

IAC-16.B3.3.1.x34294

INTERNATIONAL RESEARCH RESULTS AND ACCOMPLISHMENTS FROM THE INTERNATIONAL  
SPACE STATION

**International Space Station Program Science Forum**

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In 2016, the International Space Station (ISS) partnership published the first-ever compilation of international ISS research publications resulting from research performed on the ISS through 2011. The *International Space Station Research Accomplishments: An Analysis of Results From 2000-2011* is a collection of summaries of over 1,200 journal publications that describe ISS research in the areas of biology and biotechnology; Earth and space science; educational activities and outreach; human research; physical sciences; technology development and demonstration; and, results from ISS operations. This paper will summarize the ISS results publications obtained through 2011 on behalf of the ISS Program Science Forum that is made up of senior science representatives across the international partnership. NASA's ISS Program Science office maintains an online experiment database ([www.nasa.gov/iss-science](http://www.nasa.gov/iss-science)) that tracks and communicates ISS research activities across the entire ISS partnership, and it is continuously updated. It captures ISS experiment summaries and results and includes citations to the journals, conference proceedings, and patents as they become available. The *International Space Station Research Accomplishments: An Analysis of Results From 2000-2011* is a testament to the research that was underway even as the ISS laboratory was being built. It reflects the scientific knowledge gained from ISS research, and how it impact the fields of science in both space and traditional science disciplines on Earth. Now, during a time when utilization is at its busiest, and with extension of the ISS through at least 2024, the ISS partners work together to track the accomplishments and the new knowledge gained in a way that will impact humanity like no laboratory on Earth. The ISS Program Science Forum will continue to capture and report on these results in the form of journal publications, conference proceedings, and patents. We anticipate that successful ISS research will continue to contribute to the science literature in a way that helps to formulate new hypotheses and conclusions that will enable science advancements across a wide range of scientific disciplines both in space and on Earth.

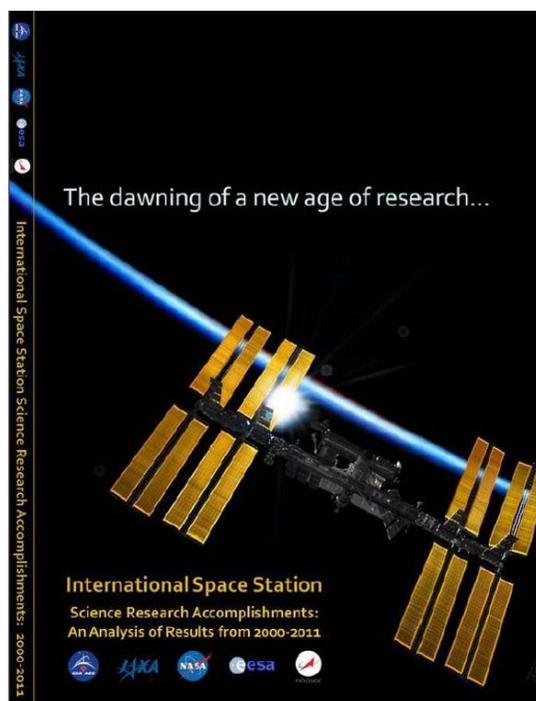


Fig 1: *International Space Station Research Accomplishments: An Analysis of Results From 2000-2011* (Image credit: NASA)

## I. INTRODUCTION

The first 15 years of utilization on the International Space Station (ISS) has led to a revolution of science in space, with scientists from around the world seeking answers to questions ranging from microbial virulence to the origins of the universe, and the returns have grown at a steady pace. Even before the assembly of ISS was completed in 2011, the on-orbit crew were busy performing experiments, and with the full complement of a 6-person crew, more than 1,600 investigations were conducted through 2011 across the international partnership (and the post-assembly period has significantly accelerated the research throughput with 2,275 total investigations through July 2016).

The National Aeronautics and Space Administration ISS Program maintains an online experiment database ([www.nasa.gov/iss-science](http://www.nasa.gov/iss-science)) that continuously tracks and communicates ISS research activities across the entire ISS partnership. The database captures ISS experiment summaries and results, and includes citations to the publications and patents as they become available. A team of professionals mine for publications from ISS research and technology development through many ways, including these examples listed below. Links to these resources\* are provided in the “References” section:

- keyword searches with various tools and search engines
- databases such as AIAA, IEEE, IngentaConnect, JSTOR, J-STAGE, ScienceDirect, Wiley
- Web of Science
- conference proceedings
- science networks such as ResearchGate
- email alerts from systems such as Pubmed, Google Scholar, Nature Partner Journal-Microgravity
- NASA Taskbook, and others
- ISS investigator and international partner websites
- personal email exchanges with ISS investigators and international partners

The ISS Program has found that after any one research activity is completed on ISS, the median time to publication is 3 years for completed data analysis and publication of results in a scientific journal. For example, it took more than 7 years for the *Cellular Biotechnology Operations Support Systems: The Effect of Microgravity on the Immune*

*Function of Human Lymphoid Tissue (CBOSS-02-HLT)* investigation to publish results, while results from the *Advanced Ultrasound in Microgravity (ADUM)* investigation were submitted to the publisher while subjects were still on ISS [1].

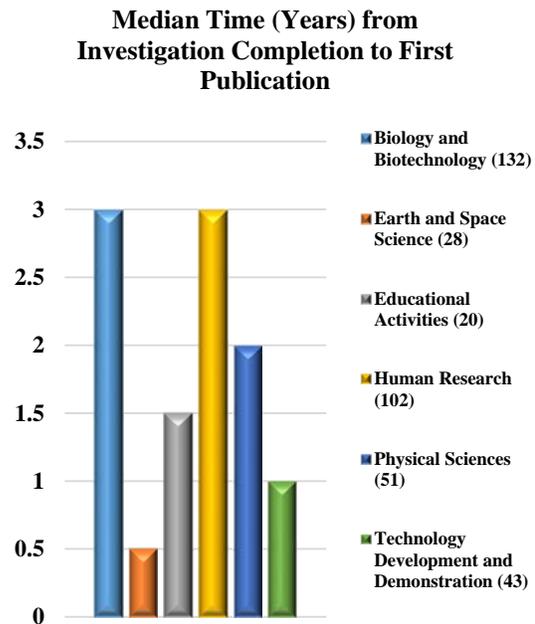


Fig 2 The median time from investigation completion to publication in a scientific journal, based on publications collected through 2015.

As a major collaborative initiative, the ISS partnership has released in 2016 the *International Space Station Research Results Accomplishments: An Analysis of Results from 2000 -2011*. The publication serves as an archival record of the internationally-sponsored ISS research results collected for investigations performed on ISS through 2011, including scientific publications from studies based on operational data [1]. These investigations represent the research of thousands of scientists around the world, and have impacts beyond the field of space research into traditional areas of science in multidisciplinary ways that no Earth-based laboratory has. Yet much like a typical laboratory on Earth, the logistics of the ISS allows for many investigations to be carried forward over several ISS crew expeditions, enabling repeated experimentation and data collection that traditional scientists would expect.

At the time of the publication's release, *International Space Station Research Results Accomplishments: An Analysis of Results from 2000 -2011* contained reference to over 1200 journal publications describing research outcomes of ISS utilization through 2011. Non-journal publications resulting from ISS utilization include 59 patents and over 400 full papers in conference proceedings through 2011.

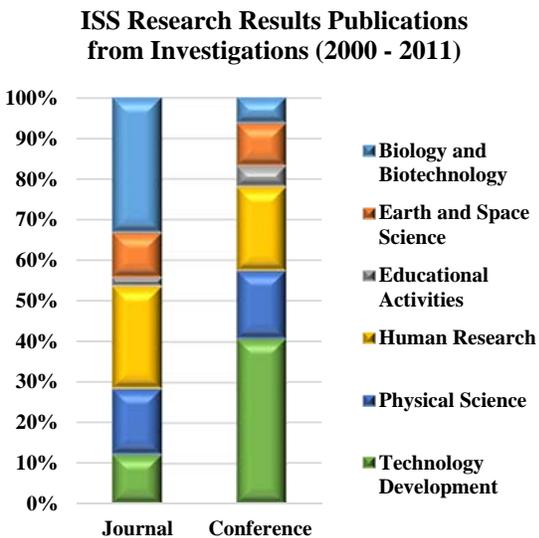


Fig 3 Journal and Conference Publication counts for investigations performed from 2000-2011. Data includes publications received as of October 2015.

This paper highlights just some of the thousands of investigation results used to develop the extensive *International Space Station Research Results Accomplishments: An Analysis of Results from 2000 - 2011* publication. By scientific discipline, the investigations are collected as follows:

- **Biology and Biotechnology** – studies of biology using microgravity conditions to gain insight into the effect of the space environment on living organisms. Areas of emphasis include cellular biology, biotechnology, and plant/animal biology.
- **Earth and Space Science** – studies of the Earth system as it relates to space. Areas of emphasis include astrobiology, astrophysics, heliophysics, Earth remote sensing, and near-Earth space environment.
- **Educational Activities and Outreach** – activities and investigations allowing students and the public to connect with the ISS mission. These activities inspire students to excel in science, technology, engineering, and math and share the

astronauts' unique view of the Earth and space with scientists and the public.

- **Human Research** – human medical research to develop the knowledge that is needed to send humans on exploration missions beyond low-Earth orbit. These studies focus on the effect of living in space on human health, and countermeasures to reduce health risks that will be incurred by living in space in the future. Areas of emphasis include physiological studies related to the effects of microgravity on bone and muscle, other physiological effects of space flight, psycho-social studies, and radiation studies.
- **Physical Science** – studies of physics and chemistry in microgravity. Areas of emphasis include materials sciences experiments, physical properties and phase transitions in polymers and colloids, fluid physics, and crystal growth experiments.
- **Technology Development and Demonstration** – studies and tests of new technologies for use in future exploration missions. Areas of emphasis include spacecraft materials and systems, and characterization and control of the microgravity environment on ISS.
- **Results from ISS Operations** – in addition to the formal, peer-reviewed scientific research and experiments, the ISS supports a large body of research using data from ISS operations, including routine medical monitoring of the crew and data that is collected in the ISS environment, both inside and outside of the ISS.

Publications from ISS results have shown that there are unique new insights, methods, and applications relevant to our life on Earth and space exploration, such as how to prevent loss of bone mass through diet and exercise and how to better define new methods of manufacturing materials composed of small colloidal or nanoparticle building blocks. ISS results have already been used in diverse applications such as robotically refueling and servicing satellites, modeling the behavior of fluids in space propulsion and water systems, and capturing hyperspectral images to help monitor and protect Earth's water supplies.

## II. RESULTS HIGHLIGHTS THROUGH 2011

The diverse array of on-orbit research has led to a steady stream of publications among the ISS partnership. One of the earliest ISS investigations that produced many different publications was also highly collaborative: the *ICE-First* investigation included investigators from France, Canada, Japan, and the United States and studied the effects of the spaceflight environment on living systems using the

*Caenorhabditis elegans* as the model organism of study. Radiobiology, muscle protein changes, ageing, development, radiation effects on living organisms, apoptosis, and DNA damage and repair were all components of the study [1]. Several publications detailed the scientific outcomes of *C. elegans* growth in microgravity under this study, but one outcome in particular was a demonstration of methods that paved the way for more streamlined future experiments. The *ICE-First-Development* component of the investigation confirmed that the methods used for growth and development of space-flown *C. elegans* allowed for normal development compared to its Earth-based counterparts, providing the potential for greater efficiency in the future designs of ISS experiments focused on addressing physiological challenges of spaceflight beyond low Earth orbit (LEO) [1].

In *PLoS One*, scientists sponsored by the European Space Agency (ESA) for the *Gravity Related Genes in Arabidopsis - A (Genara-A)* investigation published molecular evidence that plant seedlings perceived microgravity as a stressful environment by documenting the depletion in proteins associated with normal plant metabolism and the increase in proteins associated with stress responses [2]. Membrane proteins were extracted from seedlings grown in space, on a 1-G reference centrifuge, and on the ground. Among 1,484 proteins identified and quantified, 80 were significantly more abundant in the seedlings grown in microgravity in space. Proteins associated with metabolism and movement of growth hormones were depleted by microgravity, while those associated with stress responses, defense, and metabolism were more abundant, indicating an increased stress response in the microgravity-grown seedlings [2].

Advancing our knowledge of our universe, investigators sponsored by the Japan Aerospace Exploration Agency (JAXA) have published observations in *Nature* from the Monitor of All-sky X-ray Image (MAXI) [3a] investigation of a “first-ever” instant that a massive black hole swallowed a star [3b], along with data that revealed the existence of a hypernova remnant estimated to be 3 million years old, perhaps the first discovery in our galaxy [3c].

The collaboration of global scientists involved in the NASA-sponsored *Alpha Magnetic Spectrometer-02* investigation have published intriguing evidence of “new phenomena” in *Physical Review Letters*, as the instrument was the first to sift through galactic cosmic rays in energy ranges beyond 200Gev, challenging theoretical models of cosmic predictions when searching for evidence of elusive dark matter [4].

AMS has now published six key publications, with many more expected in the near future.

The *HICO and RAIDS Experiment Payload - Hyperspectral Imager for the Coastal Ocean (HREP-HICO)* was an investigation that used a hyperspectral imager that separated reflected light into 128 wavelength channels, revealing information about the composition of water and land along the coasts. *HICO* data gave scientists a unique new tool for managing critical sources of drinking water in the Great Lakes area because of its ability to estimate chlorophyll-*a* concentrations (an indicator of both healthy and harmful phytoplankton in the water), and allowing for the identification of some Harmful Algal blooms (HABs). The U S Environmental Protection Agency (EPA) conducted a demonstration project using *HICO* data to assess water quality in a variety of coastal environments. Overall, results from *HICO* have demonstrated the use of hyperspectral data in the management of both inland and coastal aquatic ecosystems, for planning and executing operations from humanitarian relief to military actions, and for identification of oil spilled from ruptured oil pipes [5]. Over twenty journal publications have been associated with *HICO* until the instrument failed in 2014, and scientists continue to use the data as a historical reference.

Research on the ISS is leading to exciting advancements in maintaining human health during long-duration microgravity missions. Scientists sponsored by the Roscosmos State Corporation for Space Activities (Roscosmos) have leveraged data gathered from long-duration spaceflight to develop new tools for biological and immunological testing in space, impacting space-related immune deficiency research while advancing health care in remote and resource-restricted areas on Earth [6]. In particular, a publication in the journal *Human Physiology* reported on the results of the *Comprehensive Study of the Pattern of Main Indicators of Cardiac Activity and Blood Circulation (Cardio-ODNT)* investigation, concluding that the age of the cosmonaut during microgravity flights on ISS is a critical factor when determining load tolerance on the circulatory system. The results of this study also indicate that the functional state of the circulatory system should particularly be studied when cosmonauts perform frequent and repetitive flights, as well as those cases with a large interval between flights and with aging [7]. A NASA and Canadian Space Agency (CSA)-sponsored investigation called *Cardiovascular and Cerebrovascular Control on Return from ISS (CCISS)* yielded a publication in the *Journal of Applied Physiology*, providing evidence that, despite some

cardiovascular changes in flight, the current program of countermeasures on the International Space Station provides sufficient stimulus to maintain cardiovascular stability under resting conditions during long-duration spaceflight and can provide insight into cardiovascular maintenance on Earth [8]. Data from NASA's *Clinical Nutritional Assessment* project published in the *Journal of Bone and Mineral Research* that diet, exercise devices with proper load, and pharmacological countermeasures are proving to mitigate the overall weightlessness-induced bone mineral loss, and has led to new research regarding the role of exercise on bone strength and fracture risk, as well as the role of magnesium in crewmembers' diet [9].

Across the international partnership, educational activities on ISS have impacted over 40 million students globally. In the journal *Langmuir*, results were published from the *Commercial Generic Bioprocessing Apparatus Science Insert - 02 (CSI-02)* educational investigation, which was designed to interest middle school students in science, technology, engineering, and math (STEM) by participating in near real-time research conducted aboard the ISS. Students observed four different experiments through data and imagery downlinked and distributed directly into the classroom via the Internet. One such experiment was the development of a "Silicate Garden". Four sodium silicates—calcium chloride ( $\text{CaCl}_2$ ), magnesium chloride ( $\text{MnCl}_2$ ), cobalt chloride ( $\text{CoCl}_2$ ), and nickel sulfate ( $\text{NiSO}_4$ )—were mixed at various concentrations for study aboard ISS and compared to those grown on Earth using identical sets of reaction chambers. Still and video images of the experiment were downlinked to the control center, revealing that in the ground samples, samples grew upward, whereas flight experiments exhibited samples that grew randomly in all directions [10]. This investigation reached 500 elementary, 3,500 secondary, 5 undergraduate, and 5 graduate students including 30 schools and 40 teachers [1].

The *PK-3 Plus* investigations sponsored by ESA and initiated collaboratively with Roscosmos examine complex plasmas in space that have revealed many interesting new phenomena. For example, researchers have been able to see the exact point at which matter changes from a liquid to a solid phase in microgravity, providing a better understanding of interactions between gases and dusty plasmas. Such results could help scientists create powders containing specific ingredients for agricultural, hygienic and medical applications for use on Earth. [1,11]. Dusty plasma studies on ISS (*PK-3+ and PK-4*) have logged over 30 scientific publications to date.

NASA's *Electronic Nose (eNose)* technology demonstration was deployed on ISS to continuously detect air contamination from spills and leaks in the crew habitat areas. This filled a technology gap between onboard alarms and complex analytical instruments by providing rapid, early identification and quantification of atmospheric changes caused by chemical species to which had been trained. A preliminary study at NASA's Jet Propulsion Laboratory (JPL) that was published in *NeuroImage* showed an ability for the eNose to accurately "sniff out" differences between human glioblastoma and melanoma cultures in laboratories on Earth [12].

### III. LOOKING AHEAD AND CONCLUSIONS

In addition to tracking ISS results publications themselves, the ISS Program tracks and shares the article citations, and impact factors and Eigenfactors of ISS publications. Currently, the majority of high-impact journal publications are produced by Biology and Biotechnology, Physical Science and Earth and Space Science investigations (Fig. 4). A primary goal for the ISS program is to communicate how ISS results spread knowledge and benefits for scientific advancements, space exploration, and on Earth. Developments in the fields of publication analysis and science valuation include the use of article citation counts as well as development of knowledge maps and visualizations, such as the UCSD Map of Science [13]. Such maps can provide ways to best navigate networks of publications to identify new and evolving areas of research, impacts of research between different disciplines, and how knowledge spreads throughout the scientific community [13]. The National Institute of Food and Agriculture has developed versions of these kinds of knowledge maps to analyze USDA intramural research that has allowed the USDA to compare their research to that of traditional agricultural sciences [14]. The US National Academies of Science has also adopted visualization methods to convey relationships and impacts of their many reports in a program called AcademyScope [15]. The ISS Program is currently performing assessments on such tools as a way to communicate ISS research outcomes in the future.

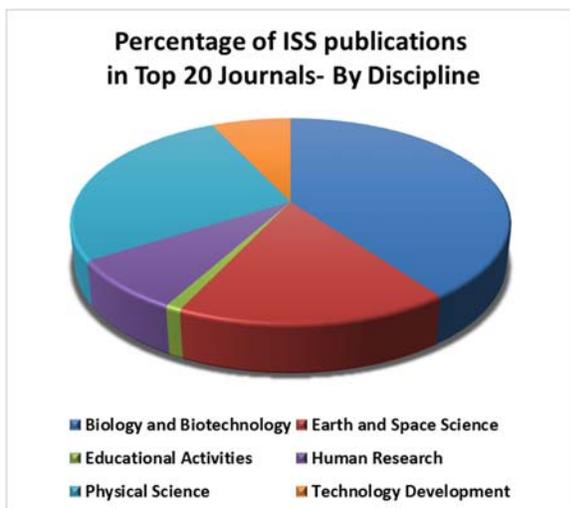


Fig 4 Comparison of ISS Publications that have been released in high impact factor journals, by discipline from 2000 – July 2016.

The *International Space Station Research Results Accomplishments: An Analysis of Results from 2000 - 2011* publication is the first time all ISS partner agencies have come together to publish a comprehensive collection of research results, and a process is in place among this partnership to keep this publication updated quarterly at [www.nasa.gov/stationresults](http://www.nasa.gov/stationresults). Because the scientific publications from ISS utilization will continue to grow, new web tools are also being developed so that scholars and the public will be able to search and download the citations more easily. As the ISS continues to be a test bed for new technology and scientific discovery, scientists and engineers around the world continue to build on ISS results, leading to greater research impacts and scientific collaboration across both space-related and non-space-related fields of science. The ISS partnership eagerly awaits results of recent collaborative research performed on the first-ever one-year ISS human expedition, 3D printing/manufacturing in space, protein crystal growth, advanced telerobotics and materials testing, new rodent research and other model organism capabilities, additional instruments to study our climate, and unique contributions to fundamental physics, all while inspiring the next generation of scientists, innovators and artists. As ISS research activities and operations continue, scientific data derived from earlier experiments will continuously be re-examined, refined, and implemented with new data

and findings, including data from other fields never considered. We anticipate successful ISS research will continue to be used to sow the seeds of new ideas and formulate new conclusions and hypotheses to be tested on future missions both in LEO and on Earth.

Top 20 Journals with ISS Results (Number of Publications)	Times Cited*
PLOS ONE (36)	303
Nature (1)	165
Proceedings of the National Academy of Sciences of the United States of America (3)	139
Science (3)	31
Physical Review Letters (23)	839
Journal of Biological Chemistry (2)	52
Chemical Communications (1)	72
Journal of Neuroscience (1)	76
Advanced Materials (1)	72
Journal of Geophysical Research (5)	179
Physical Review D - Particles, Fields, Gravitation and Cosmology (1)	2
Optics Express (2)	35
Scientific Reports (6)	41
Chemistry - A European Journal (1)	73
Geophysical Research Letters (1)	22
NeuroImage (1)	23
Journal of Chemical Physics (4)	41
Langmuir (2)	18
Physical Review E, Statistical, Nonlinear, and Soft Matter (11)	212
The Astrophysical Journal (1)	9

Fig 5 A listing of the Top 20 Journals (by 2015 Eigenfactor®) with ISS publications in them, as of August 2016. Eigenfactor® is an estimate of the percentage of time users spend with a journal, with citations from influential journals ranked higher. \*Indicates the number of times that ISS research results from the journal have been cited in other journals (source Thomson-Reuters, Web of Science).

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- <http://www.liebertpub.com/>
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- <http://dlib.eastview.com/>
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- <http://www.jstor.org/>
- [www.researchgate.net](http://www.researchgate.net)
- <http://www.ncbi.nlm.nih.gov/pubmed>
- <http://scholar.google.com/>
- <http://www.nature.com/npjimgrav/>
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- <http://www.ams02.org/>
- <http://hico.coas.oregonstate.edu/publications/publications.shtml>
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