National Aeronautics and
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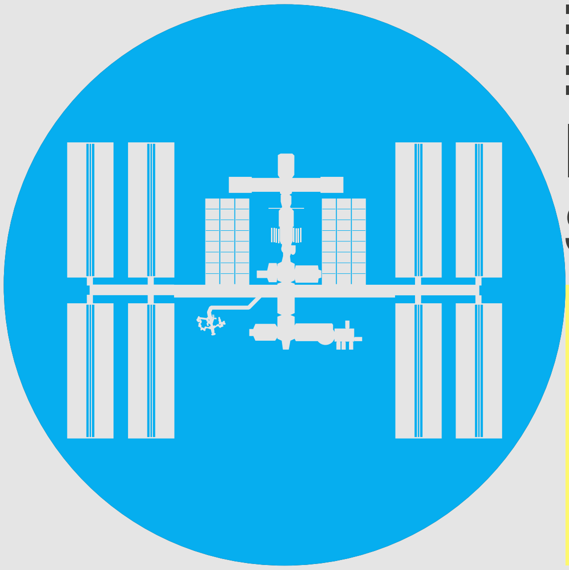

INTERNATIONAL SPACE STATION

ANNUAL HIGHLIGHTS of RESULTS

2024

Annual Highlights of Results From the International Space Station

Oct. 1, 2023 – Sept. 30, 2024

A product of the International Space Station Program Science Forum

This report was developed collaboratively by the members of ASI (Agenzia Spaziale Italiana), CSA (Canadian Space Agency), ESA (European Space Agency), JAXA (Japan Aerospace Exploration Agency), NASA, and Roscosmos. Visit the **Space Station Research Results Library** to find all previous and current editions of the Annual Highlights of Results from the International Space Station.

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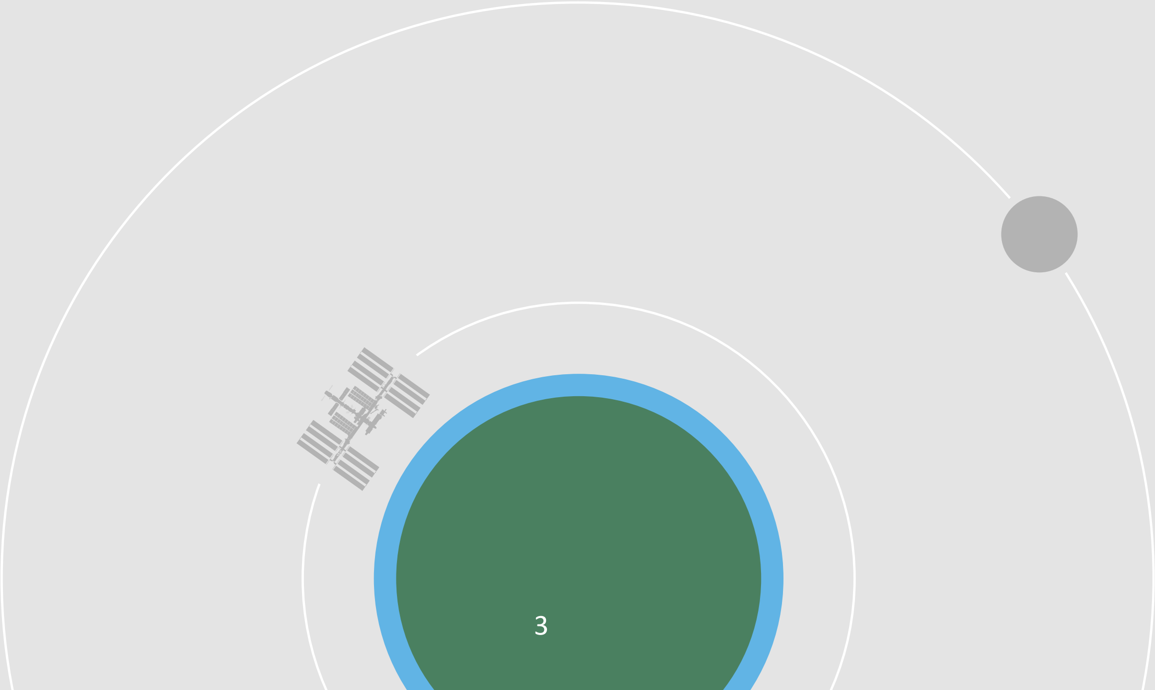


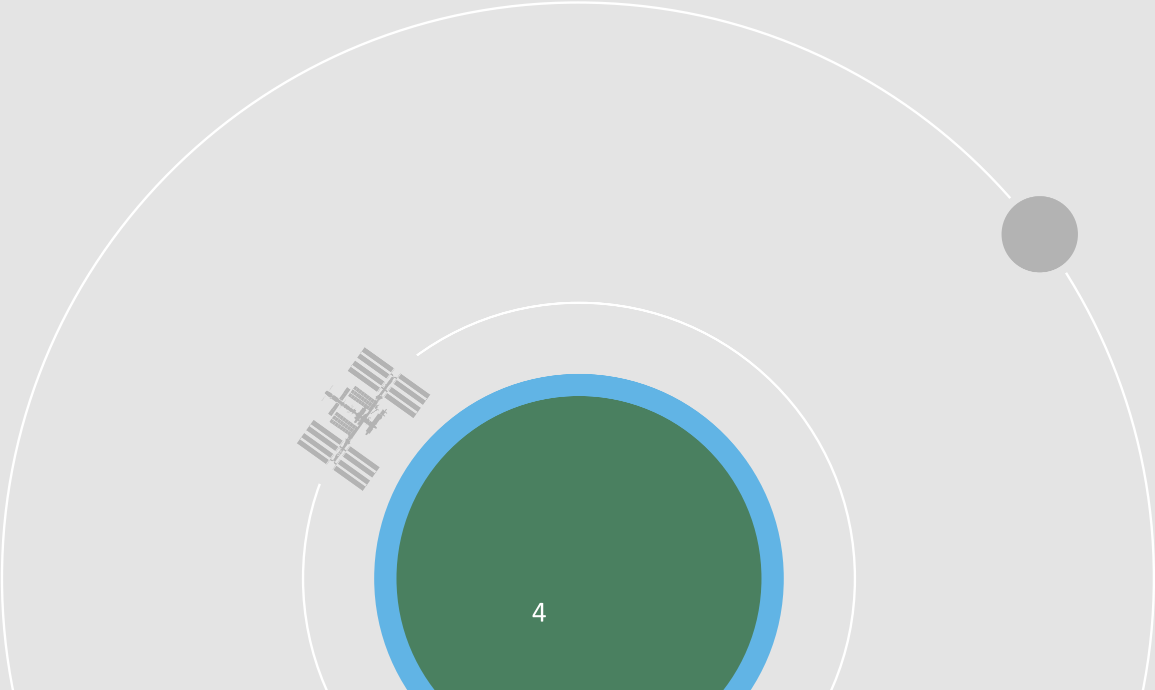
Letter From the International Space Station Program Science Forum

In 2024, the International Space Station celebrated many firsts and new successes, thanks to the collaboration that strengthens its mission. Over the last 25 years, the space station has become a premier orbiting laboratory, enabling over 4,000 groundbreaking experiments representing over 100 different nations. Just this year, we saw the first live human heart tissue 3D bioprinted on station as well as the first metal 3D print of liquified stainless steel. A compact robotic surgeon was remotely operated by doctors on Earth, and over 300,000 photos of Earth – more than all of 2023 – were taken in the first half of 2024 alone to give us a unique perspective of our home planet. This year brought 14 visiting vehicles, a third Private Astronaut Mission, more than 40,000 pounds of cargo delivered, and over 400 investigations conducted by the 25 crew members who called station home.

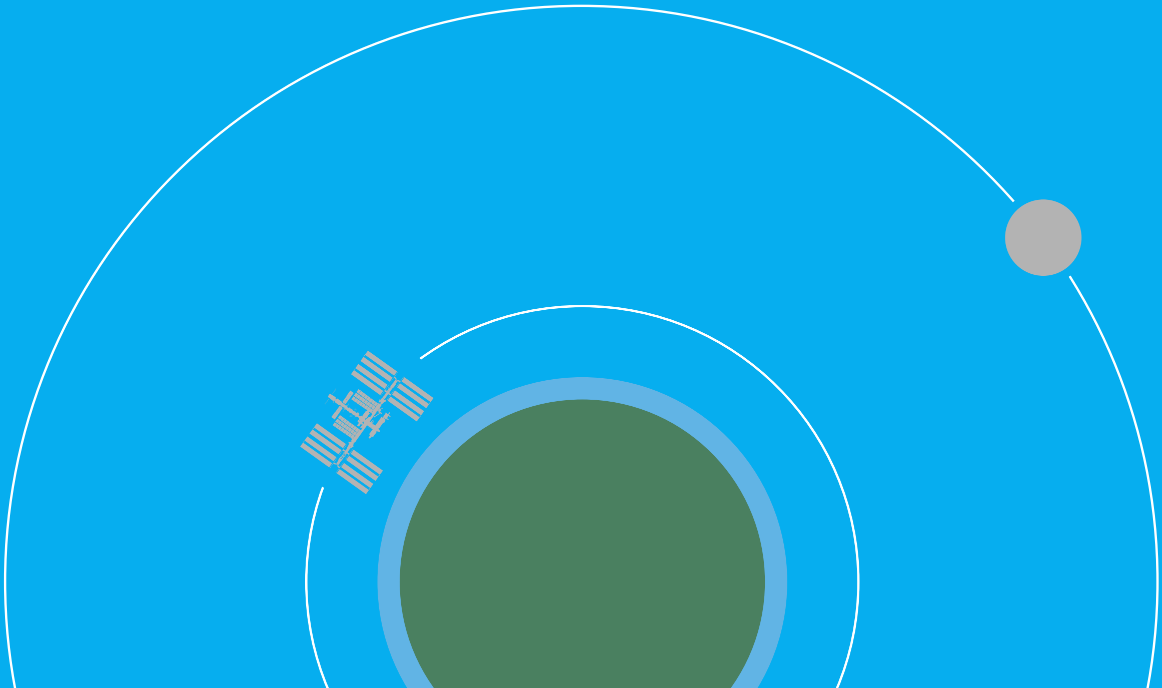
This *2024 Annual Highlights of Results* showcases a small selection of scientific achievements that represent the high quality and diverse research capabilities of the space station and the teams that support its ongoing mission. Through the science that the space station enables, we continue to make history with results from innovative research that cannot be replicated on the ground. This research not only prepares us with new technologies and countermeasures to push farther into the universe, but also improves life on Earth and inspires the next generation of scientists and explorers.

The International Space Station has a wealth of knowledge that can be passed on to commercially developed space stations and the next generation of space research. We look forward to another year of new and continuing research, maximizing humanity's laboratory in space.

Jennifer Buchli, NASA, International Space Station Chief Scientist
Program Science Forum Chair

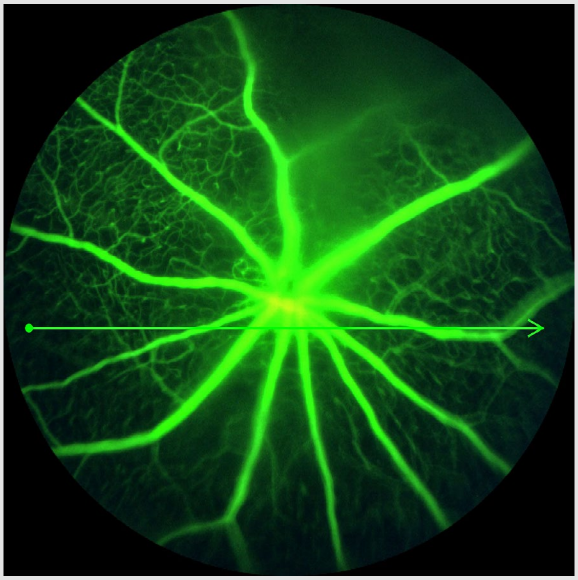


Expedition 70 Flight Engineers (from left) Mike Barratt, Matthew Dominick, and Loral O'Hara participate in an **Earth photography** session inside the cupola, the International Space Station's "window to the world." The orbital complex was soaring 259 miles above West Virginia in the United States at the time of this photograph. NASA ID: iss070e132893.



KEY TAKEAWAYS

- A total of 361 publications were collected in FY-24. These publications include peer-reviewed scientific studies or other literature such as books and patents published recently or years prior. More than 80% of the publications collected in FY-24 were from research sponsored by NASA and JAXA.
- In FY-24, the predominant area of study for publications was Earth and Space science. The results obtained were primarily generated via Derived Results, studies that retrieve open data from online sources to make new discoveries. These Derived publications indicate a 39% return on investment.
- A total of 4,438 publications have been gathered since the beginning of station, and about 16% of this literature has been published in top-tier journals.
- The year-over-year growth of top-tier publications has been greater than the growth of regular publications. In 13 years, there was a 22% growth of top-tier publications and a 0.47% growth of regular publications.
- Almost 80% of top-tier results have been published in the past seven years.
- Station research continues to surpass national and global standards of citation impact.
- This year, a simplified hierarchy map showing the nested categories of station disciplines, subdisciplines, and selected keywords is presented to represent the more than 15,000 topic key words generated by the studies.
- Station research has seen a remarkable growth of international collaboration since its first days of assembly in 1999. Currently, about 40% of the research produced by station is the result of a collaboration between two or more countries.
- To date, the United States has participated in 23% of international collaborations.
- Of the nearly 4,000 investigations operated on station since Expedition 0, approximately 59% are identified as completed. From this subset of completed investigations, studies directly conducted on station rather than *Derived Results* have produced the most scientific results. This pattern differs from analyses conducted with all publication data.



Rodent Research-28 fluorescein angiogram of the microvascular circulation of the mouse retina. Image courtesy: Oculogenex Inc.
NASA ID: jsc2023e054752.

INTRODUCTION

The International Space Station is a state-of-the art laboratory in low Earth orbit. Since the year 2000, distinguished researchers from a myriad of disciplines around the world have been sending equipment and investigations to station to learn how space-related variables affect the human body, plant and microbial life, physical processes, equipment function, and more. Sophisticated remote sensing techniques and telescopes attached to station also observe the Earth and the universe to enhance our understanding of weather patterns, biomass changes, and cosmic events.

Investigations can be operated remotely from Earth with ground control support, directly on station with the help of crew members, or autonomously (without human assistance). The most recent science conducted on station has engaged private astronauts to advance the research endeavors of the commercial sector. The improvement of these science operations (i.e., how data is collected and returned) has led to more reliable scientific results. Additionally, extensive domestic and international collaboration bridging academic institutions, corporations, and funding agencies has produced high quality and impactful research that inspires new generations of students, researchers, and organizations looking to solve problems or innovate in emerging fields.

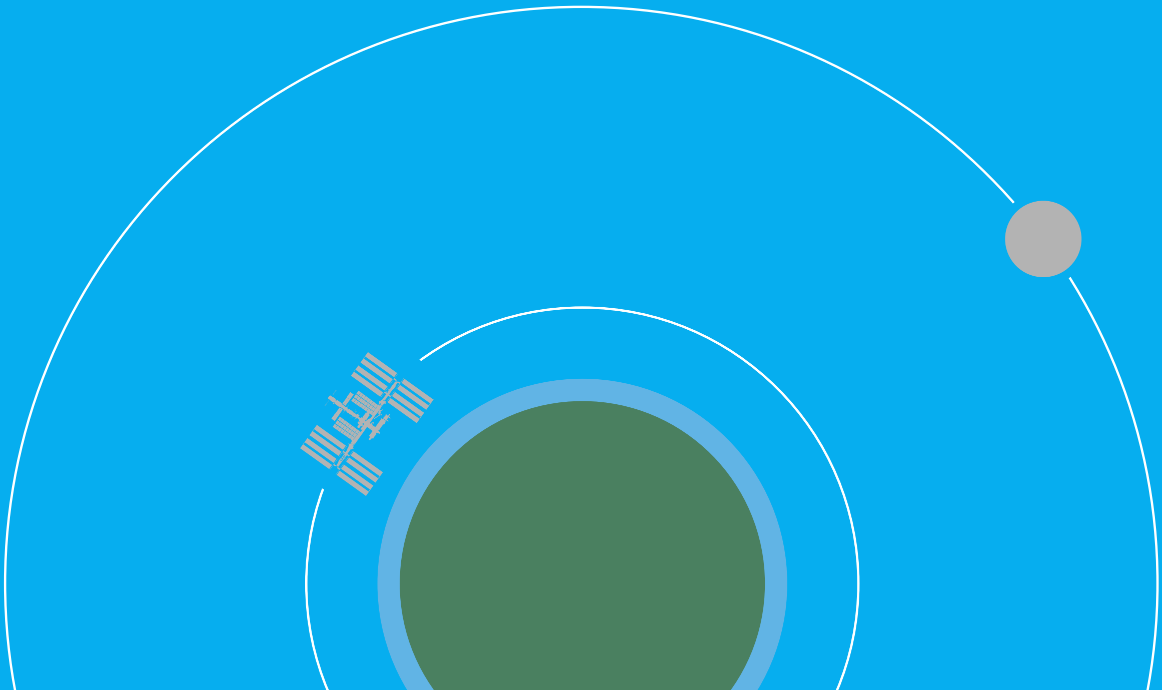
The studies highlighted in this report are only a small, representative sample of the research conducted on station in the past 12 months. Many more groundbreaking findings were reported in fiscal year 2024 (FY-24), including:

- Plant adaptation through the adjustment of regulatory proteins, which can lead to sustainable food production on the Moon and Mars (**BRIC-LED-001**).
- A connection between downregulated mitochondrial gene pathways and neurotransmitter signaling dysfunction that could assist the development of new pharmaceutical or nutritional therapies to prevent strength loss in neuromuscular disorders. (**Microbial Observatory-1**).
- The precise measurement of hydrogen isotopes to provide a better assessment of dark matter (**AMS-02**).
- The adaptation of a permanent flow cytometer in space that enables the examination of blood counts, hormones, enzymes, nucleic acids, proteins, and biomarkers to assess crew health in real time (**rHEALTH**).
- The behavior of oil-in-water drops in microgravity (i.e., oil drops grow over time, but drop displacement decreases). Understanding the behavior of oils, dyes, and detergents can lead to a safer environment and sustainability of emulsion technologies in the food, pharmaceutical, paint, and lubrication industries (**FSL Soft Matter Dynamics-PASTA**).

Fundamental and applied research conducted on station improves the state of scientific understanding. Whether it is through the examination of microgravity and radiation effects, or through the testing of countermeasures, new materials, and computing algorithms; the hard work of integrating flight operations with scientific objectives is carried out to protect our planet, improve our health, and learn more about our place in the universe.

The following pages aim to demonstrate how station is revolutionizing science through cooperation, curiosity, and ingenuity. Projects that may have begun as simple ideas are now shaping the way we think about and operate in space to advance our goal of going to the Moon and beyond.

NASA astronaut and Expedition 70 Flight Engineer Jasmin Moghbeli poses in front of the Kibo laboratory module's **Advanced Plant Habitat** housing tomato plants for an experiment investigating how the plant immune system adapts to spaceflight and how spaceflight affects plant production. NASA ID: iss070e073612.



Bibliometric Analyses: Measuring Space Station Impacts

Literature associated with space station research results (e.g., scientific journal articles, books, patents) is collected, curated, and linked to investigations. The content from these publications is classified based on how the results are obtained. The current classifications are:

- **Flight Preparation Results** - publications about the development work performed for an investigation or facility prior to operation on space station.
- **Station Results** - publications that provide information about the performance and results of an investigation or facility as a direct implementation on station or on a vehicle to space station.
- **Derived Results** - publications that use open data from an investigation that operated on station. Access to raw data for new researchers expands global knowledge and scientific benefits.
- **Related** - publications that indirectly lead to the development of an investigation or facility. To date, over 2,200 publications have been identified as Related. This count of Related publications is 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.

Facilities consist of the infrastructure and equipment on station that enable the research to be conducted (e.g., workstation "racks" containing power, data and thermal control, furnaces, crystallization units, animal and plant habitats). Investigations are research projects with one or multiple science objectives. Investigations may use a facility to execute the experiments. A publicly accessible database of space station investigations, facilities, and publications can be found in the **Space Station Research Explorer (SSRE)** website.

Through bibliometric analyses, the examination of publications and citations in different categories, we learn about research productivity, quality, collaboration, and impact. These measurements allow our organization to identify trends in research growth to better plan and support new scientific endeavors. The analyses included in this report serve to answer questions related to fiscal year data and total publication data to promote research accountability and integrity and ensure benefits to humanity.

Station research produced in FY-2024

Between Oct. 1, 2023, and Sept. 30, 2024, we identified a total of **361** publications associated with station research. Of these 361 publications, 52 were published in Biology and Biotechnology, 176 in Earth and Space, 5 in Educational and Cultural Activities, 40 in Human Research, 56 in Physical Science, and 32 in Technology Development and Demonstration. This publication count broken out by research discipline and space agency is shown in **Figure 1A**. Of the 361 publications, 41 were classified as Flight Preparation Results, 178 as Station Results, and 140 as Derived Results. Because Derived Results are new scientific studies generated from shared data, derived science is an additional return on the investment entrusted to station. In FY-24, this return on investment was 39%; a 12% increase from FY-23. **Figure 1B** shows this publication data broken out by research discipline and publication type.

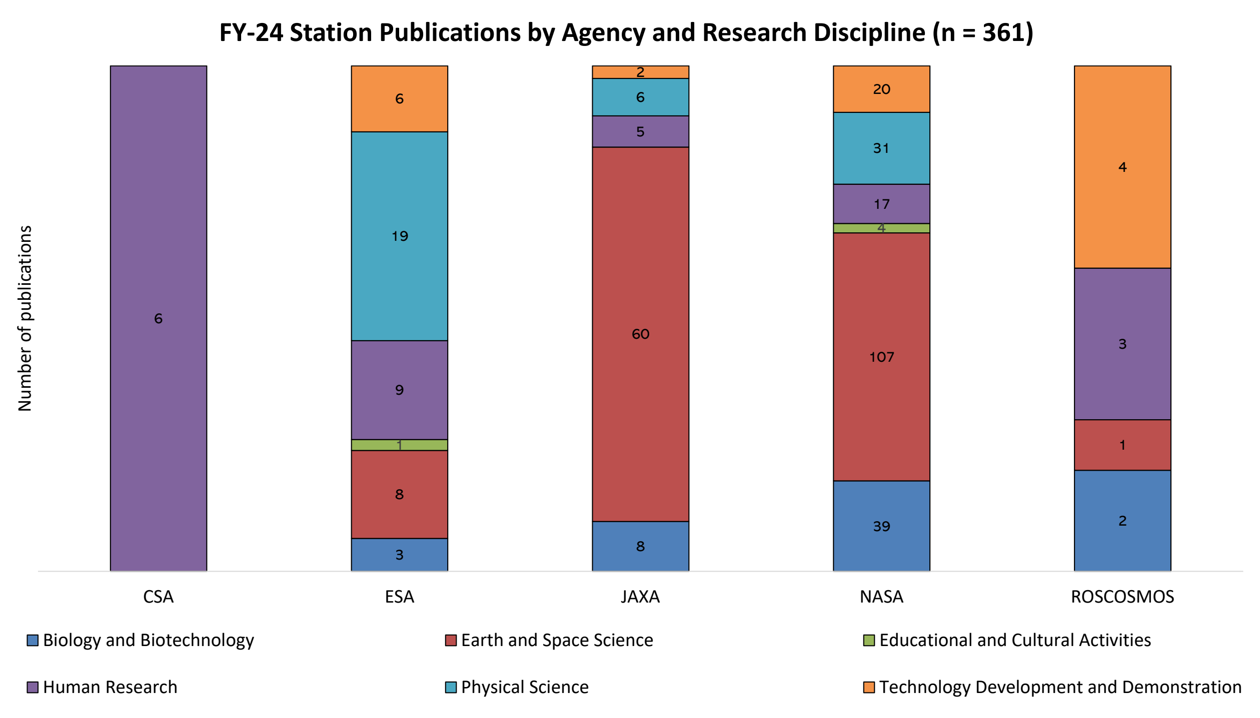


Figure 1A. A total of 361 publications were collected in FY-24. Over 80% of the publications reported results in Earth and Space, primarily from investigations associated with NASA and JAXA research.

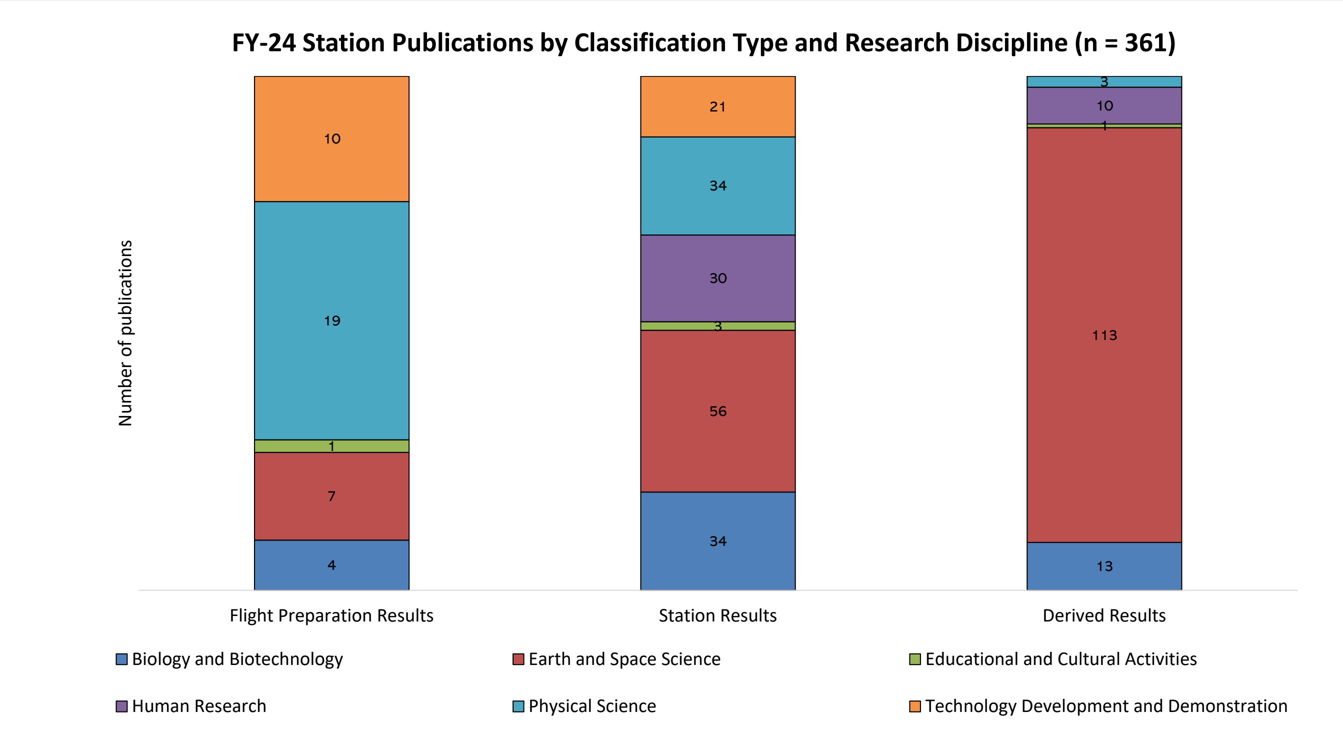


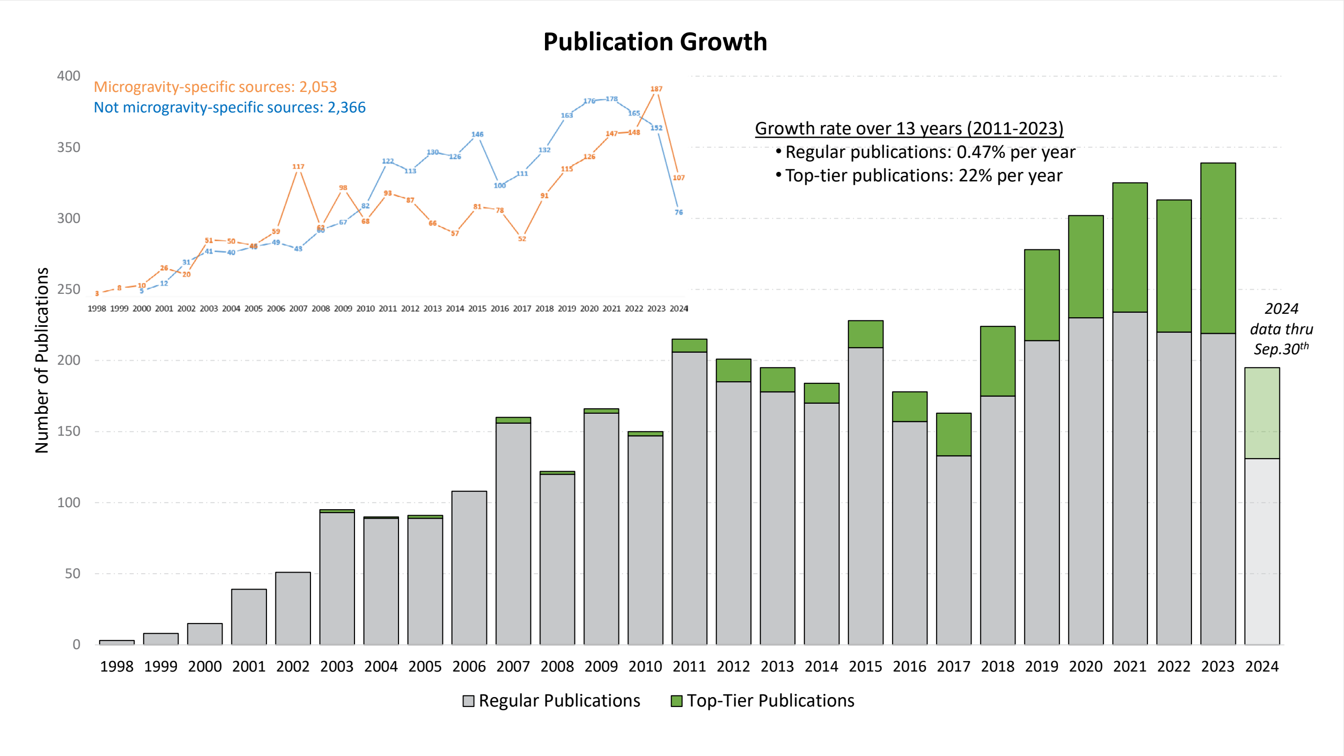
Figure 1B. A total of 361 publications were collected in FY-24. Most publications in Earth and Space came from Derived Results associated with NASA and JAXA research. These Derived Results demonstrate a return on investment of 39%, a 12% increase from FY-23.

Overall growth, quality, impact, and diversity of station research

Growth: A total of **4,438** publications have been collected since station began operations with 176 publications (4%) from work related to facilities on station. In **Figure 2A**, we show the growth of both regular and top-tier science over the years. Top-tier publications are studies published in scientific journals ranked in the top 100 according to Clarivate^{TM} (Web of Science^{TM})[1], a global database that compiles readership and citation standards to calculate a journal's Eigenfactor Score[2] and ranking. Regular publications include literature published in sources that may be specific to microgravity research but are not ranked.

Our data shows that over a 13-year period from 2011 to 2023, regular publications grew 0.47% per year and top-tier publications grew 22% per year. Some of the subdisciplines that have experienced most growth from station research are astrophysics (707 publications), Earth remote sensing (266 publications), fluid physics (245 publications), and microbiology (214 publications).

Quality: About 16% of station results have been published in top-tier journals. However, in **Figure 2B** we zoom in to examine the growth of top-tier publications given their station science discipline, showing that almost 80% of top-tier research has been published in the past seven years. Currently, a total of 696 articles have been published in top-tier journals and about 53% of this total are Derived Results from Earth and Space science investigations.

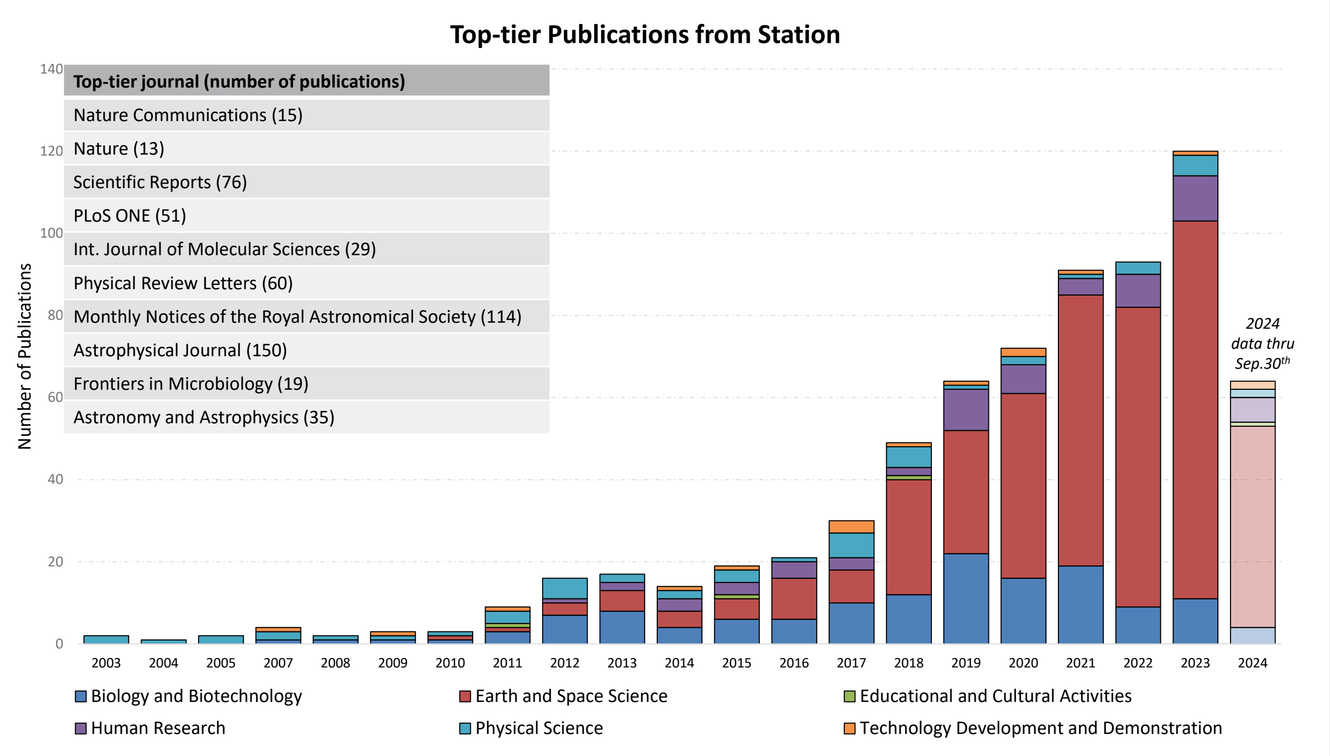


Publication Growth

Growth rate over 13 years (2011-2023)
- Regular publications: 0.47% per year
- Top-tier publications: 22% per year

2024 data thru Sep.30th

Figure 2A. Growth of regular and top-tier research publications over time. About 16% of station results have been published in top-tier journals. Inset shows the growth of microgravity- and non-microgravity-specific sources used in regular publications.



Top-tier Publications from Station

Top-tier journal (number of publications)
Nature Communications (15)
Nature (13)
Scientific Reports (76)
PLoS ONE (51)
Int. Journal of Molecular Sciences (29)
Physical Review Letters (60)
Monthly Notices of the Royal Astronomical Society (114)
Astrophysical Journal (150)
Frontiers in Microbiology (19)
Astronomy and Astrophysics (35)

2024 data thru Sep.30th

Figure 2B. Growth of top-tier research publications by station research discipline (n = 696). There has been a significant increase of top-tier articles published since 2018, with a little over 50% emerging from Derived Results in Earth and Space science. Table inset shows the top-tier journals with most station research published.

Impact: Previous analyses have demonstrated that the citation impact of station research has superseded national and global standards since 2011 (See **Annual Highlights of Results FY-2023**). This pattern continues today.

Diversity: Station science covers six major science disciplines, 73 subdisciplines, and thousands of topic keywords within each subdiscipline. A precise visualization of such abundant diversity would be overwhelming and impenetrable. However, plotting a few topic keywords within each sub-discipline succinctly shows the breadth of science station has to offer (**Figure 3**). For a better appreciation of station's diversity, see the **interactive hierarchy diagram** online. Note that some topics, such as radiation, are studied from multiple perspectives (e.g., radiation measurement through physical science, radiation effects through human research, and shielding through technology development). Topic keywords were obtained using Clarivate™ (Web of Science™). [1]

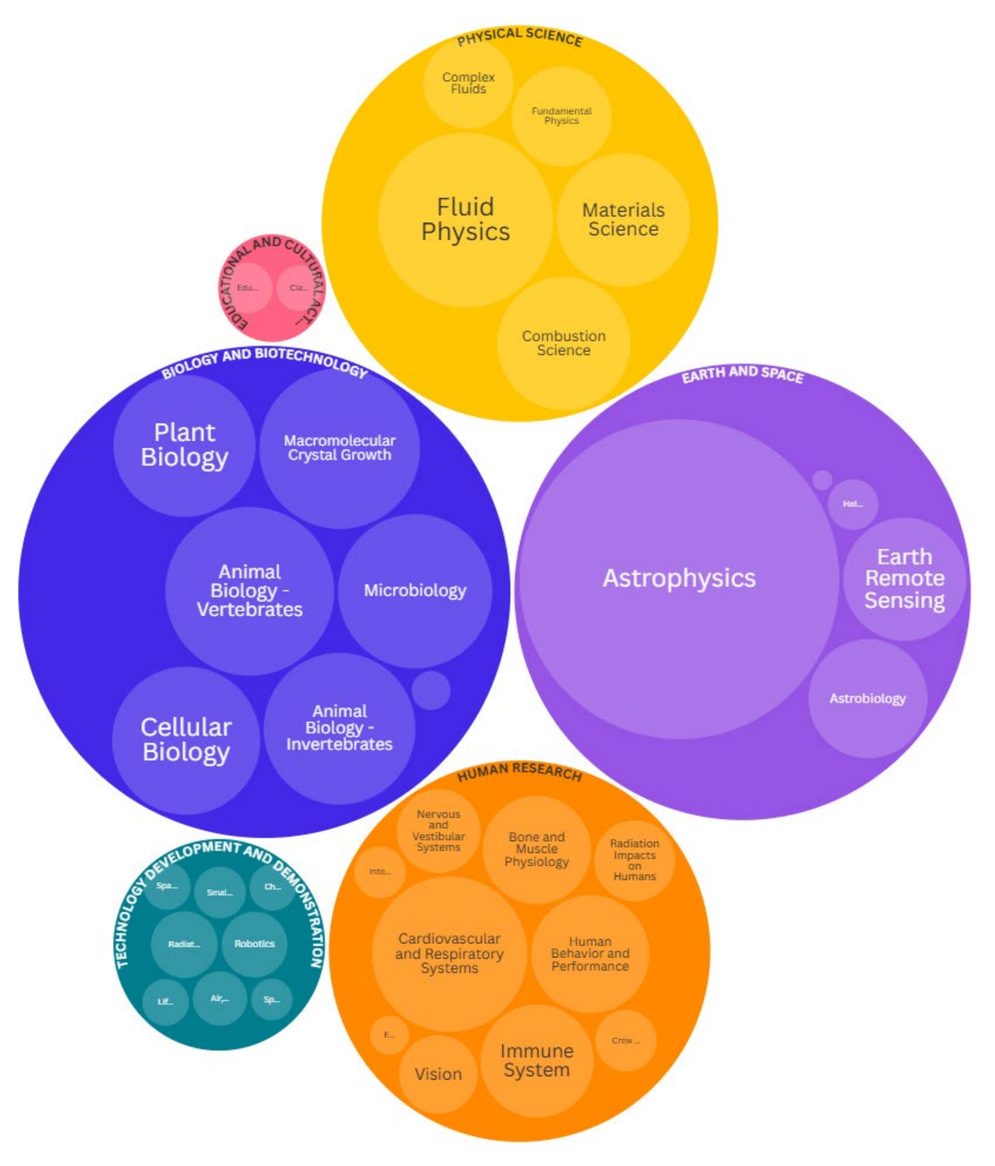


Figure 3: Station Research Diversity. Thousands of topic keywords were identified in connection with station research (N = 18,607). To zoom in and see some of the most prevalent topics on station, view the **interactive hierarchy diagram**.

Station research collaboration

Previous analyses have shown the growth of collaboration between countries throughout the years based on co-authorship (See **Annual Highlights of Results FY-2023**). In a new analysis conducted with country data obtained through Dimensions.ai[3] (n = 3,309 publications), we calculated that about 40% of the publications produced from station research are collaborations between several countries, and about 60% are intercollegiate collaborations within individual countries. As seen in the space agency networks in **Figure 4**, the United States participates in approximately 23% of the collaborations with other countries, making it the most collaborative country.

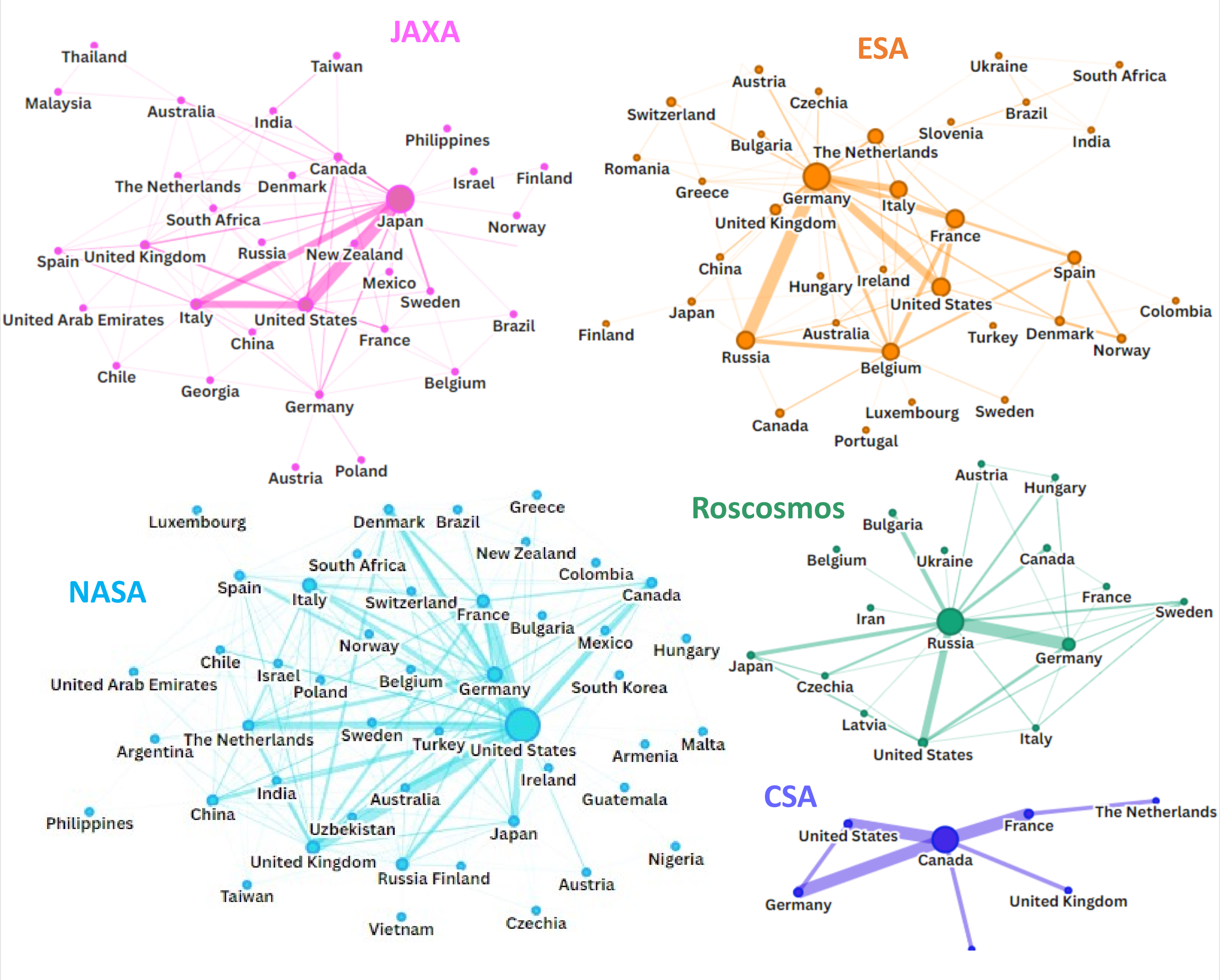


Figure 4: Country collaboration in station research based on publication co-authorship. Networks include up to five countries collaborating in an investigation. Nodes and links from countries that published their research independently are not included.

From research ideas to research findings

Nearly 4,000 investigations have operated since Expedition 0; with a subset of 2,352 investigations (approximately 59%) marked as complete. These completed investigations have concluded their science objectives and reported findings. In **Figure 5**, we show the citation output from publications exclusively tied to completed investigations. In this Sankey diagram, *Times Cited* corresponds to the count of publications with at least one citation in each publication type (Station Results, Flight Preparation Results, and Derived Results). This citation count adequately parallels the total number of citations per publication and allows the **visualization** of a comprehensible chart. This analysis demonstrates that most completed investigations have reported results directly from studies conducted on station, followed by studies conducted in preparation to go to space, and finally by studies derived from open science available online. Likewise, results obtained straight from station receive more citations (e.g, over 46,000) than Flight Preparation (3,636 citations) or Derived results (936 citations). This pattern differs from analyses including all publication data in Figures 1 and 2.

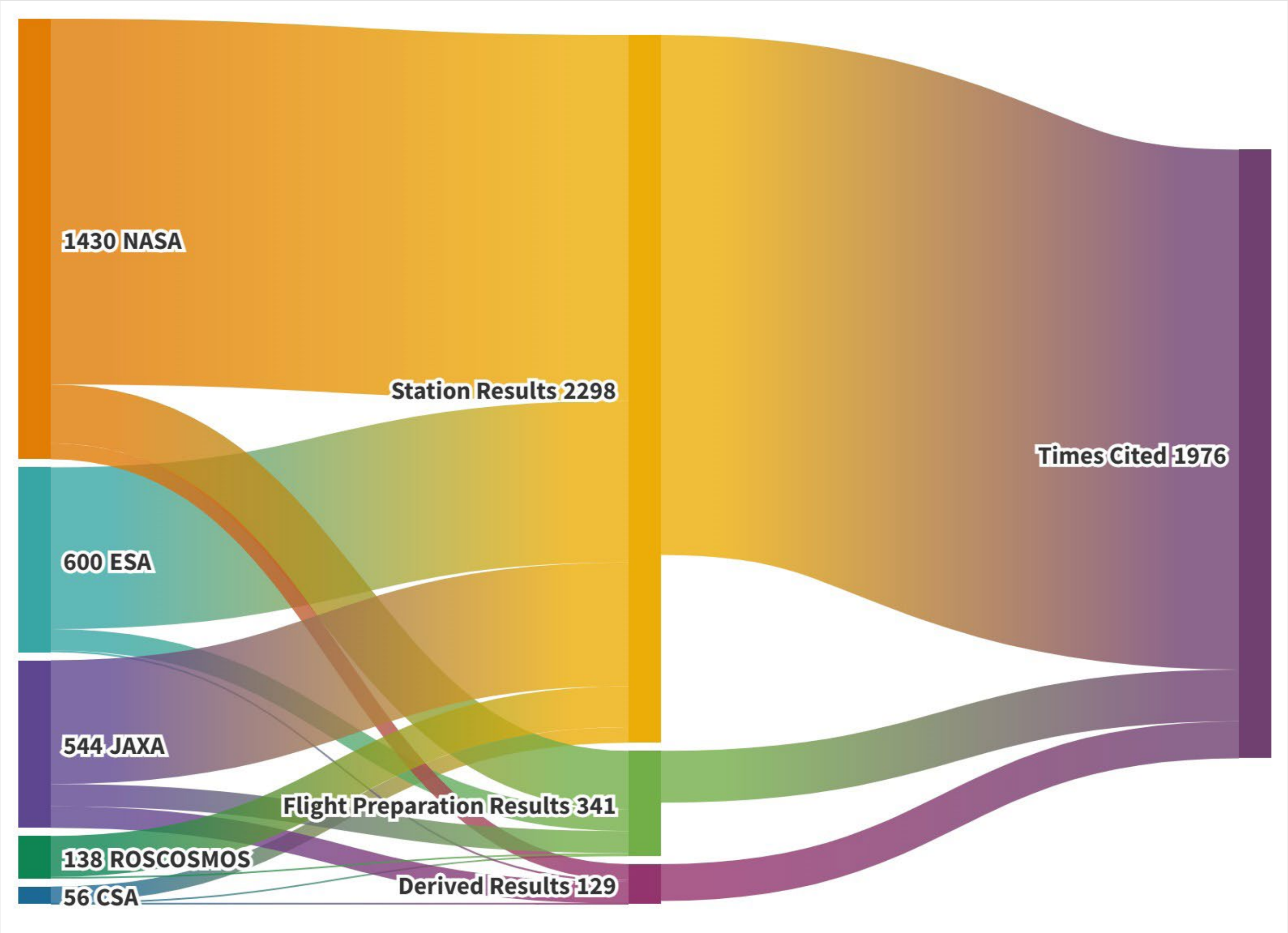


Figure 5: Citation outcome from publications tied to completed investigations. When analyses focus on completed investigations, there are more publications and citations associated with research conducted on station than research conducted in preparation to fly new investigations or research derived from online open data. To examine specific source-destination paths, view the **interactive Sankey diagram**.

Linking Space Station Benefits

Space station research results lead to benefits for human exploration of space, benefits to humanity, and the advancement of scientific discovery. This year's *Annual Highlights of Results from the International Space Station* includes descriptions of just a few of the results that were published from across the space station partnership during the past year.

Space station investigation results have yielded updated insights into how to live and work more effectively in space by addressing such topics as understanding radiation effects on crew health, combating bone and muscle loss, improving designs of systems that handle fluids in microgravity, and determining how to maintain environmental control efficiently.

EXPLORATION

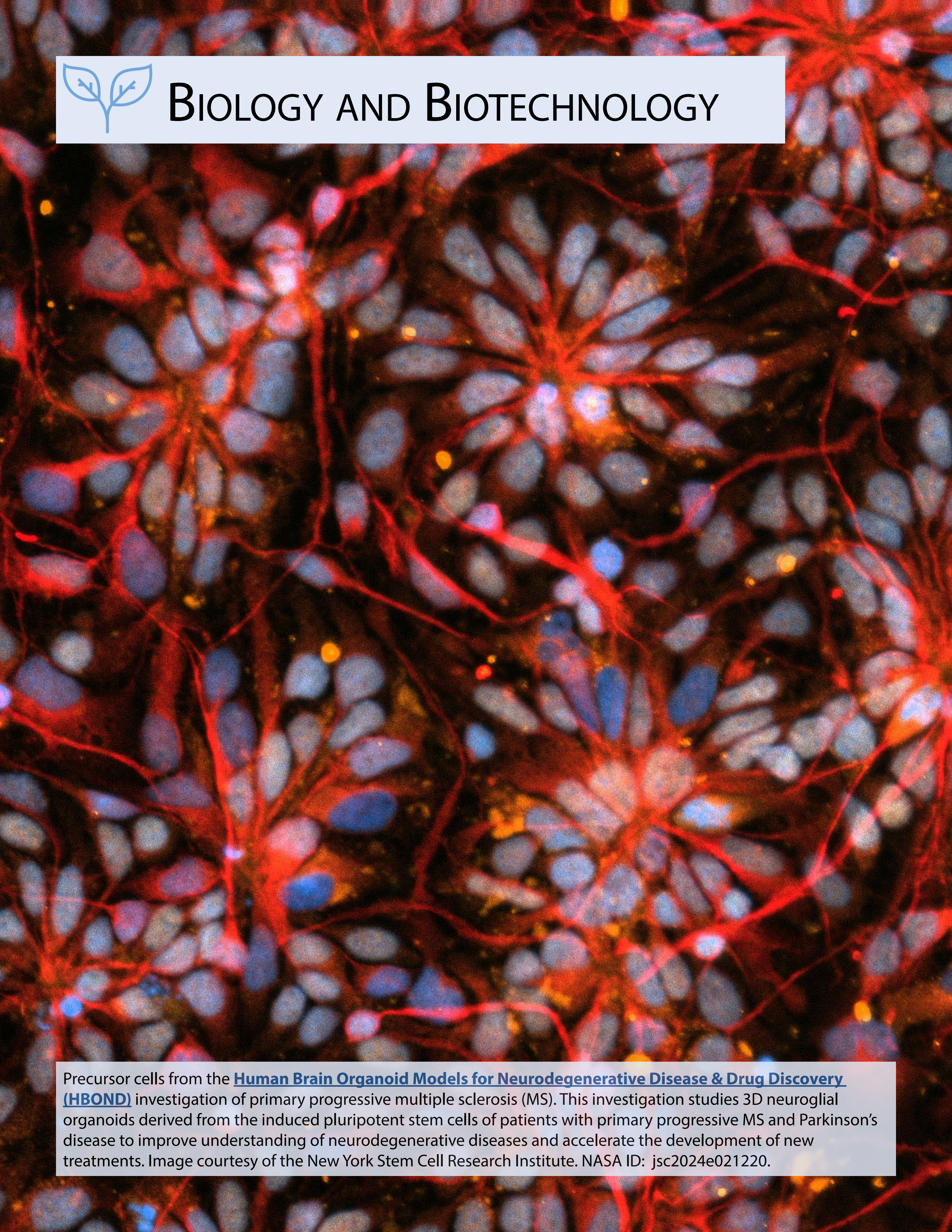
Results from the space station provide new contributions to the body of scientific knowledge in the physical sciences, life sciences, and Earth and space sciences to advance scientific discoveries in multi-disciplinary ways.

DISCOVERY

Space station science results have Earth-based applications, including understanding our climate, contributing to the treatment of disease, improving existing materials, and inspiring the future generation of scientists, clinicians, technologists, engineers, mathematicians, artists, and explorers.

BENEFITS FOR HUMANITY

Biology and Biotechnology



Precursor cells from the **Human Brain Organoid Models for Neurodegenerative Disease & Drug Discovery (HBOND)** investigation of primary progressive multiple sclerosis (MS). This investigation studies 3D neuroglial organoids derived from the induced pluripotent stem cells of patients with primary progressive MS and Parkinson's disease to improve understanding of neurodegenerative diseases and accelerate the development of new treatments. Image courtesy of the New York Stem Cell Research Institute. NASA ID: jsc2024e021220.

Highlights in Biology and Biotechnology

The space station laboratory provides a platform for investigations in the biological sciences that explore the complex responses of living organisms to the microgravity environment. Lab facilities support the exploration of biological systems, from microorganisms and cellular biology to the integrated functions of multicellular plants and animals.

EXPLORATION

Microgravity profoundly affects human physiology, causing conditions such as muscle atrophy and reduced bone density. The ESA investigation **Cytoskeleton**, which flew to station in March 2016, examined the molecular signals in mammalian cells sensitive to mechanical forces exerted in the environment to understand how proliferation, programmed cell death, gene expression, and cytoskeleton structure (i.e., interlinked protein filaments in the cell) react to microgravity.

In a new study published in *npj Microgravity*, researchers cultured a model of human bone cells (i.e., MG-63) for approximately 34 hours in the **BioLab incubator** along with control samples in 1g centrifuge[4]. Like primary human bone cells, MG-63 cells are responsive to mechanical loading, so they provide a suitable model for experimentation.

Researchers identified 24 regulatory pathways affected by microgravity. Among them were the cell proliferation and DNA repair pathways, which showed most genes downregulated. Other pathways associated with inflammation, cell stress, and iron-dependent cell-death showed most genes upregulated.

Complementary analyses showed a reduction in cell proliferation and nuclear size (Figure 6) as well as changes in chromatin organization and microtubule structure after exposure to microgravity. These alterations likely reflect cell cycle arrest that could lead to decreased DNA repair capacity and faster aging of the cell.

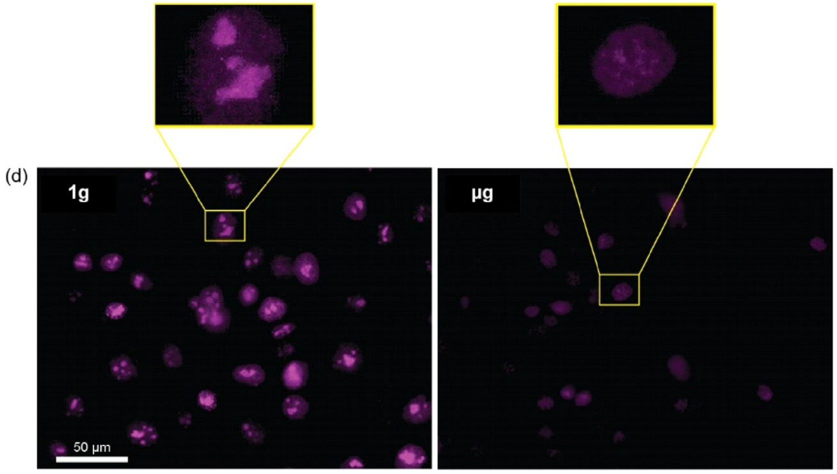


Figure 6. Immunoflourescent staining of cells in ground control (1g) and microgravity. Reduced proliferation is observed in microgravity cells. Reduced intensity of the stain indicates smaller nuclei size. *Image adopted from Garbacki, npj Microgravity.*

This new insight enhances the understanding of cell physiology and pathology and may assist the development of therapies to prevent Earth- and space-related health conditions affecting the musculoskeletal system, such as osteoporosis, skin atrophy, and excessive scar tissue in wound healing.

EXPLORATION

On long-term spaceflight missions, the risk to astronauts from space radiation increases. In the absence of Earth's atmosphere, protons and heavy ions from galactic cosmic rays increase the dose-equivalent rate of space radiation one hundred to three hundred times on station, potentially contributing to tumor progression in cancer, circulatory disease, and cognitive risks. The JAXA investigation **Study on the Effect of Space Environment to Embryonic Stem Cells to Their Development (Stem Cells)** examined how space radiation affects the development and DNA of embryonic mouse stem cells.

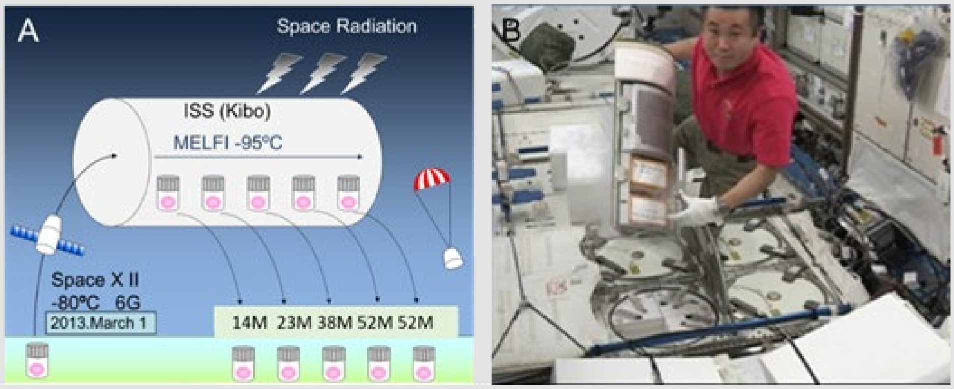


Figure 7. (A) The space experiment of "Stem cells". (B) Astronaut Koichi Wakata exchanging the dosimeter "PADLES", which was attached to the embryonic mouse stem cell package in the MELFI freezer. *Image provided by the Stem Cells research team.*

In a new study published in the *International Journal of Molecular Sciences,* researchers kept frozen wild-type and mutated embryonic stem cells missing the H2AX gene on station for over four years to measure the radiation doses absorbed and resulting biological effects [5] (Figure 7). The H2AX gene is known to play a role in DNA repair, so an H2AX-deficient stem cell is rendered unable to repair any DNA damage caused by radiation. Comparable ground control cells were irradiated with iron ion (Fe) particles using a medical accelerator. Upon return of the cells to Earth, researchers thawed and cultured the cells at different time intervals (0, 2, 8, 24, and 48 hours) to examine the expression profile over time. Then they conducted in-depth RNA-sequencing analyses to identify the genes that respond to DNA damage and those that regulate their expression.

Researchers reported a total of 830 mSv of accumulated space radiation after four years and revealed more altered genes during longer incubation times (24 and 48 hours). Some of the genes increasingly expressed were involved in the degradation of the extracellular matrix and halting of early differentiation. The overall pattern of gene expression was similar across wild-type and H2AX-deficient cells, but the transcriptome profile of a few genes changed greatly in H2AX cells, and this alteration made them more sensitive to radiation.

Further analyses showed that space radiation enhances the expression of three genes (p21, Trp53inp1, and Mdm2) along with the activation of the protein p53. This protein appears to influence the expression of these genes by halting the erroneous proliferation of cells that form tumors. Researchers explained that the increased expression of these genes was not simply the result of being stored on station, but a direct consequence of space radiation as Fe ions.

This study demonstrates that longer exposure to radiation results in more modifications of repair proteins and the DNA damage caused by radiation has severe effects on the organism. This finding could help researchers identify the genes that respond to DNA damage and support development of ways to prevent cancers caused by radiation.

EXPLORATION

The NASA investigation **[Advanced Plant Experiment-07 (APEX-07)]** studies how multiple environmental differences associated with spaceflight affect the genetic expression of plants. Specifically, researchers are interested in investigating how processes controlled by RNA (e.g., turning genes on and off) are impacted by spaceflight in the roots and shoots of plants.

Previous research has shown that very short telomeres in humans can negatively impact health and longevity whereas hyper-long telomeres are a hallmark of cancer cells. Further study could help determine whether telomere length changes are reliable wellness indicators across different species.

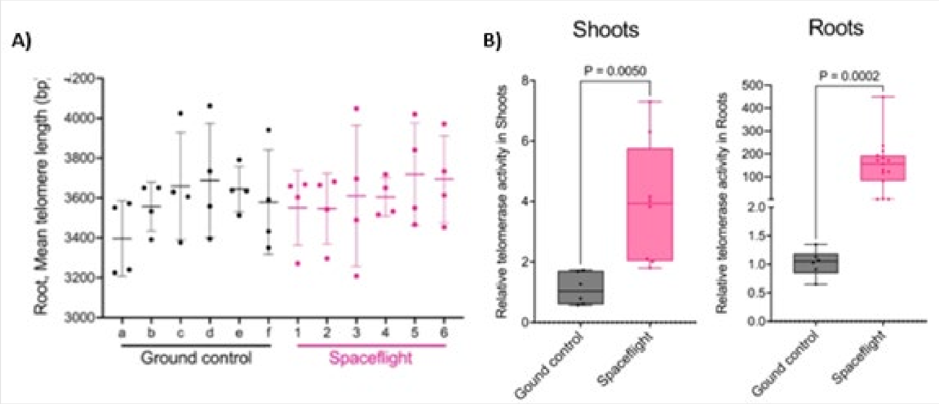


Figure 8. Charts showing average and unchanged telomere length during spaceflight (panel A) despite a significant increase in telomerase activity (panel B). *Charts adopted from Barcenilla, Nature Communications*.

In a study recently published in *Nature Communications*, researchers investigated the effects of spaceflight on plant telomeres, telomerase (the enzyme that synthesizes telomeres) and genome oxidation.^{6} Arabidopsis thaliana, the model species for plant research, was grown on station for twelve days in the **Veggie** facility. Comparable Veggie conditions were used for the gravity control group on Earth, and a Random Positioning Machine (RPM) simulated microgravity on the ground.

After the samples were returned to Earth, biochemical analyses revealed that the shoots and roots of Arabidopsis seedlings grown in space retained their telomere length despite a significant increase in telomerase activity and genome oxidation. Similar findings in the ground control samples led researchers to conclude that the induction of telomerase activity was independent of telomere length (Figure 8). Notably, plants with increased telomerase activity exhibited decreased genome oxidation, suggesting a potential role for telomerase in redox biology.

These findings advance the understanding of plant survival mechanisms in space and may provide important clues for supporting food production on future exploration missions.

If you are interested in learning about plant growth facilities on station, how to execute plant experiments in space, and research sponsors, read our **Researcher's Guide to: Plant Science**. *This guide also includes a comprehensive review of plant science results detailing plant responses to environmental changes.*

DISCOVERY

Stem cells reproduce and differentiate into different cell types, and microgravity alters cell metabolism and function. The NASA investigation **Generation of Cardiomyocytes From Human Induced Pluripotent Stem Cell-derived Cardiac Progenitors Expanded in Microgravity (MVP Cell-03)**, examined the effect of microgravity on the proliferation of cardiac progenitor cells, cells that originate from stem cells and await further specialization. Promising results in this fundamental research have direct impacts on drug development, disease modeling, and regenerative medicine applications.

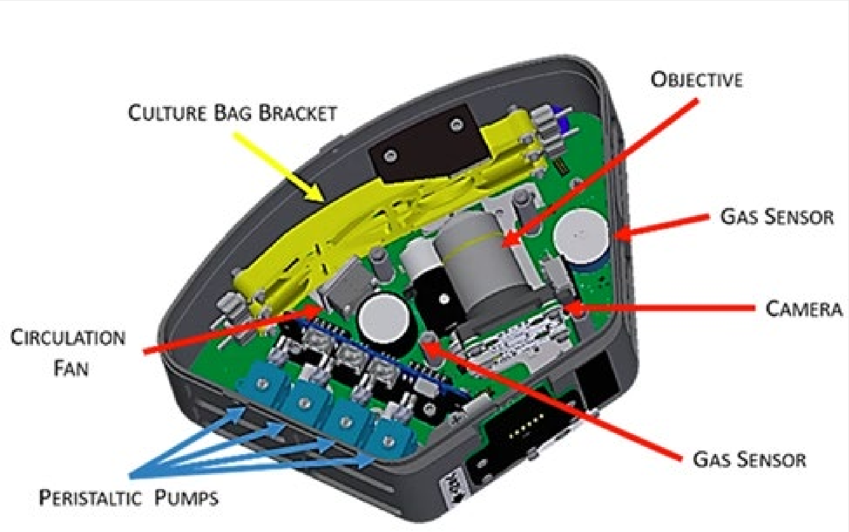


Figure 9. MVP Module on station. *Image adopted from Hwang, npj Microgravity.*

In a recent study published in *npj Microgravity,* researchers cultured cardiac 3D human-induced pluripotent stem cells (HiPSC) on station for three weeks, and live cultures were returned to Earth for analysis.[7] A platform that included simulated Earth gravity on station allowed researchers to isolate gravity from radiation effects (Figure 9).

Initial RNA-sequencing analyses showed changes to gene expression, mostly upregulated genes associated with cell-division, differentiation, proliferation, as well as cardiac muscle tissue development and function. Additional analyses showed decreased expression of genes associated with extracellular matrix regulation, cardiac fibrosis, senescence, and apoptosis. Finally, comparing long-term exposure data to a previous study of cells exposed to microgravity for only three days,[8] researchers concluded that many of the improved properties and functions of cells are maintained in long-term cultures.

HiPSC-derived heart cells have potential for use in drug development and regenerative cell therapy, but such uses require large numbers of cells (heart repair, for example, requires an estimated 109 to 1010 cells per patient). Combining microgravity and tissue engineering could be a cost-effective way to increase the production of heart cells and may also generate cells with superior properties.

These findings of enhanced production of cardiac progenitor cells in space add to the research of cell proliferation in space that has been observed in bone marrow and adipose stem cells. Improvements to cell culture flight hardware, imaging systems, and other tools on station could help researchers test new hypotheses in the future.

DISCOVERY

The Roscosmos investigation **Studying the Features of the Growth and Development of Plants, and Technology for their Culturing in Spaceflight on the ISS RS (Rastenia-Pshenitsa (Plants-Wheat)** aims to understand the impact of spaceflight on plant growth and development. Uncovering genetic changes in plants after months of microgravity exposure informs the design and manufacturing of greenhouses for future space stations. Moreover, the production of high energy, low mass food sources in-flight reduces the need for continuous resupply and enhances crew members' independence in long distance space missions.

While extensive research has confirmed that leafy greens grown in space are equivalent to those grown on Earth, the quality of space-grown grain crops has not been determined. A new study published in *Plants* examines the quality of wheat grains grown in space, specifically super dwarf wheat species with a short life cycle.[9] Grain parameters included size, weight, and asymmetry of the kernels. Researchers hypothesized that increased asymmetry of the kernels could damage the composition of starch, impacting flour grade. Researchers used multiple imaging tools to measure the parameters of interest from wheat grains grown in space and on the ground. Some methods appeared more effective in assessing the asymmetry of the kernels.

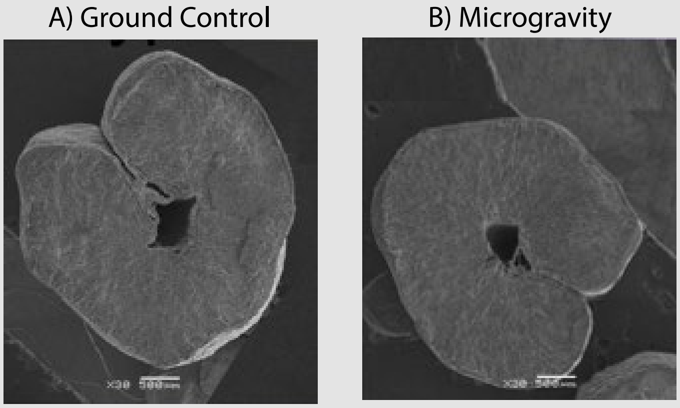


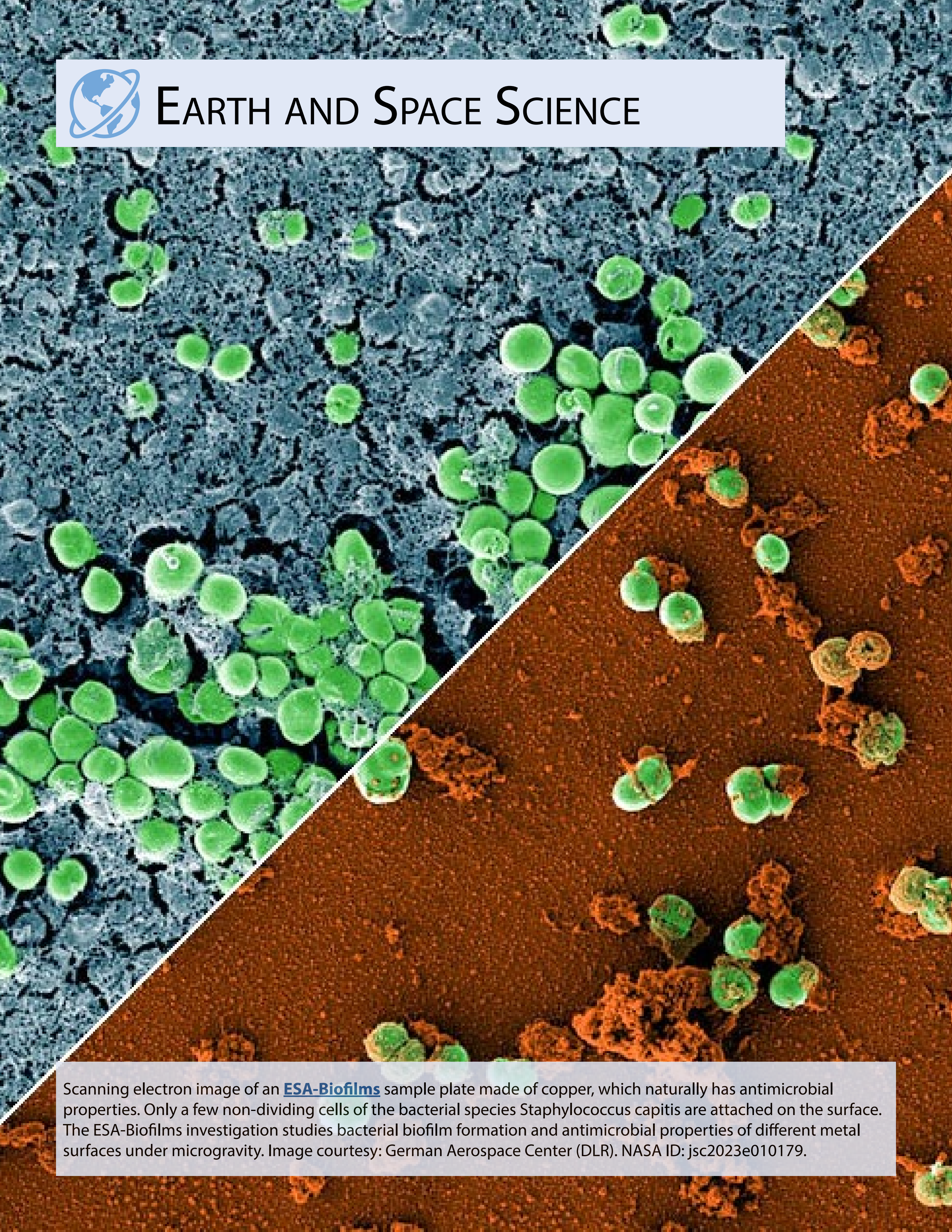
Figure 10. Kernel asymmetry compared between ground and space conditions. *Image adopted from Aniskina, Plants.*

Analyses conducted on Earth upon return of the samples showed that wheat grains produced in microgravity were smaller and had through-holes but were equally round as the kernels grown on Earth. Space-grown kernels also showed longer starch granules, which indicated low salt concentrations, changes in starch content, and inferior baking quality. Although small differences in asymmetry were identified within each separate group (i.e., changes between left/right or top/bottom parts of the kernels), there were no significant differences in asymmetry between wheat kernels grown in space and on the ground (Figure 10).

Researchers argue that if optimal conditions are artificially created in space (i.e., reduced water stress, hypoxia, gravity loss), then the quality of wheat grains and flour are likely to be the same as Earth grown wheat.

Growing plants on station serves as a source of food, in-situ production of pharmaceuticals, air regeneration, water recycling, and a haven for psychological well-being. These findings contribute to the advancement of space agriculture and the creation of sustainable closed-loop ecosystems.

EARTH AND SPACE SCIENCE



Scanning electron image of an **ESA-Biofilms** sample plate made of copper, which naturally has antimicrobial properties. Only a few non-dividing cells of the bacterial species Staphylococcus capitis are attached on the surface. The ESA-Biofilms investigation studies bacterial biofilm formation and antimicrobial properties of different metal surfaces under microgravity. Image courtesy: German Aerospace Center (DLR). NASA ID: jsc2023e010179.

HIGHLIGHTS IN EARTH AND SPACE SCIENCE

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

DISCOVERY

ESA's **Atmosphere-Space Interactions Monitor (ASIM)** was launched to station in early April 2018 and installed on the Columbus external payload facility a few weeks later (Figure 11). Since that time, ASIM has been continuously monitoring the Earth's upper atmosphere with a mission to study sprites, jets, Emission of Light and Very Low Frequency perturbations due to Electromagnetic Pulse Sources (ELVES), and Terrestrial Gamma-ray Flashes (TGFs) occurring during thunderstorm activity.

TGFs are phenomena related to thunderstorms and lightning but occurring above them or from within a storm cloud and directed upward. The ASIM Modular X- and Gamma-ray Sensor's high energy detector is used to detect TGFs while its low energy detector is used to image TGFs once identified. Notably, ASIM was the first space-based instrument with TGF imaging capability.

Figure 11. View of ASIM installed on the Columbus External Payload Facility. NASA ID: iss057e055411.

In a study published in *Scientific Reports,* investigators used ASIM data to identify and discuss three bright TGF events with similar durations and observation distances.[10] The investigators correlated data from ASIM with data from several other lightning detection systems, both on the ground and in space, to obtain details on the three TGFs' lightning parent events.

In all three TGF events, the parent convective cell developed 15 to 45 minutes before the TGF event. One of the three TGF events occurred close to the southwest coast of Mexico, an area with much better lightning flash detection capability than the other two events. In this case, investigators noted that: a) the TGF occurred when lightning rates dropped (from 3.7/minute to 1.1/minute in the area of study) and b) negative lightning flash rates went almost silent for five minutes and then sharply increased in the minute just before the TGF occurred. It's believed this trend may be evidence of a strong buildup of negative potential in the cloud, which may be a requirement for the TGF to occur.

Research such as this allows investigators to better understand TGF phenomena and increases our limited understanding of the thunderstorm conditions that contribute to TGF formation.

EXPLORATION

An international team of researchers used the **CALorimetric Electron Telescope (CALET)** attached to station externally to study the relationship between ElectroMagnetic Ion Cyclotron (EMIC) waves and electron precipitation from the Earth's radiation belts to the upper atmosphere. JAXA's investigation CALET answers questions regarding high energy astrophysics, including the origin of cosmic rays, discovering evidence of nearby cosmic ray sources, and the existence of dark matter (Figure 12).

In a new study, however, the instrument sensitivity to million electron volts (MeV) enabled it to be used to study radiation belt electron precipitation[11]. Data from the Van Allen probes was combined with data from CALET, where the Van Allen probes provided the EMIC wave data and CALET was used to characterize the MeV electron precipitation events from its low Earth orbit perspective.

EMIC waves are a form of plasma wave in the Earth's magnetosphere and can drive electron precipitation events lasting several hours. Electrons in the radiation belts can cause hazards to both humans and electronics, while electrons precipitated into the upper atmosphere can result in changes to the atmospheric chemistry and subsequent ozone depletion.

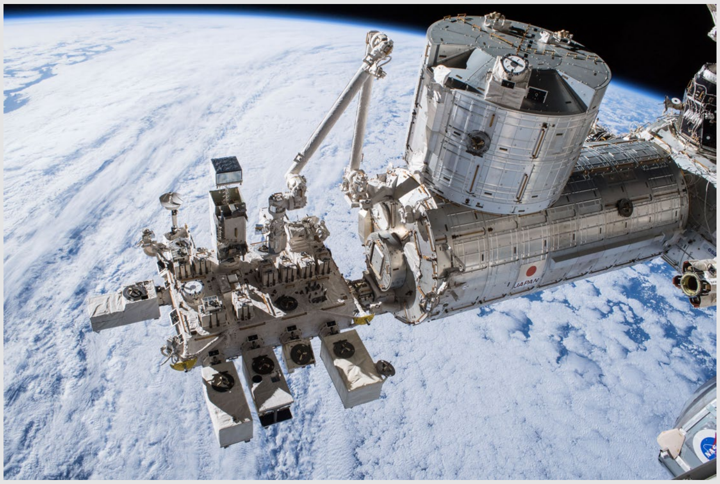


Figure 12. View of the Kibo laboratory module from the Japan Aerospace Exploration Agency. It includes CALET and other payloads. NASA ID: iss055e006395.

With this research published in *Geophysical Research Letters*, researchers used CALET to confirm that long duration EMIC waves can drive electron precipitation into the Earth's atmosphere lasting multiple hours. The magnitude of the electron precipitation can vary significantly over time, depending on several factors (wave properties, resonance, and population of the trapped electrons).

Studies such as this help scientists better understand and characterize the hazards associated with this area around our planet.

If you are interested in learning more about Earth observations from station, including past, present, and future remote sensing investigations, as well as funding opportunities to develop new investigations, read our ***Researcher's Guide to: Earth Observations.***

EXPLORATION

JAXA's external **[Monitor of All-sky X-ray Image (MAXI)]** experiment was launched on STS-127 in July 2009 and was the first experiment platform to be installed on the Japanese Experiment Module (JEM) Exposed Facility. MAXI is a survey instrument with the primary goals of conducting early detection of X-ray transient events and providing long-term monitoring of X-ray fluctuation of known sources. It can scan the sky for both hard and soft X-rays, defined as 6-20 keV and 2-6 keV X-rays, respectively. Similarly, intensity is categorized as high (> 0.6 photons s–1 cm–2) or low (< 0.6 photons s–1 cm–2), resulting in classifications of Low-Hard (LH) and High-Soft (HS) states.

In a paper published in *Monthly Notices of the Royal Astronomical Society*, researchers combined MAXI X-ray data with optical data sets from the Zwicky Transient Facility (ZTF) and the Las Cumbres Observatory Global Telescope (LCOGT) network to study five Aquila X-1 (Aql X-1) outbursts in a ~3.6 year period starting in 2016.[12] The purpose of the study was to develop a greater understanding of the mechanisms behind X-ray and optical wavelength outbursts from Aql X-1, a low-mass X-ray binary system located in the Aquila constellation (Figure 13).

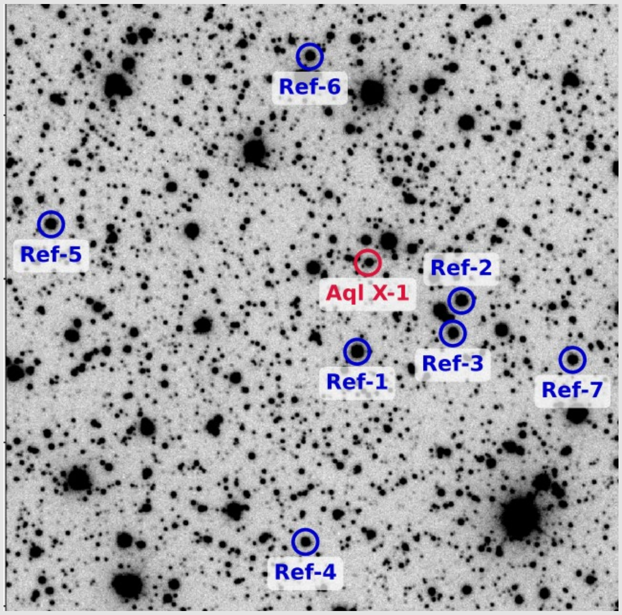


Figure 13. Sky chart with seven reference stars to identify Aql X-1. *Image adopted from Niwano, Monthly Notices of the Royal Astronomical Society*.

Three of the five outbursts transitioned from an LH to an HS state, while the other two were present only as LH events. The researchers showed that although the HS optical spectral energy distribution outbursts could theoretically originate from either the accretion disc (irradiated disc model) or as synchrotron radiation from the jet, the data fits a simplified irradiated disc model. Optical color correlation in the HS state was also supported by the simplified irradiated disc model.

Survey instruments such as MAXI are invaluable in tracking targets of interest, identifying changes such as the outbursts described in this paper, and promoting collaboration with other research platforms such as the ZTF, LCOGT, and Neutron star Interior Composition Explorer (NICER).

BENEFITS FOR HUMANITY

NASA's external Earth Surface Mineral Dust Source Investigation (EMIT) was developed by the Jet Propulsion Laboratory, launched to the space station on July 14, 2022, and installed robotically. Its primary goal is to assess the mineral composition of dust in the Earth's dust source regions and generate maps of these regions, but EMIT researchers have shown it can also be used to locate and quantify methane and carbon dioxide point sources effectively.

To perform its mission, EMIT uses an imaging spectrometer to analyze reflected solar radiation spanning the visible-to-shortwave infrared wavelengths (381 to 2493 nm). It collects data in 80 km wide paths, covering 1,360,000 km^2 per day, with a resolution of ~60m per pixel as the station orbits the Earth. The 381 to 2493 nm wavelengths used for dust analysis are also well suited to allow identification and quantification of methane and carbon dioxide sources, the two main human generated greenhouse agents.

In a 30-day study published in *Science Advances*, emissions from sources such as power plants, cement plants, petroleum infrastructure, landfills, and coal mine vents were located and quantified (Figure 14). For example, the EMIT researchers showed the largest oil and gas methane emissions come from Turkmenistan (731 ± 148 tons/hour), Kazakhstan (207 ± 11 tons/hour), Iran (87 ± 48 tons/hour), and Uzbekistan (86 ± 22 tons/hour), findings that are consistent with previous studies.[13] Also, two large carbon dioxide plumes (~1571 and ~3511 tons/hour) were identified as belonging to two coal-fired power plants in the Xinjiang Uygur Autonomous region of China.

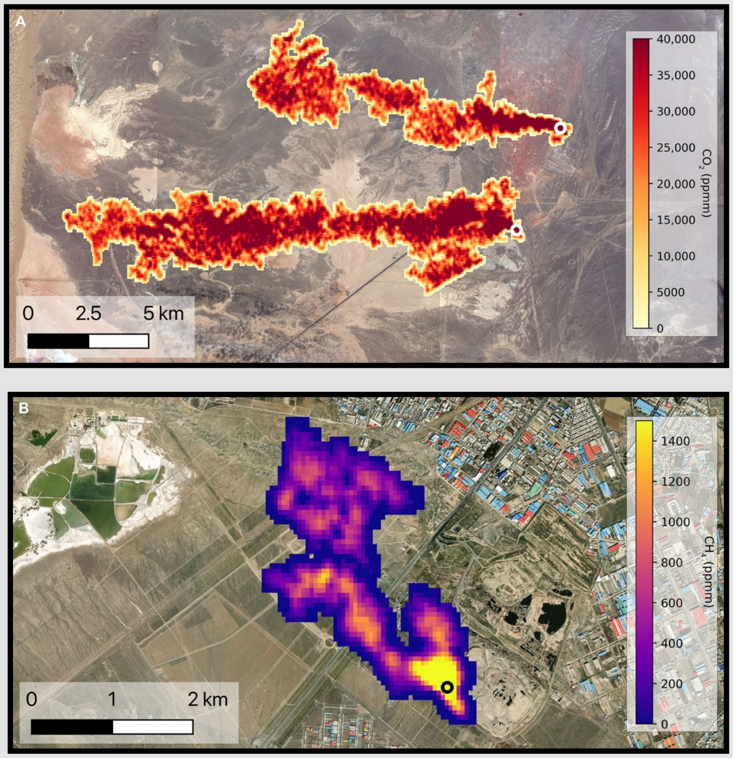


Figure 14. Carbon dioxide plumes from two power plants (top image) and methane plumes from a landfill. *Image adopted from Thorpe, Science Advances*.

Carbon dioxide and methane are primary anthropogenic agents (human-produced agents) driving environmental changes and need to be budgeted, categorized by source and sector, and quantified in order to better understand and address environmental concerns. Platforms such as EMIT give researchers the tools to accomplish this important task.

BENEFITS FOR HUMANITY

The Roscosmos-ASI-ESA investigation **Multiwavelength Imaging New Instrument for the Extreme Universe Space Observatory (Mini-EUSO)** is a state-of-the-art multipurpose telescope designed to examine terrestrial, atmospheric, and cosmic ultraviolet emissions entering Earth's atmosphere. Its optical system of 36 multianode photomultiplier tubes capable of detecting single photons allows exceptional imaging during day/night and night/day transitions (Figure 15). Mini-EUSO has been onboard station since August 2019 and is the first mission of a larger program (JEM-EUSO) that includes about 300 scientists from 16 countries.

Figure 15. Digitized image of space debris around Earth. *Image adopted from Mini-EUSO research team video.*

Data from Mini-EUSO has recently been used to test a new machine learning algorithm to detect space debris and meteors when space objects move across the field of view of the telescope. The study, published in the *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, reports that the highly sensitive algorithm, called **Refined Stacking Method and Convolutional Neural Network (R-Stack-CNN)**, is an improved version of a previous machine learning method expected to become more significant and useful as increasing traffic of satellites and spacecraft sharing the same orbits add to the risk of collisions.[14] Millions of unidentified pieces of space debris could be removed from their orbit once detected.

The R-Stack-CNN model showed precision of 88.2%, a 2% improvement over the standard method used before, and detected 63.4% more events. Researchers improved the detection of space debris and meteors by using many instances of simulated and real data, enabling offline detection, and including light curves that provide information about the rotation rates of the objects and their physical characteristics. These upgrades allowed researchers to reduce false positives and increase the reliability of the algorithm.

Despite the challenges of detecting opaque objects with a moving telescope, a changing background of clouds, light emissions from cities, Moon reflections, and the small fraction of optimal conditions during twilight, researchers employed an advanced neural network used in computer vision that allowed them to classify information more accurately.

The R-Stack-CNN algorithm could be implemented on ground-based telescopes or satellites to identify space debris, meteors, or asteroids and increase the safety of space activities.

HUMAN RESEARCH

Frozen blood samples collected aboard the International Space Station after return to Earth as part of the B Complex investigation. The investigation examines whether a daily B vitamin supplement can prevent or mitigate Space Flight Associated Neuro-ocular Syndrome (SANS) and assesses how an individual's genetics may influence the response. NASA ID: jsc2024e050837.

Highlights in Human Research

Space station research includes the study of risks to human health that are inherent in space exploration. Many research investigations address the mechanisms of these risks, such as the relationship to the microgravity and radiation environments as well as other aspects of living in space, including nutrition, sleep, and interpersonal relationships. Other investigations are designed to develop and test countermeasures to reduce these risks. Results from this body of research are critical to enabling missions to the lunar surface and future Mars exploration missions.

EXPLORATION

In the first few days of microgravity exposure, astronauts experience space motion sickness as well as orientation and navigation difficulties due to incoherent information from the vestibular system. Impaired spatial awareness affects astronauts' ability to perform complex spatial tasks and can lead to errors operating machinery in space. The CSA investigation **Wayfinding** examines how exposure to microgravity affects spatial orientation skills in astronauts and how long cognitive and neurological changes persist after return to Earth. A better understanding of spatial processes in astronauts allows researchers to find new strategies to improve the work environment and reduce the impact of microgravity on the spatial cognition of astronauts.

In a recent study published in *Brain Sciences*, 16 astronauts underwent Magnetic Resonance Imaging brain scans while they completed a spatial task that consisted of identifying the location from which the astronaut was looking at other objects in a virtual environment; in a non-spatial control task, participants were required to identify those objects irrespective of their location in the environment[15]. The spatial task required astronauts to integrate multiple perspectives into a coherent mental representation to infer the location from a view within their environment, a cognitive function that is critical for effective orientation and navigation. The same experimental protocol was completed by astronauts before and after spaceflight.

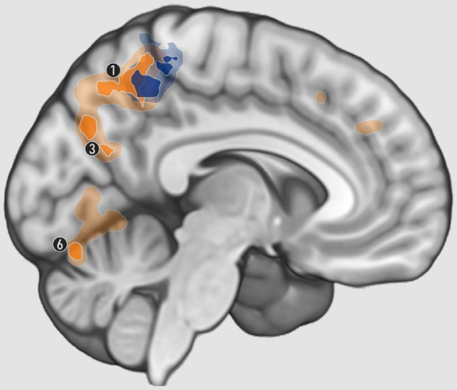


Figure 16. Brain activity after spaceflight. Areas in orange show increases, areas in blue show decreases. *Image adopted from Burles, Brain Sciences.*

Results showed reduced activity in spatial processing regions of the brain after spaceflight, particularly in the precuneus and left angular gyrus (Figure 16). These brain regions are known for their involvement in visuospatial imagery and orientation of spatial attention, respectively. Importantly, reduced brain activity was not correlated with behavioral performance or gray matter volumes. This outcome suggests some brain rewiring and adaptation ensues during spaceflight to allow the integration of new sensory inputs.

Discovering that there is a reduced reliance on typical visuospatial processing after some time in microgravity and that new neurocognitive changes emerge to help integrate spatial information are crucial for developing new procedures and technologies to assist astronauts to both prepare for space missions and, importantly, recover their spatial abilities upon their return to Earth.

DISCOVERY

Loss of body mass in long-duration spaceflight may be the result of improper energy balance, including changes in metabolism and variations in energy expenditure during exercise. ESA's investigation **Astronaut's Energy Requirements for Long-Term Space Flight (Energy)** examines the impact of physical activity and diet on metabolism in microgravity to better understand the changes observed in the body composition of astronauts during long-term spaceflight.

In a recent study published in *npj Microgravity*, researchers measured the ratio of carbon dioxide to oxygen (i.e., respiratory ratio) as well as the burn rate of carbohydrates and fats before and after meals in 11 male astronauts after a 3-month space mission (Figure 17). Experimental manipulation of diet and physical activity were monitored using food diaries and a multi-sensor wearable device that recorded body movement. The outcome measure of body composition (i.e., fat and fat-free mass) was obtained by inspecting total body water distribution.[16]

Figure 17. ESA astronaut Thomas Pesquet in the Columbus Module using the Pulmonary Function System to perform a series of oxygen uptake measurements after prescribed meals and scheduled fluid collections. NASA ID: iss050e055526.

During flight for fasting and non-fasting conditions, results showed a switch in fuel utilization that consisted of more carbohydrate than lipid burn in microgravity. However, when comparing in-flight to ground nutrient oxidation, changes in fat and carbohydrate burn appeared statistically significant in the fasting condition only.

This meal-based difference suggested to the researchers that the metabolic switch to a carbohydrate-burn preference is associated with the change in diet between ground and spaceflight and not physical activity or energy balance, although potential complications with nutrient assimilation due to microgravity need further study. Additional analyses showed that a diet high in fat and protein in space did not produce the expected result of more lipid burn, as has been repeatedly observed on Earth. Finally, because the body composition of each astronaut was unique, researchers hypothesize that this initial state can also influence metabolic outcomes during flight.

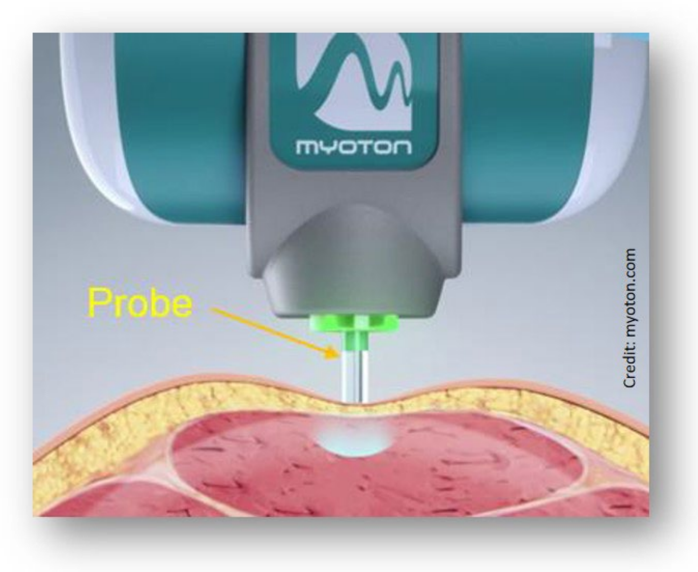
These metabolic changes seen in microgravity resemble those in people with chronic diseases such as Type 2 diabetes and obesity, so it is important to continue monitoring astronaut metabolism, diet, and exercise regimens to prevent the development of insulin resistance and protect astronaut health and performance in long-duration missions.

BENEFITS FOR HUMANITY

The ESA investigation **Muscle Tone in Space (Myotones)** monitors muscular deconditioning in crew members by examining muscle tone, stiffness, and elasticity via changes to fascia, the connective tissue that covers, connects, and supports the muscles. A better understanding of muscle tone in resting conditions could lead to the development of rehabilitation treatments for crew members and people on Earth.

Astronauts perform daily exercise to mitigate the effects of spaceflight on musculoskeletal health, but monitoring the effectiveness of these countermeasures has been limited to pre- and postflight timeframes due to the unsuitability of measuring technologies for spaceflight.

In a new study published in *Scientific Reports*, researchers used a non-invasive hand-held monitoring device (MyotonPRO) to measure passive muscle stiffness as an indicator of muscle strength and maintenance (Figure 18). The measurements were obtained before, during, and after spaceflight for more than 6 months and from different parts of the body, including muscles in the lower leg, the thigh, the foot, the lower back, as well as the neck and shoulders.[17]



Credit: myoton.com

Figure 18. Graphical representation of monitoring device MyotonPRO.

Analyses revealed that this novel tool can take measurements accurately, as corroborated by other pre-existing and reliable technologies (i.e., ultrasound imaging and skin thermal imaging) that were employed in space and remotely operated from the ground. Additional results showed that most muscles appeared to retain their stiffness during spaceflight except for some lower leg muscles required for proper gait (Tibialis Anterior and Soleus). This finding suggests that current exercise countermeasures effectively mitigate muscle disuse in space.

This new portable technology directly benefits astronauts in long-duration exploration missions and patients on Earth receiving medical attention in rural communities. Moreover, correct identification of the muscles that are most negatively impacted by spaceflight could help researchers target problem areas to maximize rehabilitation.

EXPLORATION

The **Respiratory Activity of Neurons (DAN)** investigation, sponsored by Roscosmos, measured maximal voluntary breath-holding capability during inhales and exhales of 16 cosmonauts to better understand the relationship between blood redistribution to the upper body during microgravity and changes in the respiratory system. Researchers measured cosmonauts' inhalations and exhalations a month before, once a month during, and several days after spaceflight. Preflight and postflight measurements were taken before and after low-body negative pressure (LBNP) tests from vertical and supine positions (Figure 19).

Figure 19. Cosmonaut Oleg Kotov, Expedition 38 Commander, during Lower Body Negative Pressure (LBNP) Exercise. NASA ID: iss038e055233.

The investigators observed increased breath-holding before, during, and after flight. Preflight and postflight findings, published in *Human Physiology*, showed increased breath-holding when participants moved from vertical to horizontal positions.[18] Space flight breath-holding times were longer compared to ground-based times, and the time values were higher each month the cosmonauts were in space. Postflight values returned to baseline, indicating the cosmonauts had not trained their lungs to hold their breaths longer. The team also noted that breath-holding times increased 5-10 minutes after the end of each LBNP test, when blood flow shifted from the lower to upper body.

The research team hypothesizes that baroreceptors play a primary role in modifying central respiratory activity. The trigger mechanism for reducing the sensitivity of the respiratory center under these conditions is the redistribution of blood to the upper half of the body, leading to an increase in blood filling and pressure in the vessels of the carotid sinus zone, activation of baroreceptors, and a subsequent reflex decrease in the inspiratory activity of respiratory neurons.

The team believes their findings could be helpful in validating the volume and intensity of physical exercise in crew members in microgravity as well the regimen and doses of drug administration that inhibit the activity of the respiratory center during the medical care for cosmonauts in long-duration space missions.

A better understanding of how the respiratory and cardiovascular systems work together in microgravity can contribute to better human health during extended space flights.

BENEFITS FOR HUMANITY

Cell-free nucleic acids include several types of DNA and RNA molecules that are present in extracellular fluids. By combining information from DNA and RNA, scientists can uncover the cellular status of distal organs and study their gene expression. Cell-free nucleic acids are suitable biomarkers for the detection of genetic and metabolic conditions, mental and physical stress, aging and inflammation and are currently being used to screen infections and diagnose cancer. The JAXA investigation **Genome and Epigenome Analysis of Circulating Nucleic Acid-based Liquid Biopsy (Cell-Free Epigenome)** analyzes cell-free DNA and RNA collected from crew members' blood plasma before, during, and after spaceflight to examine molecular responses of the human body to spaceflight. This "liquid biopsy" method is minimally invasive, does not require a long recovery period, and can be easily performed by other crew members (Figure 20).

In a new study published in *Nature Communications*, researchers obtained liquid biopsies from six astronauts who lived and worked on station for over four months to detect molecular changes in internal tissues.[19]

Analyses showed increased numbers of mitochondrial DNA copies and RNA from mitochondrial genes. These results suggest that a broad range of tissues release mitochondrial components into the plasma during spaceflight, making mitochondrial dysregulation a central health risk.

An additional comparative analysis to mouse plasma RNA revealed that nearly 50% of disease-related molecular changes in the mouse and human samples were associated with microgravity. These analyses confirm previously reported dysregulation of mitochondria, cell organelles involved in energy production, and cell growth.

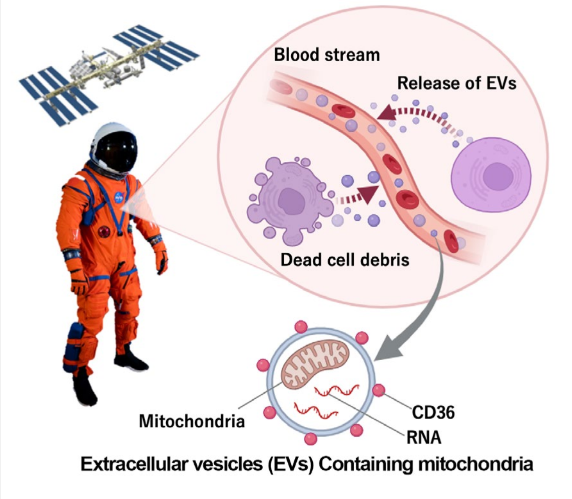


Figure 20. Graphical representation of a liquid biopsy for the analysis of cell-free DNA and RNA. *Image provided by the Cell-Free Epigenome research team.*

Biopsies from fluid samples enable the early detection of psychological and physiological biomarkers that could be useful in health monitoring and recovery programs postflight. An in-depth understanding of the molecular changes that occur in the human body in response to spaceflight is critical to safe space exploration in the future.

DISCOVERY

Radiation in space poses a risk to crew member health, and spending more time in space increases that risk. The Roscosmos investigation **Pille-MKS: Determine the Value of the Accumulated Radiation Dose in a Visiting Crewmember (Pille-ISS)** examines radiation build-up in crew members who have traveled to station in the last two decades to better understand how potential intensification of absorbed radiation affects humans.

In a new study published in *Life Sciences in Space Research*, researchers analyzed thousands of data points obtained from the passive dosimeter Pille-ISS over a 19-year period.[20] Analysis revealed that the Pille system, though limited in its temporal resolution because it does not record in real time like an active dosimeter, can accurately map the radiation environment of the space station in 15-minute and 90-minute segments (Figure 21).

Figure 21. The Pille thermoluminescent dosimeter system including memory card and display for results. *Image adopted from Pinczés, Life Sciences in Space Research.*

Previous studies have shown that only about 5% of total station mission time is spent in the South Atlantic Anomaly (SAA) region, but astronauts may absorb more than 50% of their total radiation dose during those passes. The SAA covers parts of South America and the southern Atlantic Ocean. Because the region normally has a weaker magnetic field and greater radiation doses, researchers set out to determine whether station's time flying over the SAA (30 minutes to an hour each day) or the overall altitude of station was more critical to radiation accumulation.

Analyses showed that the altitude of station plays a more significant role in radiation levels than the amount of time spent flying over the SAA. Therefore, the high altitude of station appears to be the main factor affecting crew health because of increased trapped solar and cosmic ray particles.

Improved radiation measurements allow researchers to identify and reduce health risks in astronauts participating in long-duration missions.

If you are interested in learning more about human research operations before, during, and after flight, as well as in-orbit research hardware, and funding opportunities, read our **Researcher's Guide to: Human Research***. This guide includes a review of the human response to living in space for an extended period.*

PHYSICAL SCIENCE

Solid Fuel Ignition and Extinction (SoFIE) insert supports the Growth and Extinction Limit (GEL) investigation test image taken in the Combustion Integrated Rack (CIR). This image was taken just prior to flame extinction while the green LED was flashing on. The LED allows the fuel surface to be seen during the burn, so that several important parameters can be evaluated, such as how far the flame is from the fuel and how much the fuel is heating up. NASA ID: jsc2024e021222.

Highlights in Physical Science

The presence of gravity greatly influences our understanding of physics and the development of fundamental mathematical models that reflect how matter behaves. The space station is the only laboratory where scientists can study long-term physical effects without the complications of gravity-related processes such as convection and sedimentation. This unique environment allows different physical properties to dominate systems, and scientists are harnessing these properties for a wide variety of investigations in the physical sciences.

The NASA-sponsored **Cold Atom Laboratory (CAL)**, a facility on board the space station, makes use of the space station's microgravity environment to study quantum phenomena in ways that aren't possible on Earth. CAL was launched to the station in March 2018, installed a few months later, and subsequently was used to produce the first Bose-Einstein Condensates (BECs) in Earth orbit.

DISCOVERY

In a recent study published in *Nature*, upgrades to the CAL science module allowed scientists to produce dual-species BECs using ^{87}Rb (Rubidium) and ^{41}K (Potassium) (Figure 22).

A BEC is a state of matter in which clouds of gas are so cold (40 to 70 billionths of a degree above absolute zero), scientists can study properties of matter not otherwise observable.

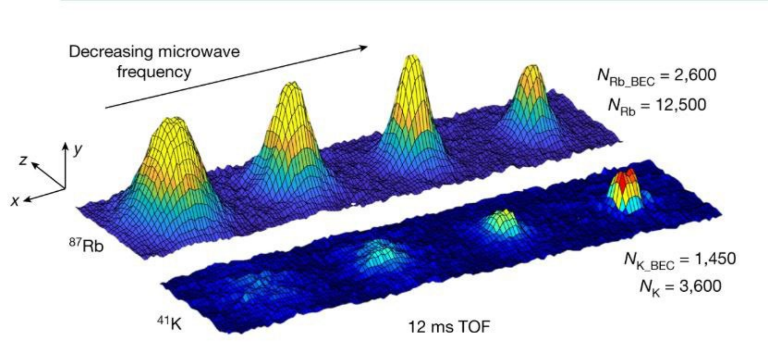


Figure 22. Simultaneous production of potassium and rubidium BECs in critically low temperatures. *Image adopted from Elliott, Nature*.

Dual-species BECs enable the study of the interaction with gravity of two quantum test masses,[21] a key capability needed to test the universality of free fall (UFF) and Einstein's theory of general relativity. CAL produces the ultra-cold gasses using an atom-chip trap with strong confinement capabilities, laser facilities to form magneto-optical traps, and microwave evaporative cooling techniques in microgravity.

Current experiment runs contain thousands (10^3) of atoms per species, but the CAL team acknowledges greater than 10^6 atoms per species will be needed to take full advantage of microgravity and set new records for sensitivity. Future work for the five CAL science teams includes increasing the number of trapped atoms per experiment run, studies of quantum chemistry and fundamental physics, and the nature of dark energy and dark matter.

CAL experiment hardware with enhanced and new capabilities is already in development on the ground. Results from CAL help us to better understand the physical world and find answers to questions that cannot otherwise be answered.

BENEFITS FOR HUMANITY

The NASA investigation **Optical Imaging of Bubble Dynamics on Nanostructured Surfaces** uses an optical imaging system to observe how different types of nanostructured surfaces affect bubbles generated by boiling. The interplay and competition between surface tension, buoyancy, and capillarity (a force that moves liquid independent of gravity, such as a paper towel absorbing water) affect bubble generation, growth, and detachment. In microgravity, researchers can eliminate buoyancy and focus on the roles of surface tension and capillarity.

The manipulation of bubble dynamics via nanostructured surfaces could improve thermal management and enable the development of bio-sensing technologies by using the physical properties of bubbles to detect particles in biological tissue.

In a new study published in *npj Microgravity*, researchers designed a quartz cuvette that contained deionized water and a microstructured copper surface attached to the top inner wall of the cuvette.[22] Via electrochemical reactions, porosity of the surface was manipulated by adjusting the molarity of the copper sulfate in which the surface was created (i.e., larger pores were obtained for surfaces with increased molar concentrations). Four different types of surfaces ranging in pore size were fabricated. A heater was attached to the exterior wall of the cuvette.

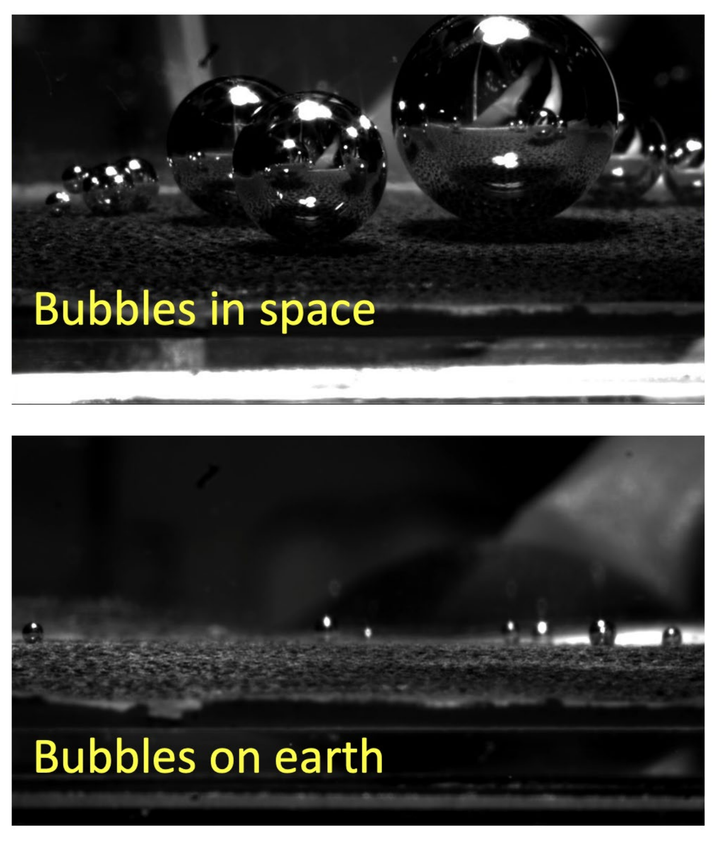


Figure 23. Comparison of bubbles generated in space versus Earth. *Image provided by the Optical Imaging of Bubble Dynamics on Nanostructured Surfaces research team*.

Results showed that vapor bubble production is up to 30 times faster in microgravity than on Earth (Figure 23). Bubbles in space are also larger and collapsed after about three minutes. However, surfaces with finer microstructures resulted in slower and longer nucleation time because of enhanced heat transfer. These outcomes suggest that the conditions of reduced convection flow, fast temperature rise, and surface type in microgravity influence bubble production and growth. Consistent differences between microgravity and ground experiments demonstrate that surface bubble dynamics are primarily driven by changes in gravity and temperature, not by surface porosity size.

These results could improve thermal systems such as the cooling of electronics, refrigeration, nuclear reactors, and heat transfer in the metal or oil industries. Additionally, fundamental insights into bubble dynamics could improve sensors that use bubble formation, including those that test biomarkers for cancers, contributing to better medical diagnoses in space and on Earth.

BENEFITS FOR HUMANITY

JAXA's **Electrostatic Levitation Furnace (ELF)** is designed to melt and solidify materials by applying a method that does not require the use of containers and can be achieved by suspending samples in mid-air. Researchers can levitate and position materials as needed using the force of attraction or repulsion between charged samples and electrodes, as well as feedback from a high-speed camera. This unique facility enables the examination of thermophysical properties (density, surface tension, and viscosity) that are difficult to measure on Earth. Such studies are supporting the development of manufacturing processes using local resources from space, which are critical to the advancement of the low Earth orbit economy and creation of lunar habitats.

In a single-case study recently published in *npj Microgravity*, researchers compared the properties of an inorganic compound (a titanate) and its derivative products (glass and crystal).[23] Identical pellet-like samples were prepared for space and ground experiments (Figure 24). The samples in microgravity were heated using four semiconductor lasers for several minutes and then cooled freely.

Researchers found that glass products processed on Earth and in microgravity exhibit nearly identical atomic structures, but the cooling rate is slower in microgravity. Differences in cooling rate between Earth and microgravity are attributable to the absence of forced convection in electrostatic levitation. This result demonstrates that the same titanate-derived glass can be manufactured in space and on Earth.

Figure 24. Neodymium titanate glass (approximately 2 mm in diameter) used for experimental and control conditions.

Additional analyses showed significant differences between the microstructures of the crystalline samples. Some microgravity samples were highly unusual and exhibited streaks of crystal grains that spanned across the entire sample, suggesting differences in the crystal nucleation and growth, likely due to unstable levitation (Figure 25).

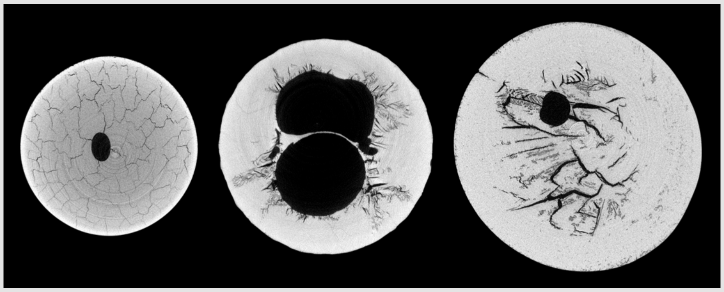


Figure 25. Microgravity samples show fractured structures upon crystallization. *Images provided by the ELF research team.*

Previous research on melt processing in microgravity has focused on metallic materials, and this study contributes to a new understanding of processing oxide glass materials with applications in optical devices and advanced display screens.

BENEFITS FOR HUMANITY

The **JAXA Colloidal Clusters** investigation explores the formation of clusters made up of negatively and positively charged particles suspended in liquid in microgravity. Researchers use the electrostatic attraction between these oppositely charged particles (polystyrene and titania) to form clusters. The microgravity conditions on the space station also help to eliminate the effects of gravity on the materials and minimize the impact of sedimentation. This study specifically aims to identify tetrahedral clusters – structures composed of four triangular faces – to enhance fundamental understanding of how these clusters form in space.

In a recent study published in the *International Journal of Microgravity Science and Application*, researchers successfully immobilized these clusters on the space station using a gel more resistant to aging.[24] Previously, the JAXA Colloidal Clusters experiment fixed colloidal particles in liquid solutions, but this new method developed a gelation method that can be used over extended periods. This advancement addresses the challenges of long waiting times and storage needs in space experiments. While gel immobilization is a common practice on Earth, space experiments often require a longer interval between the preparation of solutions and the actual experiments. Preparing this new gelation technique is expected to be valuable for future space experiments involving various soft matter systems.

These gels were specifically created to ensure low background interference in all the analytical techniques used to analyze the samples, including neutron scattering experiments at Australia's Nuclear Science and Technology Organisation (ANSTO).

The structures within tetrahedral clusters can be studied as models for understanding particle aggregation behavior in nature. By characterizing these clusters, scientists can gain insights into the building blocks of future photonic materials—materials that manipulate light. The tetrahedral clusters returned to Earth are of particular interest because their size allows them to scatter light in the visible to near-infrared range, making them useful for optical or laser communications (Figure 26).

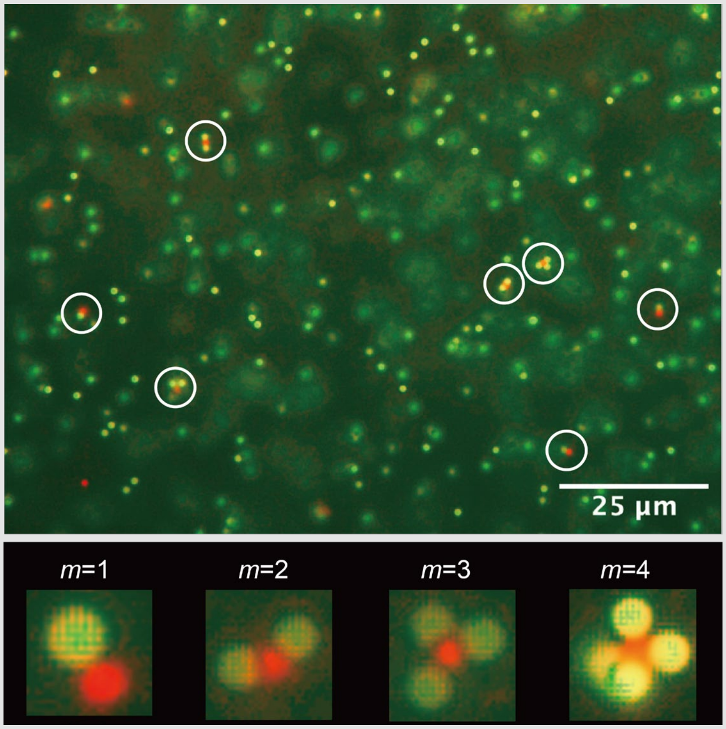


Figure 26. Fluorescence micrograph of colloidal clusters obtained in a space experiment. The sample was immobilized in a polymer gel. Magnified images of clusters with association numbers m = 1-4 are also shown. Negatively charged (green fluorescence) and positively charged (red fluorescence) polystyrene particles were used. *Image provided by the JAXA Colloidal Clusters research team*.

These clusters hold potential for the development of novel optical materials, and even for possible cloaking devices. Each new advancement in optical communications can contribute to improved data transmission rates between Earth and deep space exploration missions such as missions to the Moon or Mars.

BENEFITS FOR HUMANITY

The ESA investigation **Multiscale Boiling** examines the process of heat transfer from a surface to a liquid, causing the liquid to boil and then change into a vapor. Researchers use a multiscale modeling approach (i.e., observations across multiple levels of time and space) to learn about this phase-change in a pool boiling configuration. Although boiling is commonly seen in everyday life, it is a complex process with applications in chemical processing, electricity production, and thermal management. Studying the dynamics of boiling heat transfer in microgravity allows researchers to observe changes that are too small or too fast on Earth due to convection and buoyancy.

New research published in the *Journal of International Communications in Heat and Mass Transfer* demonstrated bubble growth using a coolant (N-perfluorohexane) in a boiling cell on station. The set-up included a focused laser that heated a foil surface for a few milliseconds without shear flow or electric field.

The initial temperature state of the fluid, known as subcooling, varied from 1°C to 5°C. Results showed that bubbles formed faster when the initial temperature of the fluid was 1°C than when the fluid temperature began at 3°C or 5°C. Delayed bubble formation occurred when the laser had to transfer more energy to the fluid.[25]

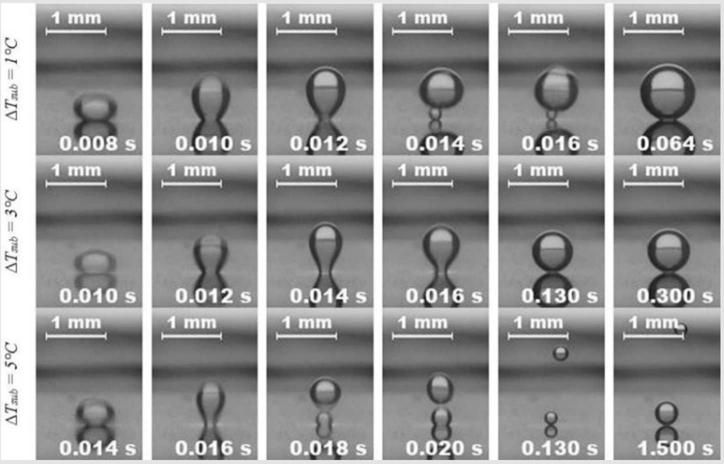


Figure 27. Changes in bubble shape, stabilization, and detachment at different temperatures. *Image adopted from Ronshin, Internal Communications in Heat and Mass Transfer.*

Moreover, bubbles grew larger when the initial temperature was 1°C and remained attached to the heater longer. Bubble shape changed from being elongated along the horizontal axis or the vertical axis. This back-and-forth reshaping led to bubble detachment (i.e., condensation), with eventual equilibrium of the bubble into a round shape (Figure 27). Once bubbles detached, they shrank at first but then remained unchanged for several seconds. These condensed bubbles then drifted downward and merged with attached bubbles. Researchers noted that smaller bubbles from fluid starting at 5°C appeared to condense faster.

These results indicate that subcooling fluid temperature influences bubble growth and condensation, potentially revealing mathematical laws in microgravity that could be explained in three stages 1) laser-induced growth, 2) round shape stability, and 3) uniform bubble growth. This pioneering investigation informs the design of space applications such as cryogenic fuel storage, propulsion, and cooling systems for electronic equipment.

If you are interested in learning about facilities and opportunities for research in fluid physics, as well as funding and launching research to station, read our **Researcher's Guide to: Fluid Physics**.

BENEFITS FOR HUMANITY

The Fundamental Research on International Standard of Fire Safety in Space – Base for Safety of Future Manned Missions (FLARE) investigation sponsored by JAXA, explores the flammability of different materials in microgravity. Prior studies have shown that the level of oxygen required for combustion decreases in microgravity, while low flow speed can increase the combustion requirement and suppress flame spread.

In a new study published in the *Proceedings of the Combustion Institute*, researchers used multiple types of cameras to analyze flame spread inside a pressure and temperature-controlled wind tunnel.[26] Results of flammability testing in microgravity were used to verify predictions made in ground-based activities.

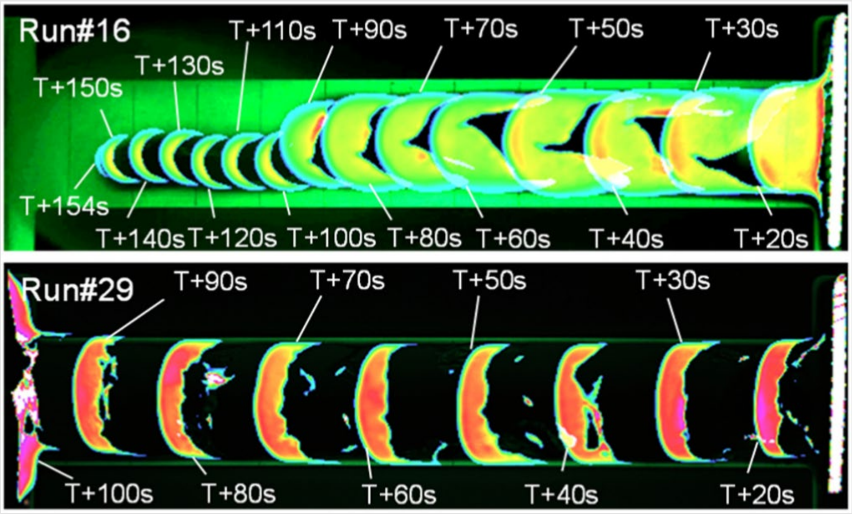


Figure 28. Sequence of infrared images showing fire extinction over time. Opposed flow of oxygen was higher in run #16 than in run #29. *Image adopted from Takahashi, Proceedings of the Combustion Institute*.

Researchers successfully replicated orbital experiments of combustion and flammability in microgravity. Nineteen experiments showed radiation loss and reduced flame spread as the opposed flow of oxygen increased (Figure 28). Results indicated that original calculations from orbital experiments overestimated the flammable region in areas of reduced air flow, after which the researchers modified their model to accurately predict the flammability limit. Researchers also found that flow speed impacts the shape of flames. Results could be used to predict flammability limits of thin, flat objects and improve understanding of flame spread in a lower-gravity environment.

Combustion science improves knowledge to support fire safety during space travel. As humans explore different gravity levels, oxygen concentrations, and pressures, there is a need to predict the flammability of various materials.

The FLARE investigation demonstrates a way to predict flammability in microgravity that could fill knowledge gaps and significantly improve fire safety aboard spacecraft on future exploration missions. New methods for evaluating the flammability of materials in high flow speed conditions also have potential applications for evaluating and reducing fire hazards on Earth.

TECHNOLOGY DEVELOPMENT AND DEMONSTRATION

Dr. Dmitry Oleynikov remotely operates a surgical robot aboard the International Space Station using controls at the Virtual Incision offices in Lincoln, Nebraska. **Robotic Surgery Tech Demo** tests techniques for performing a simulated surgical procedure in microgravity using a miniature surgical robot that can be remotely controlled or teleoperated from Earth. Image courtesy of the University of Nebraska-Lincoln. NASA ID: jsc2024e041215.

Highlights in Technology Development and Demonstration

Future exploration — the return to the Moon and human exploration of Mars — presents many technological challenges. Studies on the space station can test a variety of technologies, systems, and materials that are needed for future exploration missions. Some technology development investigations have been so successful that the test hardware has been transitioned to operational status. Other results feed new technology development.

EXPLORATION

The NASA [Microgravity Investigation of Cement Solidification (MICS)]() observed hydration reactions and microstructure formation in cement paste on the space station. As part of the human exploration roadmap, it is important to develop methods for civil engineering, construction, and manufacturing of industrial materials using the local environment. Due to the extensive costs associated with transporting materials to space, future missions require sustainable methods for constructing industrial materials and habitats to protect humans and equipment from extreme environments. Researchers use different types of regolith to learn more about hydration reactions and solidification in a low gravity environment.

Recently in the field of materials science, 2D to 3D reconstruction has become widely used to predict mechanical and physical properties. In a new *npj Microgravity* publication, artificial intelligence was used to create 3D models from microscope image scans of tri-calcium silicate cement samples formed on the space station.[27] The artificial intelligence model allows for prediction of mechanical and physical properties that can only be adequately captured in 3D. Additionally, the deep-learning model could be used to scale up 2D models for use in large scale concrete structures.

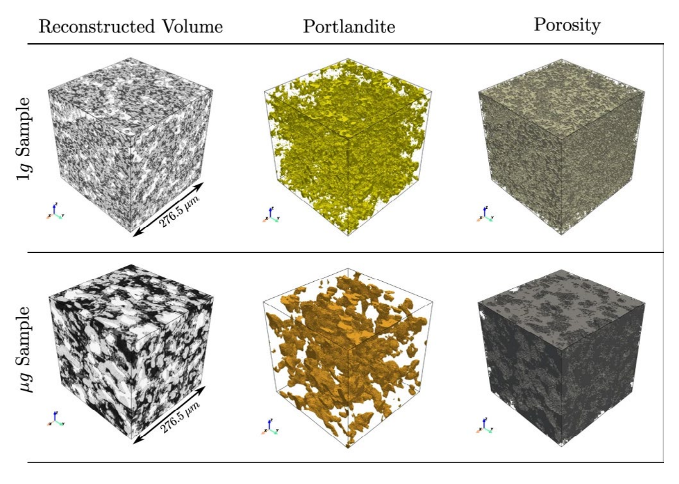


Figure 29. 3D reconstructed cement samples compared between Earth (1g) and microgravity. *Image adopted from Saseendran, npj Microgravity*.

Researchers found that the hydrated space-returned samples had approximately 70% more porosity content than ground samples (Figure 29). It is important to identify porosity and trapped air potentials when planning for infrastructure on the Moon because these characteristics influence the strength of any concrete-like material.

Results from this investigation help to improve researchers' understanding of cement hardening, crystal growth and hydration kinetics, and pore distribution. Results from the MICS investigation may be used to improve concrete properties. Improved cement properties could also help enhance infrastructure practices on Earth through better structural integrity and reduced carbon dioxide emissions.

DISCOVERY

The **Experimental Studies Of The Possible Development Of Microscopic Deterioration Of ISS RS Module Structural Elements When Impacted By The Components Of The Station's External Atmosphere And Conditions Promoting The Life Of Microflora On Pressure Hull Surfaces Under MLI (Test)** investigation, conducted by Roscosmos and the Russian Academy of Sciences, used hardware on the external environment of the space station to determine the potential for biological life to persist in the vacuum of space.

In a new study published in *Scientific Reports*, researchers selected three different types of microorganisms previously found on the exterior of the space station (bacteria, fungi, and archaea) and evaluated their survivability in the harsh environment of space.[28]

To assess survivability, researchers deposited the three microorganisms onto cotton wool and wrapped the cotton around a metal rod. The metal rod and cotton were exposed directly to the space environment with no material interference. In other exterior facilities, special barriers such as metal casings, membranes, filters, and glasses, may mitigate the full range of space physical factors on microorganisms. The experiment hardware was installed on the exterior of space station via a spacewalk, where it remained for segments of 12 and 24 months.

Researchers found that bacteria, fungi, and archaea can survive the harsh conditions of space for at least two years (Figure 30). Compared to ground controls, archaea showed slow growth and fungi showed increased resistance to radiation and a reduced reaction to stress factors such as disinfectants. A cyst-like form was also observed in the archaea species, which displayed the presence of a novel multilayer thickened cell membrane.

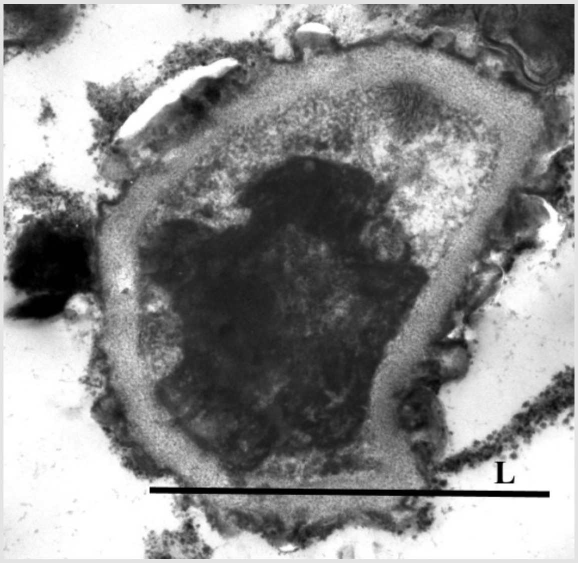


Figure 30. Scanning electron microscope image of Methanosarcina mazei S-6T cell (archaea) from the isolate obtained after the 24-months exposure. *Image adopted from Deshevaya, Scientific Reports*.

Researchers hypothesize that enhanced survival of these microorganisms is due to partial freezing and dehydration in space. It is also possible that the outer fibers of cotton wool provided mild shielding from the Sun's ultraviolet radiation, and the microorganisms located on the inner fibers of cotton wool were partially protected from ultraviolet radiation effects, increasing their survival odds.

These results take researchers a step closer to understanding how the seeds of life can be propagated through space. Understanding the survivability of microorganisms during space travel could help prevent the return of harmful microbes to Earth and limit biological contamination of spacecraft or other planetary bodies.

EXPLORATION

The ESA investigation **Fiber-optic Active Dosimeter (Lumina)** uses an embedded dosimeter in a high-speed fiber optic to measure, in real-time, radiation levels on station by darkening the fiber optic after exposure to ionizing energy photons. Higher radiation doses lead to more signal loss at the end of the fiber, allowing researchers to use this information to monitor radiation changes.

Signal loss is additionally examined using different optical fibers (infrared and visible light) to better understand fiber behavior after extended periods of time in space. Accurate measurement of ionizing radiation on station could help crew members respond to radiation flares, allowing them to implement a plan of action prior to a hazardous incident.

Lumina arrived on station in 2021 and operated for more than 699 days before the first analysis was conducted (Figure 31). In a new study published in *IEEE Transactions on Nuclear Science*, researchers reported that the Lumina instrument detected slight increases in radiation levels related to solar particle events or solar flares.[29]

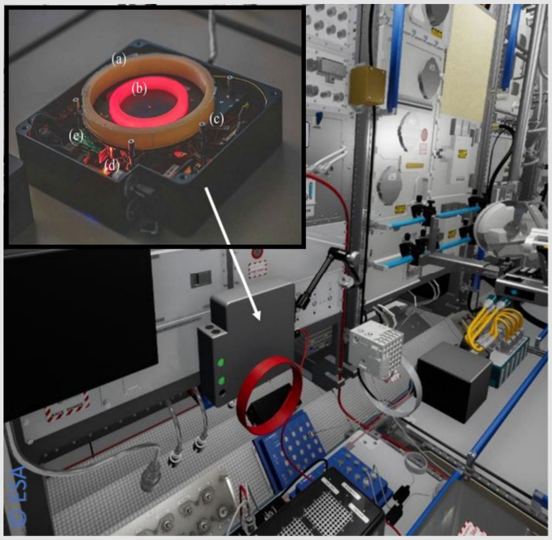


Figure 31. Digital mockup of the Columbus module on station. Inset shows fiber coils and boards inside the investigation. *Image adopted from Roche, IEEE Transactions on Nuclear Science*.

These increases were primarily observed near Earth's poles and sometimes over the South Atlantic Region. Additionally, the fiber optic designed for visible light spectrum measurements appeared more sensitive and better able to detect changes in radiation.

Results from this proof-of-concept study demonstrate that the technology employed in Lumina can effectively track radiation and assist the crew in mitigating the risks associated with high energy emissions.

DISCOVERY

Crew members on station have been breathing the same air for years. Inhaling small particles suspended in the air, known as bioaerosols, can cause allergies as well as nose and eye irritation, so an air revitalization system is necessary to clean the air. The NASA investigation **Aerosol Sampling Experiment (Aerosol Samplers)** uses powerful microscopes to examine airborne particles returned from station. A better understanding of the sizes, shapes, composition, and origin of the particles onboard can inform the design of particulate monitors and spacecraft fire detectors for crew health, safety, and comfort.

To learn how elevated moisture on station, typically found in hygiene, exercise, food, and plant habitat areas, affects microbial growth, researchers collected dust samples from vacuum bags from residential homes on Earth and on station. Characterization of bacterial and fungal communities residing in the dust were performed while dust was exposed to varying moisture conditions.

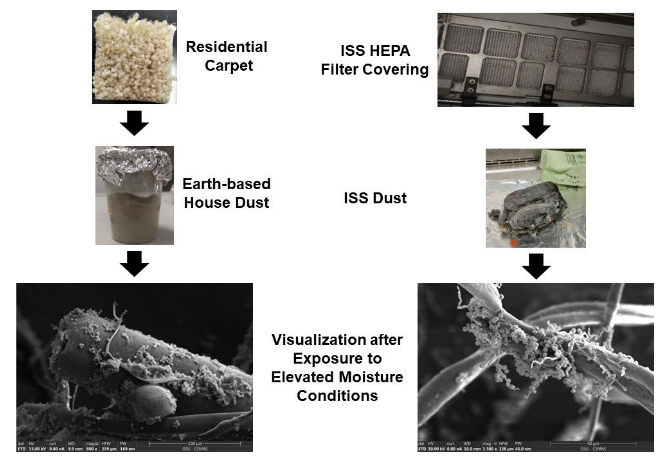


Figure 32. Fungal communities on Earth and station. *Image provided by the Aerosol Samplers research team*.

The results published in *Scientific Reports* revealed that fungal communities in Earth samples were much more diverse than station samples with Aspergillus being most abundant on station while on Earth Epicoccum dominated.[30] This finding applied to both high and low moisture conditions (Figure 32). Analyses also demonstrated a higher bacterial diversity on Earth than on station, with an abundant family of Paenibacillaceae on station, and Staphylococcaceae and Bacillaceae on Earth. Between fungi and bacteria, fungi appeared to be more sensitive to increased moisture both on the station and on Earth.

As human activity increases in space for both low Earth orbit and beyond, it becomes increasingly important for life support engineers, toxicologists, and biologists to fully understand the risk to health from the accumulation of microorganisms in a confined space. These findings enable future spacecraft designers to create healthy indoor microbiomes that support crew health, spacecraft integrity, and planetary protection.

If you are interested in learning more about microbial contamination on station, how to execute microbial experiments in space, and research sponsors, read our **Researcher's Guide to: Microbial Research**. *This guide also includes a comprehensive review of microbial research describing the genetic characteristics and interactions of microbes with plants and humans.*

DATA-DRIVEN WORD CLOUD

🟦 Biology and Biotechnology
🟥 Earth and Space Science
🟪 Human Research
🟦 Physical Science
🟧 Technology Development and Demonstration

Figure 33. Word cloud of investigations with the most scientific impact based on citation counts. Larger labels represent more citations. Label colors represent station research disciplines.

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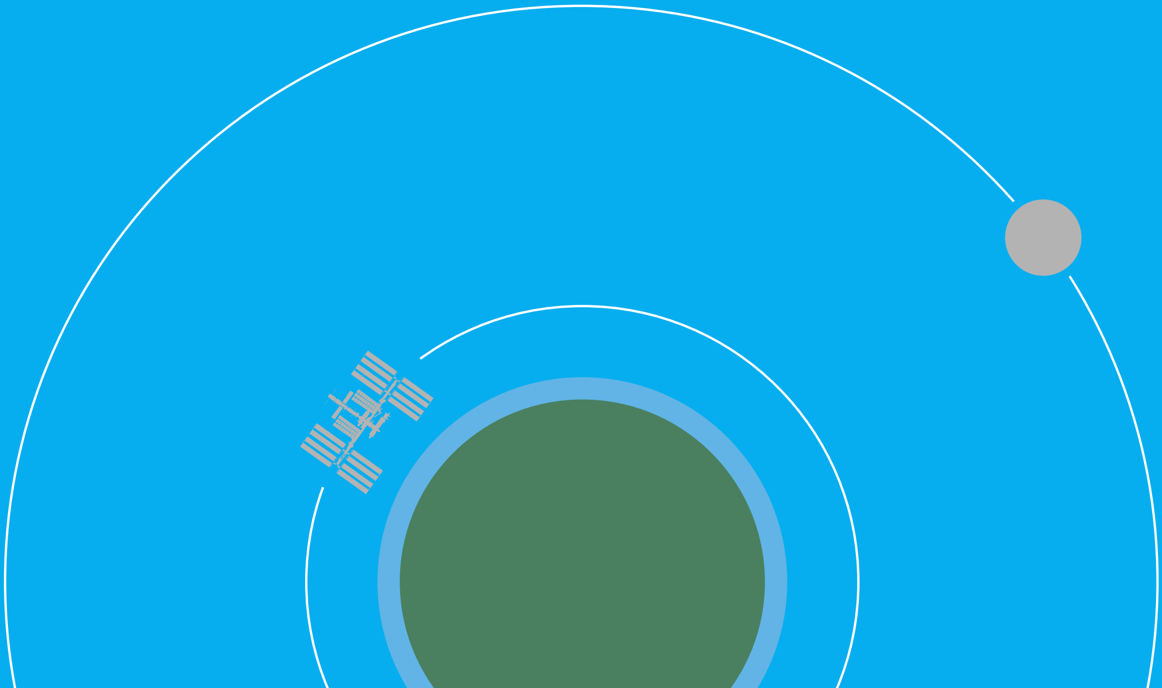
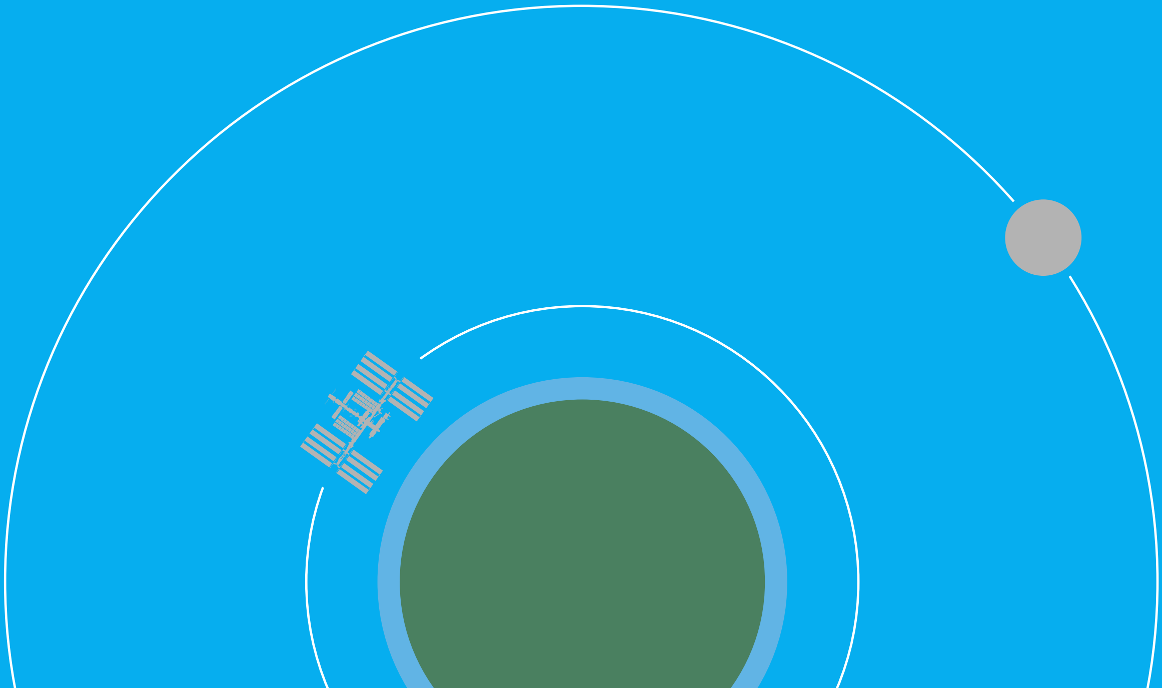
NASA astronaut and Expedition 71 Flight Engineer Mike Barratt replaces fuel bottles and other components inside the **Combustion Integrated Rack** located inside the Intenational Space Station’s Destiny laboratory. NASA ID: iss071e439784.



Clockwise from bottom, NASA astronauts Matthew Dominick, Jeanette Epps, Suni Williams, Mike Barratt, Tracy C. Dyson, and Butch Wilmore, pose for a team portrait inside the vestibule between the Unity module and the Cygnus space freighter from Northrop Grumman. Dyson holds a photograph of NASA astronaut Patrica Hilliard for whom the Cygnus spacecraft, S.S. Patricia "Patty" Hilliard Robertson, is named after. NASA ID: iss071e321342



LIST OF ARCHIVED SPACE STATION PUBLICATIONS

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(Listed by category and alphabetically)

BIOLOGY AND BIOTECHNOLOGY

Advanced Plant EXperiment-07 (APEX-07) — Barcenilla BB, Meyers AD, Castillo-Gonzalez C, Young P, Min J, et al. Arabidopsis telomerase takes off by uncoupling enzyme activity from telomere length maintenance in space. *Nature Communications*. 2023 November 29; 14(1): 7854. DOI: 10.1038/s41467-023-41510-4.

Assessment of myostatin inhibition to prevent skeletal muscle atrophy and weakness in mice exposed to long-duration spaceflight, Muscle Atrophy of Muscle Sparing in Transgenic Mice, Effects of the Space Environment on the Blood and Lymphatic Vessels of the Head and Neck, the Knee and Hip Joints, and the Eyes, Rodent Research-6, Rodent Research Hardware and Operations Validation (Rodent Research-3-Eli Lilly, Rodent Research-1 (CASIS), Rodent Research-9 (RR-9), RR-6, Rodent Research-1) — Ilangovan H, Kothiyal P, Hoadley KA, Elgart R, Eley GD, et al. Harmonizing heterogeneous transcriptomics datasets for machine learning-based analysis to identify spaceflown murine liver-specific changes. *npj Microgravity*. 2024 June 11; 10(1): 1-11. DOI: 10.1038/s41526-024-00379-3.

Autonomous Biological System (ABS) — MacCallum T, Anderson G, Poynter J, Ishikawa Y, Kobayashi K, et al. The ABS (Autonomous Biological System): Spaceflight results from a bioregenerative closed life support system. *SAE Technical Paper*. 2000 July 10; 2000-01-2340: 14. DOI: 10.4271/2000-01-2340. *

Biological Research in Canisters-23 (BRIC-23) — Hauserman MR, Ferraro ME, Carroll R, Rice K. Altered quorum sensing and physiology of Staphylococcus aureus during spaceflight detected by multi-omics data analysis. *npj Microgravity*. 2024 January 8; 10(1): 1-12. DOI: 10.1038/s41526-023-00343-7.

Biomolecule Extraction and Sequencing Technology (BEST) — Castro CL, Schwengers O, Stahl-Rommel SE, Nguyen HN, Dunbar B, et al. Bacterial genome sequences of uncharacterized Chitinophaga species isolated from the International Space Station. *Microbiology Resource Announcements*. 2024 April 23; 13(6): e0007524. DOI: 10.1128/mra.00075-24.

BRIC-LED Tech Demo (BRIC-LED-001) — Olanrewaju GO, Haveman NJ, Naldrett MJ, Paul AL, Ferl RJ, et al. Integrative transcriptomics and proteomics profiling of Arabidopsis thaliana elucidates novel mechanisms underlying spaceflight adaptation. *Frontiers in Plant Science*. 2023 November 27; 14: 1260429. DOI: 10.3389/fpls.2023.1260429.

Cellular Mechanotransduction by Osteoblasts in Microgravity (Cellular Mechanotransduction by Osteoblasts) — Wubshet N, Cai G, Chen SJ, Sullivan M, Reeves M, et al. Cellular mechanotransduction of human osteoblasts in microgravity. *npj Microgravity*. 2024 March 21; 10(1): 35. DOI: 10.1038/s41526-024-00386-4.

Characterization of Biofilm Formation, Growth, and Gene Expression on Different Materials and Environmental Conditions in Microgravity (Space Biofilms) — Flores P, Luo J, Mueller DW, Muecklich F, Zea L. Space biofilms - An overview of the morphology of Pseudomonas aeruginosa biofilms grown on silicone and cellulose membranes on board the International Space Station. *Biofilm*. 2024 June; 7: 100182. DOI: 10.1016/j.bioflm.2024.100182.

Characterization of Biofilm Formation, Growth, and Gene Expression on Different Materials and Environmental Conditions in Microgravity (Space Biofilms) — Herrera-Jordan K, Pennington P, Zea L. Reduced Pseudomonas aeruginosa cell size observed on planktonic cultures grown in the International Space Station. *Microorganisms*. 2024 February 16; 12(2): 393. DOI: 10.3390/microorganisms12020393.

CYTOSKELETON — Garbacki N, Willems J, Neutelings T, Lambert C, Deroanne C, et al. Microgravity triggers ferroptosis and accelerates senescence in the MG-63 cell model of osteoblastic cells. *npj Microgravity*. 2023 December 16; 9(1): 1-16. DOI: 10.1038/s41526-023-00339-3.

Determining Muscle Strength in Space-flown Caenorhabditis elegans (Micro-16) — Soni P, Edwards H, Anupom T, Rahman M, Lesanpezeshki L, et al. Spaceflight induces strength decline in Caenorhabditis elegans. *Cells*. 2023 October 17; 12(20): 2470. DOI: 10.3390/cells12202470.

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Effects of Microgravity on the Structure and Function of Proximal and Distal Tubule MPS (Kidney Cells, Kidney Cells-02) — Jones-Isaac KA, Lidberg KA, Yeung CK, Yang J, Bain J, et al. Development of a kidney microphysiological system hardware platform for microgravity studies. *npj Microgravity*. 2024 May 11; 10(1): 1-9. DOI: 10.1038/s41526-024-00398-0.

Effects of Microgravity on the Structure and Function of Proximal and Distal Tubule MPS (Kidney Cells) — Lidberg KA, Jones-Isaac KA, Yang J, Bain J, Wang L, et al. Modeling cellular responses to serum and vitamin D in microgravity using a human kidney microphysiological system. *npj Microgravity*. 2024 July 9; 10(1): 75. DOI: 10.1038/s41526-024-00415-2.

Effects of Spaceflight on endothelial function: molecular and cellular characterization of interactions between genome transcription, DNA damage and induction of cell senescence (Endothelial Cells) — Balsamo M, Barravecchia I, Mariotti S, Merenda A, De Cesari C, et al. Molecular and cellular characterization of space flight effects on microvascular endothelial cell function – Preparatory Work for the SFEF Project. *Microgravity Science and Technology*. 2014 November 16; 26: 351-363. DOI: 10.1007/s12217-014-9399-4. *

Epigenetic change in Arabidopsis thaliana in response to spaceflight - differential cytosine DNA methylation of plants on the ISS (APEX-04) — Zhou M, Riva A, Gauthier ML, Kladde MP, Ferl RJ, et al. Single-molecule long-read methylation profiling reveals regional DNA methylation regulated by Elongator complex subunit 2 in Arabidopsis roots experiencing spaceflight. *Biology Direct*. 2024 April 30; 19(1): 33. DOI: 10.1186/s13062-024-00476-z.

European Modular Cultivation System (EMCS) — Brinckmann E. ESA hardware for plant research on the International Space Station. *Advances in Space Research*. 2005 January; 36(7): 1162-1166. DOI: 10.1016/j.asr.2005.02.019. *

Experiment Cube #15 Mission 2 — Ecker Cohen O, Neuman S, Natan Y, Levy A, Blum YD, et al. Amorphous calcium carbonate enhances osteogenic differentiation and myotube formation of human bone marrow derived mesenchymal stem cells and primary skeletal muscle cells under microgravity conditions. *Life Sciences in Space Research*. 2024 May; 41: 146-157. DOI: 10.1016/j.lssr.2024.02.007.

GeneLAB — Zhang Y, Du X, Zhao L, Sun Y. Construction of dose prediction model and identification of sensitive genes for space radiation based on single-sample networks under spaceflight conditions. *International Journal of Radiation Biology*. 2024 March 12; 1-14. DOI: 10.1080/09553002.2024.2327393.

GeneLAB, Assessment of myostatin inhibition to prevent skeletal muscle atrophy and weakness in mice exposed to long-duration spaceflight (Rodent Research-3-Eli Lilly) — Masarapu Y, Cekanaviciute E, Andrusivova Z, Westholm JO, Bjorklund A, et al. Spatially resolved multiomics on the neuronal effects induced by spaceflight in mice. *Nature Communications*. 2024 June 11; 15(1): 4778. DOI: 10.1038/s41467-024-48916-8.

GeneLAB, Muscle Atrophy of Muscle Sparing in Transgenic Mice, Systemic Therapy of NELL-1 for Osteoporosis, Multi-Omics Analysis of Human Microbial-Metabolic Cross-talk in the Space Ecosystem, Effects of Spaceflight on Gastrointestinal Microbiota in Mice: Mechanisms and Impact on Multi-System Physiology (Rodent Research-1 (CASIS), Rodent Research-5 (RR-5), Multi-Omics-Mouse (MHU-2), Rodent Research-7 (RR-7)) — Mathyk BA, Tabetah M, Karim R, Zaksas V, Kim J, et al. Spaceflight induces changes in gene expression profiles linked to insulin and estrogen. *Communications Biology*. 2024 June 11; 7(1): 692. DOI: 10.1038/s42003-023-05213-2.

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GeneLAB, RNA Interference and Protein Phosphorylation in Space Environment Using the Nematode Caenorhabditis elegans (CERISE)— He X, Zhao L, Huang B, Zhang G, Lu Y, et al. Integrated analysis of miRNAome and transcriptome reveals that microgravity induces the alterations of critical functional gene modules via the regulation of miRNAs in short-term space-flown C. elegans. *Life Sciences in Space Research*. 2024 August; 42: 117-132. DOI: 10.1016/j.lssr.2024.07.001.

GeneLAB, Rodent Research-6, The Role of CDKN1a/p21 Pathway in Microgravity-Induced Bone Tissue Regenerative Arrest - A Spaceflight Study of Transgenic CDKN1a/p21-Null Mice in Microgravity, Genome and Epigenome Analysis of Circulating Nucleic Acid-based Liquid Biopsy (RR-6, RR-10, Cell-Free Epigenome) — Akinsuyi OS, Xhumari J, Ojeda A, Roesch LF. Gut permeability among Astronauts during space missions. *Life Sciences in Space Research*. 2024 May; 41: 171-180. DOI: 10.1016/j.lssr.2024.03.003.

Generation of Cardiomyocytes from Human Induced Pluripotent Stem Cell-derived Cardiac Progenitors Expanded in Microgravity (MVP Cell-03) — Hwang H, Rampoldi A, Forghani P, Li D, Fite J, et al. Space microgravity increases expression of genes associated with proliferation and differentiation in human cardiac spheres. *npj Microgravity*. 2023 December 9; 9(1): 88. DOI: 10.1038/s41526-023-00336-6.

Human iPSC-based 3D Microphysiological System for Modeling Cardiac Dysfunction in Microgravity (Engineered Heart Tissues) — Mair DB, Tsui JH, Higashi T, Koenig PM, Dong Z, et al. Spaceflight-induced contractile and mitochondrial dysfunction in an automated heart-on-a-chip platform. *Proceedings of the National Academy of Sciences of the United States of America*. 2024 October; 121(40): e2404644121. DOI: 10.1073/pnas.2404644121.

International Space Station Internal Environments (ISS Internal Environments) — Laranja SR, Fejer BG, Ridenti MA, Amorim J, Swenson CM. Ion density climatology based on FPMU measurements on board the International Space Station. *Journal of Geophysical Research: Space Physics*. 2023 December 20; 128(12): e2023JA031980. DOI: 10.1029/2023JA031980.

International Space Station-Microbial Observatory of Pathogenic Viruses, Bacteria, and Fungi (ISS-MOP) Project (Microbial Tracking-2) — Simpson AC, Sengupta P, Zhang F, Hameed A, Parker CW, et al. Phylogenomics, phenotypic, and functional traits of five novel (Earth-derived) bacterial species isolated from the International Space Station and their prevalence in metagenomes. *Scientific Reports*. 2023 November 6; 13(1): 19207. DOI: 10.1038/s41598-023-44172-w.

International Space Station Summary of Research Performed (ISS Summary of Research) — Chua CY, Jimenez M, Mozneb M, Traverso G, Lugo R, et al. Advanced material technologies for space and terrestrial medicine. *Nature Reviews Materials*. 2024 June 3; 1-14. DOI: 10.1038/s41578-024-00691-0.

Investigation of the Osteoclastic and Osteoblastic Responses to Microgravity Using Goldfish Scales (Fish Scales) — Hattori A, Suzuki N. Receptor-mediated and receptor-independent actions of melatonin in vertebrates. *Zoological Science*. 2024 January 12; 41(1): 105-116. DOI: 10.2108/zs230057.

Japan Aerospace Exploration Agency Protein Crystallization Growth (JAXA PCG) — Dubova KM, Dubovskii PV, Utkin YN, Samygina VR. Effect of microgravity on the crystallization of cardiotoxin from the venom of spectacled cobra Naja naja. *Crystallography Reports*. 2023 December; 68(6): 900-904. DOI: 10.1134/S1063774523601144.

JAXA Mouse Habitat Unit Technical Verification, JAXA Mouse Habitat Unit-5 (Mouse Habitat Unit-4 (Mouse Habitat Verification), Mouse Habitat Unit - 5) — Ouchi T, Kono K, Satou R, Kurashima R, Kimura M, et al. Upregulation of Amy1 in the salivary glands of mice exposed to a lunar gravity environment using the multiple artificial gravity research system. *Frontiers in Physiology*. 2024 June 25; 15: 14pp. DOI: 10.3389/fphys.2024.1417719.

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KAR 01 - KAR 14 — Lee J, Kim Y, Yi SY, Kim KS, Kang SW, et al. An overview of Korean astronaut's space experiments. *Acta Astronautica*. 2010 October; 67(7-8): 934-941. DOI: 10.1016/j.actaastro.2010.06.006. *

Mammalian Early Embryogenesis Under Microgravity State in Space (Space Embryo) — Wakayama S, Shimazu T, Yamamori T, Osada I, Umehara M, et al. Effect of microgravity on mammalian embryo development evaluated at the International Space Station. *iScience*. 2023 November 17; 26(11): 108177. DOI: 10.1016/j.isci.2023.108177.

Mammalian Early Embryogenesis Under Microgravity State in Space (Space Embryo) — Wakayama T, Wakayama S, Suzuki T, Yamazaki C. Frozen egg cultivation apparatus, and method for cultivating frozen eggs. *United States Patent and Trademark Office*. US20230287339A1. 2023 September 14. *

Mechanisms of Gravity Resistance in Plants From Signal Transformation and Transduction to Response (Resist Tubule) — Hoson T, Soga K, Wakabayashi K, Hedrich R, Suzuki M, et al. Suppression of bolting in the Arabidopsis hmg1 mutant under microgravity conditions in space – Possible involvement of lipid rafts. *Biological Sciences in Space*. 2024; 38: 18-26. DOI: 10.2187/bss.38.18.

Microbial Tracking Payload Series (Microbial Observatory-1) — Irby I, Broddrick J. Microbial adaptation to spaceflight is correlated with bacteriophage-encoded functions. *Nature Communications*. 2024 May 15; 15(1): 3474. DOI: 10.1038/s41467-023-42104-w.

Microbial Tracking Payload Series (Microbial Observatory-1) — Miliotis G, McDonagh F, Singh NK, O'Connor L, Tuohy A, et al. Genomic analysis reveals the presence of emerging pathogenic Klebsiella lineages aboard the International Space Station. *Microbiology Spectrum*. 2023 December 12; 11(6): e0189723. DOI: 10.1128/spectrum.01897-23.

Microbial Tracking Payload Series (Microbial Observatory-1) — Sengupta P, Muthamilselvi Sivabalan SK, Singh NK, Raman K, Venkateswaran KJ. Genomic, functional, and metabolic enhancements in multidrug-resistant Enterobacter bugandensis facilitating its persistence and succession in the International Space Station. *Microbiome*. 2024 March 23; 12(1): 62. DOI: 10.1186/s40168-024-01777-1.

Microbial Tracking Payload Series (Microbial Observatory-1) — Thorn V, Xu J. Mitogenome Variations in a Global Population of Aspergillus fumigatus. *Journal of Fungi*. 2023 October; 9(10): 995. DOI: 10.3390/jof9100995.

Microgravity Expanded Stem Cells — Ghani F, Zubair AC. Discoveries from human stem cell research in space that are relevant to advancing cellular therapies on Earth. *npj Microgravity*. 2024 August 21; 10(1): 1-9. DOI: 10.1038/s41526-024-00425-0.

NanoRacks-Heart Effect Analysis Research Team conducting Fly Investigations and Experiments in Spaceflight (NanoRacks-Heart Flies, GeneLAB) — Samson F, Bhat A, Sayyah Z, Reinsch SS, Blaber EA. Diacylglycerol kinase is downregulated in the Drosophila seizure mutant during spaceflight. *Gravitational and Space Research*. 2024 January 01; 12(1): 41-45.

Pick-and-eat Salad-crop Productivity, Nutritional Value, and Acceptability to Supplement the ISS Food System (Veg-04A, Veg-04B) — Bunchek JM, Hummerick ME, Spencer LE, Romeyn MW, Young MH, et al. Pick-and-eat space crop production flight testing on the International Space Station. *Journal of Plant Interactions*. 2024 January 18; 19(1): 2292220. DOI: 10.1080/17429145.2023.2292220.

Rodent Research-6 (RR-6) — Gonzalez E, Lee MD, Tierney BT, Lipieta N, Flores P, et al. Spaceflight alters host-gut microbiota interactions. *npj Biofilms and Microbiomes*. 2024 August 29; 10(1): 1-19. DOI: 10.1038/s41522-024-00545-1.

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Rodent Research Hardware and Operations Validation, Commercial Biomedical Testing Module-3: Assessment of sclerostin antibody as a novel bone forming agent for prevention of spaceflight-induced skeletal fragility in mice, Commercial Biomedical Testing Module-3: STS-135 space flight's affects on vascular atrophy in the hind limbs of mice (Rodent Research-1, CBTM-3-Sclerostin Antibody, CBTM-3-Vascular Atrophy, GeneLAB, and others) — Zhang Y, Zhao L, Sun Y. Using single-sample networks to identify the contrasting patterns of gene interactions and reveal the radiation dose-dependent effects in multiple tissues of spaceflight mice. *npj Microgravity*. 2024 April 4; 10(1): 45. DOI: 10.1038/s41526-024-00383-7.

Rodent Research Hardware and Operations Validation, Effects of the Space Environment on the Blood and Lymphatic Vessels of the Head and Neck, the Knee and Hip Joints, and the Eyes (Rodent Research-1, Rodent Research-9 (RR-9)) — Li K, Desai R, Scott RT, Steele JR, Machado M, et al. Explainable machine learning identifies multi-omics signatures of muscle response to spaceflight in mice. *npj Microgravity*. 2023 December 12; 9(1): 90. DOI: 10.1038/s41526-023-00337-5.

Spaceflight Effects on Vascular Endothelial and Smooth Muscle Cell Processes (STaARS BioScience-3) — Scotti MM, Wilson BK, Bubenik JL, Yu F, Swanson MS, et al. Spaceflight effects on human vascular smooth muscle cell phenotype and function. *npj Microgravity*. 2024 March 28; 10(1): 41. DOI: 10.1038/s41526-024-00380-w.

Spaceflight Environment Induces Remodeling of Vascular Network and Glia-Vascular Communication in Mouse Retina (Rodent Research-18 (RR-18)) — Braun JL, Fajardo VA. Spaceflight increases sarcoplasmic reticulum Ca2+ leak and this cannot be counteracted with BuOE treatment. *npj Microgravity*. 2024 July 19; 10(1): 1-7. DOI: 10.1038/s41526-024-00419-y.

STaARS BioScience-4 — Biancotti JC, Espinosa-Jeffrey A. Metabolomic profiling of the secretome from human neural stem cells flown into space. *Bioengineering*. 2024 January; 11(1): 11. DOI: 10.3390/bioengineering11010011.

Study on the Effect of Space Environment to Embryonic Stem Cells to Their Development (Stem Cells) — Yoshida K, Hada M, Hayashi M, Kizu A, Kitada K, et al. Transcriptome analysis by RNA sequencing of mouse embryonic stem cells stocked on International Space Station for 1584 days in frozen state after culture on the ground. *International Journal of Molecular Sciences*. 2024 January; 25(6): 3283. DOI: 10.3390/ijms25063283.

Studying the Features of the Growth and Development of Plants, and Technology for their Culturing in Spaceflight on the ISS RS (Rastenia-Pshenitsa (Plants-Wheat))— Aniskina TS, Sudarikov KA, Levinskikh MA, Gulevich AA, Baranova EN. Bread wheat in space flight: Is there a difference in kernel quality?. *Plants*. 2024 January; 13(1): 73. DOI: 10.3390/plants13010073.

Tissue Engineered Muscle as a Novel Platform to Study Sarcopenia (Cardinal Muscle) — Kim S, Ayan B, Shayan M, Rando TA, Huang NF. Skeletal muscle-on-a-chip in microgravity as a platform for regeneration modeling and drug screening. *Stem Cell Reports*. 2024 July 6; 19(8): S2213-6711(24)00190-5. DOI: 10.1016/j.stemcr.2024.06.010.

Transcriptional and Post Transcriptional Regulation of Seedling Development in Microgravity (Plant RNA Regulation, Plant Signaling) — Land ES, Sheppard J, Doherty CJ, Perera IY. Conserved plant transcriptional responses to microgravity from two consecutive spaceflight experiments. *Frontiers in Plant Science*. 2024 January 8; 14: 20pp. DOI: 10.3389/fpls.2023.1308713.

Transcriptome analysis and germ-cell development analysis of mice in the space (Mouse Habitat Unit -1 (MHU-1/ Mouse Epigenetics)) — Yoshikawa M, Ishikawa C, Li H, Kudo T, Shiba D, et al. Comparing effects of microgravity and amyotrophic lateral sclerosis in the mouse ventral lumbar spinal cord. *Molecular and Cellular Neuroscience*. 2022 July; 103745. DOI: 10.1016/j.mcn.2022.103745. *

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Whole Genome Fitness of Bacteria Under Microgravity (Bacterial Genome Fitness) — Sharma G, Zee PC, Zea L, Curtis PD. Whole genome-scale assessment of gene fitness of Novosphingobium aromaticavorans during spaceflight. *BMC Genomics*. 2023 December 16; 24(1): 782. DOI: 10.1186/s12864-023-09799-z.

EARTH AND SPACE SCIENCE

Alpha Magnetic Spectrometer - 02 (AMS-02) — Aguilar-Benitez M, Alpat B, Ambrosi G, Anderson H, Arruda MF, et al. Properties of cosmic deuterons measured by the Alpha Magnetic Spectrometer. *Physical Review Letters*. 2024 June 28; 132(26): 261001. DOI: 10.1103/PhysRevLett.132.261001.

Alpha Magnetic Spectrometer - 02 (AMS-02) — Aguilar-Benitez M, Ambrosi G, Anderson H, Arruda MF, Attig N, et al. Temporal structures in positron spectra and charge-sign effects in galactic cosmic rays. *Physical Review Letters*. 2023 October 13; 131(15): 151002. DOI: 10.1103/PhysRevLett.131.151002.

Alpha Magnetic Spectrometer - 02 (AMS-02) —Aguilar-Benitez M, Cavasonza LA, Alpat B, Ambrosi G, AMS-02 Collaboration, et al. Properties of cosmic-ray sulfur and determination of the composition of primary cosmic-ray carbon, neon, magnesium, and sulfur: Ten-year results from the Alpha Magnetic Spectrometer. *Physical Review Letters*. 2023 May 25; 130(21): 211002. DOI: 10.1103/PhysRevLett.130.211002. *

Alpha Magnetic Spectrometer - 02 (AMS-02) — Beischer B, von Doetinchem P, Gast H, Kirn T, Schael S. Perspectives for indirect dark matter search with AMS-2 using cosmic-ray electrons and positrons. *New Journal of Physics*. 2009 October 10; 11(10): 105021. DOI: 10.1088/1367-2630/11/10/105021. *

Alpha Magnetic Spectrometer - 02 (AMS-02) — Haino S, AMS-02 Collaboration. The performance of the AMS-02 silicon tracker evaluated during the pre-integration phase of the spectrometer. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*. 2011 February 21; 630(1): 78-81. DOI: 10.1016/j.nima.2010.06.032. *

Alpha Magnetic Spectrometer - 02 (AMS-02) — Pan X, Yuan Q. Injection spectra of different species of cosmic rays from AMS-02,ACE-CRIS and Voyager-1. *Research in Astronomy and Astrophysics*. 2023 November; 23(11): 115002. DOI: 10.1088/1674-4527/acf443.

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Alpha Magnetic Spectrometer - 02 (AMS-02) — Zhu C, Yuan Q, Wei D. Studies on Cosmic-Ray Nuclei with Voyager, ACE, and AMS-02. I. Local interstellar spectra and solar modulation. *The Astrophysical Journal*. 2018 August 16; 863(2): 119. DOI: 10.3847/1538-4357/aacff9. *

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Atmosphere-Space Interactions Monitor (ASIM) — Bjorge-Engeland I, Ostgaard N, Sarria D, Marisaldi M, Mezentsev A, et al. Evidence of a new population of weak terrestrial gamma-ray flashes observed from aircraft altitude. *Geophysical Research Letters*. 2024 September 16; 51(17): e2024GL110395. DOI: 10.1029/2024GL110395.

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Atmosphere-Space Interactions Monitor (ASIM) — Gomez C, Diaz F, Roman F, Neubert T, Reglero V, et al. Implementation of electromagnetic measurements with satellite data for TLEs determination and classification. *2023 International Symposium on Lightning Protection (XVII SIPDA)*, Suzhou, China; 2023 October 9-13. 1-7. DOI: 10.1109/SIPDA59763.2023.10349152.

Atmosphere-Space Interactions Monitor (ASIM) — Soler S, Gordillo-Vasquez FJ, Perez-Invernon FJ, Jockel P, Neubert T, et al. Parameterizations for global thundercloud corona discharge distributions. *Atmospheric Chemistry and Physics*. 2024 September 16; 24(18): 10225-10243. DOI: 10.5194/acp-24-10225-2024.

Atmosphere-Space Interactions Monitor (ASIM) — van der Velde OA, Navarro-Gonzalez J, Fabro F, Reglero V, Connell PH, et al. Imaging of 3 bright terrestrial gamma-ray flashes by the atmosphere-space interactions monitor and their parent thunderstorms. *Scientific Reports*. 2024 March 23; 14(1): 6946. DOI: 10.1038/s41598-024-57229-1.

Atmosphere-Space Interactions Monitor, STP-H5-Lightning Imaging Sensor (ASIM, STP-H5 LIS) — Koehn C, Heumesser M, Chanrion O, Reglero V, Ostgaard N, et al. Employing optical lightning data to identify lightning flashes associated to terrestrial gamma-ray flashes. *Bulletin of Atmospheric Science and Technology*. 2024 April; 5(1): 2. DOI: 10.1007/s42865-024-00065-y.

CALorimetric Electron Telescope (CALET) — Adriani O, Akaike Y, Asano K, Asaoka Y, Bagliesi MG, et al. The CALorimetric Electron Telescope (CALET) for high-energy astroparticle physics on the International Space Station. *Journal of Physics: Conference Series*. 2015 July; 632(1): 012023. DOI: 10.1088/1742-6596/632/1/012023. *

CALorimetric Electron Telescope (CALET) — Adriani O, Akaike Y, Asano K, Asaoka Y, Berti E, et al. Direct measurements of cosmic - ray iron and nickel with CALET on the International Space Station. *Advances in Space Research*. 2024 March 27; epub: 11pp. DOI: 10.1016/j.asr.2024.03.052.

CALorimetric Electron Telescope (CALET) — Akaike Y, Adriani O, Asano K, Asaoka Y, Berti E, et al. Direct measurements of cosmic rays with the calorimetric electron telescope on the international space station. *SciPost Physics Proceedings*. 2023 September 29; (13): 040. DOI: 10.21468/SciPostPhysProc.13.040. *

CALorimetric Electron Telescope (CALET) — Adriani O, Akaike Y, Asano K, Asaoka Y, Berti E, et al. Direct measurement of the spectral structure of cosmic-ray electrons + positrons in the TeV Region with CALET on the International Space Station. *Physical Review Letters*. 2023 November 9; 131(19): 191001. DOI: 10.1103/PhysRevLett.131.191001.

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(Listed by category and alphabetically)

Genes in Space-9 — Kocalar S, Miller BM, Huang A, Gleason EJ, Martin K, et al. Validation of Cell-Free Protein Synthesis Aboard the International Space Station. *ACS Synthetic Biology*. 2024 March 15; 13(3): 942-950. DOI: 10.1021/acssynbio.3c00733.

International Space Station Archaeological Project - Sampling Quadrangle Assemblages Research Experiment (SQuARE) — Walsh JS, Graham S, Gorman A, Brousseau C, Abdullah S. Archaeology in space: The Sampling Quadrangle Assemblages Research Experiment (SQuARE) on the International Space Station. Report 1: Squares 03 and 05. *PLOS ONE*. 2024 August 7; 19(8): e0304229. DOI: 10.1371/journal.pone.0304229.

Optical Sensors based on CARbon materials: QUantum Belgium (Ice Cube #8 - OSCAR QUBE) — Beerden Y, Vandebosch R, Ermakova A, Nesladek M, Hruby J. Long-Term Stability Assessment of Quantum Diamond Magnetometers in Low Earth Orbit. *IGARSS 2024 - 2024 IEEE International Geoscience and Remote Sensing Symposium; 2024 July.* 465-468, DOI: 10.1109/IGARSS53475.2024.10641354

Synchronized Position Hold, Engage, Reorient, Experimental Satellites-Zero-Robotics (SPHERES-Zero-Robotics) — Saenz-Otero A, Katz JG, Mohan S, Miller DW, Chamitoff GE. ZERO-Robotics: A student competition aboard the International Space Station. *2010 IEEE Aerospace Conference*, Big Sky, MT; 2010 March. 1-11. DOI: 10.1109/AERO.2010.5446894. *

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Assessment of the effect of space flight on bone quality using three-dimensional high resolution peripheral quantitative computed tomography (HR-pQCT) (TBone) — Kemp TD, Besler BA, Gabel L, Boyd SK. Predicting bone adaptation in astronauts during and after spaceflight. *Life*. 2023 November 9; 13(11): 2183. DOI: 10.3390/life13112183.

Astronaut's Energy Requirements for Long-Term Space Flight (Energy) — Le Roux E, Chery I, Schoeller DA, Bourdier P, Maillet A, et al. Substrate metabolism in male astronauts onboard the International Space Station: the ENERGY study. *npj Microgravity*. 2024 March 27; 10(1): 1-11. DOI: 10.1038/s41526-024-00360-0.

Biomedical Analyses of Human Hair Exposed to a Long-term Space Flight (Hair) — Gu X, Han Y, Shao Y, Ma W, Shao Z, et al. Gene expression changes reveal the impact of the space environment on the skin of ISS astronauts. *Clinical and Experimental Dermatology*. 2023 October; 48(10): 1128-1137. DOI: 10.1093/ced/llad178.

Cartilage-Bone-Synovium (CBS) Micro-Physiological System (MPS) Investigation Using the Multi-purpose Variable-G Platform (MVP Cell-06) — Dwivedi G, Flaman L, Alaybeyoglu B, Frank EH, Black RM, et al. Effects of dexamethasone and IGF-1 on post-traumatic osteoarthritis-like catabolic changes in a human cartilage-bone-synovium microphysiological system in space and ground control tissues on earth. *Frontiers in Space Technologies*. 2024 March 14; 5: DOI: 10.3389/frspt.2024.1358412.

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Capillary Flow Experiment , Human Exploration Research Opportunities - Differential Effects on Homozygous Twin Astronauts Associated with Differences in Exposure to Spaceflight Factors, International Space Station Summary of Research Performed (CFE, Twins Study, ISS Summary of Research) — Mason CE, Green J, Adamopoulos K, Afshin EE, Baechle JJ, et al. A Second Space Age Spanning Omics, Platforms, and Medicine Across Orbits. *Nature*. 2024 June 11; 632: 995-1008. DOI: 10.1038/s41586-024-07586-8.

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Effects of Microgravity on the Haemopoietic System: A Study on Neocytolysis (Neocytolysis) — Risso A, Turello M, Antonutto G. Neocytolysis and alterations of erythrocytes over a short term spaceflight. *Journal of Gravitational Physiology*. 2008 December; 15(2): 10pp. *

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Medical Proteome Analysis of Osteoporosis and Bone Mass-related Proteins Using the Kibo Japanese Experiment Module of International Space Station (Medical Proteomics) — Ino Y, Ohira T, Kumagai K, Nakai Y, Akiyama T, et al. Identification of mouse soleus muscle proteins altered in response to changes in gravity loading. *Scientific Reports*. 2023 September 22; 13(1): 15768. DOI: 10.1038/s41598-023-42875-8. *

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Physiological Factors Contributing to Postflight Changes in Functional Performance (Functional Task Test, Time Perception in Microgravity) — Clement GR, Kuldavletova O, Macaulay TR, Wood SJ, Navarro Morales DC, et al. Cognitive and balance functions of astronauts after spaceflight are comparable to those of subjects with bilateral vestibulopathy. *Frontiers in Neurology*. 2023 October 27; 14: 11pp. DOI: 10.3389/fneur.2023.1284029.

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Recovery of Functional Sensorimotor Performance Following Long Duration Space Flight (Field Test) — Tomilovskaya ES, Bekreneva M, Rukavishnikov IV, Kofman IS, Kitov VV, et al. Qualitative analysis of the presence of gaze-evoked nystagmus in astronauts after long term space flights. Results of "Field test" experiment. *Acta Astronautica*. 2024 November; 224: 82-88. DOI: 10.1016/j.actaastro.2024.07.026.

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The Effect of Long Duration Hypogravity on the Perception of Self-Motion (VECTION) — Jorges B, Bury N, McManus M, Bansal A, Allison RS, et al. The effects of long-term exposure to microgravity and body orientation relative to gravity on perceived traveled distance. *npj Microgravity*. 2024 March 13; 10(1): 1-8. DOI: 10.1038/s41526-024-00376-6.

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Vision Impairment and Intracranial Pressure (VIIP) — Brunstetter TJ, Zwart SR, Brandt K, Brown DM, Clemett SJ, et al. Severe spaceflight-associated neuro-ocular syndrome in an astronaut with 2 predisposing factors. *JAMA Ophthalmology*. 2024 July 5; 142 (9): 808–817. DOI: 10.1001/jamaophthalmol.2024.2385.

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Columnar-Equiaxed Transition in Solidification Processing for the Transparent Alloys Instrument, DEvice for the study of Critical LIquids and Crystallization - Directional Solidification Insert, Metastable Solidification of Composites: Novel Peritectic Structures and In-Situ Composites for the Transparent Alloys Instrument, Solidification along a Eutectic Path in Ternary Alloys Experiment, Solidification along a Eutectic Path in Binary Alloys for the Transparent Alloys Instrument, International Space Station Summary of Research Performed (Transparent Alloys - CETSOL, DECLIC-DSI, Transparent Alloys - METCOMP, Transparent Alloys - SETA, Transparent Alloys-SEBA, ISS Summary of Research) — Akamatsu S, Bottin-Rousseau S, Witusiewicz VT, Hecht U, Plapp M, et al. Microgravity studies of solidification patterns in model transparent alloys onboard the International Space Station. *npj Microgravity*. 2023 October 18; 9(1): 1-12. DOI: 10.1038/s41526-023-00326-8.

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