National Aeronautics and
Space Administration

Annual Highlights of Results *from the* INTERNATIONAL SPACE STATION 2023

Annual Highlights of Results from the International Space Station

Oct. 1, 2022 - Sept. 30, 2023

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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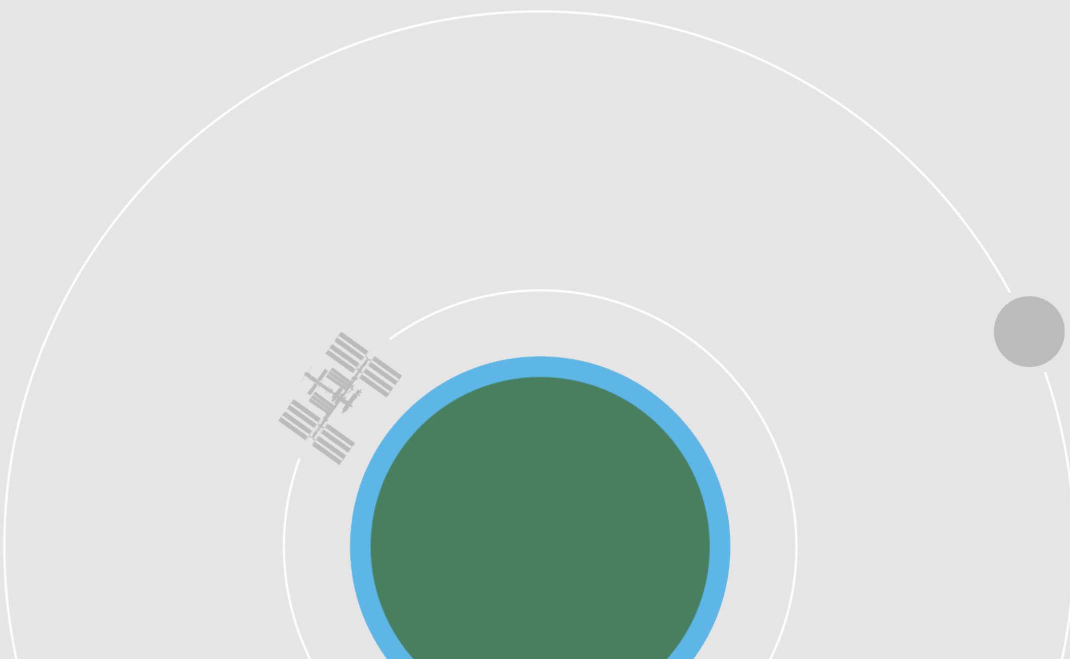


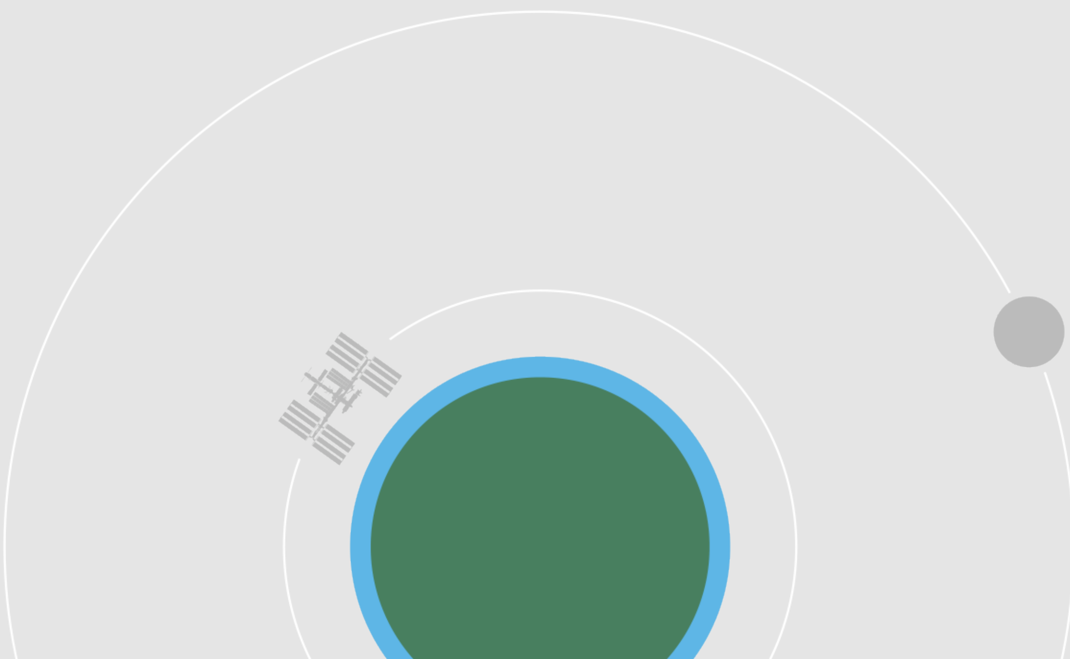
Letter From the Chief Scientist

In 2023, the International Space Station celebrated its 25th year of operations. Over the last 25 years, the space station has transformed into an orbiting laboratory with research capabilities that enable scientists from over 109 different nations to conduct over 3,300 groundbreaking experiments in an extreme and unique environment. The science enabled by the space station to date has led to transformative technologies through space-based innovations, improved human health on Earth and in space, supported technology developments for future exploration programs beyond low Earth orbit, and facilitated STEM-based programs to foster the development of tomorrow's leaders. Over the past year, the scientific resources for conducting research on station have been challenged by changes in flight plans and anomalies in transport vehicles, resulting in delays in science operations. Despite these challenges, approximately 500 investigations were conducted on space station and two Private Astronaut Missions were supported in 2023. This *2023 Annual Highlights of Results* showcases a selection of breakthrough scientific achievements that represent the high quality and diverse research capabilities of the space station and investigative teams.

The International Space Station is planned to extend through 2030, after which it is expected commercially developed space stations will be viable destinations in low Earth orbit. The coming years of transition to commercial space stations will mark a new era of challenges to meet the growing needs of scientific research and commercial development. The station's scientific community embraces this new era of opportunity while continuing to maximize this one-of-a-kind orbiting laboratory for the benefit of humanity.

Jennifer Buchli, NASA, International Space Station Chief Scientist

Dr. Meghan Everett, International Space Station Deputy Chief Scientist



Introduction

After 25 years of international collaboration operating the largest and most technologically advanced laboratory in low Earth orbit, the current decade of research results has seen thousands of researchers around the world completing their investigations, analyzing their data, and publishing their findings.

Through close examination of station client feedback obtained since 2002, station program managers, administration personnel, and technical staff have improved their processes and software tools to enhance communication with research teams for better in-flight data collection and sample return. These refinements affect experiment results and the conclusions researchers draw. The enhanced planning and coordination of investigation launch, stowage, crew time allocation, accessibility to station's research capabilities (i.e., facilities), and data delivery are critical to the effective operation of scientific projects for accurate results to be shared with the scientific community, sponsors, legislators, and the public.

Over 3,700 investigations have operated since Expedition 1, with more than 250 active research facilities, the participation of more than 100 countries, the work of more than 5,000 researchers, and over 4,000 publications. The growth in research (Figure 1) and international collaboration (Figure 2) has prompted the publication of over 560 research articles in top-tier scientific journals with about 75 percent of those groundbreaking studies occurring since 2018 (Figure 3).

Bibliometric analyses conducted through VOSviewer[1] measure the impact of space station research by quantifying and visualizing networks of journals, citations, subject areas, and collaboration between authors, countries, or organizations. Using bibliometrics, a broad range of challenges in research management and research evaluation can be addressed. The network visualizations, stacked charts, and line graphs provided in this introduction demonstrate the growth and influence of station research.

Introduction

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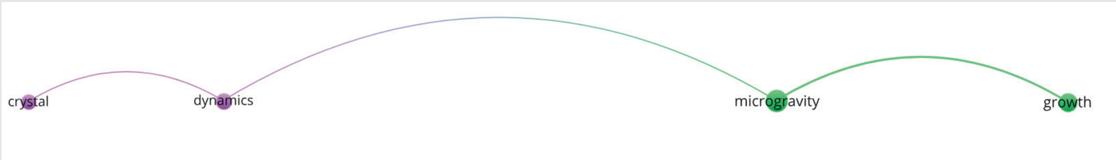

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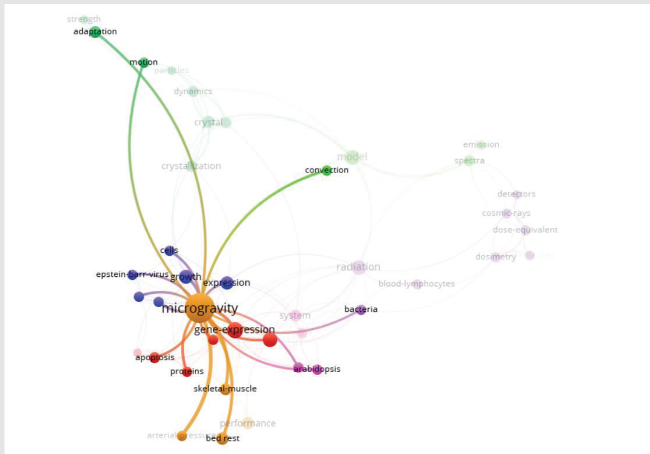

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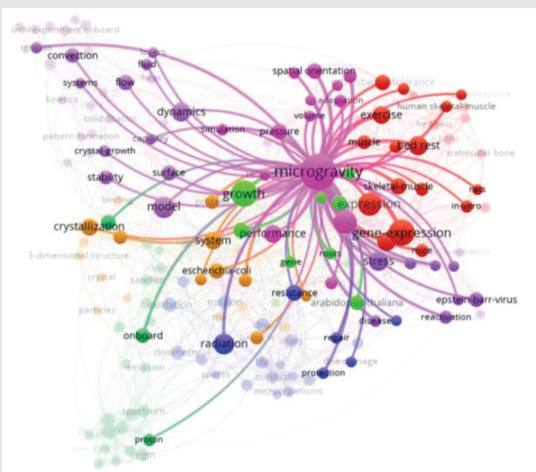

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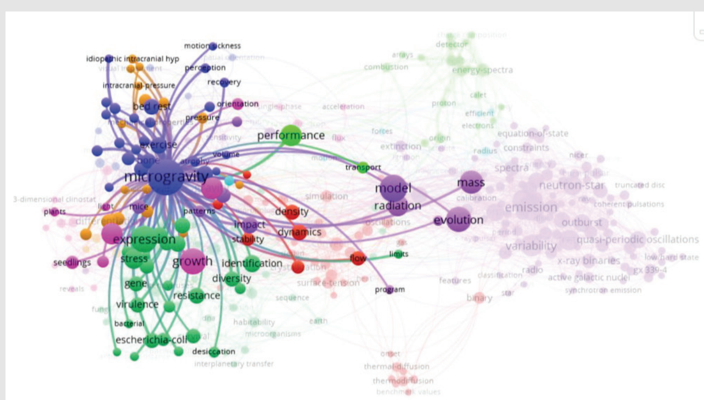


Figure 1. Bibliometric mapping of station research growth over time. Count of the keyword microgravity co-occurring at least five times with other research keywords at different time periods. **A) 1999-2005**: n=11; **B) 2006-2011**: n=49; **C) 2012-2017** n=69; **D) 2018-Sep. 2023**: n=115. The node size represents the number of publications containing the research keywords (larger nodes = more publications), the distance between nodes represents relatedness between research keywords, and the colors represent different research areas.

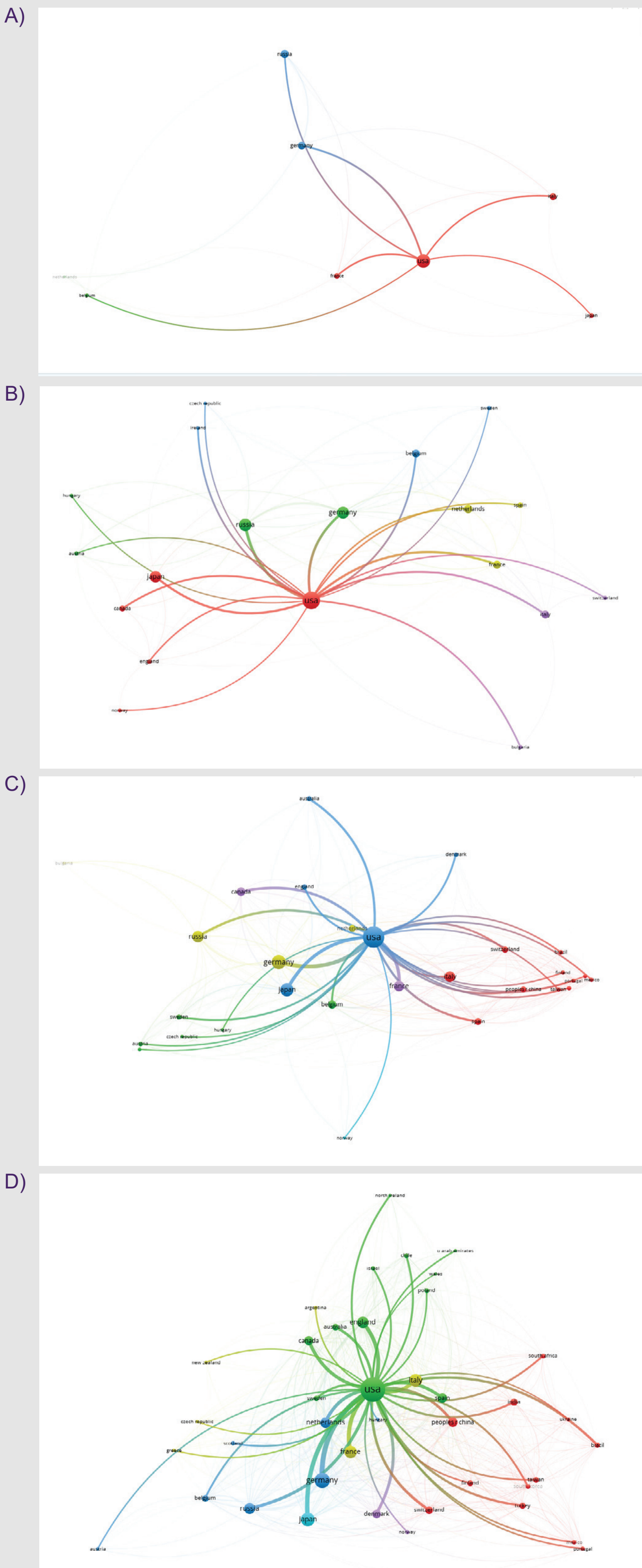


Figure 2. Bibliometric mapping of station collaboration growth over time. Measurement of co-authorship strength (i.e., total line thicknesses) between the United States and other countries in the network at different time periods. **A) 1999-2005**: total link strength = 19 **B) 2006-2011:** total link strength = 74; **C) 2012-2017:** total link strength = 150; **D) 2018-Sep. 2023:** total link strength = 442. Nodes represent the number of publications for each country. Distance and color are not relevant indicators in this chart.

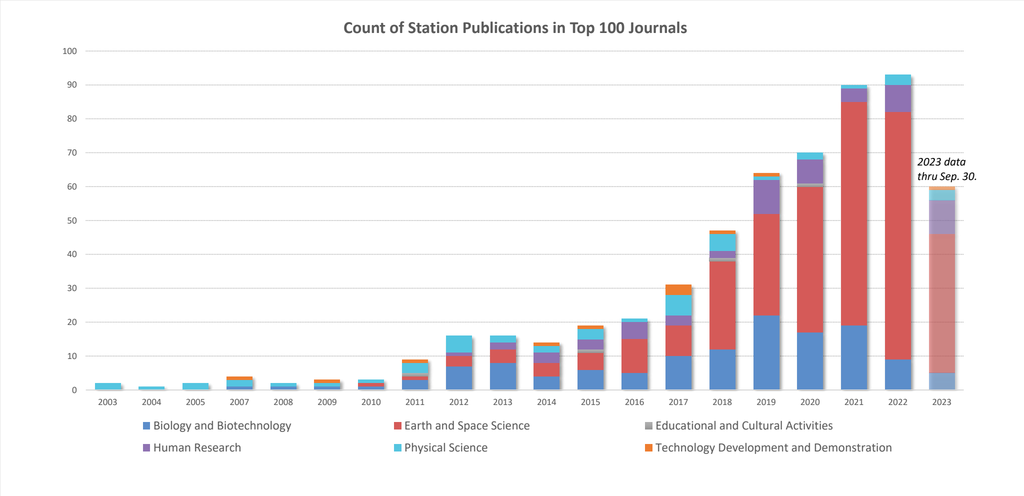


Figure 3. Count of publications reported in journals ranked in the top 100 according to global standards of Clarivate. A total of 567 top-tier publications through the end of FY-23 are shown by year and research category.

In this year's edition of the *Annual Highlights of Results*, we report findings from a wide range of topics in biology and biotechnology, physics, human research, Earth and space science, and technology development – including investigations about plant root orientation, tissue damage and repair, bubbles, lightning, fire dynamics, neutron stars, cosmic ray nuclei, imaging technology improvements, brain and vascular health, solar panel materials, grain flow, as well as satellite and robot control.

The findings highlighted here are only a small sample representative of the research conducted by the participating space agencies – ASI (Agenzia Spaziale Italiana), CSA (Canadian Space Agency), ESA (European Space Agency), JAXA (Japanese Aerospace Exploration Agency), Roscosmos, and NASA - on station in the past 12 months.

Many more studies in fiscal year (FY-23) revealed remarkable results, such as finding reduced fat accumulation in the bone marrow (MARROW), identifying gene mutations, that preserve muscle (Molecular Muscle), improving optical beams for enhanced communication between spacecraft and ground stations (SOLISS), detecting bacterial antibiotic resistance during spaceflight (Plazmida), observing abnormal cell division of human neural stem cells (STaARS Bioscience-4), among others. A full list of all the publications collected in FY-23 can be found at the end of this report.

A publicly accessible database of space station investigations and publications can be found in the Space Station Research Explorer (SSRE) website, and all editions of the *Annual Highlights of Results from the International Space Station* can be found through the Space Station Research Results Library.

1. Van Eck NJ, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics. 2010; 84(2):523-538. DOI: 10.1007/s11192-009-0146-3.

Introduction

Between Oct. 1, 2022, and Sept. 30, 2023, we identified a total of **330** articles associated with station research. Of these 330 articles, 268 appeared in peer-reviewed journals, 59 in conference proceedings, and 3 in gray literature such as books, magazines, technical reports, or patents. Articles are also categorized based on how authors obtained their results. There were 204 publications that reported direct implementation of the science aboard station (i.e., Results), 37 that reported development of the payload prior to operation on station (i.e., Flight Preparation), and 89 that emerged as follow-ups to station science (i.e., Derived). Because derived articles are new scientific studies generated from shared data, derived science is an additional return on the investment trusted to station science. For FY-23, this return on investment was 27 percent. Full definitions of these publication types (i.e, Results, Flight Preparation, and Derived) categories can be found on page 8 of this report.

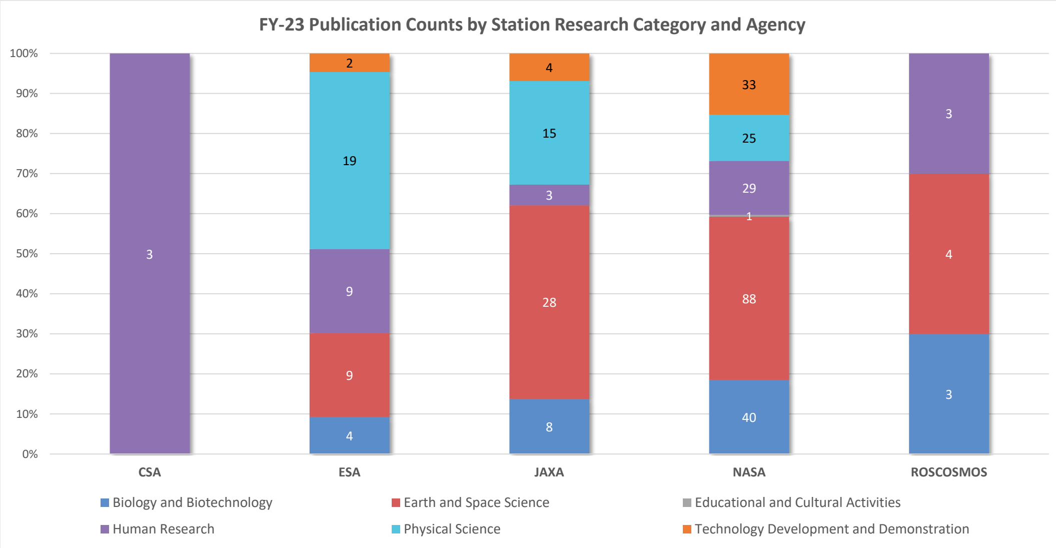


Figure 4. Count of publications by agency and station research category. A total of 330 articles were collected in FY-23.

Figure 4 shows a stacked chart with the count of articles collected in FY-23 broken out by space agency and research category. In summary, we found three articles for CSA, 43 articles for ESA, 58 articles for JAXA, 10 articles for Roscosmos, and 216 articles for NASA. Of the 330 articles collected in FY-23, 66 were articles published prior to Oct. 1, 2022.

MEASURING SPACE STATION IMPACTS

The significant impact of sustained international multidisciplinary research in microgravity can be observed through the findings published in world-class scientific journals that adhere to a rigorous scientific peer-review process.

With the assistance of *Clarivate*, a global database that collects publication and journal information for annual journal ranking and metrics, we identified the top findings produced by station researchers. One parameter, the journal's Eigenfactor Score[2], ranks each journal based on readership and influence, including the different citation standards of each discipline.

From Oct 1, 2022, to Sept 30, 2023, 78 articles appeared in top-tier journals. Of those 78 articles, 21 were reported in top 20 journals (see Table 1).

	Clarivate Analytics® Rank	Journal (Number of Publications in FY-23)
ISS Publications in Top 20 Sources	1	Nature Communications (3)
	2	Nature (2)
	3	Scientific Reports (7)
	4	Science (1)
	5	PLoS ONE (1)
	15	Physical Review Letters (5)
	16	Science Advances (1)
	18	International Journal of Molecular Sciences (6)
ISS Publications in Top 100 Sources	25	Frontiers in Immunology (1)
	30	Cell Reports (1)
	31	Monthly Notices of the Royal Astronomical Society (22)
	33	Astrophysical Journal (19)
	36	Advanced Energy Materials (1)
	42	Frontiers in Microbiology (2)
	49	Sensors (1)
	64	Geophysical Research Letters (2)
	80	Remote Sensing (1)
	89	Optics Express (1)
	95	Frontiers in Plant Science (1)

Table 1. A total of 78 articles were published in top-tier journals in FY-23: 21 articles in top 20 (green) and 57 articles in top 100 (yellow). Data ranked according to Clarivate Journal Citations Reports (JCR) Eigenfactor score.

In addition to the research diversity and top-tier results obtained from station, a comparison of station science to global and US standards of category-normalized citation impact (i.e., adjusted impact of a publication based on its research area) shows greater influence of station science since 2010 compared to other research endeavors taking place domestically or internationally. The authority of station research was particularly prominent in 2019, and it continues to hold its place in the scientific community to date. Figure 5 illustrates this important comparison.

Figure 5. Citation impact (normalized by research area) of station science publications compared to national and global standards.

2. *West JD, Bergstrom TC, Bergstrom CT. The Eigenfactor Metrics™: A Network approach to assessing scholarly journals. College and Research Libraries. 2010;71(3). DOI: 10.5860/0710236.*

Introduction

The high impact of space station is in great part attributed to the researchers who conduct transformative science in low Earth orbit. As shown in Table 2, four studies published in FY-23 have already received much acclaim from others in their field.

Investigation	Category	Space Agency	Publication Title and Journal	Publication Type	Citations
Neutron star Interior Composition Explorer (NICER)*	Earth and Space Science	NASA-SMD	Polarized x-rays constrain the disk-jet geometry in the black hole x-ray binary Cygnus X-1, *Science*.	Derived	20
EML Batch 1 - NEQUISOL Experiment	Physical Science	ESA	Anomalous kinetics, patterns formation in recalescence, and final microstructure of rapidly solidified Al-rich Al-Ni alloys, *Acta Materialia*.	Results	13
Cold Atom Lab	Physical Science	NASA-BPS	A space-based quantum gas laboratory at picokelvin energy scales, *Nature Communications*.	Results	9
Mini-EUSO	Earth and Space Science	Roscosmos-ASI-ESA	Observation of night-time emissions of the Earth in the near UV range from the International Space Station with the Mini-EUSO detector, *Remote Sensing of Environment*.	Results	5

Table 2. List of articles published in FY-23 that have been widely recognized in a short period of time. *NICER reported two additional FY-23 publications with over 10 citations.

Advancements in technology and research on station have inspired students all over the world to pursue STEM careers, encouraged researchers to explore bold questions, and incentivized economies through the initiation of businesses in the space industry. While some of the most decisive steps toward space commercialization are recent, researchers from small and large companies, academic institutions, and government agencies have been conducting experiments in space since 2005 through the International Space Station National Lab. Today, the hard work is paying off. In FY-23, we collected 39 publications from investigations sponsored by National Lab with fascinating results in droplet behavior for the improvement of condensing systems (Drop Vibration), the reliable use of a genome examination and editing tool (Ax-1 CRSPR), the identification of specific gut bacteria involved in bone loss (Rodent Research-5), the use of neural networks for improved image analysis (Spaceborne Computer-2), and much more. In addition to the accomplishments of the International Partners and NASA on space station, National Lab's alternative route to send investigations to space have demonstrated that new paths can be explored to expand research in microgravity for the advancement of science and benefit of humanity.

Introduction

EVOLUTION OF SPACE STATION RESULTS

The archive of Space Station investigations went online in 2004. Since that time, changes to methods for tracking investigations and publications have been implemented, including increased differentiation between research disciplines and a re-characterization of publication fields. Currently, the following publication types are included in the Program Science Toolbox:

- Flight Preparation Results - publications about the development work performed for the investigation, facility, or project prior to operation on the Space Station.
- Station Results - publications that provide information about the performance and results of the investigation, facility, or project as a direct implementation on station or on a vehicle to space station.
- Derived Results - publications that use data from an investigation that operated on ISS, but the authors of the article are not members of the original investigation team. Derived Results articles have emerged as a direct outcome of the open-source data initiative, which gives access to raw data for new researchers to analyze and publish innovative results, expanding global knowledge and scientific benefits.
- Patents - applications filed based on the performance and results of the investigation, facility, or project on station, or on a vehicle to space station.
- Related - publications that lead to the development of the investigation, facility, or project.

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 ISS partnership during the past year.

EXPLORATION

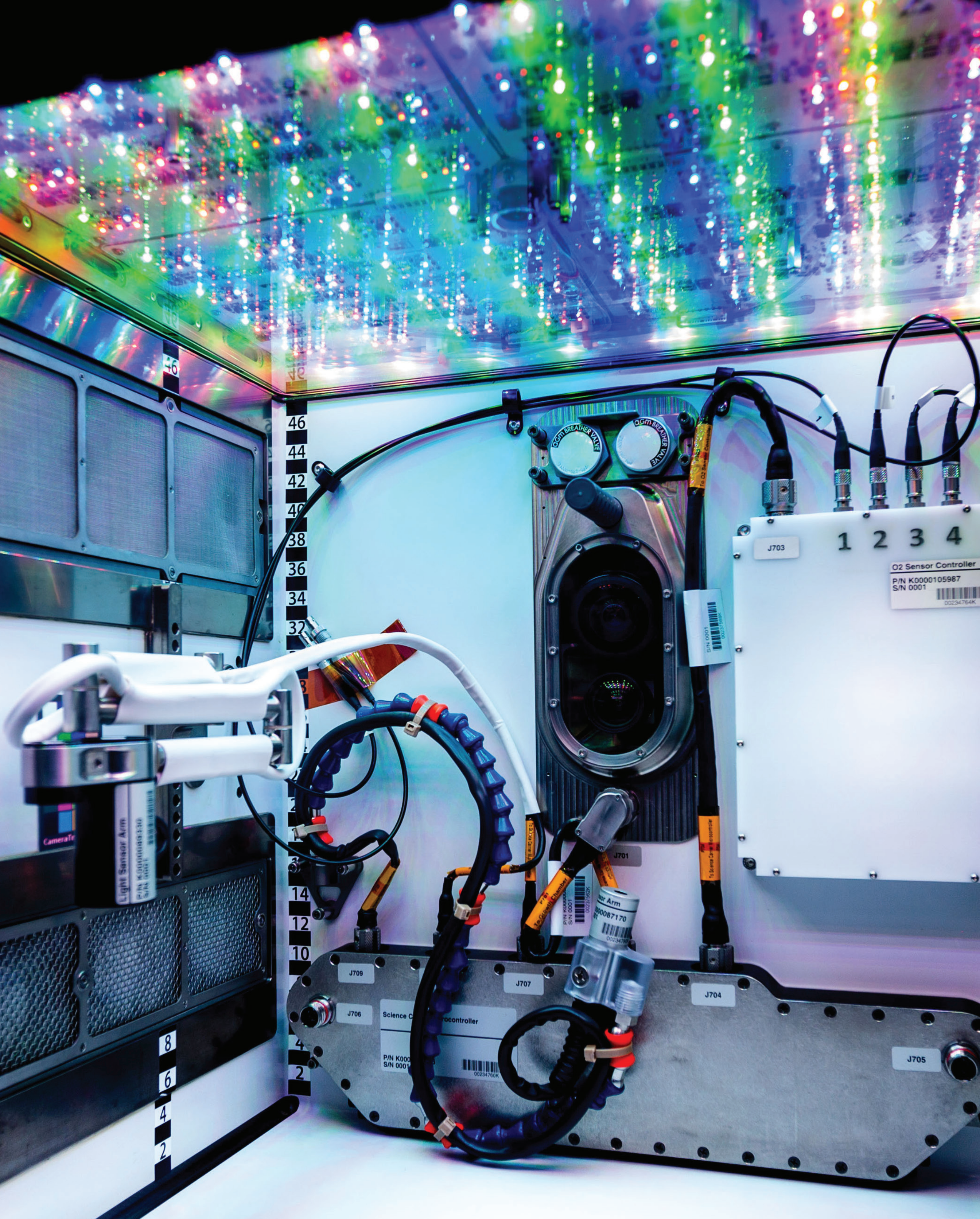
Space station investigation results have yielded updated insights into how to live and work more effectively in space by addressing such topics as understanding radiation effects on crew health, combating bone and muscle loss, improving designs of systems that handle fluids in microgravity, and determining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

DISCOVERY

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.

BENEFITS FOR HUMANITY

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.



Advanced Plant Habitat (APH) flight unit at NASA's Kennedy Space Center in Florida. This is an exact replica of the unit that was delivered to space station for its first investigation, **Plant Habitat-01**. Developed by NASA and ORBITEC, the APH is the largest plant chamber built for NASA to conduct automated plant growth studies on station. NASA ID: jsc2020e003415.

The space station laboratory provides a platform for investigations in the biological sciences that explores 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. From the beginning of station to date, more than 900 articles have been published in the area of Biology and Biotechnology.

The NASA investigation **Biotube-Magnetophoretically Induced Curvature in Roots (Biotube-MICRO)** examines how plant amyloplasts, which are involved in the production of starch and plant root orientation, respond to magnetic gradients in microgravity. On Earth, amyloplasts are dense particles that sediment in the direction of gravity, inducing the downward growth of plant roots. The presence of magnetic gradients additionally displaces amyloplasts and induces curvature.

In a recent study published in *Scientific Reports*, researchers used *Brassica rapa* seeds to understand the effect of magnetic gradients on transcriptional responses of genes related to growth, metabolism, auxin (hormones), and stress in microgravity. A strong magnetic gradient was generated using ferromagnetic wedges that exceeded the magnetic force to which plants respond. Researchers expected the roots to curve away from the wedges.

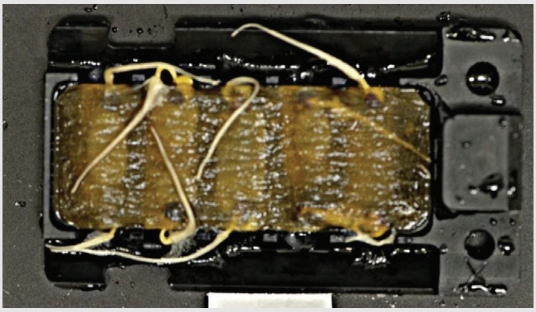


Figure 6. Germination and root curvature of *Brassica rapa* seeds in microgravity. *Image adopted from Hasenstein, Scientific Reports.*

Researchers compared the germination, root curvature, and transcription of 16 genes in four tissue types of seedlings grown in space versus seedlings grown on the ground in static and clinorotated conditions, taking into account the magnetic and non-magnetic fields in which the seeds were placed. Results showed that the presence of a magnetic field did not affect germination but did induce curvature (Figure 6). However, curvature also occurred in non-magnetic chambers, presumably in response to hydrotropism. Magnetic fields in space also did not affect transcription activity involved in metabolism, indicating that magnetic fields are not detrimental to plants.

However, the size of amyloplasts increased in microgravity but decreased during the clinorotation condition on the ground. This outcome indicates that plants perceive gravity, but ground control experimentation is not a suitable replacement for research conducted under weightlessness. These results call for more investigation on the role of starch metabolism to develop scientists' understanding of how space affects plant root growth in a weightless environment.

It is worth highlighting that the crew was not involved in the operation of this experiment because all procedures were controlled remotely from the ground. High-tech systems on-board station allow researchers to monitor their experiments remotely and obtain reliable results without involving crew time.

Hasenstein KH, Park MR, John SP, Ajala C. High-gradient magnetic fields and starch metabolism: Results from a space experiment. Scientific Reports. 2022 October 29; 12(1): 18256. DOI: 10.1038/s41598-022-22691-2.

The Roscosmos and NASA investigation **Tissue Regeneration - Bone Defect (Rodent Research-4 CASIS)** examines the processes, changes, and outcomes of wound healing after exposure to microgravity. Effective tissue repair after injury could result in fewer health complications and reduced costs. While the main objective of the overall investigation is to learn about regeneration and healing of bone tissue, a recent study published in *The International Journal of Molecular Sciences* focuses on the healing of skin tissue.

In the new study, researchers analyzed the connective tissue from the thigh dermis of 40 mice (10 in microgravity and 30 in multiple control groups) after ~23 days of spaceflight. Connective tissue in the dermis plays a significant role in adaptation to different gravity conditions, with its fibers (type-I and type-III collagens) providing the structure, strength, and elasticity for the skin. Mast cells in connective tissue assist in fiber reconstruction of the dermis and other internal organs through the secretion of proteins, enzymes, and growth factors.

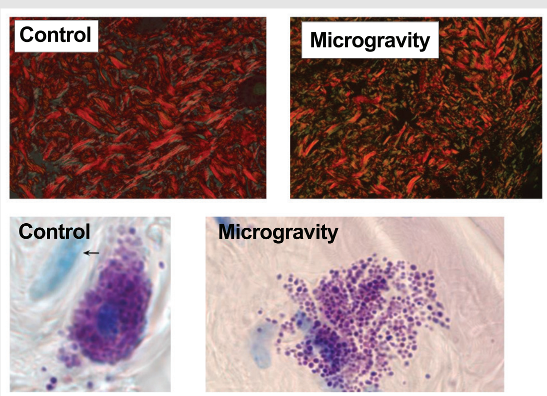


Figure 7. Connective tissue (top row) and mast cell (bottom row) differences between control and microgravity samples. *Image adopted from Shishkina, International Journal of Mofecular Life Sciences.*

Compared to control mice, experiment mice sent to space showed increased interfascicular spaces in the connective tissue, shorter and tangled fibers forming a cellular web, and more type-III fibers than type-I fibers (Figure 7). Disappearance of reticular fibers around the mast cells and more degranulation were also observed. Although the size of mast cells in the spaceflight group remained the same as that in controls, the mast cells showed protuberances as well as excess secretion of small granules after microgravity exposure. According to the researchers, these changes to mast cells may indicate a more active granule metabolism or an adaptation to gravity changes.

This pioneering study characterizes the structure of supporting connective tissue in mice after spaceflight. Its results are an initial step toward discovering the mechanisms of tissue remodeling, which could lead to the treatment of degenerated tissue through the development of pharmaceuticals that assist the renewal of connective tissue in diseased organs.

In 2021, the ESA investigation **Space Omics Analysis of the Skin Microbiome of Diabetic Foot Ulcers (Ice Cubes #9 – Project Maleth)** from the Mediterranean country Malta, conducted its first biomedical science experiment in space to examine the effects of spaceflight and microgravity on human skin tissue microbiome.

Malta has a high prevalence of diabetes. Patients suffering from this disease have reduced blood flow to their extremities and develop nerve damage that results in weakness and numbness of the hands and feet. Consequently, up to 25 percent of patients develop diabetic foot ulcers (DFU) that can become infected. The microbiome present in

Shishkina VV, Kostin A, Volodkin A, Samoilova V, Buchwalow I, et al. The remodeling of dermal collagen fibrous structures in mice under zero gravity: The role of mast cells. International Journal of Molecular Sciences. 2023 January 18; 24(3): 1939. DOI: 10.3390/ijms24031939.

these ulcers forms a biofilm that makes the host's immune system and systemic antibiotics unable to penetrate the ulcer, making it very difficult to treat. Infected and untreated DFUs may progress into bone infections (i.e., osteomyelitis) that would require amputation to save the patient.

Astronauts, like diabetics, develop thinner and drier skin susceptible to damage while their compromised immune system further delays wound recovery. The similarities in skin profiles between astronauts and diabetics allow researchers to understand bacterial diversity in DFUs under two environmental conditions, Earth and microgravity.

Figure 8. Mixed bacteria culture from a diabetic foot ulcer obtained before spaceflight. *NASA ID: jsc2021e0933545*

In the most recent study published in *Heliyon*, researchers obtained six skin tissue samples (Figure 8) along with its microbiome from Type-2 diabetes patients with DFUs with the goal of identifying differences in the microorganisms using 16S rRNA gene sequencing. Analyses revealed different sample structures between tissue types, more similarity and clustering in the Earth control samples, and more diversity of bacterial species without clustering in the microgravity samples. Additional analyses showed that certain bacteria survive, adapt, and thrive more in station's DFU tissue samples. In particular, a high abundance of *Pseudomonas* and *Morganella* was identified.

The data collected through this investigation is now part of the GeneLab repository. Subjecting skin tissue to microgravity helps researchers understand the adaptation and survival of disease-causing bacteria to improve wound healing in diabetic patients and astronauts under the stresses of disease or space.

Through multiple JAXA investigations on station – **Transcriptome analysis and germ-cell development analysis of mice in the space (MHU-1)**, **Mouse Habitat Unit Technical Verification (MHU-4)**, **and** **Mouse Habitat Unit-5 (MHU-5)** – researchers are examining physiological and gene expression changes in mice after exposure to partial and full microgravity.

Although more than 40 percent of the human body's total mass is comprised of skeletal muscle, little is known about how different levels of mechanical loading and unloading impact the cellular and molecular processes of muscle fibers. Given that muscle wasting conditions are associated with loss of strength, deformity, disability, and increased mortality, this new station research could greatly benefit the development of countermeasures for

Gatt C, Tierney BT, Madrigal P, Mason CE, Beheshti A, et al. The Maleth program: Malta's first space mission discoveries on the microbiome of diabetic foot ulcers. Heliyon. 2022 December; 8(12): e12075. DOI: 10.1016/j.heliyon.2022.e12075.

astronauts and treatments for patients on Earth.

In a study recently published in *Communications Biology*, researchers sought to investigate how skeletal muscle myofibers (slow-twitch and fast-twitch) in calf muscles responded to different levels of gravity (Earth artificial gravity, lunar gravity, and microgravity) to better understand protein regulation and degradation. In particular, researchers wanted to learn whether lunar gravity (i.e., one-sixth of Earth gravity) was enough to retain healthy muscle fibers.

These results demonstrated that lunar gravity meets the minimum gravitational threshold needed to prevent full muscle atrophy. However, the transcriptome of mice in lunar gravity resembled that of mice in microgravity more than mice in artificial Earth gravity or ground controls. This result suggested that the expression of some genes is better regulated by a gravitational load higher than one-sixth gravity. Finally, researchers found that lunar gravity, like microgravity, induces slow-to-fast myofiber transitions. That is, there was downregulation of genes associated with mitochondrial function and ATP production in

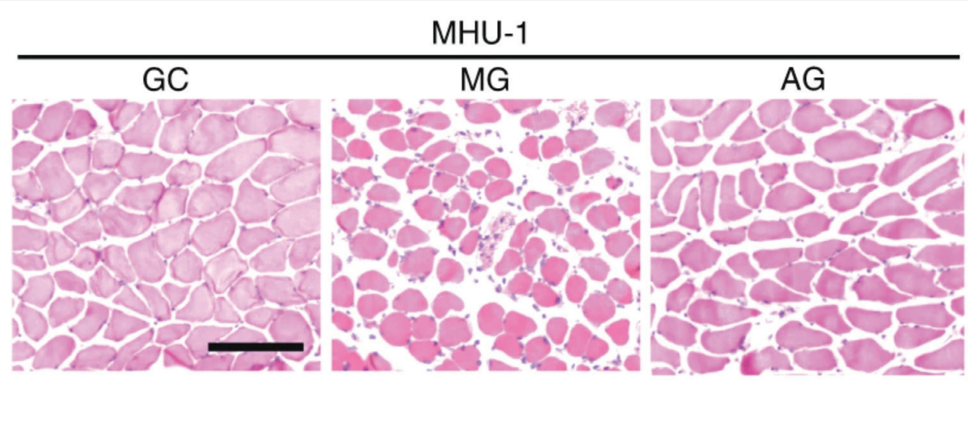


Figure 9. Cross-section of calf muscle in mice. Muscile fiber sfrom ground control (GC) and lunar gravity (AG) were more alike than to muscle fibers exposed to microgravity (MG). *Image adopted from Hayashi, Communications Biology.*

Researchers used the Multiple Artificial-gravity Research System (MARS) on the space station to manipulate the level of gravity and examine skeletal muscle changes in 24 young male mice after one month of exposure to the different gravitational loads.

Researchers conducted histological and RNA sequencing analyses approximately two days after landing and found a 40 percent reduction in myofiber size in the MG group but not in the AG or GC groups (Figure 9).

mice exposed to microgravity and lunar gravity, consequently affecting muscle metabolism to support contractions.

Through this study, researchers demonstrated that an artificial gravity system is critical to understanding the response of muscle fibers and improve therapies for skeletal muscle health in astronauts.

Hayashi T, Fujita R, Okada R, Hamada M, Suzuki R, et al. Lunar gravity prevents skeletal muscle atrophy but not myofiber type shifts in mice. Communications Biology. 2023 April 21; 6(1): 424. DOI: 10.1038/s42003-023-04769-3.

Scanning electron image of monospecies biofilm isolated from the space station. The image was colored to visualize the bacterial cells (orange) embedded in the biofilm matrix (blue). The ESA-Biofilms investigation studies **bacterial biofilm** formation and antimicrobial properties of different metal surfaces under microgravity. NASA ID: jsc2023e010175

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. From the beginning of station to date, more than 900 articles have been published in the area of Earth and Space Science.

The Roscomos-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 raining down on Earth. Its optical system of 36 multianode photomultiplier tubes capable of detecting single photons allow exceptional imaging during day/night and night/day transitions (Figure 10). Mini-EUSO is the first mission of a larger program (JEM-EUSO) with about 300 scientists from 16 countries.

In FY-23, five publications described the advanced technology of the telescope. In one of the publications, released in the *Journal of Physics: Conference Series*, researchers demonstrated the proper functionality of Mini-EUSO, with regular collection of ultraviolet emissions data since 2019.

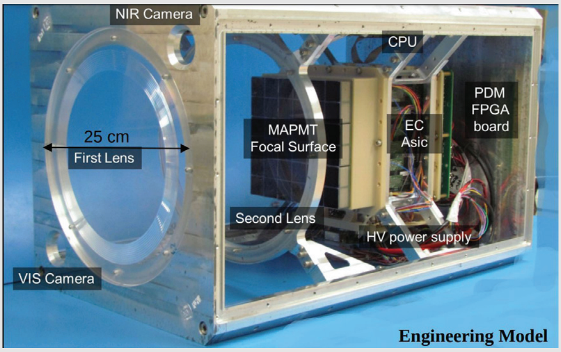


Figure 10. Mini-EUSO mock-up displaying three main compartments (optics, focal surface, and data acquisition). *Image adopted from Marcelli, Journal of Physics: Conference Series.*

Air showers, a cascade of ionized particles and electromagnetic radiation that produce a streak of fluorescent light when ultrahigh-energy cosmic rays enter the Earth's atmosphere, have been studied by ground telescopes located in the Northern and Southern hemispheres. Observing the fluorescent light from space with a telescope such as Mini-EUSO allows researchers to determine the energy of the cosmic rays, the arrival direction, and the position of the shower.

The high spatial and temporal resolution of Mini-EUSO provides the capability to study Transient Luminous Events (TLEs), Emission of Light and Very Low Frequency perturbations due to Electromagnetic Pulse Sources (ELVES), meteors, strange quark matter, space debris, marine phytoplankton bioluminescence, marine pollution, geomagnetic disturbances, ultra-high energy cosmic rays, and climate effects.

The ESA investigation **Atmosphere-Space Interactions Monitor (ASIM)**, which has been installed externally on the station's Columbus module since early 2018, monitors thunderstorm activity and its impact on the Earth's atmosphere and climate. From the top of station without cloud obstacles, ASIM can better detect different types of transient luminous events such as blue jets, red sprites, green ghosts, halos, and ELVES to provide in-depth data of these high energy emissions.

Marcelli L, Battisti M, Belov A, Bertaina M, Cambiè G, et al. The Mini-EUSO telescope on board the ISS: in-flight operations and performances. Journal of Physics: Conference Series. 2022 November; 2374 (1): 012048. DOI: 10.1088/1742-6596/2374/1/012048

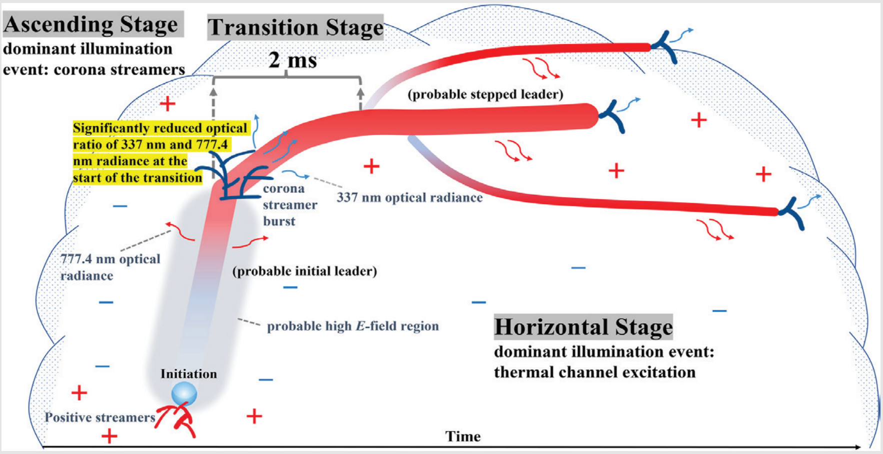


Figure 11. Diagram showing the stages of in-cloud lightening development. *Image adopted from Huang Geophysical Research Letters.*

This advanced technology provides weather information to alert communities, martime vessels, and aircraft in the path of dangerous storms. A NASA ScienceCast video further demonstrated all the benefits of this investigation.

In a new study published in the journal of *Geophysical Research Letters*, researchers combined radio signals and optical imaging to study the transition of 30 in-cloud flashes in detail. Researchers identified lightning changes that transitioned from upward leaders (i.e., positively charged "cold" lightning initiated and rising from a tall building, tower, or wind turbine) to scattered horizontal emissions across the clouds (Figure11). From space, this phenomenon was observed as blue radiance that rapidly dissipated at the onset of the transition compared to red radiance that remained virtually unchanged. An observation of reduced blue/red optical ratio coinciding with *initial breakdown pulses* (i.e., early electromagnetic field pulses emitted by lightning), led researchers to suggest that changes in the electromagnetic field form large currents of leader channels. Therefore, lightning transitions may begin when the electric charge in the main leader channel has reached its maximum.

Additional cloud-to-ground measurements reported similar transitions from upward and stepped leaders (i.e., lightning that develops downward in quick steps), suggesting a connection. Researchers hypothesize that upward and stepped leaders have different physical properties.

The **NASA investigation Neutron star Interior Composition Explorer (NICER)** analyzes neutron stars, bright star residues that remain after the explosion of massive stars, providing new insights into their nature and behavior. NICER also includes the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) to demonstrate a GPS-like capability by detecting bright millisecond pulses in the cosmos (i.e., pulsars) to enable autonomous navigation throughout the solar system and beyond.

In a new study published in *The Astrophysical Journal*, researchers updated mathematical models of timing accuracy to investigate the rotational period of six pulsars. This study was a significant undertaking from an international collaboration of six countries (Chile, the Netherlands, France, Germany, Poland, Japan, and the US). The accurate measurement of

Huang A, Cummer S, Pu Y, Chanrion O, Neubert T, et al. Transition in optical and radio features during the early development of negative intracloud leader. Geophysical Research Letters. 2022 November 28; 49(22): e2022GL100594. DOI: *10.1029/2022GL100594*.

pulsars' rotational period allows researchers to infer their properties and prompt their classification. Additionally, precise timing calculations allow researchers to examine the potential effects of pulsar rotation on gravitational waves.

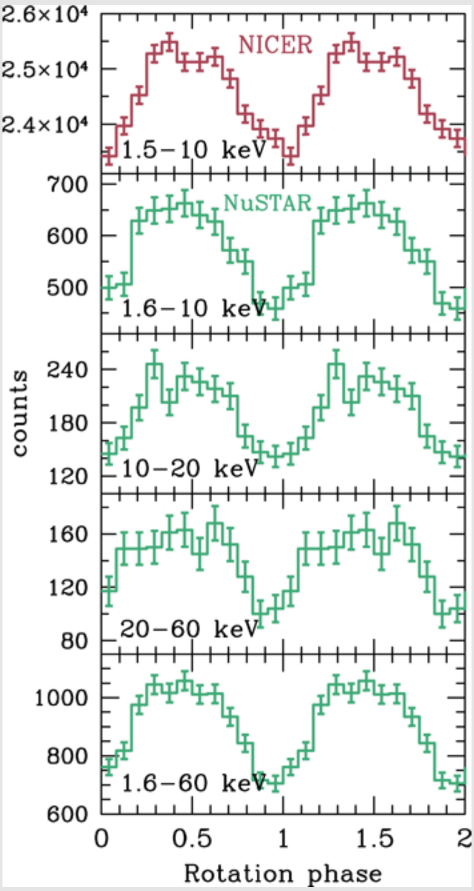
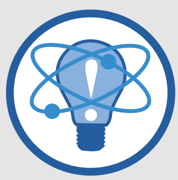


Figure 12. Two rotation cycles for one of the five pulsars examined by NICER and NuSTAR. Data from multiple space instruments allowed researchers to adjust previous calculations to better understand the spinning of neutron starts. *Image adopted from Ho, The Astrophysical Journal.*

Through calculations of multiple data obtained from NICER, Chandra, and NuSTAR, researchers reported new, corrected rotation numbers for two pulsars by considering when the actual pulse occurred and the time of arrival of the pulse to Earth (Figure 12). Additionally, the timing baselines of three pulsars were extended three to four times over previous calculations. For a young energetic pulsar, researchers detected 15 glitches over 4.5 years of data collection. These glitches in pulsar monitoring denote timing irregularities that may result from detached superfluid vortices.

These advances in precise measurement enhances the understanding of pulsar properties and their effects on our solar system and planet.



The JAXA investigation **CALorimetric Electron Telescope (CALET)** is a high-resolution particle detector able to distinguish different types of particles from cosmic rays and dark matter. It includes an imaging and a total absorption calorimeter to measure energy loss and to observe the paths of high-energy cosmic ray nuclei. The hardware was launched to station in 2015 and installed on the Japanese Experiment Module Exposure Facility. Analysis of CALET data provides new insight into the source of cosmic rays, the nature of energy particle acceleration mechanisms, and the characteristics of interstellar space in our galaxy.

In a new study published in *Physical Review Letters*, through an extensive collaboration between Japan, Italy, and the United States, researchers examined helium particles from a large energy interval (~40 Giga-electron-volts to ~250 Tera-electron-volts) collected from 2015 to 2022. CALET measurements demonstrated that the helium spectrum fluctuates from lower to higher energy, and its

Ho WC, Kuiper LM, Espinoza CM, Guillot S, Ray PS, et al. Timing six energetic rotation-powered X-ray pulsars, including the fast-spinning young PSR J0058-7218 and Big Glitcher PSR J0537-6910. The Astrophysical Journal. 2022 November 1; 939(1): 7pp. DOI: 10.3847/1538-4357/ac8743.

most significant deviation shows energy increases (Figure 13). These measurements agree with other space instruments such as PAMELA, AMS-02, DAMPE, and CREAM.

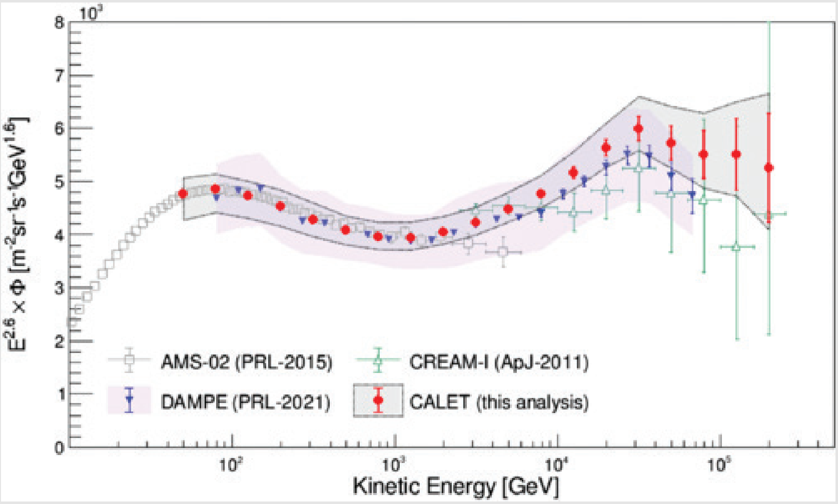


Figure 13. Cosmic ray helium spectrum as measured by multiple space instruments. *Image adopted from Adriani, Physical Review Letters.*

Unexpectedly, researchers found that at lower energies (slow-moving particles), there was a "hardening" of the spectrum – more helium nuclei than expected were found, whereas at higher energies (fast-moving particles), less helium was found. The presence of these "features" (increase and decrease of the particle flux depending on the energy) allowed researchers to assess which statistical model best explained these trends.

This study allows researchers to understand how cosmic rays travel and propagate through the galaxy, providing additional discrimination between the theoretical models proposed to explain their behavior and improve our understanding of cosmic ray origins.

Adriani O, Akaike Y, Asano K, Asaoka Y, Berti E, et al. Direct measurement of the cosmic-ray helium spectrum from 40 GeV to 250 TeV with the Calorimetric Electron Telescope on the International Space Station. Physical Review Letters. 2023 April 27; 130(17): 171002. DOI: 10.1103/PhysRevLett.130.171002.

The CSA investigation **Space Health** utilizes the **Bio-Monitor** system for physiological monitoring before, during, and after a mission to the space station to assess the effect of space travel on heart health. NASA ID: jsc2022e062020.

Publication Highlights

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. From the beginning of station to date, more than 800 articles have been published in the area of Human Research.

The CSA investigation **Cardiac and Vessel Structure and Function with Long-Duration Space Flight and Recovery (Vascular Echo)** studies the effect of spaceflight on the stiffening of blood vessels, which can lead to elevated blood pressure and the progression of cardiovascular conditions.

In a brief communication published in *Aerospace Medicine and Human Performance*, researchers compared two different types of ultrasound technologies (traditional 2D and advanced 3D) to see if imaging quality differences would reveal the effectiveness of a countermeasure used to reduce cephalad (headward) fluid shifts in space (i.e., venoconstrictive thigh cuffs). Due to its manual operation, traditional 2D ultrasound has resulted in measurement errors that impact the reproducibility of the studies.

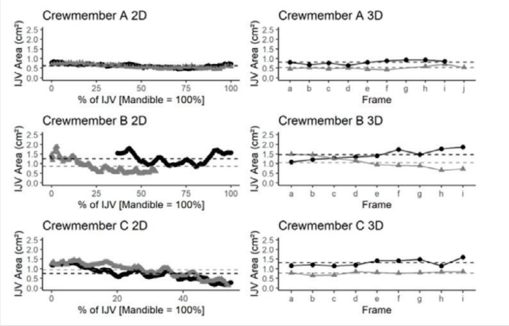


Figure 14. 2D and 3D imaging of the internal jugular vein in three crew members. 2D imaging was unreliable and it did not allow researchers to detect differences between baseline (black) and the effect of wearing thigh cuffs (gray). *Image adopted from Patterson, Aerospace Medicine and Human Performance.*

In the study, researchers revealed that motorized and semi-automated 3D ultrasound identified a 35 percent size reduction of the internal jugular vein after three crewmembers wore thigh cuffs for four hours during spaceflight (Figure 14). These changes were missed by the 2D option. The finding indicates that 3D ultrasound can more adequately measure cardiovascular anatomy than 2D ultrasound and demonstrates that venous congestion (i.e., pooled blood in lower extremities not flowing to the heart) is effectively diminished by thigh cuffs.

The large probe head, constant scan speed, and fixed contact with crucial body parts make the motorized 3D ultrasound superior to standard 2D technologies. This research demonstrates that 3D ultrasound allows non-expert sonographers to take precise measurements of challenging body parts to accurately assess vascular changes during spaceflight.

The ASI instrument **Light Ions Detector for ALTEA (LIDAL)**, installed in the Columbus module in January 2020, was designed to measure cosmic particles, light and heavy ions from phosphorous (P) to iron (Fe), in a wide range of energies. In a new study published in *Life Sciences in Space Research*, researchers report on the functionality of the instrument.

Patterson C, Greaves DK, Robertson AD, Hughson RL, Arbeille P. Motorized 3D ultrasound and jugular vein dimension measurement on the International Space Station. Aerospace Medicine and Human Performance. 2023 June 1; 94(6): 466-469. DOI: 10.3357/AMHP.6219.2023.

Publication Highlights

Human Research

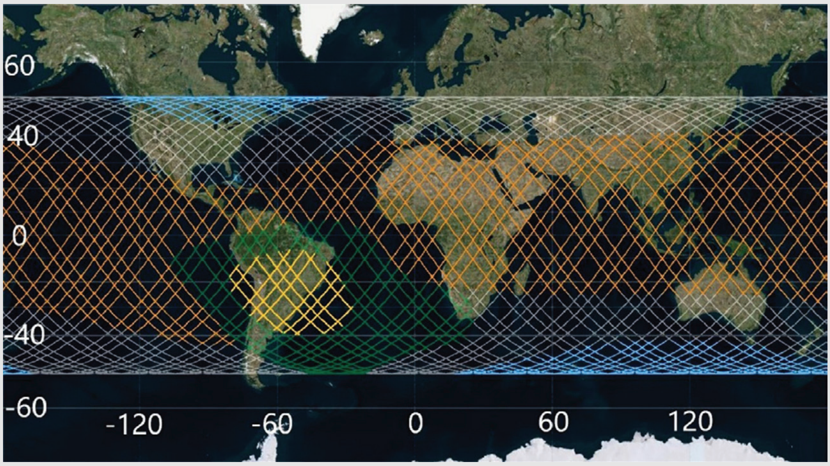


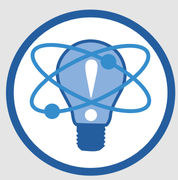
Figure 15. Regions of high latitude in blue, low latitude in orange and the excluded South Anomaly (SAA) region in yellow and green. *Image adopted from Di Fino, Life Sciences in Space Research.*

LIDAL takes into account the position of the detector inside station, which was moved along station's axes X, Y, and Z, the geomagnetic region (high/low latitude), and time-of-flight (ToF) of detected ions. The time-of-flight parameter adds information about the kinetic energy or velocity of the particles, enhancing the recognition of ions fundamental to understanding the effects of radiation on the human body.

LIDAL upgrades the particle detection capabilities of a previous investigation, ALTEA, by using three Silicon Detector Units between two plastic scintillators for the fast timing of ToF measurement. These enhancements increase the sensitivity to cosmic ray ions for improved data acquisition.

Initial measurements of LIDAL with 17 months of data collection confirm the highly variable radiation field of station. Researchers found that the measurements of particles differ depending on the orientation of the detector due to the shielding arrangement of station. This study distinguished, for the first time, forward particles arriving to station from Earth and backward particles going to Earth from station. The radiation field peculiarities depended on whether particles were influenced by the Earth's shadow or passed through more mass inside the station as shown by LIDAL measurements. Additionally, flux and dose rate values are lowest at low latitudes and highest at high latitudes (Figure 15), but the total integrated dose is larger at low latitudes because the space station spends more time near the equator.

The LIDAL detector system allows the conversion of measurements from particle charge and velocity to radiation risk indices to enable researchers to determine the level of radiation exposure for crewmembers and devise countermeasures.



The ESA and Roscosmos investigation **Brain-DTI** measures structural and functional changes in the brain after spaceflight to search for clues of adaptation to microgravity, especially in areas of the brain involved in visual perception, balance, and orientation.

In a new study published in *Communications Biology*, researchers examined brain functional connectivity changes of cosmonauts (Figure 16) after spaceflight and eight months later to learn which changes remained and which changes reverted to baseline. Functional connectivity, estimated through resting-state functional MRI, refers to the coordinated function that exists between

Di Fino L, Romoli G, Amantini GS, Boretti V, Lunati L, et al. Radiation measurements in the International Space Station, Columbus module, in 2020-2022 with the LIDAL detector. Life Sciences in Space Research. 2023 May 6; epub: 30pp. DOI: 10.1016/j.lssr.2023.03.007.

different regions of the brain. For example, distinct areas of the brain work in concert to enable walking or reading.

Previous studies have revealed structural and functional changes after months in microgravity. Some of these findings are associated with microgravity-induced fluid shifts, such as larger ventricles, redistribution of cerebrospinal fluid, while other findings rather suggest possible neural adaptation, including gray and white matter increases in sensorimotor areas, and reduced activity of the vestibular system. In the current work, the researchers explored functional connectivity changes in a resting state that suggested adaptation in areas of vestibular and motor function as well as multisensory integration.

An assessment of brain activity while at rest in 15 cosmonauts revealed decreased functional connectivity after spaceflight in the left posterior cingulate cortex, an area involved in change detection, long-term memory, and divergent thinking. This decreased connectivity persisted at the 8-month follow-up. Additional decreases observed in the bilateral insula, which processes salient stimuli, returned to pre-flight levels after the mission. Increased connectivity was found in the right angular gyrus and was sustained during the follow-up period. This region is involved in verticality processing as well as detecting mismatches between actual and expected sensory outcomes. The sense of verticality has gained importance in view of the planned missions to the Moon and Mars during which crew landing capabilities must be optimal. A final analysis showed that the changes in functional connectivity were independent of structural changes in the brain during flight. Together, changes were mostly found in higher-order brain regions, suggesting adaptation at the level of multimodal integration.

Figure 16. ESA astronaut Thomas Pesquet on the space station, showing on the tablet his brain scanned pre-flight for the BRAIN-DTI project.

These results demonstrate the adaptability and plasticity of the brain under extreme conditions and provide new insight into the workings of the central nervous system. This newfound knowledge may contribute to the development of targeted countermeasures or ways of monitoring brain adaptations to promote healthy brain function and adaptation, as well as improved treatments for vestibular disorders.

Findings from various research studies tracking astronaut health in space are archived in the **International Space Station medical monitoring** investigation. This collection contains a wealth of knowledge regarding the effects of spaceflight on multiple body systems. A Roscosmos study classified as medical monitoring on station reported new findings about biomarkers of endothelial and immune function in the journal *npj Microgravity*.

The lining of blood vessels, known as the endothelium, plays an important role in blood circulation and vascular injury recovery. Endothelial cells serve metabolic and endocrine functions through the exchange of metabolites and hormones between

Jillings S, Pechenkova E, Tomilovskaya ES, Rukavishnikov IV, Jeurissen B, et al. Prolonged microgravity induces reversible and persistent changes on human cerebral connectivity. Communications Biology. 2023 January 13; 6(1): 46. DOI: 10.1038/s42003-022-04382-w.

the bloodstream and surrounding tissues. Despite its importance to human health, little is known about the impact of spaceflight on the endothelium.

In the study, researchers examined the function of the endothelium and its interaction with the immune system by collecting indicators of blood flow and immune health (i.e., anticoagulant receptors, various white blood cells, and cytokine secretions). Blood samples were obtained from 15 crew members before and after spaceflight.

Results showed increases and decreases in different blood-based indicators after spaceflight (Figure 17). Notably, these varying changes characterized the state of the immune system. That is, higher concentrations of biomarkers indicating endothelial dysfunction correlated with increased production of proteins that regulate immune responses. These results suggest a tendency toward increased blood clotting upon return to Earth. Changes to biomarkers involved in both endothelial function and inflammation may in turn affect the immune response.

Understanding the effect of spaceflight on blood vessel damage and blood flow enables researchers to develop countermeasures that prevent coagulation during long duration missions to the Moon or Mars.

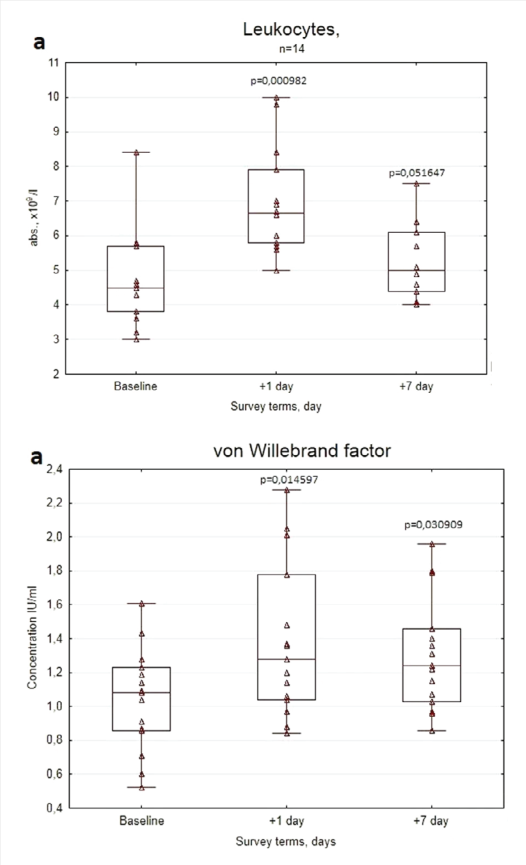


Figure 17. Data on von Willebrand factor, a protein involved in blood flow arrest, and leukocyte concentrations before spaceflight (baseline), one day and seven days after spaceflight. Increased endothelial dysfunction tends to occur in tandem with increased production of multiple white cell types one day after spacelfight. *Image adopted from Kuzichkin, npj Microgravity.*

Kuzichkin DS, Nichiporuk IA, Zhuravleva OA, Markin AA, Rykova MP, et al. Endothelial dysfunction markers and immune response indices in cosmonauts' blood after long-duration space flights. npj Microgravity. 2022 November 2; 8(1): 1-9. DOI: 10.1038/s41526-022-00237-0.

A view of a transparent **FLUIDICS** sphere aboard space station. The FLUIDICS investigation studies the dynamics of liquid sloshing to better understand turbulence in spacecraft tanks and to optimize fuel use. NASA ID: iss066e146914.

Publication Highlights

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. From the beginning of station to date, more than 700 articles have been published in the area of Physical Science.

The investigation **The Materials International Space Station Experiment-13-NASA (MISSE-13-NASA)** encompasses a group of experiments that examine the effect of the space environment on material quality. MISSE experiments fly similar materials on multiple missions to better understand degradation, predict durability, ensure feasibility of in-space manufacturing, and prepare for long-term use of materials in a harsh environment.

For 10 months, a promising low-cost, high-performing semiconductor material known as Metal Halide Perovskites (MHP) that absorbs sunlight and converts it into electrical energy was exposed to the space environment as encapsulated thin films. Confocal microscopy analysis conducted postflight on the ground showed localized surface defects (i.e., bubbles) that resulted from trapped moisture, and 13 percent of its surface was optically inactive. However, the surface flaws, carrier recombination lifespan, and response to solar exposure were repaired or improved after 15 hours of solar illumination of the sample (Figure 18).

These results demonstrate that MHPs in microgravity have a stable response to solar light, can be restored, and have a good charge lifespan that assists in overcoming the known longevity issues of MHP devices. Improved MHPs could lead to enhancements in solar cells, light emitting diodes, and optoelectronic devices, which could in turn assist in the development of life support systems, telecommunications, and electric propulsion systems to support space exploration.

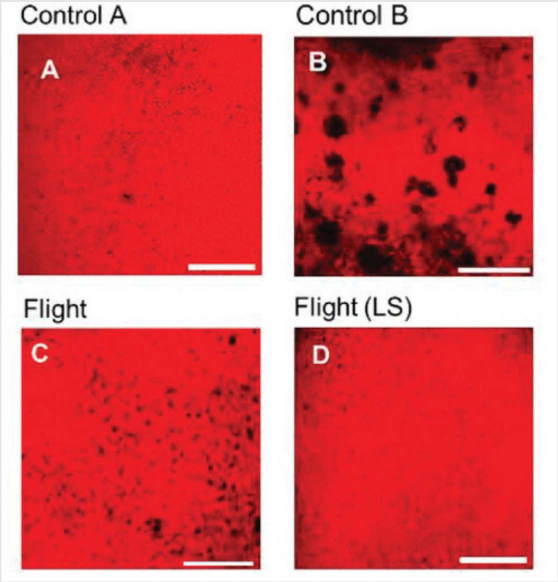


Figure 18. Confocal flourescence images of Earth control samples (A and B, with and without a layer of silicon dioxide, repectively), fligh (C) and flight sample after light exposure (D). *Images adopted from Delmas, Advanced Energy Materials.*

The JAXA investigation **Hourglass** examines the behavior of granular materials in various low-gravity environments aiming to enhance the design of spacecraft, landers, and other mobility systems.

The Moon, Mars, and asteroids in our solar system can be covered by a layer of loose material known as regolith. To ensure the

Delmas W, Erickson S, Arteaga J, Woodall M, Scheibner M, et al. Evaluation of hybrid perovskite prototypes after 10-month space flight on the International Space Station. Advanced Energy Materials. 2023 May 19; 13(19): 2203920. DOI: 10.1002/aenm.202203920.

proper functioning of the equipment developed for use on the celestial surface, it is essential to conduct a ground test that verifies the reaction force and the sinkage caused by loose regolith. Previous research has employed computerized simulations to predict equipment performance in the most challenging environments.

A recent study published in *npj Microgravity* provides verification of the hypothesis of granular flows by analyzing data from experiments conducted on the station under various levels of artificial gravity (0.063 to 2.0 times Earth's gravity).

The hourglass device was designed to control the flow of alumina beads, silica sand, Toyoura sand, and five variations of regolith simulants as analogous grains (Figure 19). Stable gravitational fields were generated by rotating a centrifuge and flipping an hourglass-shaped instrument in the Japanese Experiment Module (JEM).

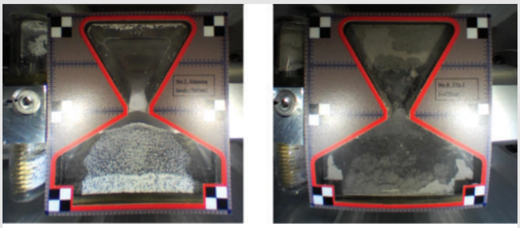


Figure 19. The state of Deposition after the hourglass is inverted and the granular particles have moved through the neck. *Image provided by Hourglass research team.*

The researchers found that the low-gravity behavior of grains generally follows previously postulated physical laws of flow rate, but with some differences. And the researchers presumed that the bulk density of the flow is unstable but decreases with gravity. In addition, the researchers observed that the specific type of granular material and slant angle in the hourglass influenced the flow rate, with powder-like material adhering, depositing, and aggregating in the device.

These findings can improve simulations and inform the development of advanced technologies for successful roving on extraterrestrial bodies.

The ESA investigation **FSL Soft Matter Dynamics - Hydrodynamics of Wet Foams (FOAM)** examines changes to liquid foams, (e.g., soap and champagne) in microgravity. On Earth, bubbles in liquids rapidly rise to the top and the liquid moves to the bottom of a container due to gravity. In microgravity, however, changes to the liquid foam are slower and can be studied in detail. Through this station research, investigators enhance the understanding of liquid foams to design better liquid systems in agriculture, brewery, detergent, and oil industries.

In a new study published in *Soft Matter*, researchers observed changes to the size and distribution of bubbles created in microgravity by mixing water with a pure and chemically stable foaming agent. Researchers tested several mixed samples using 11 different liquid amounts (e.g., 15 percent water, 20 percent water, up to 50 percent water) to identify which liquid percentage most effectively led to the growth and dispersion of the bubbles (transitioning from a soft gel-like network of packed bubbles to a more liquefied solution). A camera recorded the changes in the samples, and manual analyses of the images occurred on Earth.

Researchers revealed that small bubbles shrank and large bubbles grew even larger over time because of pressure dynamics in the bubbles (Figure 20). Additionally,

Ozaki S, Ishigami G, Otsuki M, Miyamoto H, Wada K, et al. Granular flow experiment using artificial gravity generator at International Space Station. npj Microgravity. 2023 August 8; 9(1): 1-13. DOI: 10.1038/s41526-023-00308-w.

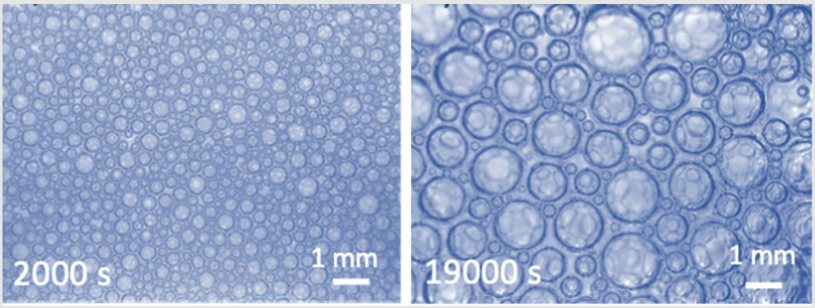


Figure 20. Changes in bubble size in a mixture of foaming agent and 25 percent liquid after approximately five and a half hours. *Image adopted from Pasquet, Soft Matter.*

researchers identified that bubbles transitioned from a crowded to a scattered arrangement when the mixture contained 39 percent liquid. This finding differed from their theoretical prediction of 31 percent liquid to observe such transition in microgravity. As packed bubbles separated and diffused, distorted polyhedral-shaped bubbles became more spherical and uniform. Weak interactions and reduced contact forces among bubbles may explain their separation and dispersion. Despite the uniqueness of these results, researchers also acknowledge similarities to phase separation in alloys and capillary pressure changes observed in biology.

By studying the mechanical properties of liquid foams, researchers can learn how to stabilize and enhance their shelf life. This research not only improves liquid systems but also contributes to the improvement of foam solidification in applications such as packaging, insulation, and car-collision prevention through metallic foams.

Pasquet M, Galvani N, Requier A, Cohen-Addad S, Hohler R, et al. Coarsening transitions of wet liquid foams under microgravity conditions. Soft Matter. 2023 August 8; 19(33): 6267-6279. DOI: 10.1039/d3sm00535f.

A preflight view of JAXA's CubeSat **WARP-01**. The satellite, developed by the University of Tsukuba and Warpspace, was deployed during the JEM Small Satellite Orbital Deployer-16 (J-SSOD-16) micro-satellite deployment mission. NASA ID: jsc2020e049613.

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. From the beginning of station to date, more than 600 articles have been published in the area of Technology Development and Demonstration.

Guatemala's **Quetzal-1** CubeSat satellite (Figure 21) was successfully deployed from the JEM Small Satellite Orbital Deployer-13 (J-SSOD-13) on space station. This investigation demonstrated passive magnetic attitude control capabilities using the Earth's magnetic field to nullify rotations in six degrees of freedom and accurately control attitude and pointing. The passive Attitude Determination and Control System (ADCS) was used to allow ground target imagery over the mission's geographical zone of interest, Guatemala. In order to reduce the size required for the hardware, the Quetzal-1 Satellite used two hysteresis rods and a 0.74 ampere-meter squared permanent magnet.

The Singular Value Decomposition (SVD) method was implemented for attitude determination together with a three-axis magnetometer and two photodiodes on each of the satellite's six sides with only the Z axis showing effects by other magnetic components within the satellite hardware. Attitude control was successfully accomplished after ± 25 degrees per second rotations on each axis immediately after deployment. Anomalies included the magnetometer occasionally transmitting zero data when the temperature dropped below 10 degrees Celsius and changes to the magnet torque and oscillation amplitude values during South Atlantic Anomaly (SAA) passes.

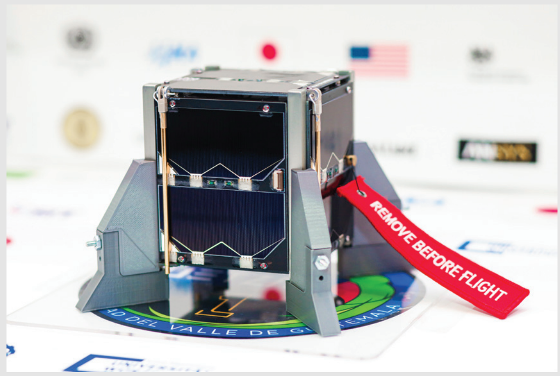


Figure 21. Photo of Quetzal-1 prior to spaceflight. Image obtained from Quetzal-1 research team.

The capability to control satellite attitude stabilization and pointing with minimal hardware is a critical factor for future orbiting satellite designs where weight and volume are limiting factors.

The NASA investigation **Spacecraft Fire Experiment-IV (Saffire-IV)** examines fire spread in different materials and under different conditions using the Cignus resupply vehicle after it leaves station.

The danger of uncontrolled fire on a spacecraft can have devastating if not fatal consequences. Materials that fly on station go through a rigorous screening process to characterize their fire hazard. However, since there is no way to properly simulate those characteristics on the ground, it is necessary to observe and study actual flame conditions

Alvarez D, Aguilar-Nadalini A, Bagur JA, Ayerdi V, Zea L. Design and on-orbit performance of the attitude determination and passive control system for the Quetzal-1 CubeSat. Journal of Small Satellites. 2023 May/June; 12(2): 1231-1247. Webpage.

in a microgravity environment. The Saffire-IV experiment provides the means to perform large scale studies of flames in microgravity conditions. The work published in the *Proceedings of the Combustion Institute* shows a methodology developed to determine the average temperature of flames spreading over a thin solid surface in microgravity using a testbed aboard a re-entering Cygnus spacecraft.

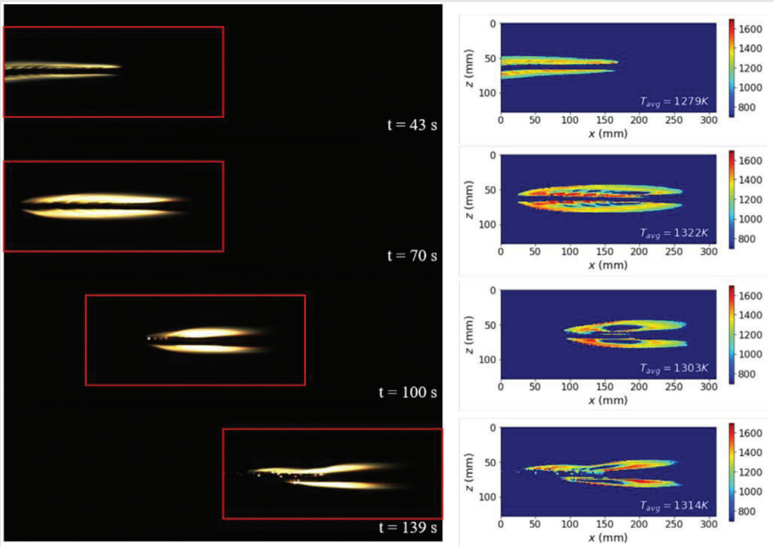


Figure 22. Camera snapshots at different times in the experiment and corresponding temperatures using broadband emissions pyrometry. *Image adopted from Thomsen, Proceedings of the Combustion Institute.*

The testbed is safely ignited while the Cygnus spacecraft is undocked and safely away from the space station as it enters the Earth's atmosphere prior to burning up during re-entry. The burn sample was 40.64 centimeter wide by 50 centimeter long and was mounted on a metal frame in the center of the flow tunnel and consisted of a thin fabric made of cotton and fiberglass called Sibal. Images of the testbed burning were taken along with data from four thermocouple and radiometers. The raw imagery was analyzed using two-color broadband emission pyrometry (B2CP) as a method to measure high temperatures. The results from imagery analysis showed an average temperature of 1300 Kelvin, which remained constant during the flame spread (Figure 22).

This study provides a better understanding of flame properties in microgravity essential to validate numerical models and develop methods to prevent and respond to the occurrence of fire accidents that could endanger the success of a mission and the safety of the crew.

The NASA investigation **Astrobee Maneuvering by Robotic Manipulator Hopping (Astrobatics)** aims to develop robotic hopping capabilities in an orbital environment (i.e., space station or artificial satellites). While robotic hopping has already been demonstrated on an asteroid surface, robotic hopping in challenging environments where the surfaces are made of different materials or there are obstacles such as tools and wiring had not been tested until now.

In a recent study published in *Acta Astronatica*, researchers tested motion theory and methodology previously developed. In the applied study on station, the robots self-tossed from a grasped handrail or a free-floating condition to another distal or proximal surface using a mechanical arm that opens and closes the robot's gripper (Figure 23).

Thomsen M, Cruz JJ, Escudero F, Fuentes A, Fernandez-Pello AC, et al. Determining flame temperature by broadband two color pyrometry in a flame spreading over a thin solid in microgravity. Proceedings of the Combustion Institute. 2023 June 7; 39(3): 3909-3918. DOI: 10.1016/j.proci.2022.07.237.

Results showed that proximal self-toss maneuvers on the space station had a greater range of motion, and displacement compared favorably to simulation models. However, tests on station showed a greater value of angular displacement, causing the robots to tumble off-axis compared to the simulation. While improvements in hardware and modeling are needed to fix this discrepancy, the results of this study demonstrate, for the first time, the successful self-toss locomotion of robots in a spacecraft.

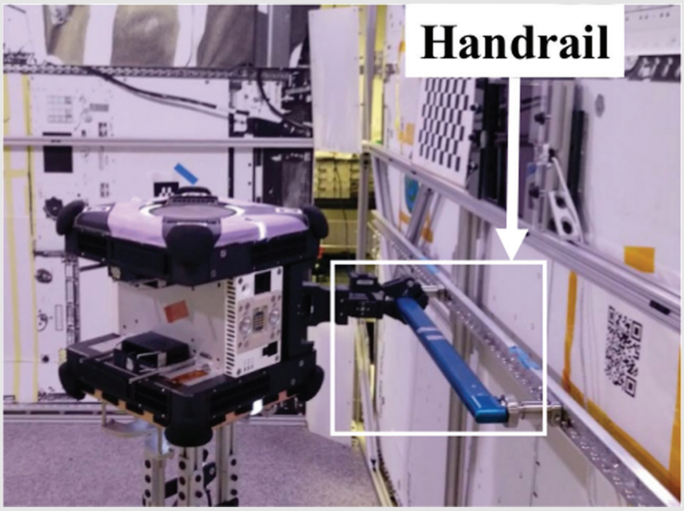


Figure 23. Test of Robot's gripper at NASA Ames Research Center. *Image adopted from Kwok-Choon, Acta Astronautica.*

Self-toss or hopping maneuvers allow robots to go across a spacecraft or celestial body surface to reach a work site without the need for propellant. These hopping maneuvers in microgravity represent a major step toward developing autonomous robots that can perform important and potentially dangerous tasks in space, reducing the risks to astronauts.

Kwok Choon ST, Romano M, Hudson J. Orbital hopping maneuvers with Astrobee on-board the International Space Station. Acta Astronautica. 2023 June; 207: 62-76. DOI: 10.1016/j.actaastro.2023.02.034.

Figure 24. Word Cloud of 31 recently ranked top-tier journals that have published station science since 2003. Larger words indicate more articles published in the journal.

List of Archived Space Station Publications

Oct. 1, 2022 - Sept. 30, 2023

BIOLOGY AND BIOTECHNOLOGY

Advanced Plant EXperiments-03-1 (APEX-03-1) — Nakashima J, Pattathil S, Avci U, Chin S, Sparks JA, et al. Glycome profiling and immunohistochemistry uncover changes in cell walls of *Arabidopsis thaliana* roots during spaceflight. *npj Microgravity*. 2023 August 22; 9(1): 1-13. DOI: 10.1038/s41526-023-00312-0.

Advanced Plant EXperiment-07 (APEX-07) — Meyers AD, Land ES, Perera IY, Canaday E, Wyatt SE. Polyethersulfone (PES) membrane on agar plates as a plant growth platform for spaceflight. *Gravitational and Space Research*. 2022 January; 10(1): 30-36. DOI: 10.2478/gsr-2022-0004.*

Analysis of a Novel Sensory Mechanism in Root Phototropism (Tropi) — Hughes AM, Vandenbrink JP, Kiss JZ. Efficacy of the random positioning machine as a terrestrial analogue to microgravity in studies of seedling phototropism. *Microgravity Science and Technology*. 2023 August 14; 35(4): 43. DOI: 10.1007/s12217-023-10066-9.

BioScience-4 (STaARS BioScience-4) — Shaka S, Carpo N, Tran V, Cepeda C, Espinosa-Jeffrey A. Space microgravity alters neural stem cell division: Implications for brain cancer research on Earth and in space. *International Journal of Molecular Sciences*. 2022 November 18; 23(22): 14320. DOI: 10.3390/ijms232214320.

BioScience-4 (STaARS BioScience-4) — Tran V, Carpo N, Cepeda C, Espinosa-Jeffrey A. Oligodendrocyte progenitors display enhanced proliferation and autophagy after space flight. *Biomolecules*. 2023 February; 13(2): 201. DOI: 10.3390/biom13020201.

Biotube-Magnetophoretically Induced Curvature in Roots (Biotube-MICRO) — Hasenstein KH, Park MR, John SP, Ajala C. High-gradient magnetic fields and starch metabolism: Results from a space experiment. *Scientific Reports*. 2022 October 29; 12(1): 18256. DOI: 10.1038/s41598-022-22691-2.

Characterization of Biofilm Formation, Growth, and Gene Expression on Different Materials and Environmental Conditions in Microgravity (Space Biofilms) — Flores P, McBride SA, Galazka JM, Varanasi KK, Zea L. Biofilm formation of *Pseudomonas aeruginosa* in spaceflight is minimized on lubricant impregnated surfaces. *npj Microgravity*. 2023 August 16; 9(1): 1-14. DOI: 10.1038/s41526-023-00316-w.

Characterization of Biofilm Formation, Growth, and Gene Expression on Different Materials and Environmental Conditions in Microgravity (Space Biofilms) — Hupka M, Kedia R, Schauer R, Shepard B, Granados-Presa M, et al. Morphology of *Penicillium rubens* biofilms formed in space. *Life*. 2023 April; 13(4): 1001. DOI: 10.3390/life13041001.

Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) Space Diagnostics (Ax-1 CRISPR) — Alon DM, Mittelman K, Stibbe E, Countryman S, Stodieck LS, et al. CRISPR-based genetic diagnostics in microgravity. *Biosensors and Bioelectronics*. 2023 October 1; 237: 115479. DOI: 10.1016/j.bios.2023.115479.

Development of the On-Board Monitoring System for Microorganisms in Potable Water on Manned Spacecraft (Micro Monitor) — Ichijo T, Uchii K, Sekimoto K, Minakami T, Sugita T, et al. Bacterial bioburden and community structure of potable water used in the International Space Station. *Scientific Reports*. 2022 September 29; 12(1): 16282. DOI: 10.1038/s41598-022-19320-3.*

Determining Muscle Strength in Space-flown Caenorhabditis elegans (Micro-16) — Soni P, Anupom T, Lesanpezeshki L, Rahman M, Hewitt Jeet, al. Microfluidics-integrated spaceflight hardware for measuring muscle strength of *Caenorhabditis elegans* on the International Space Station. *npj Microgravity*. 2022 November 7; 8(1): 1-12. DOI: 10.1038/s41526-022-00241-4.

Effect of the Space Environment on the Neural Integration System and Aging of the Model Animal C. elegans (Neural Integration System / Molecular Muscle) — Kim B, Alcantara, Jr. AV, Moon J, Higashitani A, Higashitani N, et al. Comparative analysis of muscle atrophy during spaceflight, nutritional deficiency and disuse in the nematode *Caenorhabditis elegans*. *International Journal of Molecular Sciences*. 2023 August 10; 24(16): 12640. DOI: 10.3390/ijms241612640.

GeneLAB — Barker RJ, Kruse CP, Johnson CM, Saravia-Butler AM, Fogle H, et al. Meta-analysis of the space flight and microgravity response of the Arabidopsis plant transcriptome. *npj Microgravity*. 2023 March 20; 9(1): 21. DOI: 10.1038/s41526-023-00247-6.

GeneLAB — Barker RJ, Lombardino J, Rasmussen K, Gilroy S. Test of Arabidopsis space transcriptome: A discovery environment to explore multiple plant biology spaceflight experiments. *Frontiers in Plant Science*. 2020 March 4; 11: 147. DOI: 10.3389/fpls.2020.00147.*

Growth of Large, Perfect Protein Crystals for Neutron Crystallography (Perfect Crystals) — Lutz WE, Azadmanesh J, Lovelace JJ, Kolar C, Coates L, Weiss KL, et al. Perfect Crystals: Microgravity capillary counterdiffusion crystallization of human manganese superoxide dismutase for neutron crystallography. *npj Microgravity*. 2023 June 3; 9(1): 39. DOI: 10.1038/s41526-023-00288-x.

Human Muscle Contraction Response in Microgravity (Human Muscle-on-Chip) — Parafati M, Giza S, Shenoy T, Mojica-Santiago JA, Hopf M, et al. Human skeletal muscle tissue chip autonomous payload reveals changes in fiber type and metabolic gene expression due to spaceflight. *npj Microgravity*. 2023 September 15; 9(1): 77. DOI: 10.1038/s41526-023-00322-y.

International Space Station Summary of Research Performed (ISS Summary of Research) — Bauer JN, Bussen M, Wise PM, Wehland M, Schneider S, et al. Searching the literature for proteins facilitates the identification of biological processes, if advanced methods of analysis are linked: A case study on microgravity-caused changes in cells. *Expert Review of Proteomics*. 2016 June 17; 13(7): 697-705. DOI: 10.1080/14789450.2016.1197775.*

International Space Station Summary of Research Performed (ISS Summary of Research) — Corydon TJ, Schulz H, Richter P, Strauch SM, Bohmer M, et al. Current knowledge about the impact of microgravity on gene regulation. *Cells*. 2023 January; 12(7): 1043. DOI: 10.3390/cells12071043.

International Space Station Internal Environments (ISS Internal Environments / Exploration ECLSS: WPA Upgrades) — Castro CL, Velez Justiniano Y, Stahl-Rommel SE, Nguyen HN, Almengor A, et al. Genome sequences of bacteria isolated from the International Space Station water systems. *Microbiology Resource Announcements*. 2023 June 7; 12(7): e00158-23. DOI: 10.1128/mra.00158-23.

International Space Station Internal Environments (ISS Internal Environments) — Foote A, Schutz K, Zhao Z, DiGianivittorio P, Korwin-Mihavics BR, et al. Characterizing biofilm interactions between *Ralstonia insidiosa* and *Chryseobacterium gleum*. *Microbiology Spectrum*. 2023 April 13; 11(2): e0410522. DOI: 10.1128/spectrum.04105-22.

International Space Station Internal Environments (ISS Internal Environments) — Moukhamedieva L, Ozerov D, Pakhomova A. The distribution of trace contaminants in the manned space station atmosphere. *Acta Astronautica*. 2022 December; 201: 597-601. DOI: 10.1016/j.actaastro.2022.09.053.

International Space Station Internal Environments (ISS Internal Environments) — Quagliariello A, Cirigliano A, Rinaldi T. Bacilli in the International Space Station. *Microorganisms*. 2022 November 22; 10(12): 2309. DOI: 10.3390/microorganisms10122309.

International Space Station Internal Environments (ISS Internal Environments) — Rybalchenko OV, Orlova OG, Kapustina VV, Popova EV, Kutnik IV. [Trends in formation of microbial communities by probiotic bacteria *Lactobacillus plantarum* 8PA-3 on various carriers in the space flight environment]. *Aviakosmicheskaia i Ekologicheskaia Meditsina (Aerospace and Environmental Medicine)*. 2022; 56(5): 85-95. DOI: 10.21687/0233-528X-2022-56-5-85-95.

International Space Station Internal Environments (ISS Internal Environments) — Velez Justiniano Y, Lim CH, Dunlap DS, Sysoeva TA. Genome sequences of three common bacterial isolates from wastewater from the Water Processor Assembly at the International Space Station. *Microbiology Resource Announcements*. 2023 January 4; 12(1): e01189-22. DOI: 10.1128/mra.01189-22.

International Space Station-Microbial Observatory of Pathogenic Viruses, Bacteria, and Fungi (ISS-MOP) Project (Microbial Tracking-2) — Simpson AC, Eedara VV, Singh NK, Damle N, Parker CW, et al. Comparative genomic analysis of *Cohnella hashimotonis* sp. nov. isolated from the International Space Station. *Frontiers in Microbiology*. 2023 June 15; 14: 1166013. DOI: 10.3389/fmicb.2023.1166013.

International Space Station-Microbial Observatory of Pathogenic Viruses, Bacteria, and Fungi (ISS-MOP) Project / Human Exploration Research Opportunities - Differential Effects on Homozygous Twin Astronauts Associated with Differences in Exposure to Spaceflight Factors (Microbial Tracking-2 / Twins Study) — Tierney BT, Singh NK, Simpson AC, Hujer AM, Bonomo RA, et al. Multidrug-resistant *Acinetobacter pittii* is adapting to and exhibiting potential succession aboard the International Space Station. *Microbiome*. 2022 December 12; 10(1): 210. DOI: 10.1186/s40168-022-01358-0.

International Space Station Summary of Research Performed (ISS Summary of Research) — Dawar A, Warmoota R. Influence of microgravity on the physiology, pathogenicity and antibiotic efficacy of microorganisms. *Journal for Research in Applied Sciences and Biotechnology*. 2022 December 1; 1(5): 24-35. DOI: 10.55544/jrasb.1.5.3.

International Space Station Summary of Research Performed (ISS Summary of Research) — Ogneva IV. Single cell in a gravity field. *Life*. 2022 October; 12(10): 1601. DOI: 10.3390/life12101601.

International Space Station Summary of Research Performed (ISS Summary of Research) — Wright H, Williams A, Wilkinson A, Harper L, Savin K, et al. An analysis of publicly available microgravity crystallization data: Emergent themes across crystal types. *Crystal Growth and Design*. 2022 October 31; 22(12): 6849-6852. DOI: 10.1021/acs.cgd.2c01056.

Investigation of the Osteoclastic and Osteoblastic Responses to Microgravity Using Goldfish Scales / International Space Station Summary of Research Performed (Fish Scales / ISS Summary of Research) — Hirayama J, Hattori A, Takahashi A, Furusawa Y, Tabuchi Y, et al. Physiological consequences of space flight, including abnormal bone metabolism, space radiation injury, and circadian clock dysregulation: Implications of melatonin use and regulation as a countermeasure. *Journal of Pineal Research*. 2023 January; 74(1): e12834. DOI: 10.1111/jpi.12834.

Japan Aerospace Exploration Agency Protein Crystallization Growth (JAXA PCG) — Okuda-Shimazaki J, Yoshida H, Lee I, Kojima K, Suzuki N, Tsugawa W, et al. Microgravity environment grown crystal structure information based engineering of direct electron transfer type glucose dehydrogenase. *Communications Biology*. 2022 December 6; 5(1): 1-13. DOI: 10.1038/s42003-022-04286-9.

JAXA Mouse Habitat Unit — Shimizu R, Hirano I, Hasegawa A, Suzuki M, Otsuki A, et al. Nrf2 alleviates spaceflight-induced immunosuppression and thrombotic microangiopathy in mice. *Communications Biology*. 2023 August 25; 6(1): 875. DOI: 10.1038/s42003-023-05251-w.

Magnetic 3D Bioprinter — Ermolaeva SA, Parfenov VA, Karalkin PA, Khesuani YD, Domnin PA. Experimentally created magnetic force in microbiological space and on-Earth studies: Perspectives and restrictions. *Cells*. 2023 January; 12(2): 338. DOI: 10.3390/cells12020338.

MELiSSA ON board DAnish Utilisation flight (MELONDAU) — Fahrion J, Dussap C, Leys N. Assessment of batch culture conditions for cyanobacterial propagation for a bioreactor in space. *Frontiers in Astronomy and Space Sciences*. 2023 April 27; 10: 15pp. DOI: 10.3389/fspas.2023.1178332.

Microbial Tracking Payload Series (Microbial Observatory-1) — Singh NK, Wood JM, Patane J, Silva Moura LM, et al. Characterization of metagenome-assembled genomes from the International Space Station. *Microbiome*. 2023 June; 11(1): 125. DOI: 10.1186/s40168-023-01545-7.

Muscle Atrophy of Muscle Sparing in Transgenic Mice (Rodent Research-1 (CASIS)) — Vigil C, Daubenspeck A, Coia H, Smith J, Mauzy C. Matrix-assisted laser desorption/ionization analysis of the brain proteome of microgravity-exposed mice from the International Space Station. *Frontiers in Space Technologies*. 2022 November 16; 3: 971229. DOI: 10.3389/frspt.2022.971229.

Phase II Real-time Protein Crystal Growth on Board the International Space Station (RTPCG-2) — Quirk S, Lieberman RL. Structure and activity of a thermally stable mutant of *Acanthamoeba* actophorin. *Acta Crystallographica Section F: Structural Biology Communications*. 2022 April 1; 78(4): 150-160. DOI: 10.1107/S2053230X22002448.*

RNA Interference and Protein Phosphorylation in Space Environment Using the Nematode Caenorhabditis elegans (CERISE) — Zhao L, Zhang G, Tang A, Huang B, Mi D. Microgravity alters the expressions of DNA repair genes and their regulatory miRNAs in space-flown *Caenorhabditis elegans*. *Life Sciences in Space Research*. 2023 May; 37: 25-38. DOI: 10.1016/j.lssr.2023.02.002.

Rodent Research Hardware and Operations Validation (Rodent Research-1) — Veliz AL, Mamoun L, Hughes L, Vega R, Holmes B, et al. Transcriptomic effects on the mouse heart following 30 days on the International Space Station. *Biomolecules*. 2023 February; 13(2): 371. DOI: 10.3390/biom13020371.

Rodent Research Hardware and Operations Validation (Rodent Research-1) — Vitry G, Finch R, McStay G, Beheshti A, Dejean S, et al. Muscle atrophy phenotype gene expression during spaceflight is linked to a metabolic crosstalk in both the liver and the muscle in mice. *iScience*. 2022 September 24; 105213. DOI: 10.1016/j.isci.2022.105213.*

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 / Space Flight Environment Induces Remodeling of Vascular Network and Glia-Vascular Communication in Mouse Retina (Rodent Research-1 / Rodent Research-9 / Rodent Research-18) — Baranowski RW, Braun JL, Hockey BL, Yumol JL, Geromella MS, et al. Toward countering muscle and bone loss with spaceflight: GSK3 as a potential target. *iScience*. 2023 July 21; 26(7): 107047. DOI: 10.1016/j.isci.2023.107047.

Role of Environmental Stress-responsive Transcription Factor Nrf2 in Space Stress (Mouse Habitat Unit -3 (Mouse Stress Defense)) — Han Y, Shi S, Liu S, Gu X. Effects of spaceflight on the spleen and thymus of mice: Gene pathway analysis and immune infiltration analysis. *Mathematical Biosciences and Engineering: MBE*. 2023 March 3; 20(5): 8531-8545. DOI: 10.3934/mbe.2023374.

Science for the Improvement of Future Space Exploration (ISS Exploration) — Alvarado KA, Garcia Martinez JB, Brown MM, Christodoulou X, et al. Food production in space from CO2 using microbial electrosynthesis. *Bioelectrochemistry*. 2023 February; 149: 108320. DOI: 10.1016/j.bioelechem.2022.108320.

Seedling Growth-1, 2, and 3 — Medina F, Manzano A, Herranz R, Kiss JZ. Red light enhances plant adaptation to spaceflight and Mars g-levels. Life. 2022 October; 12(10): 1484. DOI: 10.3390/life12101484.

Space Flight Environment Induces Remodeling of Vascular Network and Glia-Vascular Communication in Mouse Retina (Rodent Research-18) — Mao XW, Stanbouly S, Holley JM, Pecaut MJ, Crapo J. Evidence of spaceflight-induced adverse effects on photoreceptors and retinal function in the mouse eye. *International Journal of Molecular Sciences*. 2023 April 17; 24(8): 7362. DOI: 10.3390/ijms24087362.

Space Omics Analysis of the Skin Microbiome of Diabetic Foot Ulcers (SpaceOMIX) (Ice Cubes #9 - Project Maleth) — Gatt C, Tierney BT, Madrigal P, Mason CE, Beheshti A, et al. The Maleth program: Malta's first space mission discoveries on the microbiome of diabetic foot ulcers. *Heliyon*. 2022 December; 8(12): e12075. DOI: 10.1016/j.heliyon.2022.e12075.

Studies on gravity-controlled growth and development in plants using true microgravity conditions (Auxin Transport) — Yamazaki C, Yamazaki T, Kojima M, Takebayashi Y, Sakakibara H, et al. Comprehensive analyses of plant hormones in etiolated pea and maize seedlings grown under microgravity conditions in space: Relevance to the International Space Station experiment "Auxin Transport". *Life Sciences in Space Research*. 2023 February; 36: 138-146. DOI: 10.1016/j.lssr.2022.10.005.

Systemic Therapy of NELL-1 for Osteoporosis (Rodent Research-5) — Bedree JK, Kerns K, Chen T, Lima BP, Liu G, et al. Specific host metabolite and gut microbiome alterations are associated with bone loss during spaceflight. *Cell Reports*. 2023 May 30; 42(5): 112299. DOI: 10.1016/j.celrep.2023.112299.

Systemic Therapy of NELL-1 for Osteoporosis (Rodent Research-5) — Ha P, Kwak J, Zhang Y, Shi J, Tran L, et al. Bisphosphonate conjugation enhances the bone-specificity of NELL-1-based systemic therapy for spaceflight-induced bone loss in mice. *npj Microgravity*. 2023 September 18; 9(1): 1-15. DOI: 10.1038/s41526-023-00319-7.

Tissue Regeneration-Bone Defect (Rodent Research-4 (CASIS)) — Shishkina VV, Kostin A, Volodkin A, Samoilova V, Buchwalow I, et al. The remodeling of dermal collagen fibrous structures in mice under zero gravity: The role of mast cells. *International Journal of Molecular Sciences*. 2023 January 18; 24(3): 1939. DOI: 10.3390/ijms24031939.

Transcriptome analysis and germ-cell development analysis of mice in the space / JAXA Mouse Habitat Unit Technical Verification / JAXA Mouse Habitat Unit-5 (MHU-1 Mouse Epigenetics/ Mouse Habitat Verification / Mouse Habitat Unit - 5) — Hayashi T, Fujita R, Okada R, Hamada M, Suzuki R, et al. Lunar gravity prevents skeletal muscle atrophy but not myofiber type shift in mice. *Communications Biology*. 2023 April 21; 6(1): 424. DOI: 10.1038/s42003-023-04769-3.

Transfer of Plasmid DNA During Conjugation in Spaceflight (Plasmid) — Ilyin VC, Orlov OI, Skedina M, Korosteleva A, Molodtsova D, et al. Mathematical model of antibiotic resistance determinants' stability under space flight conditions. *Astrobiology*. 2023 March 31; 23(4): 407-414. DOI: 10.1089/ast.2022.0076.

Transfer of Plasmid DNA During Conjugation in Spaceflight (Plasmid) — Ilyin VC, Skedina M, Solovieva ZO, Artamonov A. Databases of the evolution of the microbiome and its drug susceptibility in astronauts and hermetic facility operators. *Journal of Space Safety Engineering*. 2023 June; 10(2): 161-165. DOI: 10.1016/j.jsse.2023.03.011.

Using Brachypodium distachyon to Investigate Monocot Plant Adaptation to Spaceflight (APEX-06) — Su S, Levine HG, Masson P. *Brachypodium distachyon* seedlings display accession-specific morphological and transcriptomic responses to the microgravity environment of the International Space Station. *Life*. 2023 March; 13(3): 626. DOI: 10.3390/life13030626.

Wound Healing and Sutures in Unloading Conditions (Suture In Space) — Cialdai F, Bacci S, Zizi V, Norfini A, Balsamo M, et al. Optimization of an ex-vivo human skin/vein model for long-term wound healing studies: Ground preparatory activities for the 'Suture in Space' experiment onboard the International Space Station. *International Journal of Molecular Sciences*. 2022 November 16; 23(22): 14123. DOI: 10.3390/ijms232214123.

EARTH AND SPACE SCIENCE

Alpha Magnetic Spectrometer - 02 (AMS-02) — Aguilar-Benitez M, Cavasonza LA, Ambrosi G, Arruda MF, et al. Temporal structures in electron spectra and charge sign effects in galactic cosmic rays. *Physical Review Letters*. 2023 April 17; 130(6): 161001. DOI: 10.1103/PhysRevLett.130.161001.

Alpha Magnetic Spectrometer - 02 (AMS-02) — Berdugo J, AMS-02Collaboration. AMS highlights. *37th International Cosmic Ray Conference (ICRC 2021)*, Online - Berlin, Germany; 2022 March 18. 016. DOI: 10.22323/1.395.0016.*

Alpha Magnetic Spectrometer - 02 (AMS-02) — Chang YH, AMS-02 Collaboration. Latest results from the AMS experiment. *JPS Conference Proceedings*; 2023. DOI: 10.7566/JPSCP.39.011006.

Alpha Magnetic Spectrometer - 02 (AMS-02) — Chen Y, Paniccia M, AMS-02Collaboration. Properties of iron primary cosmic rays: Results from the Alpha Magnetic Spectrometer. *37th International Cosmic Ray Conference (ICRC 2021)*, Online - Berlin, Germany; 2022 March 18. 129. DOI: 10.22323/1.395.0129.*

Alpha Magnetic Spectrometer - 02 (AMS-02) — Donato F, DiMauro M, Manconi S. On the interpretation of the latest AMS-02 cosmic ray electron spectrum. *37th International Cosmic Ray Conference (ICRC 2021)*, Online - Berlin, Germany; 2022 March 18. 154. DOI: 10.22323/1.395.0154.*

List of Archived Space Station Publications

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Alpha Magnetic Spectrometer - 02 (AMS-02) — Faldi F, Bertucci B, Tomassetti N, Vagelli V. Real-time monitoring of solar energetic particles outside the ISS with the AMS-02 instrument. *Rendiconti Lincei. Scienze Fisiche e Naturali.* 2023 June; 34: 339-345. DOI: 10.1007/s12210-023-01156-2.

Alpha Magnetic Spectrometer - 02 (AMS-02) — Korsmeier M, Cuoco A. The role of systematic uncertainties on our understanding of cosmic-ray diffusion: An analysis of AMS-02 data from lithium to oxygen. *37th International Cosmic Ray Conference (ICRC 2021),* Online - Berlin, Germany; 2022 March 18. 176. DOI: 10.22323/1.395.0176.*

Alpha Magnetic Spectrometer - 02 (AMS-02) — Liu Z, Paniccia M, Zhang C, AMS-02Collaboration. Properties of cosmic aluminum nuclei: Results from the Alpha Magnetic Spectrometer. *37th International Cosmic Ray Conference (ICRC 2021),* Online - Berlin, Germany; 2022 March 18. 110. DOI: 10.22323/1.395.0110.*

Alpha Magnetic Spectrometer - 02 (AMS-02) — Molero M, Casaus J, Mana C, VelascoFrutos MA. Anisotropy of positron and electron fluxes measured with the Alpha Magnetic Spectrometer on the ISS. *37th International Cosmic Ray Conference (ICRC 2021),* Online - Berlin, Germany; 2022 March 18. 120. DOI: 10.22323/1.395.0120.*

Alpha Magnetic Spectrometer - 02 (AMS-02) — Vagelli V, Graziani M. The AMS-02 detector on the ISS - Status and highlights after 11 years on orbit. *Journal of Physics: Conference Series*. 2023 February; 2429(1): 012002. DOI: 10.1088/1742-6596/2429/1/012002.

Alpha Magnetic Spectrometer - 02 (AMS-02) — VelascoFrutos MA, Casaus J, Mana C, Molero M. Anisotropy of protons and light primary nuclei in cosmic rays measured with the Alpha Magnetic Spectrometer on the ISS. *37th International Cosmic Ray Conference (ICRC 2021),* Online - Berlin, Germany; 2022 March 18. 108. DOI: 10.22323/1.395.0108.*

Alpha Magnetic Spectrometer - 02 (AMS-02) — Yan Q, Choutko V. Properties of heavy secondary fluorine cosmic rays results from the Alpha Magnetic Spectrometer. *37th International Cosmic Ray Conference (ICRC 2021),* Online - Berlin, Germany; 2022 March 18. 104. DOI: 10.22323/1.395.0104.*

Alpha Magnetic Spectrometer - 02 (AMS-02) — Yan Q, Choutko V. Properties of secondary cosmic ray nuclei: Eleven-year results from the Alpha Magnetic Spectrometer. *Proceedings of 38th International Cosmic Ray Conference — PoS (ICRC2023)*, Nagoya, Japan; 2023 July 25. 078. DOI: 10.22323/1.444.0078.

An Educational CubeSat Developed at the Technical University of Moldova (TUMnanoSAT) — Bostan V, Secrieru N, Ilco V, Melnic V, Martiniuc A, et al. Tumnanosat nanosatellite and Kibocube program. *2020 13th International Conference on Communications (COMM)*, Bucharest, Romania; 2020 June 18. 503-508. DOI: 10.1109/COMM48946.2020.9142025.*

Astrobiology Exposure and Micrometeoroid Capture Experiments (Tanpopo) — Kawaguchi Y, Sugino T, Tabata MJ, Okudaira K, Imai E, et al. Fluorescence imaging of microbe-containing particles shot from a two-stage Light-gas gun into an aerogel. *Origins of life and evolution of the biosphere: The Journal of the International Society for the Study of the Origin of Life*. 2014 August 3; 44: 43-60. DOI: 10.1007/s11084-014-9361-x.*

Atmosphere-Space Interactions Monitor (ASIM) — Huang A, Cummer S, Pu Y, Chanrion O, Neubert T, et al. Transition in optical and radio features during the early development of negative intracloud leader. *Geophysical Research Letters*. 2022 November 28; 49(22): e2022GL100594. DOI: 10.1029/2022GL100594.

Atmosphere-Space Interactions Monitor (ASIM) — Li D, Luque A, Lehtinen NG, Gordillo-Vasquez FJ, Neubert T, et al. Multi-pulse corona discharges in thunderclouds observed in optical and radio bands. *Geophysical Research Letters*. 2022 July 16; 49(13): e2022GL098938. DOI: 10.1029/2022GL098938.*

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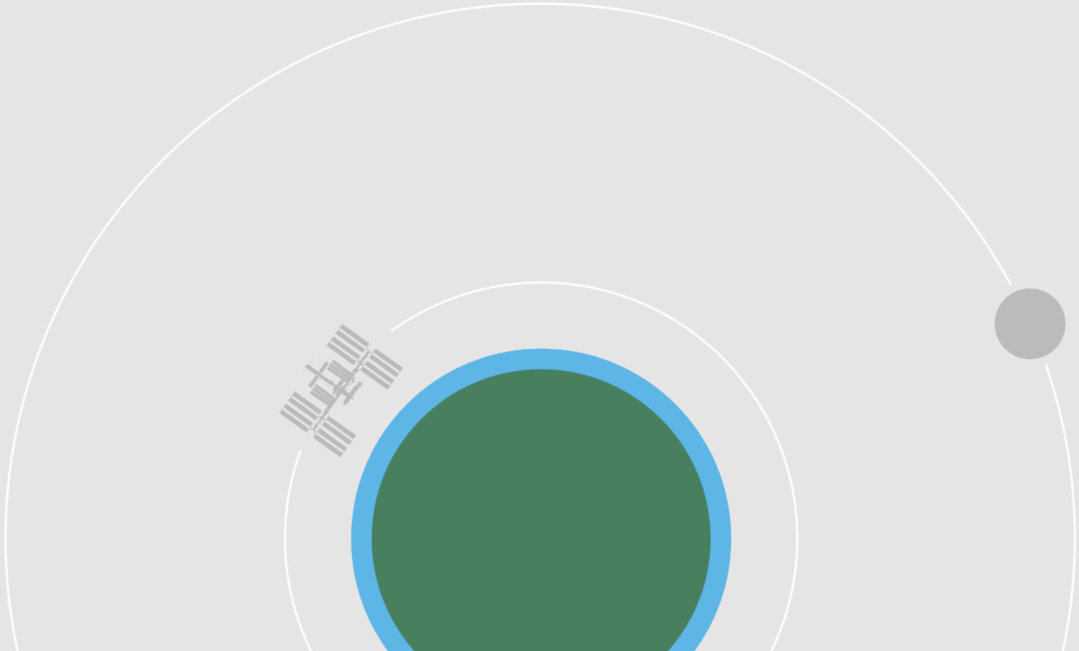

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