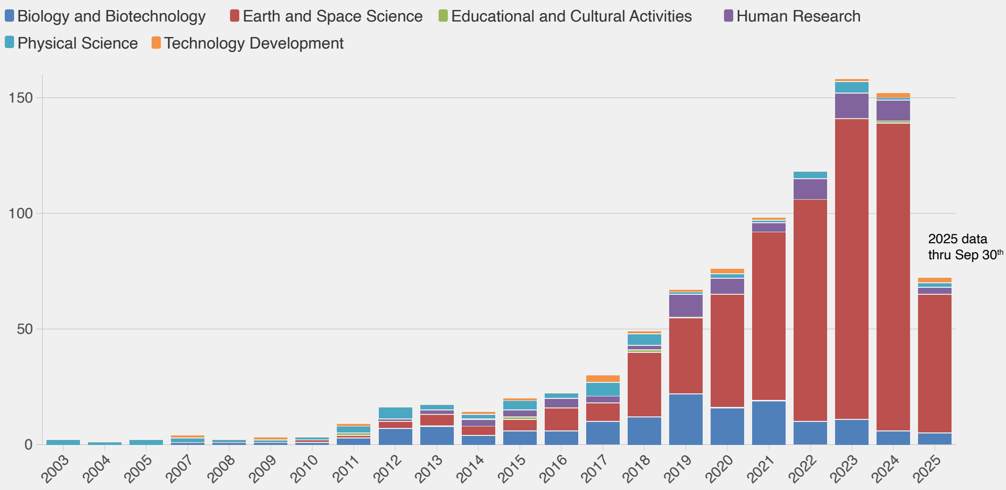


Figure 2B. Top-tier publication growth by station research discipline. *A total of 935 top-tier publications were collected through the end of FY25. Approximately 85% of top-tier research has been published since 2018.*

Impact: Previous analyses have demonstrated that the citation impact of station research has exceeded national and global standards since 2011 (See Annual Highlights of Results FY23). This trend continues today, highlighting the sustained influence and recognition of research conducted aboard the station. In the current analysis, we identified 3,596 citing publications, corresponding to a total of 108,183 citations, underscoring the widespread dissemination and utilization of station-generated knowledge. **Figure 3** shows that research in Earth and Space Science and Human Research leads in citation impact, reflecting the disciplines' particularly strong contributions and high visibility.

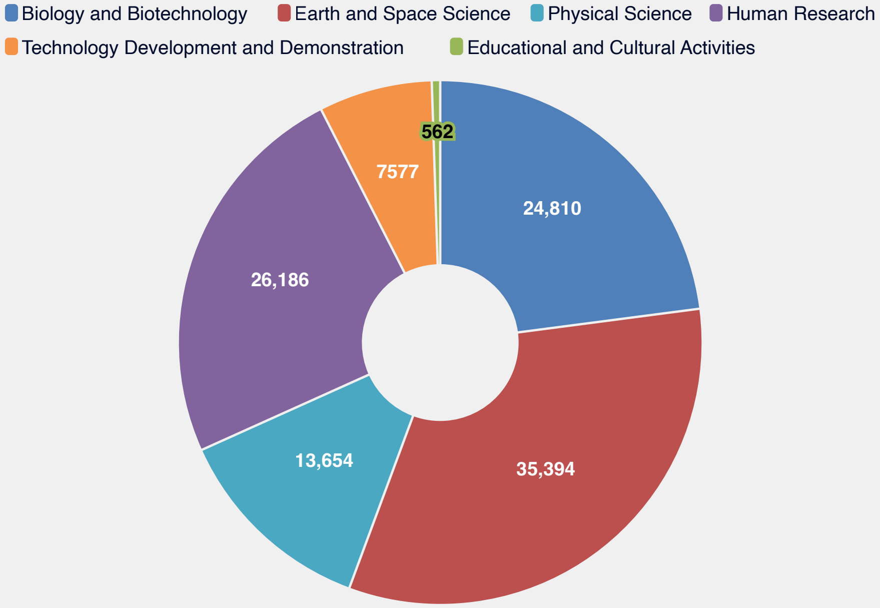


Figure 3. Citation impact by research discipline. *With more than 108,000 citations from nearly 3,600 papers, studies in Earth and Space Science and Human Research stand out as the most influential areas of station research.*

Diversity: Station science spans six major disciplines, 73 subdisciplines, and thousands of topic keywords within each subdiscipline. A precise visualization of this level of diversity would be overwhelming and difficult to interpret. Instead, the number of publications in each subdiscipline, as shown in **Figure 4**, succinctly illustrates the breadth of science the station has to offer.

Within Human Research, the subdisciplines with the highest publication output include *Crew Healthcare Systems, Cardiovascular and Respiratory Systems, Nervous and Vestibular Systems, and Integrated Physiology*. In Biology and Biotechnology, leading areas include *Microbiology, Cellular Biology, and*

Plant Biology. For Technology Development and Demonstration, the most active subdisciplines are *Small Satellites and Control Technologies, Radiation Measurement, and Robotics*. In Earth and Space Science, *Astrophysics and Remote Sensing* continue to expand the station's research diversity, while in Physical Science, the leading publication areas are *Fluid Physics, Materials Science, and Fundamental Physics*.

For a deeper appreciation of the station's research diversity, see the interactive sunburst diagram available online.

Figure 4. Station Research Diversity. *Distribution of station research publications across six major disciplines and 73 subdisciplines. The sunburst chart illustrates the diversity and breadth of station science, highlighting publication counts within each subdiscipline.*

Station Research Collaboration

Previous analyses have shown increased research collaboration within each space agency (See Annual Highlights of Results FY24). In a new analysis using country data, we found that approximately 41% of station research publications result from collaborations between multiple countries, while about 59% represent intercollegiate collaborations within individual countries. Nearly 46% of international collaborations are driven by Earth and Space Science projects, whereas about 30% of domestic collaborations stem from Biology and Biotechnology research.

Figure 5 shows that, between 2002 and 2024, research collaborations between countries grew at a faster rate (20% per year) compared to those within individual countries (8.9% per year). This trend suggests that international collaborations are gradually becoming the preferred pathway for station researchers, particularly after 2018. This trend toward globalized research appears to be emerging despite challenges in misaligned funding cycles, language barriers, differences in institutional frameworks, and limited opportunities for direct interaction. While these international collaborations for station research are associated with higher citation impact, $t(2237) = 3.34$, $p < 0.05$, the small effect size ($d = 0.12$) indicates that the practical significance of this difference may be limited and could vary by research discipline.

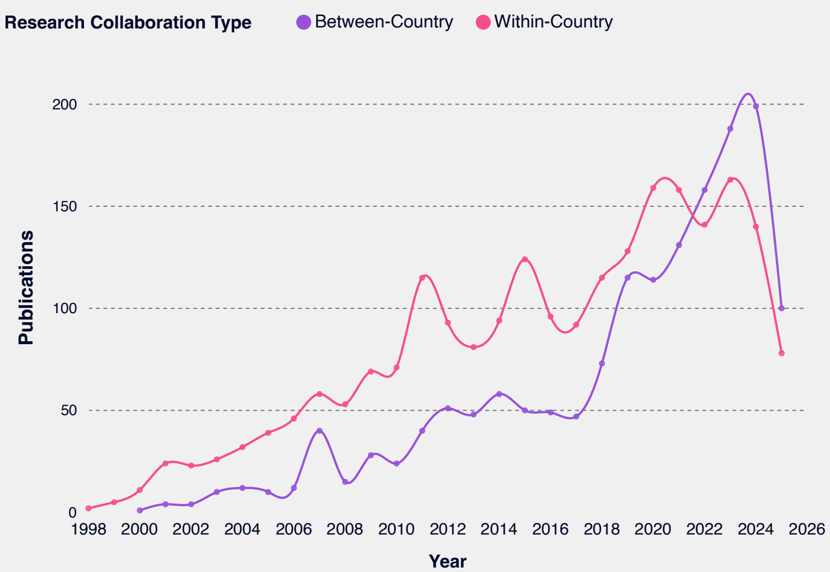


Figure 5. Research Collaboration Growth. *International research collaborations have grown more rapidly than domestic collaborations, particularly after 2018, indicating an increasing trend toward cross-border partnerships in station research. Earth and Space Science appears to be the key driver of these international collaborations.*

Another important dimension of collaboration in station research lies in the diversity of participating organizations. A wide range of entities contribute to the work conducted on station, including universities, research institutes, centers, business organizations (LLCs, Ltds, corporations, and associations), hospitals, and funding agencies. The level and nature of their involvement vary by research discipline and space agency. It is worth noting that country and affiliation data were obtained for a subset of publications through Dimensions.ai[3] (n = 3,818 publications).

Figure 6 highlights the overlap among these organizational collaborations, emphasizing the importance of diverse partnerships in advancing complex station research. The figure shows that JAXA and NASA maintain broad collaborations across multiple sectors. Academic institutions support JAXA's and NASA's Biology and Biotechnology as well as Earth and Space Science investigations, while academic institutions primarily advance ESA's Physical Science research. In contrast, Roscosmos relies more on institutes and research centers to achieve its scientific goals. Note that the data in Figure 6 are presented using log-transformed values to preserve structure and enhance visualization.

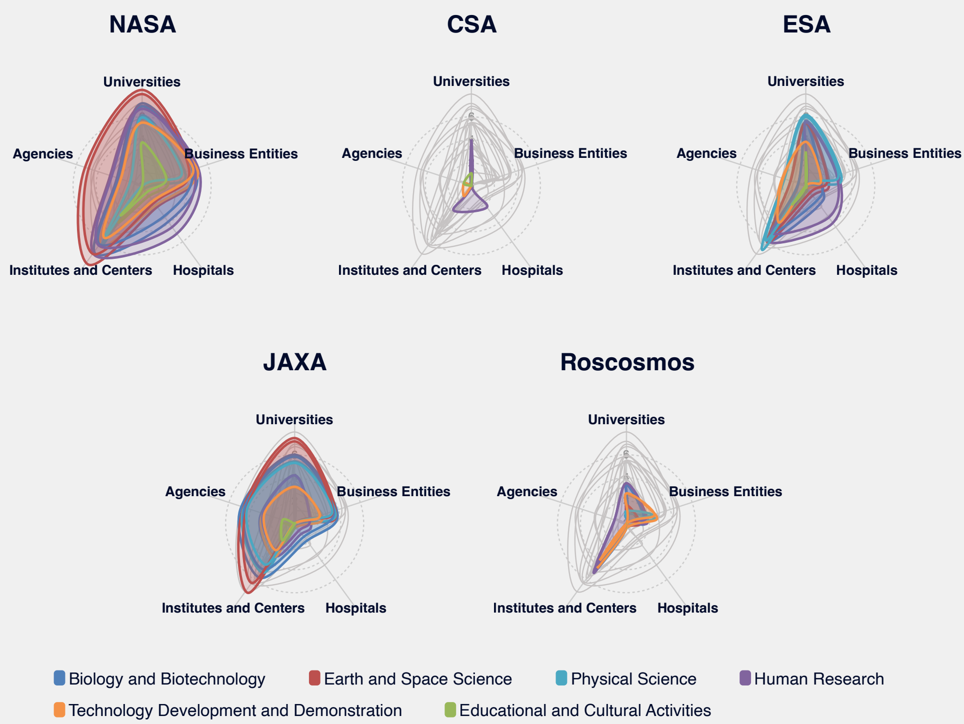


Figure 6. Diversity of organizational collaboration in station research across partner agencies. *ESA, JAXA, and NASA show broad engagement across industry sectors.*

Agency Contributions to Station Research Over 25 Years

After 25 years of station operations, it is important to reflect on the remarkable achievements made possible through the dedication of engineers, scientists, and program administrators who have coordinated countless moving parts to achieve mission goals and deliver benefits to humanity. **Figure 7** compares the total output in investigations, facilities, publications, and citations across the five partner agencies. NASA's overall activity demonstrates both a high research volume and substantial scientific impact. ESA and JAXA exhibit well-rounded contributions with strong scientific influence across all categories. In contrast, Roscosmos shows a larger share of investigations relative to publications and citations, suggesting that much of its research may be operational in nature or internally disseminated rather than widely published. Finally, CSA – similar to ESA and JAXA – maintains consistent representation across all categories, albeit on a smaller scale. Across all partner agencies, the number of investigations consistently exceeds the number of facilities, underscoring that research productivity on the station extends well beyond infrastructure development.

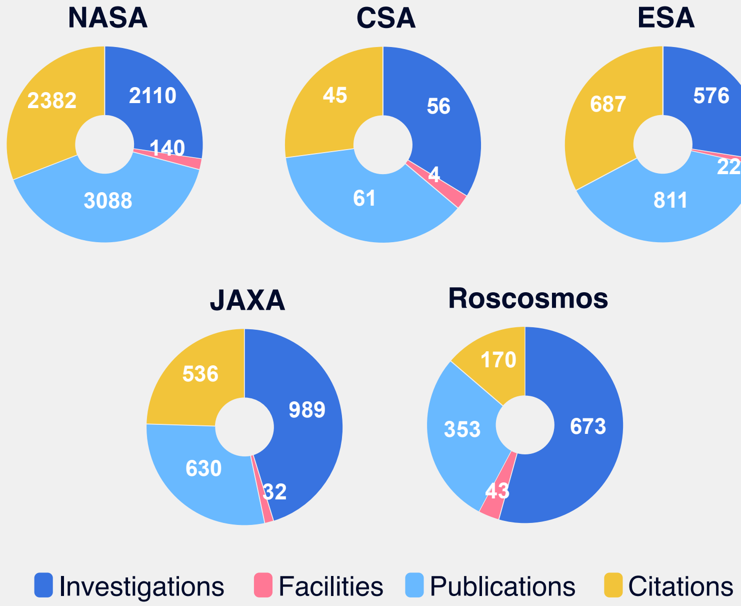


Figure 7. Research contributions by space station partner agencies. *The figure shows the total number of investigations, facilities, publications, and citations associated with each partner agency. Collectively, the data highlight the complementary roles of all partners in advancing station research and utilization.*

TOP CONTRIBUTING AFFILIATIONS IN STATION RESEARCH

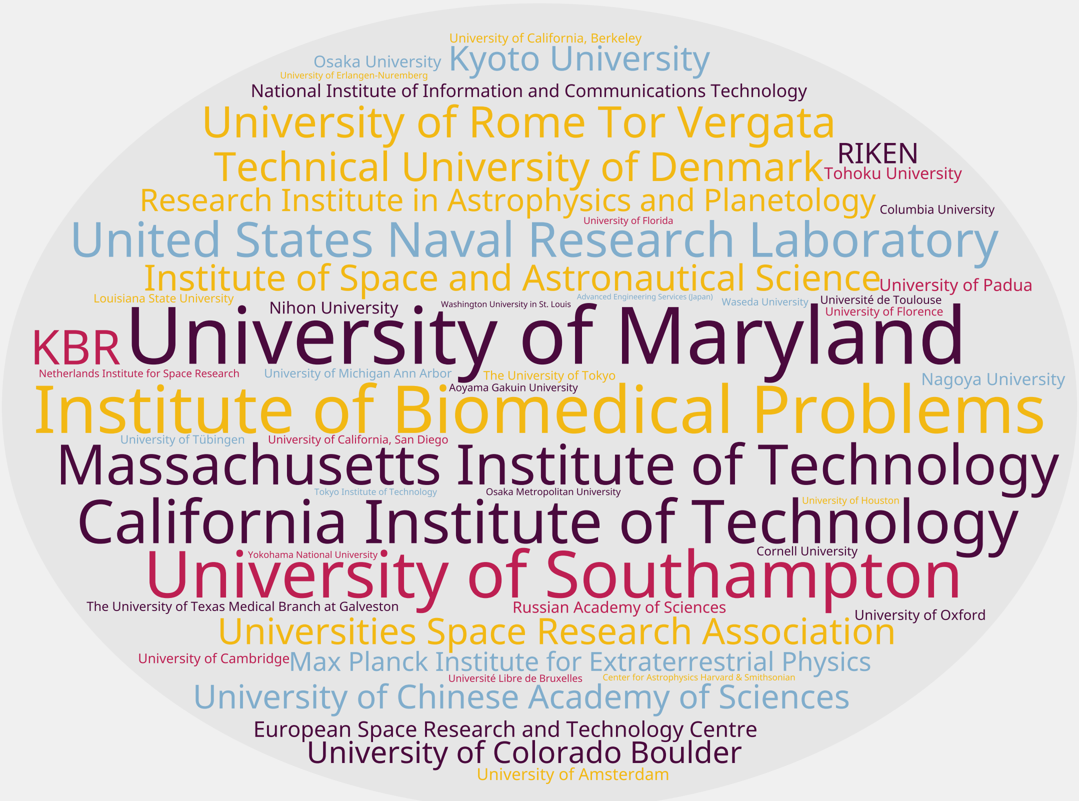


Figure 8. Word cloud of organizational affiliations. *Larger labels indicate organizations that appear more frequently as contributors to station research publications, highlighting their greater involvement and influence within the station research community. Centers, as well as funding and space agencies, were excluded from the analysis.*

Badges For Space Station Results

Space station research results contribute to human space exploration, advance scientific discovery, and provide benefits to humanity. This year's *Annual Highlights of Results from the International Space Station* includes select descriptions of research conducted over the past year, along with representative badges that identify each investigation's primary benefit.

EXPLORATION

The exploration badge identifies results that provide insights into how to live and work more effectively in space, addressing topics such as radiation effects on crew health, strategies to combat bone and muscle loss, improved designs for fluid-handling systems in microgravity, and methods for maintaining efficient environmental control.

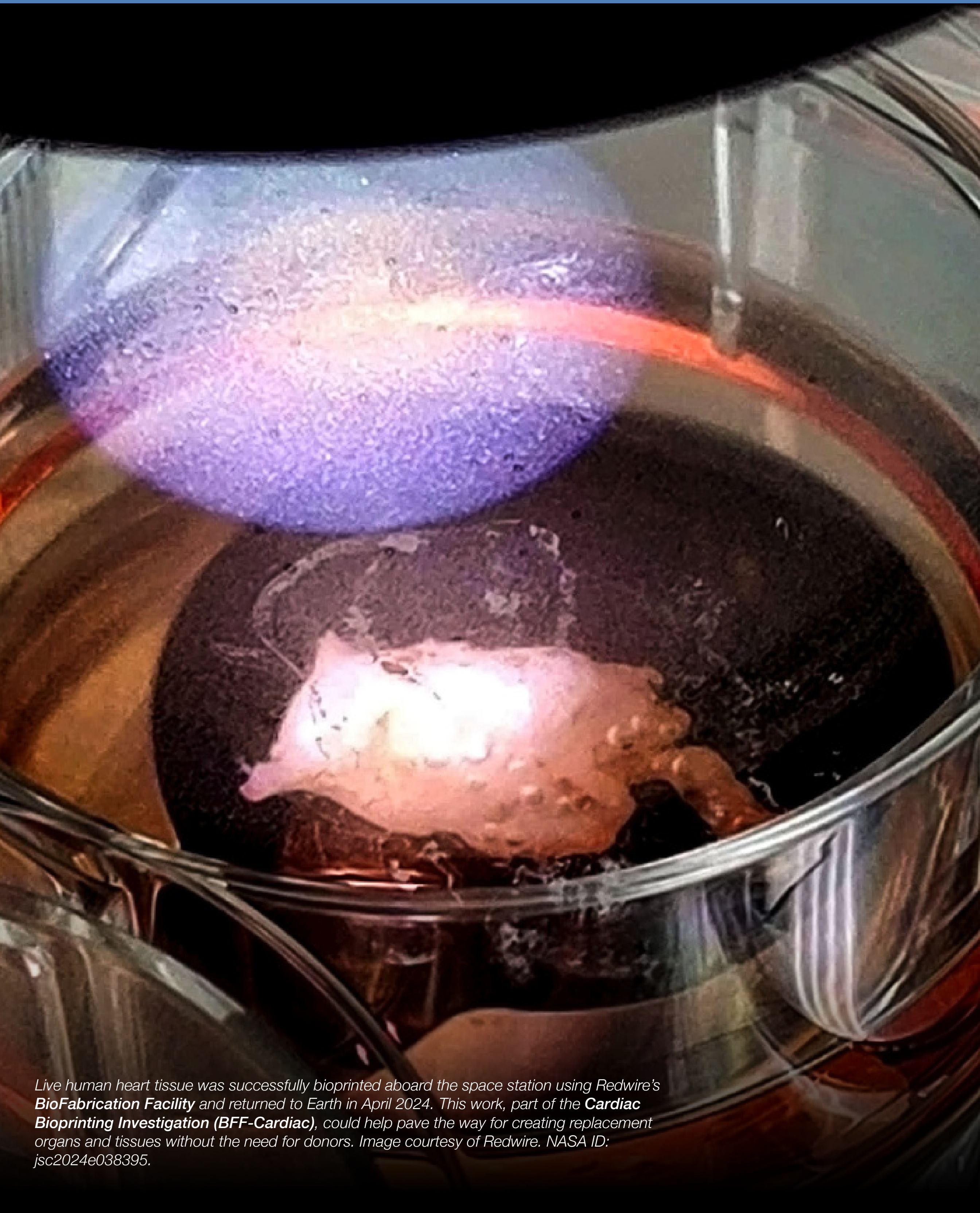
DISCOVERY

The discovery badge identifies results that contribute new knowledge across the physical sciences, life sciences, and Earth and space sciences, advancing scientific discovery in multidisciplinary ways.

BENEFITS FOR HUMANITY

The benefits-for-humanity badge identifies results with Earth-based applications, including advancing our understanding of the environment, contributing to disease treatment, improving existing materials, and inspiring future generations of scientists, clinicians, technologists, engineers, mathematicians, artists, and explorers.

BIOLOGY and BIOTECHNOLOGY



*Live human heart tissue was successfully bioprinted aboard the space station using Redwire's **BioFabrication Facility** and returned to Earth in April 2024. This work, part of the **Cardiac Bioprinting Investigation (BFF-Cardiac)**, could help pave the way for creating replacement organs and tissues without the need for donors. Image courtesy of Redwire. NASA ID: jsc2024e038395.*

Highlights in
Biology and Biotechnology

The space station laboratory provides a platform for biological science investigations that explore how living organisms respond to microgravity. Its facilities support research on biological systems ranging from microorganisms and cellular biology to the integrated functions of multicellular plants and animals.

EXPLORATION

ASI's investigation **Multidisciplinary Approach to the Analysis of the Functional Alterations Induced by Microgravity in Human Satellite Cells, and Study of Possible Countermeasures (MYOGRAVITY)** investigates how microgravity affects human satellite cells, which are essential for muscle growth, maintenance, and repair, by analyzing molecular, cellular, and functional changes.

In a new study, researchers isolated satellite cells from muscle biopsies of an astronaut before spaceflight and from a healthy, age- and sex-matched volunteer. The cells were cultivated under different conditions aboard the space station to analyze cellular and transcriptional changes induced by real microgravity, compared to satellite cells cultivated on Earth. Moreover, muscle precursor cells and skeletal muscle tissue, always derived from biopsies, from the same astronaut before and 30 hours after a long-duration spaceflight were analyzed for their biological properties and transcriptomic profile, respectively.

The main results of this study, showing that prolonged exposure to real microgravity strongly affects the biology and functionality of satellite cells, are published in *npj Microgravity*. Specifically, researchers demonstrated that microgravity significantly affected muscle precursor cell maturation and organization, revealing altered gene expression, which involves muscle-specific microRNAs (myomiRs), and dramatically impaired formation of muscle fiber precursors (myotubes) compared to ground controls.

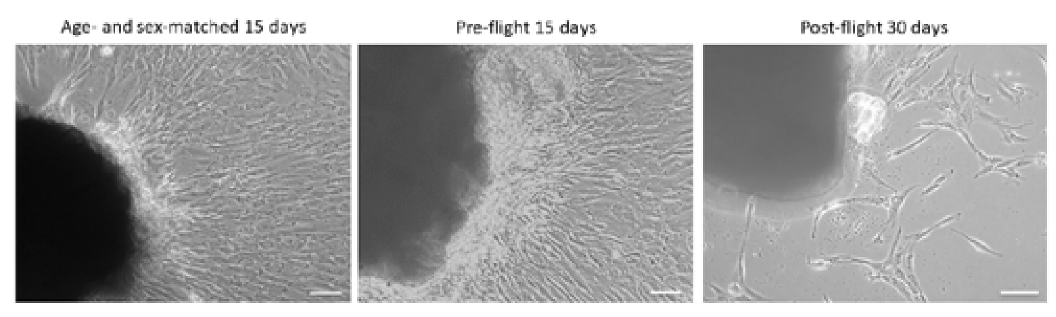


Figure 9. *Microscope images show human muscle cells migrating from muscle tissue samples over time, comparing an age- and sex-matched control with an astronaut before and after spaceflight. Image adapted from Di Filippo, npj Microgravity.*

Prolonged exposure to real microgravity strongly affected the biology and functionality of the astronaut's satellite cells, which became less responsive to activating stimuli and showed a strongly reduced proliferation rate. Noteworthy, exposure to microgravity translated into morphological changes and almost inability to fuse into myotubes. RNA-Seq analysis of post- vs pre-flight muscle tissue showed that genes involved in muscle structure and remodeling are promptly activated after landing following a 30-hour-duration space flight, while genes involved in the myelination process and neuromuscular junction organization appeared downregulated. These results suggest a prompt readaptation of the skeletal muscle contractile machinery to the normal gravitational loading after landing from a long-duration spaceflight, although this early readaptation is not accompanied by a rapid recovery of the innervation pattern. Reasonably, a condition of inefficient regeneration is likely to occur in muscles of post-flight astronauts following muscle damage.

This research provides new insight into the biological mechanisms underlying muscle loss in space. For space exploration, these insights can guide the development of more effective countermeasures to protect astronaut muscle health on missions to the Moon, Mars, and beyond. On Earth, the findings have important applications for treating muscle-wasting conditions, age-related muscle degeneration, and rehabilitation following injury or prolonged immobilization.

EXPLORATION

The objectives of the **JAXA Mouse Habitat Unit (MHU)** missions – MHU-1, MHU-4, and MHU-5 – center on understanding how different gravity conditions during long-term spaceflight affect gene expression and reproductive cell development in mice. MHU-1 investigates the molecular and epigenetic effects of microgravity and artificial 1 g on various organs and the offspring of mice, aiming to reveal how prolonged space exposure influences mammalian biology at a cellular level. MHU-4 and MHU-5 extend these goals by exploring the effects of partial gravity (1/6 g, simulating lunar conditions) on physiological and genetic responses, with particular interest in stress-related gene expression and germline impacts. Collectively, these missions provide critical insights into how gravitational changes influence mammalian health, with implications for future human space exploration.

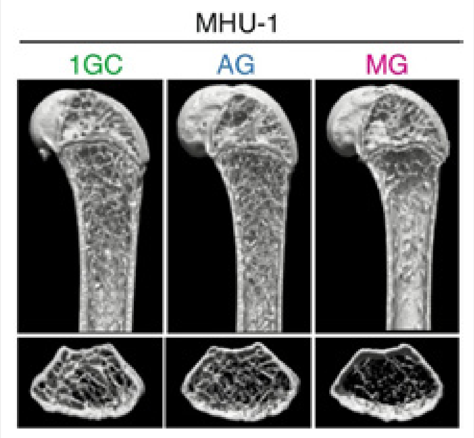


Figure 10. *Femur bone mass examined using micro–computed tomography. The images show that bone quality is better preserved under artificial gravity conditions. Image adapted from Okamura, Scientific Reports.*

In a new study published in *Scientific Reports*, researchers sought to understand how different gravitational environments – microgravity, lunar gravity (1/6 g), and Earth gravity (1 g) – affect the skeletal and immune systems of mammals during prolonged space travel. Long-duration spaceflight is known to induce physiological stresses, such as bone density loss and immune organ atrophy, but the mechanisms and thresholds of these effects at the molecular level remain unclear. Using mice housed aboard the station, the team examined how varying gravity levels influence gene expression and tissue integrity in bone, thymus, and spleen.

The study revealed organ-specific sensitivity to reduced gravity, with partial gravity mitigating some but not all microgravity-induced effects.

The study used male C57BL/6J mice flown on three separate missions (MHU-1, MHU-4, and MHU-5) aboard the station, where they were housed in specialized centrifuge-equipped habitats that simulated different gravity conditions: microgravity, 1 g (artificial gravity), and 1/6 g (lunar gravity). Mice were maintained in space for 25–35 days, after which behavioral tests were performed, and tissues including bone, thymus, and spleen were collected for histological, biochemical, and RNA sequencing analyses. Bone density significantly decreased in microgravity but was partially recovered in 1/6 g and fully recovered in 1 g; osteoblast and osteoclast gene expression changes reflected these findings. Thymic atrophy occurred under microgravity but was partially prevented by both 1 g and 1/6 g, although gene expression in the thymus did not fully return to baseline at 1/6 g. In the spleen, structural integrity remained largely unchanged across conditions, but gene expression patterns showed partial normalization in 1/6 g compared to microgravity. Overall, the study revealed organ-specific sensitivity to reduced gravity, with partial gravity mitigating some but not all microgravity-induced effects.

This research is vital for understanding how varying gravity levels affect critical physiological systems, helping define the minimum gravitational threshold needed to maintain health during long-duration space missions. The findings inform countermeasure development to protect astronaut bone and immune health in environments like the Moon or Mars. Additionally, insights into how gravity influences gene expression and tissue integrity may have broader biomedical applications on Earth, such as in aging, osteoporosis, and immune dysfunction.

BENEFITS FOR HUMANITY

The NASA investigation **Bacteria Resistant Polymers in Space** tests whether two non-fouling polymer coatings – TMA/CAA and TMA/SA – maintain their bacteria-resistant properties in microgravity as they do on Earth. By comparing bacterial adhesion on coated versus uncoated aluminum samples in space and ground-based environments, the investigation seeks to understand how microgravity affects biofilm formation. This research aims to identify materials that can reduce microbial contamination on high-contact surfaces, which is critical for both crew health and equipment longevity during long-duration space missions. Ultimately, findings may also inform the development of bacteria-resistant surfaces for use in healthcare and other terrestrial settings.

Biofilms pose a serious threat in space environments, where they can damage mechanical systems and increase health risks for astronauts due to limited medical resources and heightened bacterial resistance. Traditional cleaning methods like antimicrobial wipes and preflight sterilization are not fully effective in preventing biofilm formation on the space station.

In a new study published in *Molecules*, researchers investigated nonfouling polyampholyte polymer coatings as a passive strat-

Figure 11. *Photos of aluminum samples with protective coating (left) and without coating (right) after being returned from the space station. Image provided by the research team.*

egy to reduce bacterial adhesion, focusing on Staphylococcus epidermidis, a common and increasingly antibiotic-resistant strain found on space station surfaces. The study aimed to determine whether these coatings could effectively reduce biofilm formation in microgravity, helping to prevent contamination during long-duration space missions.

Identical samples were tested on Earth as gravity-based controls. The payload was designed to autonomously introduce bacteria to the coated and uncoated samples in orbit, with exposure lasting 32 days in space and 3 days on Earth post-return. Biofilm formation was analyzed macroscopically through photography and microscopically using confocal microscopy. Results showed that overall biofilm coverage was significantly lower in microgravity, with the TMA/SA coating consistently demonstrating the least bacterial adhesion. Although the TMA/CAA coating showed the greatest reduction in adhesion between Earth and space conditions, nonuniform coating application limited the statistical significance of the findings.

This research identifies passive surface coatings that can help prevent harmful bacterial biofilms in space, reducing risks to astronaut health and spacecraft systems during long-duration missions. By minimizing the need for active cleaning and disinfection, these coatings can conserve limited resources like time, water, and disinfectants aboard spacecraft. On Earth, such nonfouling materials could be applied in hospitals, water treatment systems, and other environments where biofilm control is critical.

EXPLORATION

The NASA investigation **Microgravity Expanded Stem Cells** explores whether microgravity enhances the expansion and proliferation of human mesenchymal stem cells (MSCs), hematopoietic stem cells (HSCs), and leukemia cancer stem cells. The study evaluates the safety, efficacy, and biological behavior of these cells when cultured in the unique microgravity environment of the space station, focusing on aspects such as gene expression and cellular morphology. A key objective is to address a critical challenge in regenerative medicine: the difficulty of producing large quantities of clinical-grade stem cells for therapeutic applications. Ultimately, the research aims to support the development of a safe, scalable, and commercially viable stem cell bioreactor in space.

In a recent study published in *PLOS ONE*, researchers investigated how true microgravity affects MSCs, an area of growing interest due to the increasing duration of human spaceflight and its largely unknown effects on cellular physiology. While earlier studies suggested that microgravity alters stem cell behavior, most relied on simulated conditions rather than actual spaceflight. Understanding the real effects of microgravity is essential not only for advancing space-based regenerative medicine but also for protecting astronaut health during extended missions.

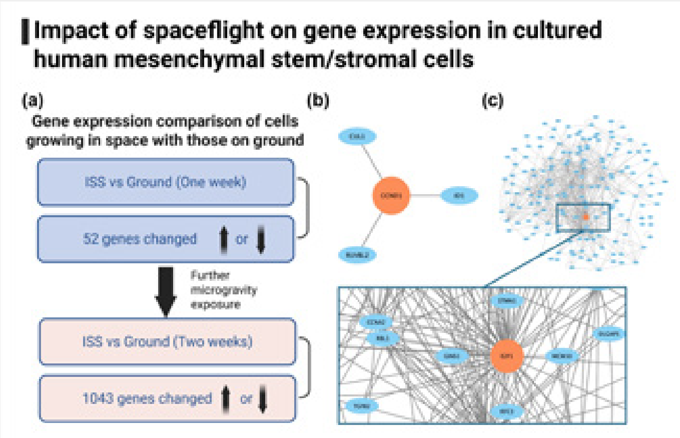


Figure 12. *Gene activity in human cells grown on the space station compared with cells grown on Earth after one and two weeks. Changes in gene expression increased over time in microgravity, revealing key regulatory genes that may act as master controls of cellular responses. Image provided by the research team.*

To close this knowledge gap, researchers cultured human MSCs aboard the station for one or two weeks using BioServe's single-well BioCell system, alongside matched ground-based controls. RNA was extracted from both flight and ground samples and analyzed via RNA sequencing to assess differences in gene expression. Principal component analysis and differential gene expression analysis revealed clear distinctions between microgravity and ground samples, indicating that microgravity significantly alters MSC gene expression. After one week in space, relatively few genes were affected, and most showed repression. However, after two weeks, a substantial increase in the number of differentially expressed genes was observed. Further pathway and enrichment analyses highlighted several biological processes influenced by microgravity, including cell cycle regulation, extracellular matrix organization, and muscle cell apoptosis. Key regulatory genes such as CCND1 and E2F1 were identified as central drivers of the MSCs' response to spaceflight.

This research offers critical insights into how microgravity influences stem cell behavior, which is vital for sustaining astronaut health during long-duration space missions. By identifying the molecular pathways and gene regulators affected by spaceflight, the findings contribute to the development of targeted countermeasures to preserve tissue function in space. On Earth, these results deepen our understanding of stem cell biology and may inform innovative regenerative medicine approaches by leveraging the beneficial effects of microgravity on stem cell function.

DISCOVERY

The Roscosmos investigation **Cytomehanarium** studies cellular mechanosensors that trigger intracellular pathways, leading to the formation of new proteins and changes in gene expression in the fruit fly Drosophila melanogaster. Previous experiments have shown alterations in reproductive tissues and gene expression that can be inherited. Building on these findings, Cytomehanarium now focuses on transgenerational epigenetic inheritance.

A new study published in *Cell Biophysics* is motivated by concerns that long-duration spaceflight can disrupt cellular structure and function, including male reproductive cells, due to changes in gravity during flight and especially during readaptation to Earth's gravity. Prior work showed that fruit fly sperm motility drops shortly after landing, likely because gravity-induced deformation of the cytoskeleton alters mechanotransduction and motor protein function. The researchers investigated whether modifying

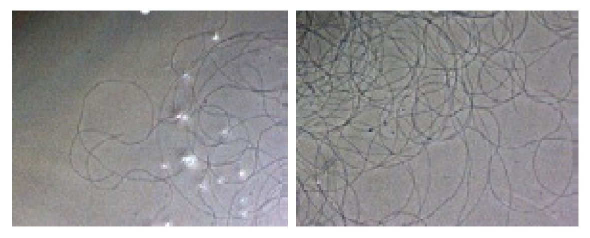


Figure 13. *Still images showing fruit fly sperm motility in flight (left) and in flight with a supplemental phospholipid diet (right). Increased motility, indicated by more movement paths, is observed under the special diet. Image provided by the research team.*

cell membrane composition – by reducing membrane cholesterol and increasing actin content – could stabilize the cytoskeleton and mitigate early post-flight declines in sperm motility through a biological countermeasure that reduces cellular stress.

The researchers conducted two spaceflight experiments aboard the Russian segment of the space station, using Drosophila melanogaster raised either on a standard diet or on a diet supplemented with essential phospholipids containing polyunsaturated fatty acids. Male flies were exposed to spaceflight or synchronous ground control conditions, and testes were collected immediately after landing or after 16 and 24 hours of readaptation to Earth's gravity. The team measured sperm motility using high-speed video microscopy and quantified cholesterol and cytoskeletal proteins (actin, tubulin, acetylated tubulin, and dynein) using fluorescence staining and Western blotting.

The results showed that spaceflight followed by early readaptation caused a significant drop in sperm motility and reductions in actin and tubulin content in flies on a standard diet. In contrast, flies receiving essential phospholipids had reduced membrane cholesterol, elevated actin levels, preserved tubulin content, and no decrease in sperm motility during the early post-flight period. These findings indicate that modifying membrane lipid composition can stabilize the cytoskeleton and protect sperm function against gravity-related mechanical stress after spaceflight.

This research identifies a practical biological countermeasure to gravity-related cellular stress that can impair reproductive function after spaceflight. For space exploration, the findings suggest a nutritional or pharmacological strategy to protect astronaut reproductive health and broader cytoskeletal integrity during long-duration missions and post-flight recovery. On Earth, the work has applications for understanding and potentially treating fertility issues and other conditions linked to cytoskeletal dysfunction, membrane composition, and mechanical stress on cells.

DISCOVERY

In 2018, Roscosmos, in collaboration with the A.A. Baikov Institute of Metallurgy and Materials Science of the Russian Academy of Sciences, launched the **Magnetic 3D Bioprinter** investigation to the space station. The investigation is designed to print complex tissue structures in microgravity. By using magnetic levitation to manipulate cells, researchers can arrange them into various 3D shapes without relying on protein filament scaffolds to maintain their architecture and integrity. This system organizes cells into predefined configurations, allowing them to mature into functional tissues.

The microgravity samples demonstrated more complete bone regeneration and superior structural organization, enhancing the tissue's functional properties.

A previous study from this investigation successfully printed cartilage-like tissue in space, paving the way for future advancements in space-based biomedical research and applications such as organ transplants, tissue engineering, and regenerative medicine. In a new study published in *Biomedical Technology*, researchers reported, for the first time, the development of an advanced biomaterial that could support human health and help astronauts address significant challenges during long-duration missions to the Moon or Mars. Given the increased likelihood of bone fractures in space, researchers developed synthetic octacalcium phosphate (OCP) bone graft, a biodegradable material that promotes new bone growth.

Between 2018 and 2023, several experiments were conducted both in space and on Earth to compare in vivo microgravity samples with those produced under normal gravity. Researchers implanted the OCP samples from both environments into damaged regions of rat skulls. The microgravity samples demonstrated more complete bone regeneration and superior structural organization, enhancing the tissue's functional properties. The microgravity samples exhibited a unique globular structure with petal-like crystals, likely due to low saturations and nucleation rates in space, which contributed to faster bone growth. Histological analysis and microtomography study of the implanted bone grafts revealed more extensive new bone formation in the microgravity samples after five months.

This research suggests that 3D printing in microgravity can produce biomaterials with superior properties that enhance bone regeneration and healing. It also enables the creation of customized medical implants or tissue-engineering constructs tailored to individual astronaut needs using computed tomography (CT) scans, reducing dependence on pre-manufactured materials from Earth. By allowing astronauts to fabricate implants on demand, directly in space, this approach could significantly lower the cost and complexity of long-duration missions.

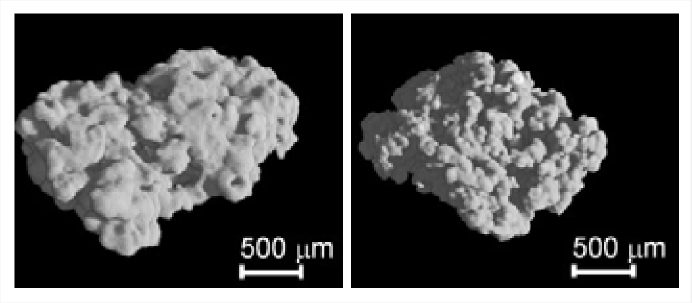


Figure 14*. Images showing calcium phosphate crystals grown in space (left) and on Earth (right). Synthetic bone graft materials developed in space showed strong support for bone growth and healthy tissue formation. Image adapted from Komlev, Biomedical Technology.*

EARTH and SPACE

The ***COronal Diagnostic EXperiment (CODEX)*** *is a solar coronagraph that launched to the space station in September 2024 to study the Sun's outer atmosphere, or corona. By blocking the Sun's bright light, CODEX can capture detailed images of the region where the solar wind begins. The data will help scientists better understand what heats and accelerates the solar wind as it travels through space. NASA ID: jsc2024e068509.*

Highlights in
Earth and Space

The space station's position in low Earth orbit provides a unique vantage point for collecting Earth and space science data. From an average altitude of about 400 kilometers, images of features such as glaciers, agricultural fields, cities, and coral reefs can be combined with data from orbiting satellites and other sources to produce the most comprehensive information available. Even with the many satellites now in orbit, the space station continues to offer unique perspectives on our planet and the universe.

DISCOVERY

The JAXA investigation **Tanpopo-3** explores the possibility of life surviving and adapting to harsh space environments, contributing to our understanding of the origin and migration of life in the solar system. Using the ExHAM facility aboard the space station, this investigation exposes microbes and plant seeds to outer space for one year. Specific goals include evaluating how manganese content affects the survival of Deinococcus bacteria, testing whether anthocyanins – pigments with antioxidant properties – help preserve the viability of purple rice seeds, and assessing whether cyanobacteria, mosses, and trees can grow in Martian regolith. Findings from this investigation may support future planetary habitation and the development of space-adapted crops and microbial systems.

Long-duration space missions require reliable plant-based food systems, but seed viability is threatened by harsh space conditions like solar radiation and vacuum exposure. Prior studies have shown that seeds exposed to the external environment of the space station suffer significant loss of germination potential. Flavonoids, such as anthocyanin, are known to protect plant tissues from UV and oxidative stress on Earth, but their protective role in space had not been fully tested. In a recent study published in *Life Sciences in Space Research*, researchers investigated whether anthocyanin-rich (purple-pigmented) rice seeds were better protected than non-pigmented seeds when exposed outside the space station, aiming to enhance seed preservation strategies for future space agriculture.

Figure 15. *White and purple rice seeds after exposure to the harsh conditions of space. Purple rice seeds showed higher germination and growth rates than white rice. Image adapted from Sugimoto, Life Sciences in Space Research.*

Researchers exposed purple-pigmented (anthocyanin-rich) and non-pigmented rice seeds to the space environment outside the space station for 440 days using sample plates with two layers: the top layer exposed to both solar light and space radiation, and the bottom layer exposed only to space radiation. Identical ground controls were stored under dry, cold conditions. After return to Earth, germination and growth rates were measured, anthocyanin content was analyzed using High-Performance Liquid Chromatography, and RNA degradation was assessed via RNA sequencing. Results showed that purple seeds had significantly higher germination and growth rates, particularly in the top layer, compared to white seeds. Anthocyanin content in purple seeds remained stable, and fewer long-lived mRNAs were degraded compared to white seeds. These findings suggest anthocyanin protects seeds from the damaging effects of solar light and radiation in space.

> *Purple-pigmented seeds had significantly higher germination and growth rates... suggesting anthocyanin protects seeds from the damaging effects of solar light and radiation in space.*

This research demonstrates that anthocyanin can protect seeds from the harmful effects of solar radiation and space exposure, which is critical for sustaining plant-based life support systems during long-duration space missions. Enhancing seed viability in space ensures a reliable food source and supports regenerative agriculture in extraterrestrial environments. On Earth, these findings may inform the development of stress-resistant crop varieties and improve seed preservation strategies in extreme or resource-limited conditions.

The ESA investigation **Atmosphere-Space Interactions Monitor (ASIM)** is a space-based observatory on the space station designed to study electrical and optical phenomena occurring above severe thunderstorms. Its primary objectives are to investigate transient luminous events (such as sprites, blue jets, and elves) and terrestrial gamma-ray flashes, which occur in the upper atmosphere due to intense thunderstorm activity. By studying high-altitude electrical discharges and cloud formation, ASIM improves our understanding of their effects on atmospheric dynamics, chemistry, climate, and the connection between thunderstorms and the upper atmosphere.

Elves are luminous rings in the lower ionosphere caused by electromagnetic pulses (EMPs) from powerful lightning discharges, but the specific sources and mechanisms behind their generation remain under investigation. Narrow Bipolar Events (NBEs), fast electrical discharges in thundercloud tops, have been theoretically proposed as potential sources of elves, but lacked direct observational evidence. A recent study published in *Geophysical Research Letters* investigates whether corona discharges at cloud tops – detected as NBEs in radio signals and blue flashes in optical data – can generate elves. By analyzing simultaneous space-based optical data from ASIM and ground-based radio measurements, the researchers aim to confirm the link between NBEs and elve formation, improving our understanding of thunderstorm-ionosphere coupling.

The researchers used optical data from ASIM aboard the space station and radio

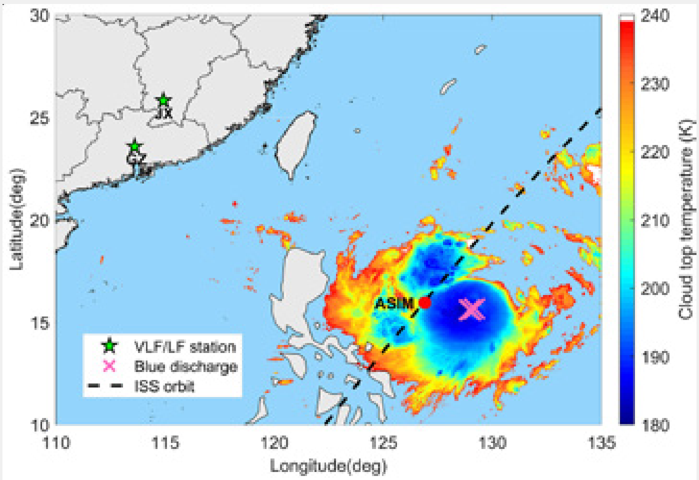


Figure 16. *Image of a tropical storm showing cloud temperatures, highlighting "elves" – brief flashes of light that occur high above thunderstorms during intense electrical activity. Image adapted from Liu, Geophysical Research Letters.*

signals from the Jianghuai Area Sferic Array (JASA) in China to capture simultaneous observations of NBEs and elves. ASIM's cameras and photometers recorded blue and ultraviolet (UV) emissions from thundercloud tops, while JASA detected radio signatures of NBEs. Events were analyzed based on the timing, brightness, and spectral characteristics to identify whether the observed emissions matched the known profiles of elves. The study found that when the peak current of negative NBEs exceeded approximately 140 kA, elves were detectable in ASIM's UV photometer data. This confirmed that corona discharges in overshooting thundercloud tops can produce sufficient electromagnetic energy to trigger elves. The study also established a correlation between the optical brightness of blue flashes and the estimated discharge current, providing a new method for assessing thunderstorm-driven impacts on the ionosphere.

This research provides the first experimental confirmation that corona discharges in thundercloud tops, specifically NBEs, can generate elves – linking thunderstorms directly to ionospheric disturbances. Understanding this connection improves our ability to model energy transfer between the lower atmosphere and space, which is important for satellite operations and communication systems affected by ionospheric conditions. The findings contribute to our understanding of the role of thunderstorms in changing environmental conditions, with potential implications for improved severe weather prediction and atmospheric models.

DISCOVERY

ESA's investigation **EXPOSE R2- Photochemistry on the Space Station (EXPOSE-R2-P.S.S.)** seeks to understand how solar ultraviolet radiation drives the chemical evolution of organic molecules in space and planetary environments. The investigation aims to experimentally test a wide range of organic compounds under the full solar UV spectrum in space, which cannot be accurately reproduced in laboratory settings on Earth. By doing so, the researchers seek to clarify how complex, life-related organic molecules may form, degrade, or transform in astrophysical environments such as comets, interstellar space, and the Martian surface and subsurface. Ultimately, the work advances understanding of the chemical pathways that could transform simple carbon-based molecules into the building blocks of life.

In a new study published in Astrobiology, the researchers investigated a subset of samples to understand how the amino acid alanine behaves under space and Mars-like conditions because ultraviolet radiation rapidly destroys organic molecules on planetary surfaces, complicating the search for biosignatures. They focused on montmorillonite clay, a common Martian mineral, to determine whether it protects amino acids from UV radiation or instead accelerates their breakdown through catalytic effects. Using experiments on station and ground-based simulations, they examined how different clay–alanine configurations influence photochemical stability. The study addresses the problem of whether organic molecules could realistically survive long enough on Mars for future missions to detect them.

> *Results showed that unprotected alanine degraded rapidly under UV radiation, while a thick clay cover significantly increased stability.*

Researchers exposed thin alanine films, alanine shielded by montmorillonite clay, and alanine–montmorillonite organoclays to space conditions for 15.5 months, with parallel ground-control and time-resolved laboratory UV-irradiation experiments. Samples were analyzed before and after exposure using a technique that tracks chemical changes, allowing researchers to measure how quickly the materials break down over time. The researchers compared configurations where clay acted as a surface cover versus intimate mixtures to distinguish shielding effects from photocatalytic interactions. Results showed that unprotected alanine degraded rapidly under UV radiation, while a thick clay cover significantly increased stability by roughly an order of magnitude. However, when alanine was intimately mixed with montmorillonite, the clay accelerated degradation through catalytic processes. The experiments also revealed that carbon dioxide produced during alanine breakdown can become trapped within clay interlayers, suggesting a potential indirect marker for past organic matter on Mars.

This research clarifies how organic molecules can be preserved or destroyed in radiation-rich environments, directly informing the search for biosignatures on Mars and other planetary bodies. For space exploration, the results guide where and how missions should look for organic compounds, emphasizing subsurface or mineral-shielded environments and the potential use of trapped CO_2 as an indirect biosignature. On Earth, the findings advance understanding of clay–organic interactions relevant to prebiotic chemistry, environmental geochemistry, and the long-term preservation or degradation of organic matter in soils and sediments.

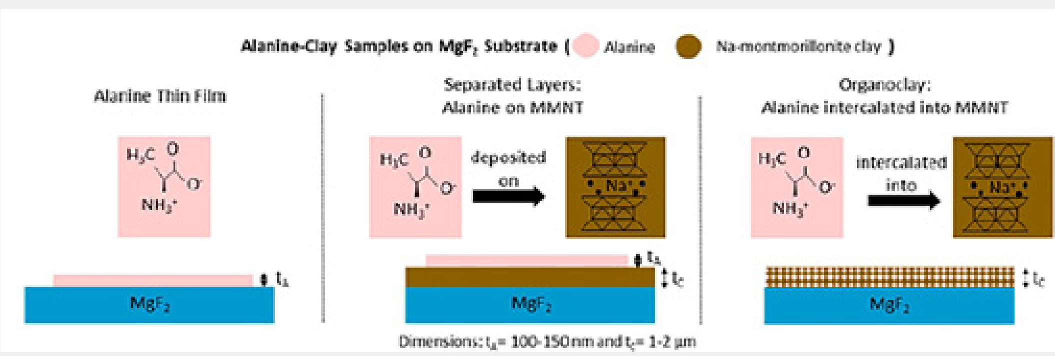
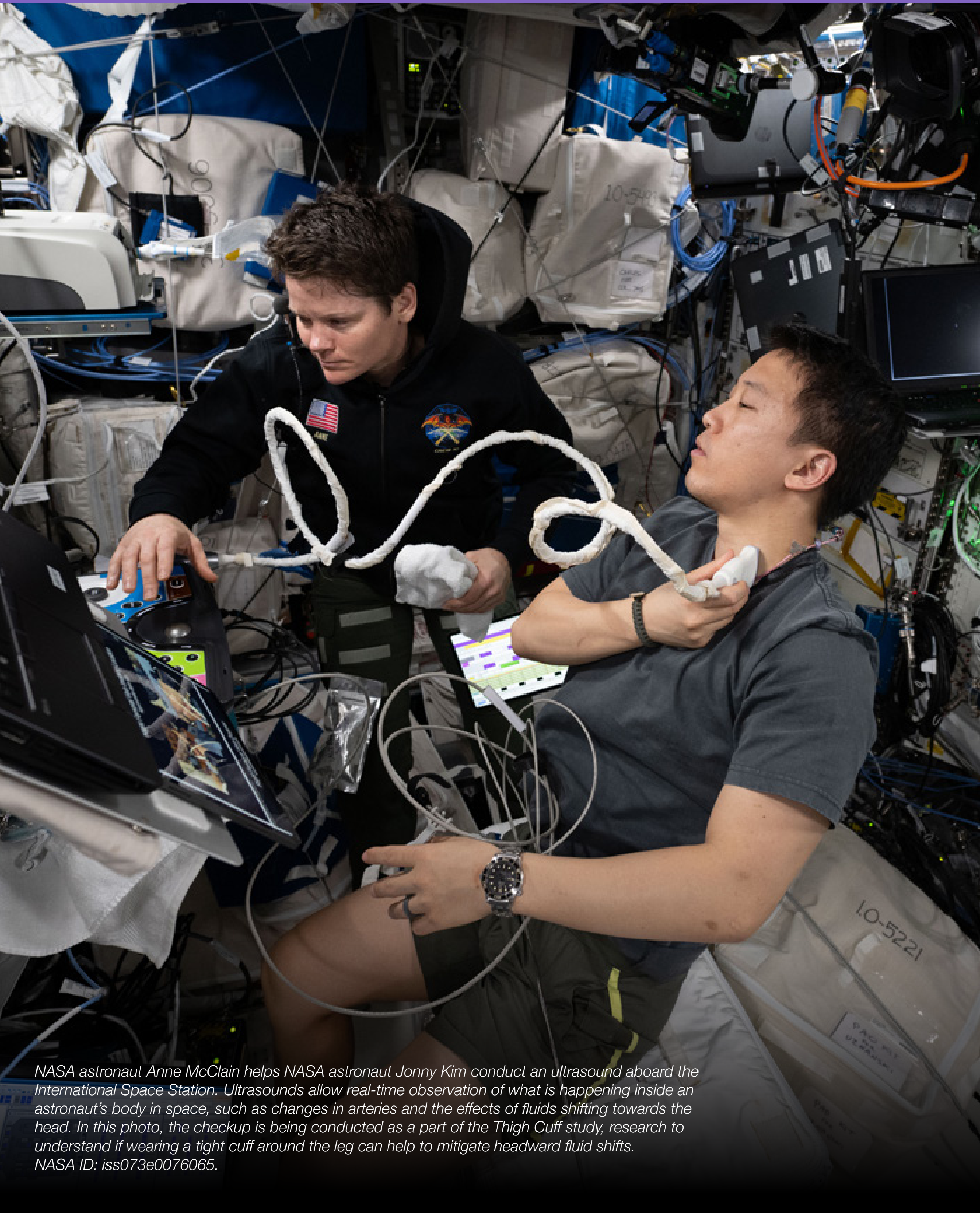


Figure 17. *Sample setups showing thin alanine film by itself (left), protected by a layer of montmorillonite clay (middle), or mixed with clay (right). Image adapted from Wipf, Astrobiology.*

HUMAN RESEARCH



NASA astronaut Anne McClain helps NASA astronaut Jonny Kim conduct an ultrasound aboard the International Space Station. Ultrasounds allow real-time observation of what is happening inside an astronaut's body in space, such as changes in arteries and the effects of fluids shifting towards the head. In this photo, the checkup is being conducted as a part of the Thigh Cuff study, research to understand if wearing a tight cuff around the leg can help to mitigate headward fluid shifts.
NASA ID: iss073e0076065.

Highlights in **Human Research**

Space station research includes the study of risks to human health that are inherent in space exploration. Many investigations examine the mechanisms behind these risks, including exposure to microgravity and radiation, as well as other factors of living in space, such as nutrition, sleep, and interpersonal relationships. Other studies focus on developing and testing countermeasures to reduce these risks. The results from this research are critical for enabling missions to the lunar surface and future exploration of Mars.

EXPLORATION

The CSA investigation, **The Effect of Long Duration Hypogravity on the Perception of Self-Motion (VECTION)**, explores how living in microgravity affects astronauts' sense of motion, orientation, and distance. In space, the brain receives different signals from the eyes, inner ear, and body, which can lead to confusion about movement and direction. By studying how these senses adapt in space and readjust after returning to Earth, scientists aim to better understand how humans perceive motion and maintain balance during long missions.

In a new study published in *Experimental Brain Research*, researchers investigated whether visual acceleration could evoke a sense of tilt in microgravity because traditional orientation cues like gravity are absent in space, often leading to spatial disorientation for astronauts. This disorientation can pose risks to astronaut safety and operational performance, particularly when navigating complex spacecraft environments or during spacewalks. They aimed to determine if visual motion could act as a substitute cue for "up" in the absence of gravity, helping the brain maintain orientation. Solving this problem could improve astronaut training, reduce cognitive load in space, and enhance safety during long-duration missions.

The researchers used virtual reality to simulate visual linear acceleration in a controlled environment aboard station and on Earth. Twelve astronauts and a group of control participants viewed mo-

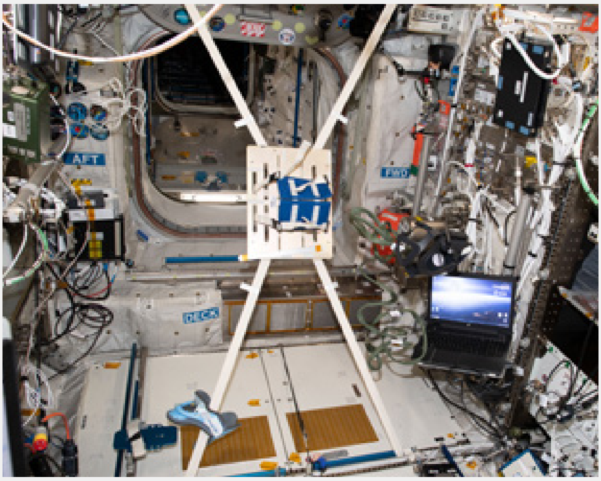


Figure 18. *VECTION experimental setup aboard the station. The central rectangular frame presents controlled visual stimuli to crew members to investigate how visual cues alone—without gravity or physical movement—can induce a sensation of motion. NASA ID: iss060e014594.*

tion through a VR headset that simulated self-motion along a corridor, either at a constant velocity or with acceleration, while their posture (sitting or supine) and gravity conditions varied across five test sessions. After each simulated motion, participants adjusted a virtual ground plane to match their perceived orientation. The key procedures aimed to assess whether visual acceleration could induce a sense of tilt and how reliably participants could judge uprightness under different conditions.

The findings can guide the development of better training protocols and countermeasures to reduce disorientation and enhance astronaut safety.

The results showed no significant evidence that visual acceleration alone induced a tilt sensation in microgravity or on Earth. However, variability in orientation judgments increased in microgravity and when participants were lying supine, confirming that the absence or misalignment of gravitational cues reduces perceptual precision.

This research helps researchers understand how the human brain perceives orientation when gravity cues are absent, a common challenge during spaceflight. By identifying the limits of visual cues in supporting spatial orientation, the findings can guide the development of better training protocols and countermeasures to reduce disorientation and enhance astronaut safety. On Earth, the insights may also benefit individuals with balance disorders, such as older adults or people with vestibular dysfunctions, by informing new fall prevention and rehabilitation strategies.

EXPLORATION

ESA's investigation **Effect of Gravitational Context on EEG Dynamics: A Study of Spatial Cognition, Novelty Processing and Sensorimotor Integration (Neurospat)** seeks to understand how the absence of gravity affects spatial cognition, sensorimotor integration, and brain function in astronauts. Using electroencephalogram (EEG) and event-related potentials, researchers examine how gravitational context influences perception, attention, memory, decision-making, and action during tasks such as visuomotor tracking, orientation discrimination, and 3D navigation. Detecting changes in brain activity in response to novelty in microgravity helps guide the development of countermeasures to reduce disorientation during critical space operations like docking and spacewalks.

Spaceflight exposes astronauts to microgravity, which can lead to temporary neurological symptoms such as disorientation, visual disturbances, and motor coordination issues – yet the underlying brain mechanisms remain underexplored. While other physiological systems have been extensively studied, the central nervous system has received comparatively little attention, despite its vital role in sustaining cognitive and motor performance. In a new study published in *Scientific Reports*, researchers addressed this gap by using EEG to investigate changes in brain activity, specifically in the beta frequency band, associated with motor control and proprioception. Their goal was to understand how microgravity affects functional brain dynamics and to inform countermeasures that support astronaut health during and after long-duration missions.

The study analyzed EEG data from five male astronauts across three phases: preflight, in-flight, and post-flight. Recordings were taken under eyes-closed and eyes-open resting conditions using a 59-channel system aboard the space station and standardized setups on Earth. Researchers focused on beta band activity (12–30 Hz) and analyzed power and functional connectivity across brain regions. Results revealed significantly increased beta power and functional connectivity during spaceflight, particularly in the sensorimotor cortex and prefrontal regions, when comparing post-flight to in-flight phases. These findings suggest that the brain adapts to microgravity through enhanced sensorimotor processing and network connectivity, likely reflecting adjustments to altered vestibular and proprioceptive input.

This research is essential for understanding how the brain adjusts to spaceflight conditions, which directly impacts astronauts' coordination, spatial orientation, and operational performance. By identifying specific neurophysiological changes, the findings support the creation of targeted interventions to preserve cognitive and motor function in space. Additionally, the insights gained have promising applications on Earth, particularly in the rehabilitation of individuals with motor impairments or vestibular dysfunctions.

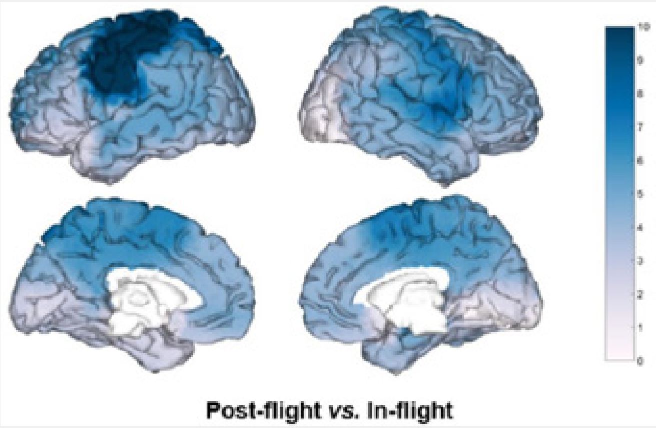


Figure 19*. Brain images showing changes in beta activity after flight, with increased signals seen in the sensorimotor cortex when the eyes are closed. Image adapted from Quivira-Lopesino, Scientific Reports.*

The NASA investigation **Assessment of Operator Proficiency Following Long-Duration Space Flight (Manual Control)** studies how long-duration spaceflight affects astronauts' ability to operate vehicles and perform complex tasks post-landing. It aims to identify the specific cognitive and sensorimotor mechanisms – such as vestibular, fine motor, and oculomotor functions – that contribute to degraded operator proficiency. The investigation also evaluates the role of fatigue and sleep deprivation to distinguish their effects from those of microgravity. Findings from this investigation inform the development of targeted countermeasures to support safe and effective surface operations on the Moon or Mars.

In a recent study published in *Scientific Reports*, researchers investigated how long-duration spaceflight impacts astronauts' ability to manually pilot complex vehicles, focusing on simulated T-38 Talon landings after returning from the space station. Although modern spacecraft rely heavily on automation, past missions have shown that system failures can require rapid manual control, making post-flight pilot proficiency critical for safety. Previous studies have indicated that astronauts often experience sensorimotor deficits, spatial disorientation, and reduced multitasking ability after spaceflight, which could impair manual landing performance. By quantifying these deficits and understanding their underlying causes, researchers can identify potential countermeasures to reduce risks in future missions where manual control may be necessary.

Five highly experienced astronaut pilots, all with extensive T-38 flight backgrounds, completed simulated T-38 landings before and after space station missions averaging 170 days in duration. They underwent four pre-flight and three post-flight test sessions, which included a seated cognitive/sensorimotor test battery, a motion perception test, and multiple landings in a full-motion simulator using a standard overhead approach. Post-flight testing occurred on the day of return (R+0), about four days later (R+4), and about eight days later (R+8), with performance compared against individual pre-flight baselines.

Long-duration spaceflight can temporarily impair critical piloting skills. Countermeasures [could] help astronauts quickly regain manual control capabilities after space missions.

On R+0, 80% of first landing attempts showed degraded performance, with issues such as difficulty maintaining altitude during banking turns, navigational errors, and higher touchdown speeds or distances, though most pilots returned to near baseline on the second attempt that same day. Cognitive tests showed small but significant declines in manual dexterity and large deficits in dual-task tracking, along with increased self-reported sleepiness, while reaction time and visual acuity were unaffected. By R+4, both piloting and driving simulation performance had returned to pre-flight levels, suggesting rapid recovery once re-exposed to the tasks.

This research shows that long-duration spaceflight can temporarily impair critical piloting skills, particularly altitude control and multitasking during complex maneuvers, which could be dangerous if automation fails during a landing. The findings highlight the need for countermeasures – such as “just-in-time” simulator training, improved cockpit displays, or tactile feedback systems – to help astronauts quickly regain manual control capabilities after space missions. On Earth, the insights into vestibular and cognitive recovery after prolonged sensory changes can inform pilot training, rehabilitation for balance disorders, and safety planning for operators in other high-risk transportation fields.

Figure 20. *Flight path used in a T-38 landing simulation. Performance was evaluated using parameters such as touchdown location and vertical speed. Image adapted from Moore, Scientific Reports.*

The Roscosmos investigation **Pille-MKS: Determine the Value of the Accumulated Radiation Dose in a Visiting Crewmember (Pille-ISS)** monitors and measures radiation doses aboard the space station using the Pille-ISS thermoluminescent dosimeter system. A key goal is to assess astronaut radiation exposure, especially during extravehicular activities (EVAs) when they are outside the station's shielding. The system also aims to collect long-term radiation data to analyze how exposure levels vary with factors like space station altitude and solar activity. This information supports efforts to improve astronaut safety and radiation protection strategies during space missions.

Long-duration space missions expose astronauts to harmful ionizing radiation. Traditional shielding materials like aluminum or polyethylene are either ineffective or impractical due to weight and structural limitations. In a recent study published in *Advances in Space Research*, the researchers aimed to develop and test a lightweight, high-performance polymer composite capable of attenuating a broad spectrum of space radiation while maintaining mechanical stability. Their study addresses the critical need for durable, efficient shielding materials that can protect crew members in spacecraft environments without compromising mission feasibility.

Figure 21. *Photo of the polymer composite fitted with radiation detectors. Image adapted from Cherkashina, Advances in Space Research.*

The researchers developed a polymer composite made of a fluoroplastic matrix filled with bismuth- and tungsten-containing radiation-protective fillers. Two identical cylindrical containers made from this composite were manufactured and equipped with internal and external radiation detectors (Pille-ISS dosimeters). These containers remained inside the Russian segment of the space station for 225 days. One container was later returned to Earth for analysis of radiation exposure and material changes. The results showed that the composite reduced radiation exposure by about 29 percent, with an average attenuation ratio of 0.71 ± 0.02. Mechanical testing revealed only a slight 12 percent decrease in bending strength, and no structural degradation or induced radioactivity was detected in the material.

This research demonstrates that a lightweight, durable polymer composite can effectively shield against harmful space radiation, a major barrier to long-duration human spaceflight. The material's stability and protective performance make it a strong candidate for use in spacecraft and space habitats to protect astronauts. On Earth, such composites could be applied in radiation shielding for medical, nuclear, or industrial environments where both protection and material efficiency are critical.

CSA's investigation **The Detrimental Effects of Long Duration Spaceflight on Human Wayfinding: The Behavioural and Neural Mechanisms Study (Wayfinding)** aims to understand how long-duration spaceflight affects astronauts' wayfinding abilities and the underlying behavioral and neurological mechanisms. The researchers seek to quantify changes in spatial orientation skills resulting from missions aboard the station and to identify associated functional and structural brain changes using behavioral testing and neuroimaging. Another key objective of this investigation is to determine whether these cognitive and neurological alterations persist after astronauts return to Earth and undergo long-term readaptation. Overall, Wayfinding provides a comprehensive picture of how spaceflight impacts spatial cognition to inform countermeasures that protect astronaut performance.

Astronauts are exposed to unique stressors during spaceflight – such as microgravity, radiation, isolation, and confinement – that are known to affect the brain. However, the detrimental impact of such stressors on the hippocampus – a brain region that is known to be highly susceptible to stress – had not been directly measured in astronauts. The hippocampus is critical for memory, learning, and spatial navigation, functions that are essential for mission performance and post-mission recovery.

Previous research relied mainly on animal models, analog environments, or whole-brain imaging approaches that could miss subtle, region-specific changes in this structure. In a new study published in *NeuroSci*, researchers provide the first direct, high-resolution evidence of whether long-duration spaceflight causes measurable hippocampal volume changes in astronauts.

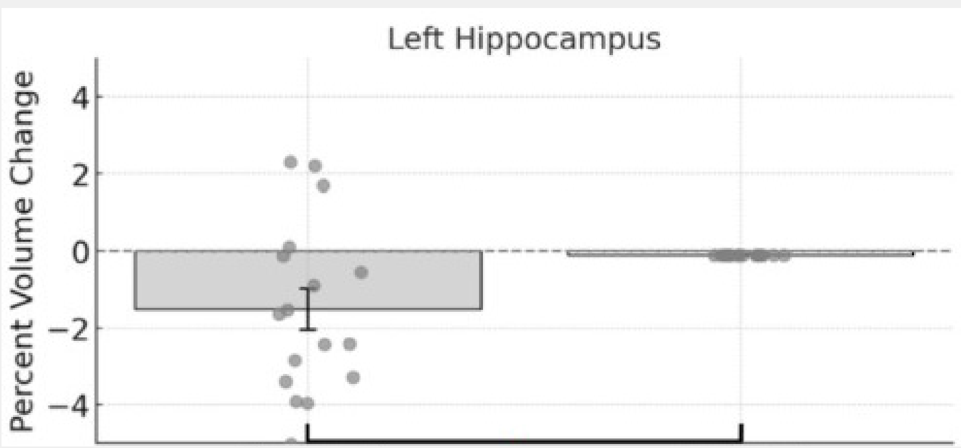


Figure 22. *Bar chart showing changes in the left hippocampus volume of astronauts compared with expected changes from normal aging in a healthy group. Astronauts experienced greater volume loss than would be expected from aging alone. Image adapted from Batool, NeuroSci.*

The researchers collected high-resolution Magnetic Resonance Imaging (MRI) scans from 17 astronauts before and after approximately six-month missions aboard the space station. They used standardized image-processing pipelines and the Harmonized Hippocampal Protocol to segment the hippocampus into anterior, body, and posterior subregions and calculate percent volume changes between pre and postflight scans. Control regions such as the amygdala and the caudate nucleus were also analyzed to test whether changes were generalized to many brain regions or specific to the hippocampus. Results showed a significant volume decrease following spaceflight in the left hippocampus overall, with pronounced reductions in the left anterior and the right body hippocampal subregions. Male astronauts exhibited greater volume loss in the right hippocampus compared to females. Importantly, the left hippocampal volume loss exceeded what would be expected from normal aging alone, indicating a spaceflight-specific effect.

Results showed a significant volume decrease following spaceflight in the left hippocampus overall, with pronounced reductions in the left anterior and the right body hippocampal subregions.

This research provides the first direct evidence that long-duration spaceflight can cause specific structural changes in the human hippocampus, a brain region essential for learning and memory, navigation, and cognitive resilience. For space exploration, the findings help identify neurological risks of extended missions and support the development of monitoring tools and countermeasures to protect astronaut cognitive performance during and after spaceflight. On Earth, the study improves understanding of how chronic stress, isolation, and environmental extremes affect the structural properties of the brain, with implications for aging research, mental health, and conditions involving prolonged confinement or stress.

PHYSICAL SCIENCE

Top view of spreading flame in ground-based test for the ***Solid Fuel Ignition and Extinction - Oscillatory Flow on Flame Spread (SoFIE-OFFS)*** *investigation. SoFIE-OFFS investigates how changes in flame behavior influence fire spread on Earth. Image courtesy of Worcester Polytechnic Institute. NASA ID: jsc2024e044216.*

Highlights in **Physical Science**

Gravity has a profound impact on our understanding of physics and the development of fundamental mathematical models describing how matter behaves. The space station is the only laboratory where scientists can study long-term physical effects without the complications of gravity-driven processes, such as convection and sedimentation. This unique environment allows other physical properties to dominate systems, which scientists are leveraging for a wide range of investigations in the physical sciences.

BENEFITS FOR HUMANITY

The ESA **FSL Soft Matter Dynamics – PASTA** investigation explores the behavior and stability of emulsions by examining how droplets coalesce, aggregate, and change in size over time. Conducting these experiments in microgravity removes the influence of buoyancy, allowing for a clearer understanding of destabilization mechanisms and simplifying the analysis of additive behavior. The study's objectives include measuring the characteristic timescales of droplet interactions, identifying distinct dynamic regimes (e.g., Brownian vs. capillary-driven motion), and testing predictive models for emulsion stability. It also lays the groundwork for future studies of more complex systems – such as multiple emulsions and Ostwald ripening – through continued development of the Fluids Science Laboratory facility.

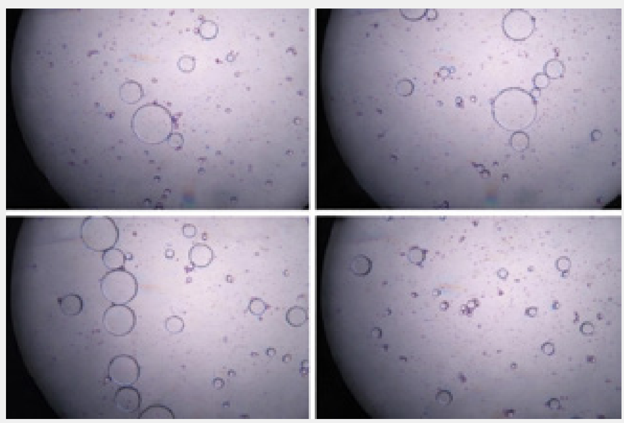


Figure 23. *Spectroscopic images capturing the emulsification process, highlighting the coalescence of small bubbles. Image adapted from Lorusso, Journal of Colloid and Interface Science.*

Emulsions, mixtures of immiscible liquids, are widely used in industries like food, pharmaceuticals, and cosmetics, yet their long-term stability is not fully understood due to complex interfacial dynamics and gravity-driven effects such as creaming and sedimentation. Traditional Earth-based studies struggle to isolate intrinsic droplet interactions because buoyancy obscures subtle forces. To overcome this, a new study published in the *Journal of Colloid and Interface Science* conducted experiments aboard station, where droplet dynamics are governed solely by Brownian motion and surface forces. The researchers aimed to uncover the fundamental mechanisms – especially coalescence and aggregation – that drive emulsion aging and destabilization, with the goal of improving formulation efficiency and reducing energy and material use.

Using Diffusing Wave Spectroscopy (DWS), the team observed droplet motion and interactions in oil-in-water emulsions stabilized by a non-ionic surfactant (i.e., gentle detergent). They tested emulsions with varying oil and surfactant concentrations, simulated emulsification in microgravity using a piston-driven mixer, and validated droplet size distributions through ground-based microscopy. Monte Carlo simulations helped interpret the DWS data by modeling photon paths and separating Brownian from ballistic motion. Results showed that droplets underwent transient ballistic motion immediately after emulsification, indicating early coalescence among small drops. Over time, a slower aging process emerged, likely involving interactions between small and large droplets, suggesting a shift in destabilization dynamics. Microgravity enabled these detailed insights into how emulsions evolve and lose stability.

[Results showed] early coalescence among small drops. These findings can improve the design of more stable, efficient emulsions –reducing energy consumption and surfactant use in various industries.

This research is significant because it reveals the intrinsic mechanisms behind emulsion aging, which are often hidden by gravity in Earth-based experiments. On Earth, these findings can improve the design of more stable, efficient emulsions – reducing energy consumption and surfactant use in various industries. In space, the insights contribute to the development of reliable systems for life support, medicine, and manufacturing in long-duration missions.

DISCOVERY

The investigation **Plasma Kristall-4 (PK-4)** sponsored by ESA and Roscosmos examines the fundamental physics of complex (dusty) plasmas under microgravity conditions. Specifically, it studies transport properties, thermodynamics, kinetics, statistical physics, and nonlinear waves and instabilities in these plasmas. By observing strongly interacting, charged microparticles, PK-4 seeks to understand self-organization, liquid phases, and flow phenomena that can form fully three-dimensional systems rather than thin layers constrained by gravity.

In a new study published in *Physics of Plasmas*, researchers focused on polarity switching – rapid oscillations of the electric field, a voltage direction change, used to stop and confine dust clouds – because it unexpectedly alters particle motion and energy. Ground-based experiments suggested only brief changes in dust temperature, but microgravity experiments revealed significant heating and unusually long cooling times that could not be explained by known mechanisms like neutral gas drag. The problem they aimed to solve was identifying the physical mechanism behind this excess heating and energy dissipation, ultimately linking it to changes in plasma screening and dust–dust interactions triggered by polarity switching.

The researchers conducted experiments using the complex plasma facility on the space station and compared the results with identical ground-based experiments under the same plasma conditions. Micrometer-sized dust particles were injected into a neon direct current glow discharge plasma, where they acted as tracers, allowing sci-

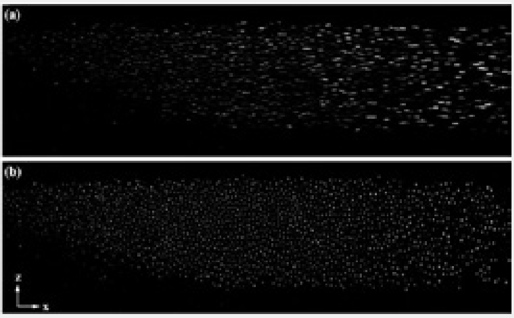


Figure 24. *Dust plasma images: (a) initial stage, and (b) bulk motion of stationary dust following polarity switching. Image adapted from McCabe, Physics of Plasmas.*

entists to observe the plasma's behavior. By flipping the electric field, the particles were held in place, preventing them from drifting. Particle Image Velocimetry was applied to high-speed camera data to measure dust velocities, temperature evolution, and spatial dynamics before and after polarity switching. They complemented the experiments with molecular dynamics simulations (YOAKμM) that modeled dust–dust interactions under changing plasma screening lengths. The results showed that, unlike ground experiments, microgravity conditions produced a sharp increase in dust kinetic temperature (i.e., faster particle movement) followed by an unusually long cooling period. Both experimental measurements and simulations indicated that this heating arises from a temporary reduction in plasma screening, causing dust cloud expansion and conversion of configurational potential energy into thermal energy.

This research reveals how dust–plasma interactions behave fundamentally differently in microgravity, uncovering a previously unrecognized heating mechanism driven by changes in plasma screening rather than simple gas drag. For space applications, these findings improve understanding of complex plasmas in environments such as the space station, planetary rings, cometary tails, and astrophysical dust clouds, where microgravity-like conditions dominate. On Earth, the results inform plasma processing, materials science, and dusty plasma experiments by clarifying how rapid electric-field changes can redistribute energy and alter particle dynamics in laboratory and industrial plasma systems.

JAXA's investigation **Thermophysical Properties Measurements of Non-Equilibrium Molten Alloys for Design of Thermal Storage Material (ELF-Thermal Storage)** aims to design phase-separated molten alloys that can efficiently store thermal energy, for safe and efficient high-temperature applications. To achieve this, the investigation measures the thermophysical properties and nucleation rates of non-equilibrium molten alloys under microgravity using the Electrostatic Levitation Furnace aboard space station, eliminating the effects of convection and container contact that hinder ground-based experiments. These measurements

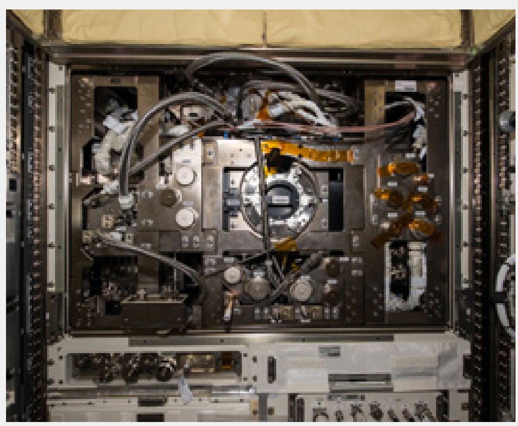


Figure 25. Photograph showing the front panel of the Electrostatic Levitation Furnace (ELF) inside the Japanese Experiment Module on the space station. NASA ID iss046e011444.

allow accurate evaluation of viscosity, surface tension, and mass transport phenomena, which are critical for modeling solidification and optimizing material performance.

> *Precise measurements of iron-copper enable researchers to model the behavior of phase-separating alloys during solidification and optimize their design for thermal energy storage.*

In a recent study published in *ISIJ International*, researchers measured the thermophysical properties of molten iron-copper (Fe–Cu) alloys, including density, surface tension, and viscosity. The results showed that the density decreases linearly with temperature, with higher copper content leading to increased density. Surface tension displayed a slightly convex temperature dependence, decreasing as copper content increased, while viscosity declined with rising temperature, and higher copper content further reduced it. These precise measurements of iron-copper enable researchers to model the behavior of phase-separating alloys during solidification and optimize their design for thermal energy storage.

This research is important because it provides accurate thermophysical data on Fe–Cu alloys, essential for designing efficient thermal energy storage materials. In space, these materials could enhance energy management on spacecraft and future space stations, where reliable high-temperature storage is critical. On Earth, phase-separating alloys could improve renewable energy systems by enabling safe, high-density heat storage to balance fluctuations in energy supply and demand.

BENEFITS FOR HUMANITY

The investigation **Materials International Space Station Experiment-13-NASA (MISSE-13-NASA)** evaluates how prolonged exposure to the low Earth orbit environment affects the performance, durability, and degradation of a wide range of advanced materials needed for current and future space missions. A series of investigations aim to generate real flight data on polymers, composites, thermal protection systems, radiation shielding materials, spacesuit components, and photovoltaic technologies to improve durability forecasting and validate ground-based predictive models. A key goal is to compare new materials and configurations against heritage benchmarks to understand erosion, radiation effects, and environmental resilience over time. Collectively, these studies support the development of lighter, more reliable, and mission-ready materials for human and robotic exploration in space, while also informing potential Earth-based applications.

Materials used in low Earth orbit are exposed to intense radiation, atomic oxygen, and extreme temperature cycling, which can degrade structural integrity and compromise long-duration space missions. To address the need for lightweight, sustainable materials that can both withstand these conditions and provide radiation shielding, a new study published in the *Proceedings of the National Academy of Sciences* investigated polylactic acid (PLA) biocomposites enhanced with biologically derived melanin. Fungal melanin was of particular interest because of its known radioprotective, antioxidant, and structural properties observed in extremophile fungi that survive high-radiation environments. The study aimed to solve the problem of material degradation and insufficient radiation protection in space by testing whether melanin-infused PLA could improve durability and shielding performance under real low Earth orbit conditions aboard the space station.

Biologically derived materials can significantly improve radiation shielding and structural stability under real spaceflight conditions.

The researchers fabricated circular disks of bare PLA and PLA biocomposites containing fungal melanin, synthetic melanin, animal melanin, or compressed mycelium, and exposed them for ~6 months to real low Earth orbit conditions on the station using platforms facing different directions. After return to Earth, flight-exposed samples were compared to ground controls using light-based imaging, surface analysis, and radiation-blocking tests to understand how the material performs and degrades. All materials experienced some degradation, but PLA infused with fungal melanin showed the lowest mass loss – up to ~89% less than pure PLA in the zenith orientation – and exhibited minimal surface wrinkling. Melanin-containing composites also reduced surface damage and chemical degradation relative to PLA alone. Importantly, all biocomposites provided radiation shielding, with fungal melanin–PLA offering superior protection of the underlying polyvinyl chloride (PVC) layer against UV and space radiation. Overall, the results demonstrated that fungal melanin significantly enhances both structural stability and radiation-shielding performance of PLA under authentic spaceflight conditions.

This research demonstrates that biologically derived materials – specifically fungal melanin–infused PLA – can significantly improve radiation shielding and structural stability under real spaceflight conditions, addressing a major challenge for long-duration human and robotic missions. For space applications, these lightweight, sustainable biocomposites could be used to protect spacecraft structures, habitats, supplies, and potentially astronauts, while also supporting future in-situ manufacturing beyond Earth. On Earth, the findings have implications for developing eco-friendly materials with enhanced radiation and UV protection for use in medical shielding, protective coatings, packaging, and resilient infrastructure in extreme environments.

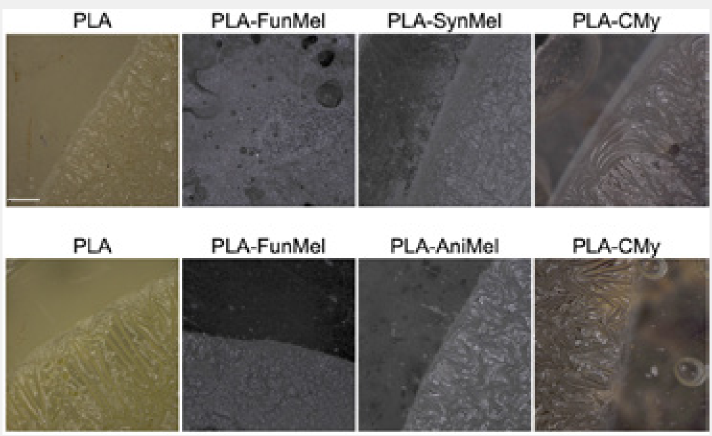
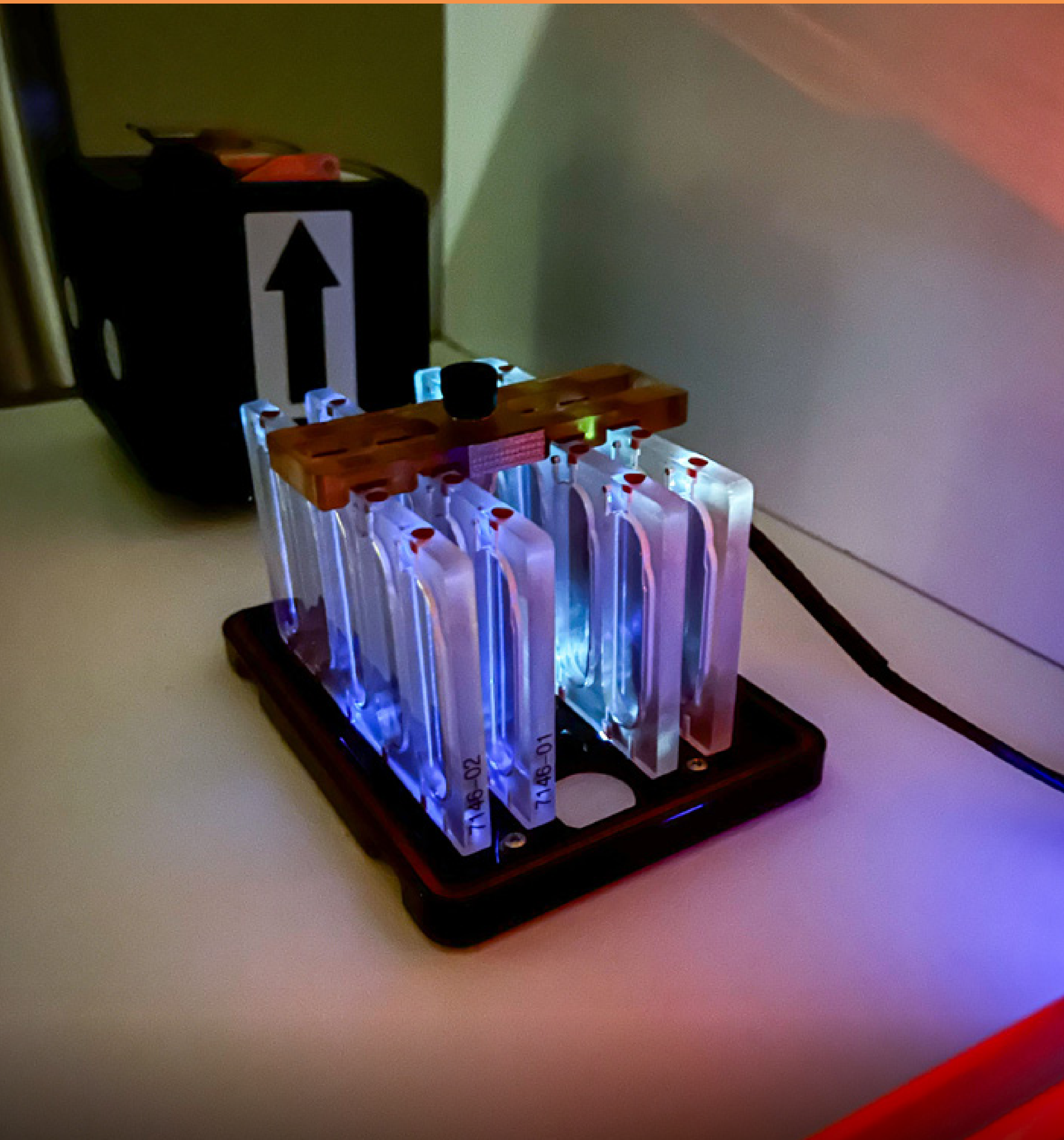


Figure 26. *Light microscopy images showing surface wrinkles on samples exposed in (A) zenith and (B) wake orientations. Fungal melanin–PLA provides enhanced UV and space-radiation protection, improving the structural stability of the underlying base layer. Image adapted from Cordero, Proceedings of the National Academy of Sciences.*

TECHNOLOGY DEVELOPMENT and DEMONSTRATION



*Agar plates for the **Germicidal Ultraviolet Light Biofilm Inhibition (GULBI)** investigation. Bacteria in space can form slimy layers called biofilms on wet surfaces where they can threaten astronaut health and damage equipment. GULBI studies how a common bacterium, P. aeruginosa, responds to germicidal ultraviolet (UV-C) light in space compared to on Earth. Finding an effective way to use UV-C light in space could provide a safer, more affordable alternative to chemical disinfectants for keeping spacecraft clean. NASA ID: jsc2025e067422.*

Highlights in **Technology Development and Demonstration**

Future exploration – the return to the Moon and human missions to Mars – presents many technological challenges. Studies on the space station allow testing of a variety of technologies, systems, and materials needed for these missions. Some technology development investigations have been so successful that the tested hardware has been transitioned to operational use, while other results inform the development of new technologies.

EXPLORATION

The JAXA investigation **Space AS-LiB** demonstrates the safe and stable operation of all-solid-state lithium-ion batteries (ASSBs) in the space environment, including under extreme temperatures and vacuum. The investigation aims to confirm that the battery's wide operating temperature range (–40 °C to 120 °C), high chemical stability, and resistance to leakage or ignition, make it suitable for space and planetary missions. It also seeks to show that performance observed in space matches ground-based results, supporting its adoption for future exploration missions.

Future lunar and Martian exploration missions require energy storage systems that can operate safely and reliably in extreme temperatures and radiation. Conventional lithium-ion batteries with liquid electrolytes have a limited temperature range (about 5–40 °C) and can suffer from safety risks like gasification, leakage, or ignition, making them unsuitable for prolonged use on the Moon or Mars without complex thermal control. ASSBs, using solid electrolytes, offer a much wider operating temperature range (–40 °C to +120 °C), improved safety, and longer lifespan, but their real-world performance in space had not been demonstrated.

In orbit, lithium-ion batteries maintained a stable charge... confirming their performance and longevity in space... with no evidence of degradation from vacuum, microgravity, or radiation exposure.

In a recent study published in *Aerospace*, researchers aimed to validate whether ground-tested ASSB performance predictions hold true in the combined space environment of microgravity, vacuum, temperature extremes, and radiation, thus addressing a critical barrier to adopting ASSBs for future space missions.

The team first conducted extensive ground-based environmental tests on sulfide-type ASSBs, including vibration, high- and low-temperature storage, high-temperature charge–discharge under vacuum, simulated lunar surface cycles, and gamma-ray irradiation,

Figure 27. *Lithium battery tested aboard the space station. Image adapted from Miyazawa, Aerospace.*

to confirm durability under space-like conditions. They then assembled a 2.1 Ah battery pack from fifteen 140 mAh ASSB cells and integrated it into the Space AS-LiB demonstration device. Over 434 days in orbit, the system completed 562 charge–discharge cycles under multiple temperature and rate conditions, with continuous performance monitoring and occasional operation of a 360° camera powered by the battery. Ground-based tests were run in parallel using identical cells to directly compare results. In orbit, the battery maintained stable charge–discharge behavior with only ~2 percent capacity loss, closely matching the ~3 percent degradation observed on the ground. These results confirmed that ASSB performance and lifetime in space can be reliably predicted from ground tests, with no evidence of degradation from vacuum, microgravity, or radiation exposure.

This research demonstrates that ASSBs can operate reliably in the harsh space environment, overcoming the temperature and safety limitations of conventional lithium-ion batteries. For space, this means more robust, lighter, and simpler power systems for lunar and Martian missions, reducing the need for complex thermal control and improving mission safety. On Earth, the same durability and wide temperature tolerance could benefit applications in extreme climates, remote power systems, electric vehicles, and renewable energy storage.

DISCOVERY

NASA's investigation **Robotic Surgery Tech Demo** evaluates whether a miniature robotic surgical system can safely and effectively perform simulated surgical tasks in a microgravity environment. The study aims to compare inflight performance data with identical ground-based tests to determine how microgravity affects robotic precision, motion, and task execution. Another key objective is to assess the impact of communication latency on remotely controlled surgical tasks performed from Earth. Overall, the results are intended to inform the design of future robotic surgical systems for long-duration space missions where in-situ medical care is required.

In a new study published in *AIAA Aviation Forum* and *ASCEND 2025*, the researchers investigated robotic telesurgery aboard the space station to address the challenge of providing safe and effective surgical care during long-duration space missions, where immediate crew return for medical care is not possible. Prior studies have shown that microgravity can impair human surgical performance, particularly for non-expert operators, raising concerns about astronauts' ability to perform complex medical procedures in space. Robotic-assisted surgery offers a potential solution by reducing coordination challenges, limiting excessive force on tissues, and minimizing the amount of equipment required in a microgravity environment. This study specifically sought to determine whether a miniature surgical robot could reliably perform autonomous and teleoperated surgical tasks in space, and to assess the effects of microgravity and communication latency on surgical performance.

Microgravity had minimal impact on robotic precision or applied forces, while communication latency significantly affected surgeon performance by increasing operative time.

The researchers conducted a technology demonstration using a miniature surgical robot (spaceMIRA) packaged within a standard EXPRESS Rack Locker, where it performed a simulated tissue dissection task involving stretching and cutting rubber-band "tissue." The experiment included two phases: an autonomous phase in which the robot executed preprogrammed surgical motions, and a telesurgery phase in which Earth-based surgeons remotely controlled the robot under real station communication latency conditions. Preflight and ground-based trials under normal gravity were conducted for comparison, and detailed kinematic, force, and positional data were collected to assess performance differences between Earth and microgravity. The results showed that microgravity had minimal impact on robotic precision or applied forces, while communication latency significantly affected surgeon performance by increasing operative time but also led to improved economy of motion through adaptive strategies. Overall, the study demonstrated that miniature robotic surgery is feasible in space and that latency – not microgravity – is the primary operational challenge for telesurgery during long-duration missions.

This research demonstrates that safe, precise robotic surgical procedures are feasible in microgravity, addressing a critical medical gap for long-duration space missions where evacuation to Earth is impossible. For space exploration, the findings support the use of compact, autonomous or remotely operated surgical systems to provide medical care on the Moon, Mars, and deep-space missions despite communication delays. On Earth, the technology has direct applications in improving access to surgical care in remote, underserved, or disaster-stricken regions, as well as advancing telemedicine and robotic-assisted surgery in extreme or resource-limited environments.

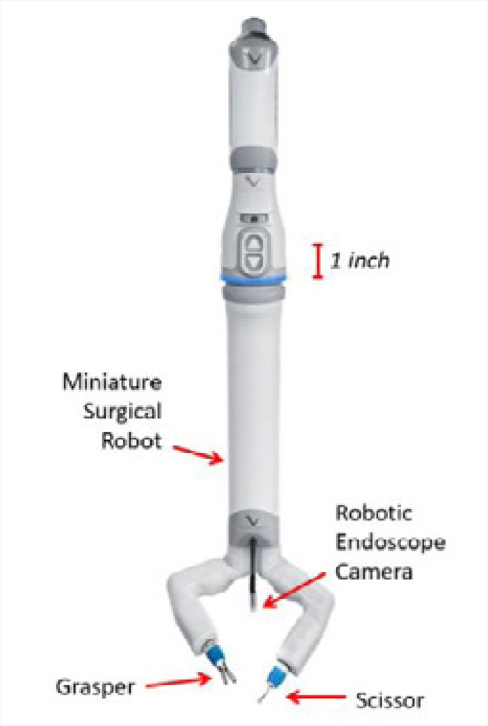


Figure 28. *Image of the miniature surgical robot spaceMIRA used aboard the space station. Image adopted from Wagner, AIAA AVIATION FORUM AND ASCEND 2025.*

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