Institute of Space and
Astronautical Science

ISAS Report 2022

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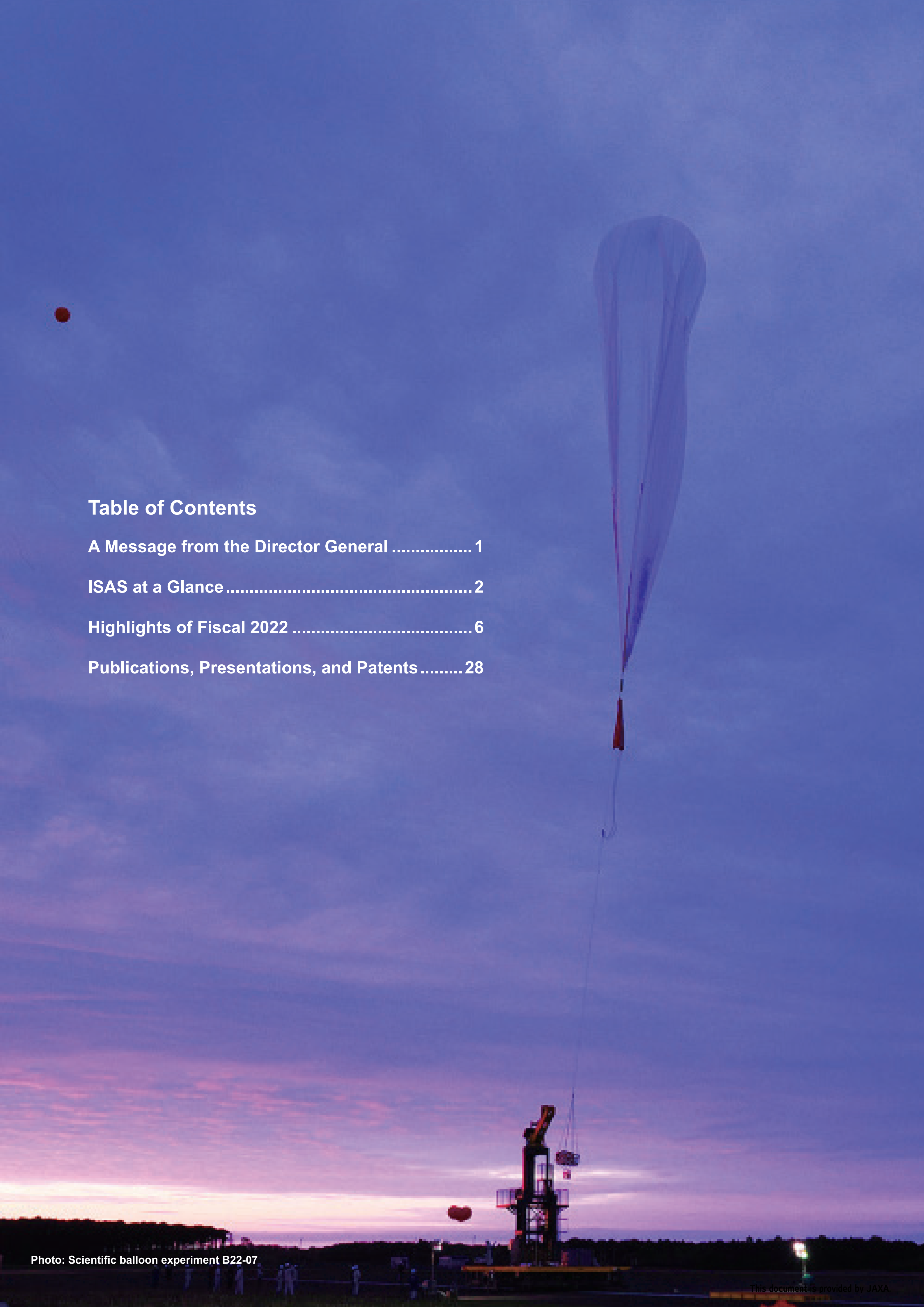


Photo: Scientific balloon experiment B22-07

A Message from the Director General

Since fiscal year 2022, we are returning to full-fledged space science with the CubeSats OMOTENASHI and EQUULEUS, launched on NASA's ARTEMIS-1 rocket in November 2022, ESA's Jupiter Icy Moons Explorer (JUICE), launched in April 2023 with JAXA's contribution through science instruments, Smart Lander for Investigating Moon (SLIM), launched in September 2023, and X-Ray Imaging and Spectroscopy Mission (XRISM), together with the Mercury Magnetospheric Orbiter MIO / BepiColombo launched in October 2018, which has been steadily transmitting observation data to Earth. Looking back, since the ASTRO-H communication anomaly in 2016, the satellite/probe launch projects led by the Institute of Space and Astronautical Science (ISAS) have been stagnant, and we have been unable to obtain new data from space, especially in the field of astrophysics, which has hindered not only academic activities but also student education and the training of early-career scientists. After a long period of stagnation, however, we finally aim to make a full-scale return to space science activities going forward.

A decision was made to terminate the observation operations of the magnetosphere observation satellite GEOTAIL, which has been in operation for more than 30 years. In addition to its many academic achievements in science, it has also become a milestone in engineering as it led to the acquisition of the orbital maneuver technology known as lunar swing-by, and spurred full-scale Japan-U.S. space science cooperation. Furthermore, we have made achievements in sounding rockets by overcoming equipment problems and scheduling/personnel adjustment issues. We have also been able to expand the opportunities for scientific balloon experiments through our ingenuity, and we have resumed experiments in Australia in addition to the current experiments in Hokkaido.

With regard to future projects, we have been proceeding with Martian Moons eXploration MMX, Demonstration and Experiment of Space Technology for INterplanetary voYage with Phaethon fLyby and dUst Science DESTINY$^+$, the next solar observation satellite SOLAR-C, and the cosmic microwave background (CMB) radiation polarization satellite mission LiteBIRD, and we have actively contributed to the study of scientific research and technology demonstration on the lunar surface.

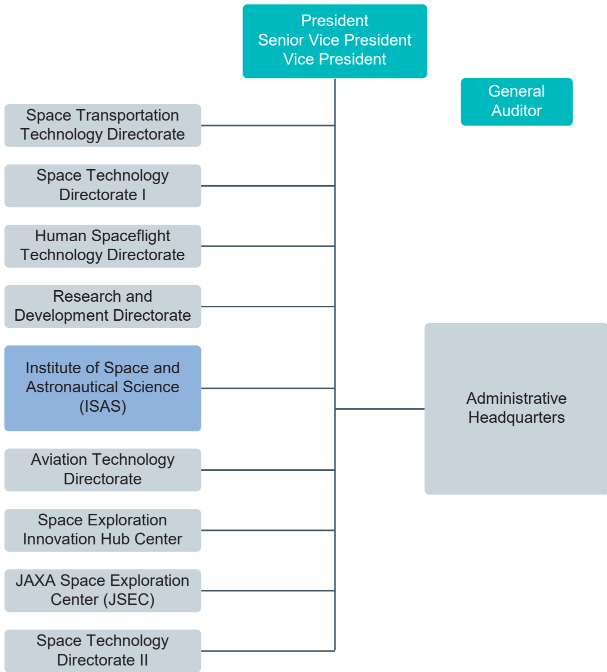
Please take a look at this summary of our activities in 2022. We appreciate your continued guidance and support.

KUNINAKA Hitoshi
Director General of ISAS / JAXA

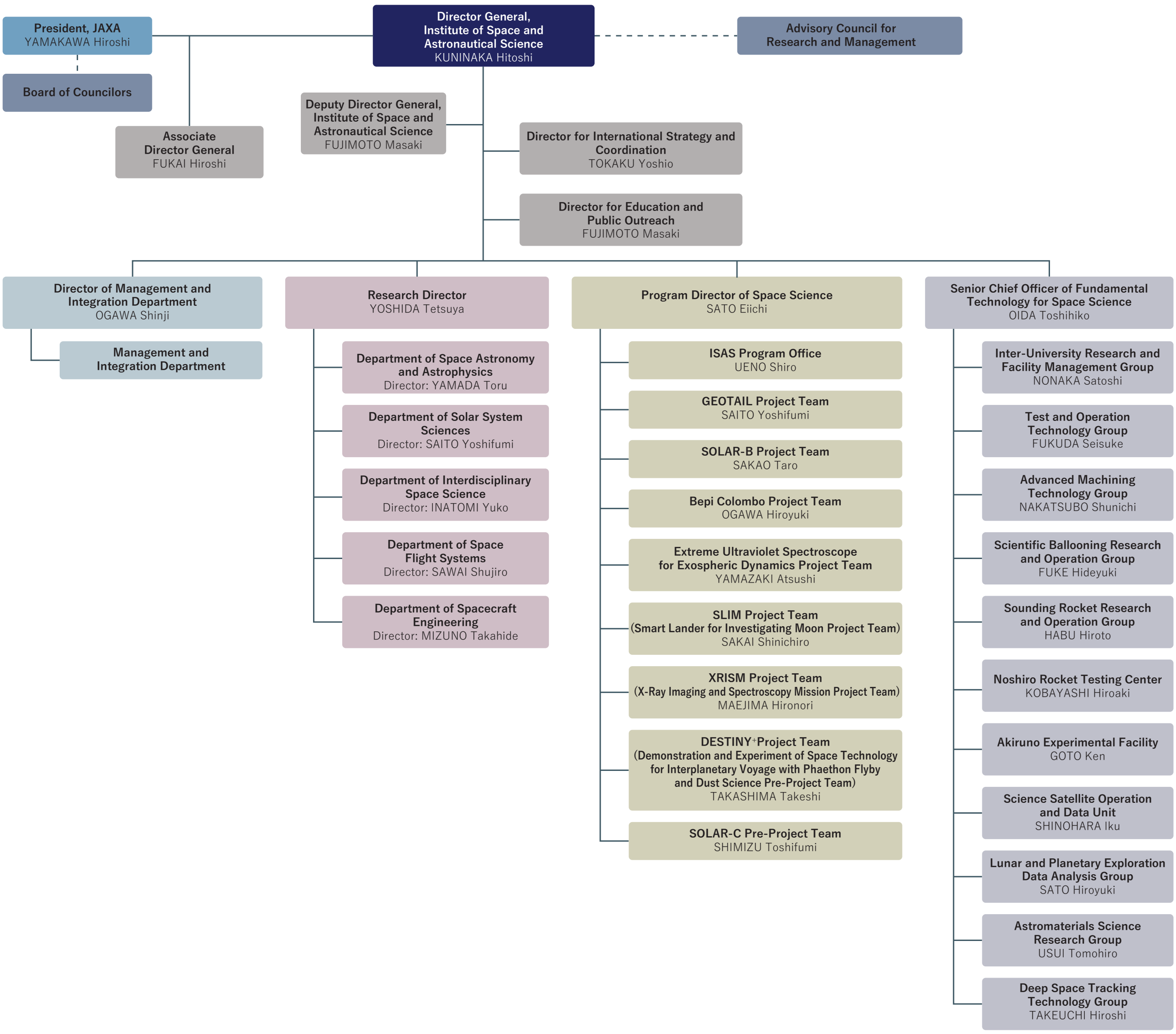
ISAS at a Glance

At JAXA, the Institute of Space and Astronautical Science (ISAS) is positioned as a central institute for the development of space science and providing graduate education. The mission of ISAS is to carry out unique and outstanding space science missions using satellites, probes, sounding rockets, atmospheric balloons, and the International Space Station in cooperation with universities, research institutes, and foreign space agencies. Our aim is to consistently promote academic research through carrying out the mission planning, development, flight experiments, operations, and production of results. Researchers at ISAS can collaborate across the boundaries of space science and space engineering, while engineers leading scientific missions with technologies requested by scientists. ISAS will make the greatest possible efforts to help Japan's space science take another large step forward and to support JAXA's great progress.

JAXA Organization Chart (as of FY2022)



ISAS Organization Chart (as of FY2022)



Space Science Programs under Operation (9) (As of FY2022)

- HINODE (SOLAR-B)
- GEOTAIL
- IKAROS
- Hayabusa2 Extended Mission
- AKATSUKI (PLANET-C)
- HISAKI (SPRINT-A)
- BepiColombo/MMO
- REIMEI (INDEX)
- ARASE (ERG)

Space Science Programs under Development (13) (As of FY2022)

- OMOTENASHI and EQUULEUS
- DESTINY+
- Hera
- SLIM
- XRISM
- JUICE
- Roman
- Martian Moons eXploration (MMX)
- LiteBIRD
- Comet Interceptor
- JASMINE
- Dragonfly
- Solar-C

Related Facilities

ISAS headquarters is located in Sagamihara City, Kanagawa Prefecture. The Institute also has close connections with other centers around Japan. Activities at these centers are coordinated to accomplish the whole range of ISAS projects.

ISAS and Sagamihara Campus Facilities

The Sagamihara Campus was established in April 1989 as the core ISAS facility. The campus, which is located in a quiet suburb about 40 km away from Tokyo with beautiful views of the Tanzawa Mountains, contains the Research and Administration Buildings, the Flight Environment Test Building, the Wind Tunnel Facility Building, the Research and Laboratory Building, etc., where tests for basic R&D and verification of onboard instruments for launch vehicles and satellites are performed. JAXA Space Exploration Innovation Hub Center's main office and the JAXA Space Education Center are also located on the Sagamihara Campus.

One of the functions of the Sagamihara Campus is to provide graduate education programs for the next generation of researchers and engineers. In addition, with the aim of promoting and accelerating inter-university research activities, researchers gather from universities across the country to perform a variety of research projects. The Sagamihara Campus also invites researchers from various countries and functions as a space research center, contributing to the progress of space science internationally.

Research / Administration Buildings

The heart of ISAS activities, these buildings comprise the Executive Director's Office, Management and Integration Department, library, conference halls, exhibition space and research rooms/laboratories.

Structure and Mechanics Test Building

Here we test the strength and rigidity of rocket elements and satellite structures, the functions of rocket interstage joints and nose fairings, etc.

Flight Environment Test Building

We run performance and function tests for scientific satellites and sounding rockets. Tests for vibration, shock, dynamic balance, etc., are conducted in the Mechanical Environmental Testing Room in this building, which is also equipped with a Magnetic Shield Room, Space Chamber, Radio Anechoic Chamber, and Scientific Satellite Assembly Room (clean room).

Advanced Facility For Space Science and Technology

This building houses various types of wind tunnels, a space plasma experiment facility, cosmic radiation experiment facility, particle calibration instrument, weightless drop test facility, etc. With these functions and capabilities, the Experiment Facility Building has been a constant creator of innovative ideas and state-of-the-art technologies that will contribute to future exploration plans.

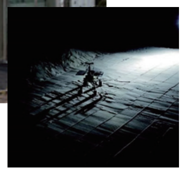
Wind Tunnel Facility

The Wind Tunnel Facility is equipped with an air source unit, transonic wind tunnel, supersonic wind tunnel, and measuring systems to enable basic research and R&D on aerodynamics during high-speed flight of rockets and spacecraft, pre-flight tests, etc.

Research Laboratory Building


This building houses experiment facilities of JAXA Space Exploration Center, Space Systems Development Department, Space Technology Development Department, and Center for Planning and Information Systems. It also has the planetary material sample curation facility, including class-1000 sample handling room and class 10000 sample preparation room.

Advanced Facility for Space Exploration

As an experimental facility to conduct technological research and development related to space exploration and ground-based applications as and innovation hub project, Advanced Facility for Space Exploration is intended to be a place that functions to promote mutual exchange with various universities, research institutes, and private companies, and to be a center that integrates a full range of experimental facility.

Communication Hall of Space Science and Exploration

The Communication Hall of Space Science and Exploration is the ISAS Visitor Center and a facility that was established to urge various universities, research institutes, and private enterprises to participate in the Space Exploration Innovation Hub activity, which is as an industry–academia collaborative research.

Guest House

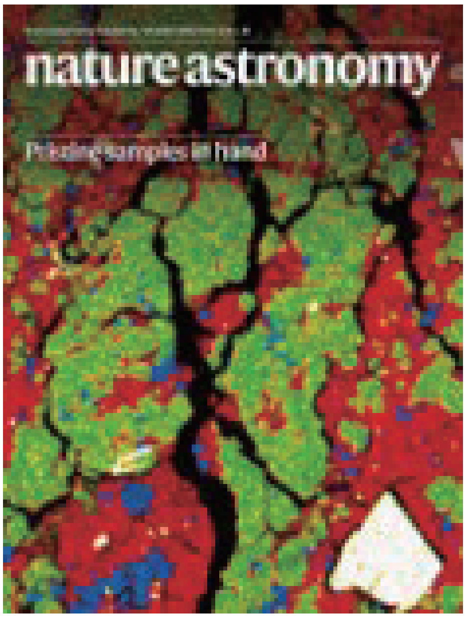
The Sagamihara Campus International Guest House provides accommodations for collaborative researchers, etc., who come from all over Japan and overseas to conduct research using the facilities of ISAS.

Ryugu Samples :
ISAS leading the initial analysis of asteroid Ryugu samples returned by the asteroid explorer Hayabusa2

The asteroid explorer Hayabusa2 project commenced in 2011 as a mission, and the spacecraft launched via HIIA Launch Vehicle No. 26 on December 3, 2014. Its destination was a C-type asteroid to be explored by the spacecraft to understand not only the origin of planets but also the origin of water in Earth's oceans and the materials of life. It then arrived at the asteroid Ryugu in 2018. After various successful missions, including two high-precision touchdowns, the re-entry capsule containing the collected samples from the asteroid Ryugu returned to Earth on December 6, 2020.

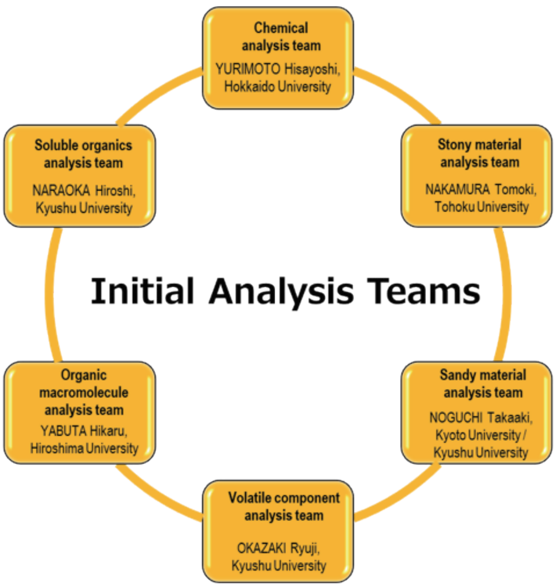
In FY2022, initial analysis (including destructive analysis) was conducted by domestic and overseas universities and institutions that have strengths in their respective analytical technologies, based on the sample catalog of the asteroid Ryugu and analysis conducted using non-destructive methods developed in the previous year. Following the initial description of the samples, six initial analysis teams and two Phase-2 curation institutes performed the initial analysis, led by the Institute of Space and Astronautical Science (ISAS), which contributed to the production of many results.

In FY2022, two initial results from the Phase-2 curation team and seven initial results papers from the initial analysis team were published in *Science* and other journals. *Science* featured Ryugu sample analysis results in a special issue.



Ryugu sample analysis paper featured on the cover of *Nature Astronomy*, Published October 13, 2022.

Science featured Ryugu sample analysis results, (Hayabusa2 is on the cover.) Published February 24, 2023.



Initial Analysis Teams: Consisted of six teams comprised of specialized sub-teams assigned to achieve Hayabusa2's scientific objectives and to reveal the multifaceted value of the samples.

Phase-2 Curation Institutions: More detailed cataloging and additional measurement and analysis.

Major research results from the analysis of samples from the asteroid Ryugu

	Journal	Title	Author	Published in	DOI
Initial Analysis Teams	*Science*	Samples returned from the asteroid Ryugu are similar to Ivuna-type carbonaceous meteorites	Yokoyama *et al.*	2022	10.1126/science.abn7850
	Science	Formation and evolution of carbonaceous asteroid Ryugu: Direct evidence from returned sample	Nakamura *et al.*	2022	10.1126/science.abn8671
	Science	Macromolecular organic matter in samples of the asteroid (162173) Ryugu	Yabuta *et al.*	2023	10.1126/science.abn9057
	Science	Noble gases and nitrogen in samples of asteroid Ryugu record its volatile sources and recent surface evolution	Okazaki *et al.*	2022	10.1126/science.abo0431
	Science	Soluble organic molecules in samples of the carbonaceous asteroid (162173) Ryugu	Naraoka *et al.*	2023	10.1126/science.abn9033
	Nature Astronomy	A dehydrated space-weathered skin cloaking the hydrated interior of Ryugu	Noguchi *et al.*	2022	10.1038/s41550-022-01841-6
	Science Advances	First asteroid gas sample delivered by the Hayabusa2 mission: A treasure box from Ryugu	Okazaki *et al.*	2022	10.1126/sciadv.abo7239
Phase-2 Curation Institutions	*Nature Astronomy*	A pristine record of outer Solar System materials from asteroid Ryugu's returned sample	M. Ito *et al.*	2022	10.1038/s41550-022-01745-5
	Proceedings of The Japan Academy, Series B	On the origin and evolution of the asteroid Ryugu: A comprehensive geochemical perspective	Nakamura *et al.*	2022	10.2183/pjab.98.015

A Message from the Director of Astromaterials Science Research Group

The initial outcomes of the Hayabusa2 sample analysis have provided significant insights into the study of extraterrestrial materials. This is further supported by the fact that these achievements have been featured in special issues of prestigious scientific journals, such as Science and Nature Astronomy.

Among these scientific findings, a noteworthy outcome is the close resemblance of the Ryugu samples to CI chondrite meteorites, which represent solar compositions. CI chondrites are considered standard materials in the solar system, and the similarity of the Ryugu samples provides a crucial clue to understanding the role of extraterrestrial matter in the formation of Earth and the origin of life. Geochemical and mineralogical observations indicate that the Ryugu samples have preserved their pristine state without alteration in Earth's environment. Additionally, fluid inclusions containing carbonate water, salts, and organic compounds have been discovered within the minerals of the Ryugu samples. From the perspective of astrobiology, a significant discovery is the detection of approximately 20,000 soluble organic compounds, including nucleic acid bases like uracil, as well as amino acids, amines, carboxylic acids, and hydrocarbons within the Ryugu samples. These findings suggest the possibility that the parent body of Ryugu was a small celestial body (planetesimal) containing water and organic matter, potentially playing a crucial role in the origin of Earth and life. Further research is expected to unravel the mysteries held by the Ryugu samples and lead to additional groundbreaking discoveries.

Finally, I would like to express my sincere admiration and gratitude to the research teams involved, including the Hayabusa2 Sample Initial Analysis Team, the Phase-2 Curation Team, and the Astromaterials Science Research Group, for their significant roles and remarkable achievements in the Hayabusa2 sample analysis activities. I sincerely hope that through continued sharing of research outcomes and further advancements in studies, we can contribute to expanding our knowledge of extraterrestrial materials in the solar system.

USUI Tomohiro
Director, Astromaterials Science Research Group

Results of initial and phase-2 curation analyses of Ryugu samples

YADA Toru
Astromaterial Science Research Group

Samples from C-type asteroid Ryugu, which returned to Earth via the Hayabusa2 spacecraft in December 2020, were distributed to an initial analysis team and the Phase-2 curation teams in June 2021 for further detailed analyses. Their research results were published in five papers from Science, seven papers from Nature Astronomy, and 19 papers from other international journals in FY2022.

As a result of the elemental analysis and high-precision chromium and titanium isotopic analysis of the Ryugu samples, it was found that they are closest to the CI chondrite, which has the composition closest to the Sun among the known planetary material samples (Yokoyama et al., 2022). This type of meteorite is very rare as only nine have been discovered out of more than 71000 meteorites found on Earth, and it is important as it is recognized as standard material in the solar system. However, there are differences, such as an absence of sulfate minerals in the Ryugu samples, the presence of which is a sign of terrestrial alteration the meteorites have experienced. Therefore, the Ryugu samples are precious as they are free from such terrestrial alteration. In addition, a fluid inclusion was discovered in iron sulfide, which is carbonated water containing salts and organic matter, revealing that the Ryugu parent body should have accreted not only H_2O ice but also CO_2 ice. CO_2 ice is thought to have existed beyond the snowline in the outer edge of the protosolar disk, suggesting that the Ryugu parent body should have formed at the outer edge of the protosolar nebula (T. Nakamura et al., 2022). The Ryugu samples contain approximately 20,000 types of soluble organic molecules, including amino acids such as uracil and alanine, which are the nucleobases of biomaterials, amines, carboxylic acids, hydrocarbons, and nitrogen-containing cyclic compounds (Naraoka et al., 2023; Oba et al., 2023, Fig. 1).

Small bodies rich in organic matter and water, such as this Ryugu parent body, were transported to the inner primitive solar system, where the proto Earth formed, due to the gravitational disturbances caused by gas giants such as Jupiter and ice giants such as Uranus, which formed in the relatively early stage of solar system formation. It is thought that they should have supplied the origin materials of the ocean and life on ancient Earth.

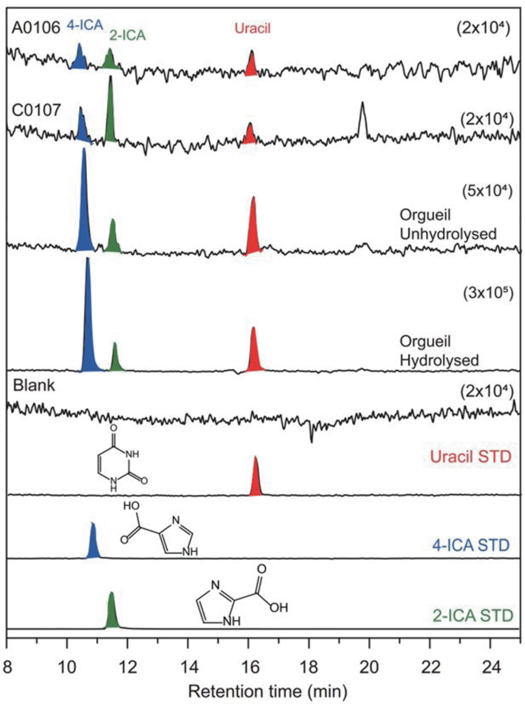


Figure 1. Uracil, a nucleic acid base detected from Ryugu samples (Oba et al., 2023). Uracil is one of the constituents of RNA and an organic molecule that is necessary for the birth of primitive life.

Samples returned from the asteroid Ryugu are similar to Ivuna-type carbonaceous meteorites

The initial analytical chemistry sub-team investigated the chemical composition, isotopic composition, origin of constituents, age of carbonates, and relationship with meteorites of the returned Ryugu samples. As a result, they found that Ryugu is the same as the Ivuna-type carbonaceous (CI) chondrite (Figure 1). This CI chondrite is a meteorite that has the same chemical composition ratio as the entire solar system, excluding gas components, and is regarded as standard material in the solar system. Ryugu was found to be the freshest sample, free from terrestrial contamination, compared to the CI meteorites. Ryugu contained large amounts of water (about 7%) and carbon (about 5%). Ryugu is mainly composed of hydrous phyllosilicates (like serpentine), including carbonates, iron sulfides, and magnetites. Most of the minerals are secondary minerals due to the aqueous alteration between the aqueous solution that occurred in the Ryugu parent body, which predates the present Ryugu. The age when the aqueous alteration occurred was about five million years after the birth of the solar system, and the temperature at that time was about 40 ˚C. Thereafter, the destruction of the parent body occurred, and the scattered fragments gathered to form the asteroid Ryugu. After the formation of Ryugu, some water evaporated from phyllosilicates, the main constituent minerals of Ryugu. It is thought that the temperature of the Ryugu samples has not exceeded 100 ˚C since the asteroid Ryugu was formed. The CI chondrite contains 13 to 20% water, twice as much as Ryugu, and it turns out that this high amount is due to contamination with water on Earth.

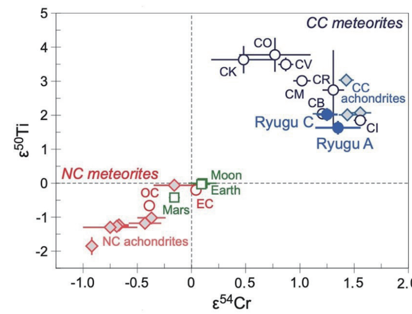


Figure 1. ^{54}Cr-^{50}Ti isotopic diagram showing Ryugu and meteorite data by high mass resolution isotopic analyses. Ryugu A and C samples are plotted in the range of carbonaceous chondrites, especially close to CI chondrites.

- Yokoyama et al. Samples returned from the asteroid Ryugu are similar to Ivuna-type carbonaceous meteorites, Science, Vol 379, Issue 6634 (2022). doi: 10.1126/science.abn7850

Formation and evolution of carbonaceous asteroid Ryugu: Direct evidence from returned samples

The initial analysis rock sub-team analyzed samples from the asteroid Ryugu recovered by the asteroid explorer Hayabusa2 (17 particles, including the third largest sample recovered by the spacecraft) at five synchrotron radiation and muon analysis facilities in Japan, the United States, and Europe using cosmochemical and physical methods. As a result, the history of Ryugu from its formation to impact destruction (formation and position in the solar system, information on astronomical materials, types of ice contained, chemical evolution due to reactions with water on the celestial surface and in the interior, effects of celestial collisions, etc.) have been clarified. In particular, they found liquid water trapped in crystals in the samples. This water was once present in the parent body of Ryugu, and was carbonated water containing salts and organic matter (Figure 1). This reveals that the Ryugu parent body was formed in the outer solar system, where CO_2 existed as ice. In addition, it was found that the Ryugu samples contain a mixture of material near the surface of the parent body and material inside the body before impact fracture. Furthermore, the hardness of the Ryugu samples, how heat is transferred, specific heat, density, etc. were measured. Using these measured physical parameters, we performed numerical simulations of the temperature change due to heating inside the Ryugu parent body after the formation of the parent body and the impact fracture process, and reproduced the formation and evolution of Ryugu on a computer. As a result, we discovered that the Ryugu parent body accumulated about two million years after the formation of the solar system, and over the next three million years, it warmed up to about 50 ˚C, and the chemical reaction between water and rock proceeded. It was found that the size of the destroyed impact object was at most about 10 km in diameter, and that the current Ryugu is made of materials from a region far from its impact region.

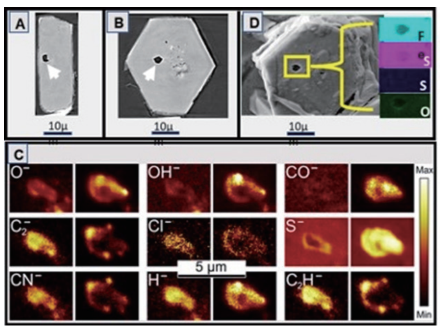


Figure 1. Fluid inclusion found in pyrrhotite of the Ryugu samples. It was determined that the fluid is carbonated water containing salts and organic matter.

- Nakamura et al. Formation and evolution of carbonaceous asteroid Ryugu: Direct evidence from returned sample, Science, Vol 379, Issue 6634 (2022). doi: 10.1126/science.abn8671

Macromolecular organic matter in samples of the asteroid (162173) Ryugu

The initial analysis Insoluble Organic Matter (IOM) sub-team conducted non-destructive analysis of Ryugu particles (analysis of untreated fine particles) and destructive analysis (analysis of insoluble residues obtained by acid treatment of samples), respectively. It was found that the main proportion was occupied by black solid organic matter (Figure 1). It was also found that the solid organic matter in the Ryugu samples consists of a polymeric structure in which aromatic carbon, aliphatic carbon, ketone groups, carboxyl groups, etc. are combined randomly. The chemical and isotopic composition of the solid organic matter in the Ryugu samples resembled those of the primitive carbonaceous chondrites. No ordered structure like graphite was observed, indicating that Ryugu's organic matter had not been heated to high temperatures. A direct relationship between the organic matter of carbonaceous asteroids and that of primitive carbonaceous chondrites has been demonstrated for the first time. Nanometer-sized spherical organic matters (nanoglobules) and a widespread diffuse carbon were found adjacent to or mixed with phyllosilicates and carbonates. These observations are evidence of chemical reactions with water, organic matter, and minerals in the Ryugu parent body. The nanoglobule organics were rich in aromatic and carbonyl carbons. The widespread diffuse carbon includes those resembling the acid-insoluble organics found in primitive carbonaceous chondrites and molecular carbonates, which are molecular carbonate precursors that are not crystalline carbonate minerals, or carbonate esters. It was found that Ryugu has more diversity in the combination of chemical composition and the morphology of solid organic matter than meteorites. This result indicates that the reaction between liquid water and organic matters in the Ryugu parent body proceeded under various conditions. Very high and low deuterium (D) and nitrogen-15 (^{15}N) areas were detected in both the Ryugu fine particles and the insoluble residues. Isotopic compositions rich in D and ^{15}N are known to occur only in low-temperature environments below -200°C, which are not found in terrestrial organic matters. Therefore, it was shown that at least some of the organic matters contained in Ryugu were formed in cryogenic environments such as interstellar molecular clouds and the outer protoplanetary disk. The hydrogen isotopic distribution of the insoluble residues separated from the Ryugu samples resembled that of the carbonaceous chondrites that experienced reaction with water in their parent bodies, and the insoluble residues lower than those experienced little water alteration. To summarize, this work makes clear the history of the chemical evolution of the composition of organic matter in a variety of ways, repeating the processes whereby primary organic matters generated in molecular clouds and disks changed in the Ryugu parent body and whereby new organic matters were synthesized from the changed molecules.

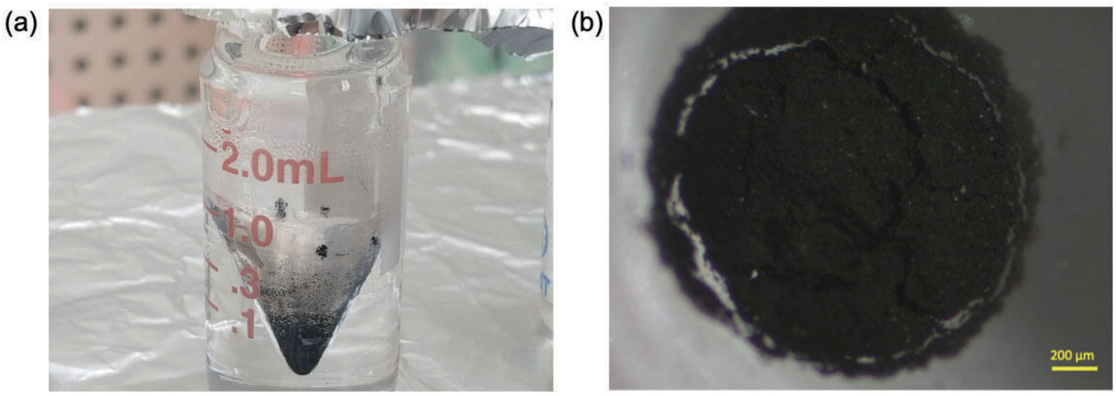


Figure 1. Images of insoluble carbonaceous residues isolated from the intact Ryugu aggregates (A0106) by HF/HCl treatment. (A) The Ryugu carbonaceous residue in a mini glass vial. (B) An overhead image of the Ryugu carbonaceous residue aliquots transferred in another mini vial.

- Yabuta et al. Macromolecular organic matter in samples of the asteroid (162173) Ryugu, Science, Vol 379, Issue 6634 (2023). doi: 10.1126/science.abn9057

Noble gases and nitrogen in samples of the asteroid Ryugu record its volatile sources and recent surface evolution

The initial analysis gas sub-team has measured (1) infrared spectroscopy and electron microscopy, (2) noble gas isotopic compositions, and (3) nitrogen isotopic compositions of Ryugu particles. Based on these results, we studied the origin of materials in the parent body of Ryugu and the evolution of surface materials after the formation of Ryugu. Allocated Ryugu particles with a diameter of less than 1 mm were pressed into pellets one by one, and the surface was observed using the methods of (1). Thereafter, the gas was extracted by stepwise heating in a vacuum, and the isotope analysis of (2) and (3) was performed. As a result of noble gas isotope analysis, primitive noble gases that were taken up in outer space by materials during the formation of the solar system were discovered. The amount thereof was found to be greater than that of any meteorite reported so far. The nitrogen isotope composition differs from sample to sample, indicating that various nitrogen-bearing substances are still preserved in the Ryugu samples (Figure 1). In addition to noble gases from the formation of the solar system, the Ryugu samples also contain two gaseous components produced by galactic cosmic rays and the solar wind. Two of the samples recovered from the first touchdown (Ryugu-A samples) that were analyzed for noble gases had been exposed to the solar wind for periods corresponding to 3500 years and 250 years, respectively, on the current orbit. Other Ryugu-A samples (8 samples) and Ryugu-C samples (6 samples) recovered from around the artificial crater contained only trace amounts of solar wind equivalent to several decades. The irradiation period of galactic cosmic rays was calculated from the amount of neon originating from galactic cosmic rays. Both the Ryugu-A samples (10 samples) and the Ryugu-C samples (6 samples) were about 5 million years old on average. If the crater on the surface of Ryugu was formed in near-Earth orbit, the period is estimated to have been 2-8 million years. The galactic cosmic-ray irradiation period obtained this time agrees well with that estimated based on crater chronology. This suggests that Ryugu moved into near-Earth orbit about 5 million years ago, and that the surface material has not undergone major changes since then. When a Ryugu sample was heated to about 100°C in a vacuum, gases originating from the solar wind and cosmic rays were released. This amount of cosmic-ray-derived neon corresponds to an irradiation period of about one million years. Visible spectroscopic observations have reported a reddish substance in the mid-latitude region of Ryugu, and the reddening is thought to be caused by heating near the Sun. Noble gas analyses suggest that Ryugu orbited close to the Sun more than a million years ago. Traces of long-term solar wind irradiation were found in the first touchdown samples, which are the very surface material, and the difference from the sample recovered in the second touchdown was clarified by noble gas isotopes.

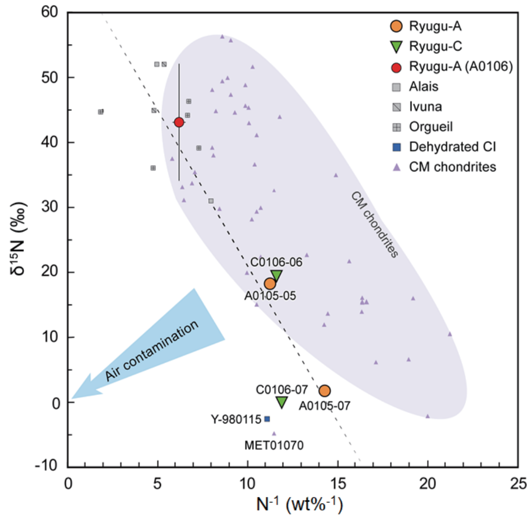


Figure 1. The Nitrogen isotope composition of the Ryugu sample grains (vertical axis, measured as the difference from Earth's atmosphere in parts per thousand) vs. the inverse nitrogen abundance (weight ratio: horizontal axis). The Ryugu grains (orange circles, green inverted triangles, red circle) each show a different nitrogen composition. CI chondrites (grey and blue squares) and CM chondrites (purple triangles, purple enclosed area) are also shown for reference. If mixed with Earth's atmosphere, the analysis data would move in the direction indicated by the blue arrow, but the effect would not be visible (Okazaki et al., 2022a).

- Okazaki et al. Noble gases and nitrogen in samples of asteroid Ryugu record its volatile sources and recent surface evolution, Science, Vol 379, Issue 6634 (2022). doi: 10.1126/science.abo0431

Soluble organic molecules in samples of the carbonaceous asteroid (162173) Ryugu

The initial analysis Soluble Organic Matter (SOM) subteam extracted various solvents from aggregate powder samples obtained by Ryugu first touchdown sampling and analyzed them with high-resolution mass spectrometry and chromatographic methods at universities and research institutes in Japan, the U.S. and Germany. As the average composition of Ryugu (A0106), the total abundance of C, H, N, S and pyrolytic O is about 20 wt% and the stable isotope composition of each element is similar to that of the Ivuna-type (CI) carbonaceous chondrite. Among 20,000 kinds of compounds represented by C, H, N, O, and S dissolved in methanol, CHOS, CHNO, CHNOS, etc. are relatively abundant, and low-molecular-weight compounds such as methylamine, ethylamine, and acetic acid were identified (Figure 1). The detection of these highly volatile asteroid surfaces indicates that they exist as molecular salts. In addition to proteinaceous amino acids (such as alanine)

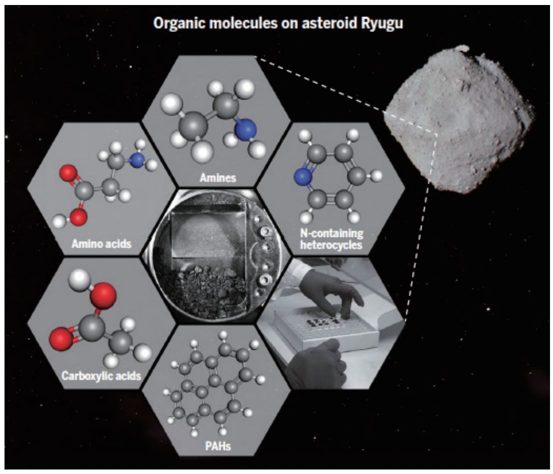


Figure 1. Various kinds of organic molecules found in Ryugu samples. 20,000 organic molecules, including amino acids, the building blocks of life, were detected from them.

used by life on Earth, non-proteinaceous amino acids (such as isovaline) were found, but amino acids with left and right structures were present in equal amounts at a ratio of 1:1. This indicates an abiotic synthetic process of those molecules. As hydrocarbons, alkylbenzenes and polycyclic aromatic hydrocarbons such as naphthalene, phenanthrene, pyrene, and fluoranthene were mainly present. These existence patterns are similar to those of hydrothermal crude oil on Earth, suggesting that they were influenced by water on the Ryugu parent body. In situ analysis of the Ryugu sample surface with methanol spray revealed that different organic molecules existed in different spatial distributions, suggesting the possibility that the organic compounds were separated during the interaction between the fluid and minerals on the Ryugu parent body. Various processes have been observed to release materials from the surface of asteroids into space, and it is possible that organic molecules on the surface of Ryugu may be transported to other celestial bodies.

- Naraoka et al. Soluble organic molecules in samples of the carbonaceous asteroid (162173) Ryugu, Science, Vol 379, Issue 6634 (2023). doi: 10.1126/science.abn9033

A dehydrated space-weathered skin cloaking the hydrated interior of Ryugu

The initial analysis sand sub-team investigated how many samples of asteroid Ryugu, 1 mm or less, collected by the asteroid explorer Hayabusa2 retained the surface they had when they were on the asteroid. Most of them were stone fragments that were destroyed by the impact during sample collection, but about 6% maintained the same surface as when they were on the asteroid. They could be broadly divided into two types of surface texture (Figure 1). The first type had a relatively smooth surface, a texture that was dotted with small holes of about 0.1 µm. In order to investigate the formation of this structure, we compared the first type of samples with the changes caused by colliding helium ions simulating the solar wind against a Ryugu particle whose surface had not changed, and found that very similar structures were created by the simulation. Based on this experiment, it was found that the first texture is one that experienced space weathering formed by the irradiation of the solar wind. The second type of texture appears to be a melted and violently foamed stone or sand surface. As a result of irradiating the Murchison meteorite, which belongs to the Mighei-type carbonaceous chondrite, with a pulsed laser to reproduce this texture, a structure similar to the second one was formed on both the surface and in the interior. In both the Ivuna-type and Mighei-type carbonaceous chondrite, after the formation of the celestial bodies from which they originated, minerals and water strongly reacted to form hydrous phyllosilicate (a type of clay). When the phyllosilicates are heated strongly, they are decomposed, releasing water vapor. In other words, the surface of the C-type asteroid is dehydrated by heat-melting space weathering caused by micrometeoroid impacts. Although the main cause of space weathering is common, the space weathering of C-type asteroid Ryugu was very different from that occurred on the Moon and the S-type asteroid Itokawa, which has been well studied. This means that airless bodies should have evolved differently depending on their different properties. On the C-type asteroid Ryugu, the effects of space weathering due to collisions and heating of micrometeoroids are more pronounced than on the S-type asteroid Itokawa. The results of this study, which indicate that dehydration of surface materials occurs due to space weathering, should explain the discrepancy between the interpretation that the entire surface of Ryugu has undergone intense heating based on the results of in-situ observations by Hayabusa2 and the absence of such trace observed in the recovered samples. C-type asteroids are the most abundant asteroids in the main belt between Mars and Jupiter. Many of them are thought to be composed of substances similar to Mighei-type and Ivuna-type carbonaceous chondrites, since water molecules or hydroxyl groups (OH) can be observed from ground observations. However, they are not observed in about 40% of cases. Although space weathering has not been cited in previous studies as the reason why they are not observed, this study suggests that it is necessary to consider space weathering in observational studies of C-type asteroids.

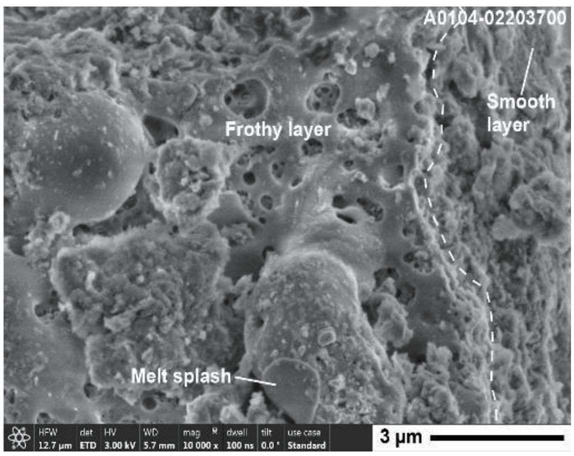


Figure 1. Space weathering of a Ryugu grain. The smooth layer on the right side of the dotted line has been subjected to space weathering from solar wind irradiation. The frothy layer visible on the left side has experienced space weathering from micrometeoroid impacts and contains deposits of thin layers of melted rock. This backscattered electron image allows us to read the complex history of Ryugu (Noguchi et al., 2022).

- Noguchi et al. A dehydrated space-weathered skin cloaking the hydrated interior of Ryugu, Nature Astronomy 7, 170–181 (2022). doi: 10.1038/s41550-022-01841-6

First asteroid gas sample delivered by the Hayabusa2 mission: A treasure box from Ryugu

The initial analysis gas sub-team conducted mass spectrometry and gas sampling of the gas components in the sample container brought back to Earth by the asteroid explorer Hayabusa2. The sampled gas was distributed to research institutes in Japan and overseas, and precise isotope analysis of gas components was performed. They found that the helium isotope ratio in the gas inside the container was 100 times more helium with a mass number of 3 (^{3}He) than in Earth's atmosphere. The isotope composition of neon was also different from that of Earth's atmosphere. As a result of examining the element abundances and helium isotope ratios of helium, neon, and argon in the container, it was found that the container gas can be explained by the mixing of the solar wind and Earth's atmosphere that leaked into the container after returning to Earth (Figure 1). Calculating from the amount of helium in the container, we found that the container gas most likely contains the solar wind released when the surface of the Ryugu sample was detached. The Hayabusa2 mission was the first in the world to return gas from a near-Earth orbit asteroid back to Earth.

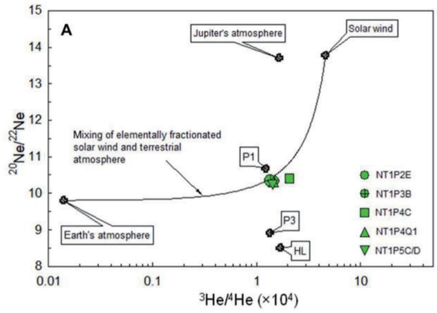


Figure 1. Helium and neon isotopic diagram showing data of gaseous components recovered from the Hayabusa2-sampler container. The container gas is plotted on the mixing line between solar wind and Earth's atmosphere, indicating the spacecraft succeeded in returning the first gas samples from the extraterrestrial body.

- Okazaki et al. First asteroid gas sample delivered by the Hayabusa2 mission: A treasure box from Ryugu, Science Advances Vol 8, Issue 46 (2022). doi: 10.1126/sciadv.abo7239

Uracil in the carbonaceous asteroid (162173) Ryugu

The initial analysis Soluble Organic Matter (SOM) sub-team conducted high-performance liquid chromatography/electrospray high-resolution mass spectrometry on solutions extracted with hot water from aggregate powder samples obtained from about 10 milligrams each of the samples of the first and second Ryugu touchdowns. We succeeded in detecting uracil, one of the nucleobases contained in the RNA of all life on Earth, and vitamin B3 (niacin), one of the coenzymes essential for the metabolism of life forms (Fig. 1). These detections show the real picture of the chemical evolution of organic molecules, and the ultimate mystery in science: how the first life began on ancient Earth. The detections strongly support the theory that extraterrestrial substances such as carbonaceous chondrite (= asteroid) material should have supplied such building blocks.

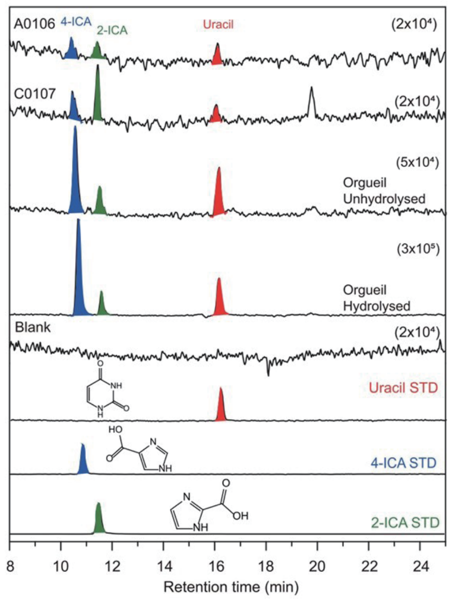


Figure 1. Uracil and its structural isomers detected from Ryugu samples. Uracil is one of the four nucleobases making up the RNA of all life on Earth.

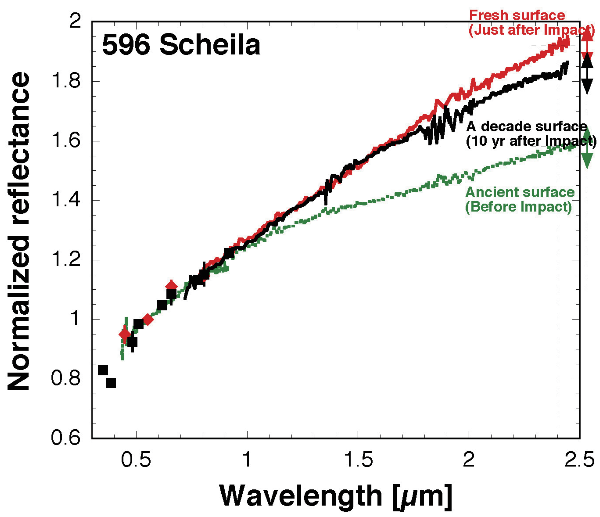
- Oba et al. Uracil in the carbonaceous asteroid (162173) Ryugu, Nature Communications volume 14, Article number: 1292 (2023). doi: 10.1038/s41467-023-36904-3

A 10-year sunburn: no change of the spectrum of a dark asteroid surface after 10 years of space weathering

HASEGAWA Sunao
Inter-University Research and Facility Management Group

When the asteroid 596 Scheila collided with an object in the asteroid belt between Mars and Jupiter in December 2010, a fresh layer of material was exposed on the asteroid surface . An international research team observed the spectrum (reflected light intensity as a function of the wavelength) from the asteroid approximately ten years later, to see how space weathering affects the surface over a genuine timescale. Within the uncertainty of the observations, the observed spectrum was consistent with that observed immediately after the 2010 impact event. This suggests that the surface colour of dark asteroids is not significantly altered by space weathering over a time period of ten years. This study is the first example that investigates spectral changes due to space weathering on the surface of an actual asteroid in the solar system. Models based on this observation suggest that asteroids with relatively young surfaces (less than approximately 1000 years) can be considered to have experienced negligible evolution through space weathering, potentially changing how we understand their properties.

The research was led by HASEGAWA Sunao, Associate Senior Researcher at ISAS JAXA, together with an international team from the National Astronomical Observatory of Japan, the University of Tokyo, Japan Spaceguard Association, Kobe University, Massachusetts Institute of Technology, European Southern Observatory, Charles University, Côte d'Azur Observatory, University of Hawaii, NASA, University of Liege, Laboratoire d'Astrophysique de Marseille, Diego Portales University, and Seoul National University.



Plot showing the change in the spectrum of 596 Scheila before and after the collision that refreshed the asteroid surface. The horizontal axis shows the wavelength of the reflected light, and the vertical axis is the reflectance intensity, normalized to the reflectance at a wavelength of 0.55 microns. The green data points are from observations taken before the impact, and therefore show the spectrum of a surface that has been weathered for many years. The red points are observations obtained immediately after the impact (fresh surface). The black data points are observations ten years after impact, showing the data for a surface subjected to space weathering for about 10 years. The arrows on the right side of the figure indicate the observational error range.

- Hasegawa, S., et al., Spectral evolution of dark asteroid surfaces induced by space weathering over a decade, *Astrophysical Journal Letters,* **939**, L9 (2022), doi:10.3847/2041-8213/ac92e4
- Hasegawa, S., et al., The Appearance of a "Fresh" Surface on 596 Scheila as a Consequence of the 2010 Impact Event, Astrophysical Journal Letters, 924, L9 (2022), doi:10.3847/2041-8213/ac415a

Unique quantum inference effect captured by cosmic X-ray polarimeter

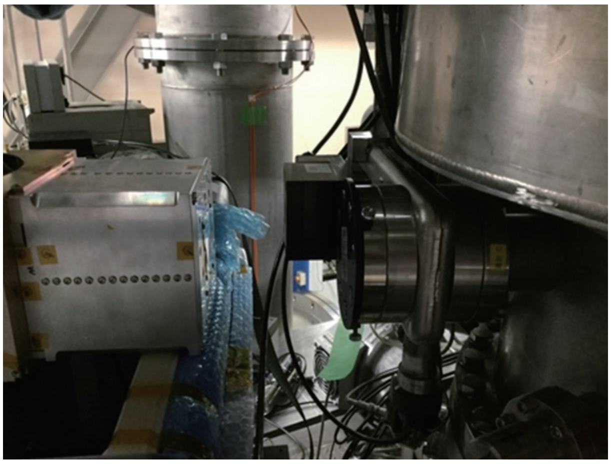
- New physics experiments opened up by a state-of-the-art space observation instrument -

WATANABE Shin
Department of Space Astronomy and Astrophysics

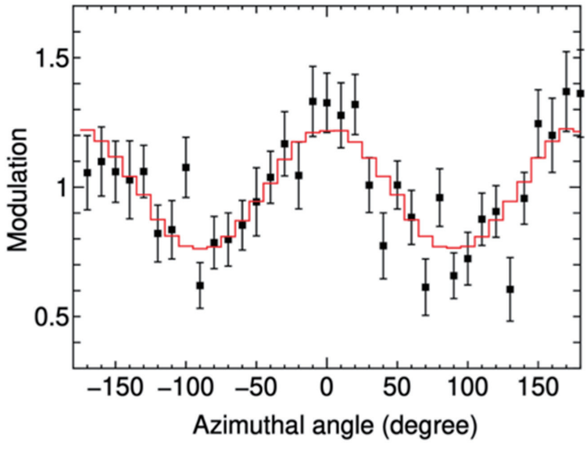
An unanticipated polarization of high-energy X-rays emitted when highly charged ions capture high-energy electrons has been discovered experimentally for the first time. The measurement used a high-energy X-ray polarization detector that was originally developed for high sensitivity space observations with the electron beam ion trap Tokyo-EBIT experiment at the University of Electro-Communications. Estimates based on atomic physics had previously suggested that the electron state transition would emit unpolarized radiation, but the measured X-rays turned out to be highly polarized. Polarization measurements of high-energy X-rays are considered valuable in atomic physics research, but their use has been hindered in the past due to the lack of detectors capable of accurate measurements. These results were achieved by combining two state-of-the-art instruments and technologies: the EBIT-CC high-energy Compton X-ray polarimeter developed for space observations and adapted for this research principally at the JAXA Institute of Space and Astronautical Science (ISAS), and the Tokyo-EBIT world-leading highly charged ion generator and experimental instrument of the University of Electro-Communications.

The experimental result regarding the unexpectedly large degree of polarization was followed up by theoretical analysis, which revealed that the observed polarization was the result of a quantum inference effect, in which waves of quantum mechanical probability interfere with one another. Normally, two waves must have the same initial state for interference to occur, but the observed polarization in this experiment was caused by two waves with different total angular momenta. In other words, this unusual interference effect was caused by two waves with different initial states.

The results of this work are therefore a good example of how cutting-edge observation instruments developed to meet the needs of the space science community can become the seeds for new discoveries in other research fields. This research was published in the US scientific journal, "*Physical Review Letters*".



EBIT-CC (left) installed at Tokyo-EBIT (right)



Azimuthal distribution of the Compton scattering angle obtained in the experiment. The black dots are experimental data. The red line is the simulation result at a polarization of 0.327 obtained from the experimental data. According to the conventional knowledge of atomic physics, it is considered to be unpolarized, in which case it should have been constant at any azimuthal angle and should have been 1.

-Nakamura, N., Watanabe, S., et al., Strong Polarization of a J=1/2 to 1/2 Transition Arising from Unexpectedly Large Quantum Interference, *Physical Review Letters,* **130**, 113001 (2023), doi:10.1103/PhysRevLett.130.113001

Hisaki witnesses Martian dust storms changing Mars's upper atmosphere: Implications for the habitability of Mars

<Hisaki (SPRINT-A)>

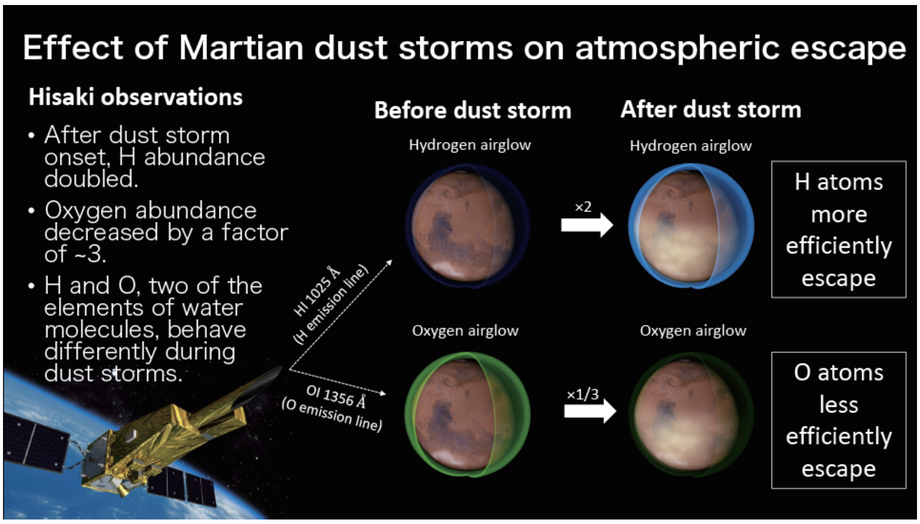
MASUNAGA Kei
Department of Solar System Sciences

The Hisaki spacecraft carries a UV spectroscope on-board. Since 2013, it has obtained UV spectra of the upper atmosphere of Jupiter, Venus, Mars, and so on. In September 2016, when a dust storm occurred on Mars, observations of the upper atmosphere of Mars were made using the Hisaki space telescope and several Martian spacecraft.

We analyzed various types of data on the upper and lower atmosphere of Mars collected by several spacecraft, including Hisaki. We found that the total amount of hydrogen and oxygen gases in the Martian upper atmosphere increases or decreases due to dust storms and atmospheric waves generated in the lower atmosphere. In particular, when dust storms occur on Mars, the amount of hydrogen gas in the upper atmosphere temporarily increases by about a factor of two and oxygen gas decreases by about a factor of three, suggesting that hydrogen gas escapes easily from Mars and oxygen gas escapes less easily from Mars.

Dust storms are known to occur seasonally on Mars, developing into major dust storms at least three times a Martian year. If the hydrogen-rich and oxygen-poor conditions we have discovered occur during each dust storm and have been repeated over hundreds of millions of years of Martian history, then the Martian atmosphere has been continually oxidized by dust storms. This suggests that in the past, Mars had a more reductive atmosphere than Mars today. In a reductive atmosphere, it is thought that the synthesis of organic matter is more likely to occur through electrical discharge phenomena such as lightning. Since organic matter is an important component of life, in the past Mars may have had an environment conducive to life, and this study may provide insights into the Martian life environment.

Our discovery has implications for JAXA's future Martian Moons eXploration (MMX) mission, the main goal of which is to bring back samples from the Martian moon Phobos to elucidate the origin of the Martian moons. As Phobos is exposed to the Martian upper atmosphere that has leaked from Mars, it is believed that the Martian atmospheric components will be transported to Phobos. Therefore, we expect to derive the pollution effects of the Martian atmosphere from the analysis results of the samples we bring back. We hope to understand the mechanisms of atmospheric escape from Mars, which will also lead to a better understanding of the Martian moons' environment for the future MMX mission.



A schematic illustration of the Hisaki's spectral observation of the Martian upper atmosphere. Analyzing hydrogen 1025Å and oxygen 1356Å emissions, we found an anticorrelation between the total amount of the hydrogen and oxygen upper atmospheres.

-Masunaga, K., et al., Alternate Oscillations of Martian hydrogen and oxygen upper atmospheres during a major dust storm, Nature Communications, 13, 6609, (2022), doi: 10.1038/s41467-022-34224-6

Solar wind plasma is prevented from entering Venusian atmosphere – Solar wind – Venus's boundary revealed by Mio's Venus swing-by

<BepiColombo/Mercury Magnetosphere Orbiter "Mio">

AIZAWA Sae
JSPS Research Fellow at ISAS

The JAXA/ESA BepiColombo mission, which is currently on its way to explore Mercury, and the ESA/NASA Solar Orbiter, which is observing the Sun from different perspectives, are both using a number of gravity-assists from Venus to change their trajectories and guide their journeys. On 9-10 August 2021, both missions flew past Venus within a day of each other, sending back observations synergistically captured from eight sensors and two vantage points in space.

Mio, one of two spacecraft of BepiColombo developed by JAXA, successfully observed the plasma environment at the boundary between the solar wind and Venusian ionosphere using multiple plasma instruments. It was initially believed that the conductivity in the Venusian ionosphere during the Solar minimum is lower than usual, making it easier for energy from the solar wind to transfer across the boundary into the Venusian environment. However, BepiColombo's observations revealed that the solar wind is prevented from entering the Venusian environment at higher altitude than anticipated, and this suggests that the collision between solar wind plasmas and the Venusian atmosphere, which is an energy transfer process, is unlikely to occur. These plasma observations during the solar minimum represent a first-ever exploration of this specific region and will contribute to the development of an updated model of energy transfer and gas dynamics on Venus based on our findings.

The fact that solar wind plasma is less likely to enter the Venusian environment than expected indicates that the atmospheric escape from the Venusian ionosphere may be lower than previously estimated. This finding has implications for our understanding of the long-term atmospheric evolution of Venus as a terrestrial-type planet, often considered Earth's twin. Further investigations through future space missions and updated gas-dynamic models are necessary to explore these processes. Additionally, our results demonstrate that variable discoveries can be made even within the operational constraints of gravity-assists of ongoing planetary missions.

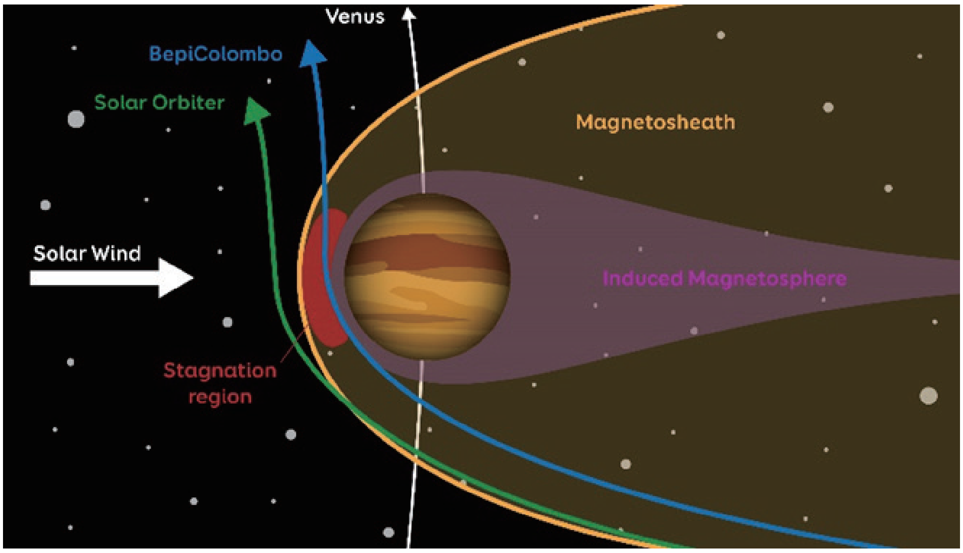


Illustration of the Venusian plasma environment and trajectory of BepiColombo
(©Thibaut Roger/Europlanet)

-Persson, M., et al., BepiColombo mission confirms stagnation region of Venus and reveals its large extent, Nature Communications, 13, 7743 (2022), doi:10.1038/s41467-022-35061-3

The first successful data assimilation for Venus's atmosphere using Akatsuki's wind data

<Venus Climate Orbiter Akatsuki (PLANET-C)>

MURAKAMI Shin-ya

Lunar and Planetary Data Analysis group/Akatsuki team

To understand the atmospheric circulations of Venus, such as super-rotation, which is a zonal wind reaching approximately 100 m/s at cloud top, we must know the time evolution of the three-dimensional wind field; however, observational data are sparse in space and time. As performed for Earth's atmosphere, data assimilation enables us to combine observational data with a numerical simulation model, to obtain improved, homogeneous data in space and time; we can estimate data using a numerical simulation model and observations.

In this research, we assimilated horizontal wind data acquired from images during the period from 01 September to 31 December 2018, including a contiguous observation period, into a simulation model run using the AFES-LETKF (Atmospheric GCM For the Earth Simulator-Local Ensemble Transform Kalman Filter) data assimilation system for Venus (ALEDAS-V) and examined the assimilation results in detail.

In a model run without data assimilation (called free run), the speed of super-rotation is 150 m/s, which is significantly faster than the observation. In a model run with data assimilation (called analysis), the simulated wind field has a similar structure to the observation; the super-rotation speed becomes 100 m/s and the location of the maximum wind field moves to the altitude of 65 km, which is around cloud top (Figure 1).

There is also an improvement in relation to the thermal tide that is considered to contribute to the generation and maintenance of the super-rotation. On zonal winds associated with a thermal tide at an altitude of 70 km, one of the local minima is at a local time of 14 hours for a free run and it moves to 12 hours for a model run with data assimilation, which is the same as the observation (Figure 2).

This research utilized only horizontal wind field data obtained by UVI 365-nm images; however, one can assimilate data of other periods or a different kind of data, such as temperature field data acquired from Longwave Infrared Camera (LIR) images, and such research will advance the understanding of the Venus atmosphere in the future.

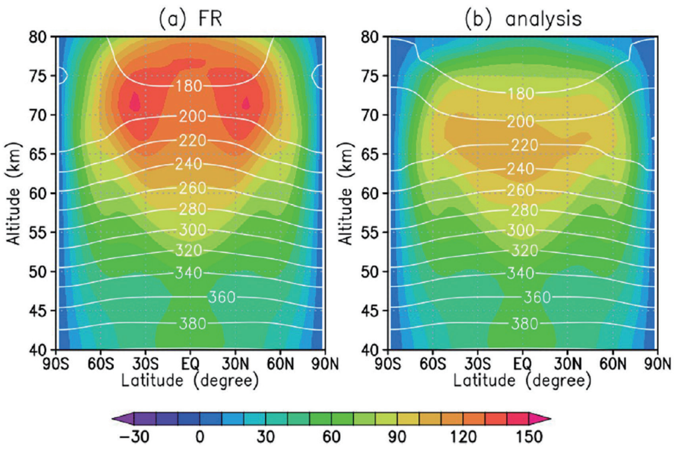


Figure 1. Latitudinal and vertical distributions of zonal-mean zonal wind (color, m/s) and temperature (contour, K) averaged over two Earth months: (a) free run and (b) analysis. (Fujisawa et al., 2022)

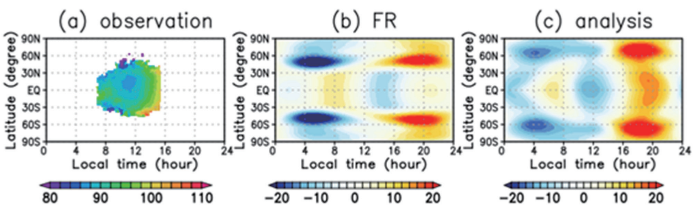


Figure 2. Local time and latitudinal distributions of zonal winds (m/s) associated with thermal tides at the cloud-top level. (a) observation, (b) free run, and (c) analysis. Taken from Figure 1 in Fujisawa et al. (2022) by deleting d-f for latitudinal winds.

-Fujisawa, Y., et al., The first assimilation of Akatsuki single-layer winds and its validation with Venusian atmospheric waves excited by solar heating, *Scientific Reports,* 12, 14577 (2022), doi:10.1038/s41598-022-18634-6

Hinode-IRIS-ALMA Observations Reveal Behaviors at the Foot of Solar Microflares

<Hinode (SOLAR-B)>

SHIMIZU Toshifumi
Department of Solar System Sciences

Solar microflares are amongst the major energy input sources that form the active nature of the solar corona. They are also an important element in understanding energy release mechanisms in the corona. We coordinated Hinode and IRIS satellite observations with ALMA's millimeter wave observation and succeeded to capture the behavior at the foot of a microflare for the first time. One of the interesting and surprising findings is that the magnitude of non-thermal energy impinging on the microflare foot was approximately 100 times smaller than the thermal energy produced in the corona. Another interesting finding is that the exact locations of the foot, which is detected as several brightening kernels, are in weak and void magnetic areas formed within a patchy distribution of strong magnetic flux at the solar surface. This provides a conceptual image that the transient energy release occurs in the corona on the sheaths of magnetic flux bundles connecting from the strong flux islands at the solar surface. These results are providing important suggestions in the understanding of physical mechanisms for transient energy release in the solar atmosphere.

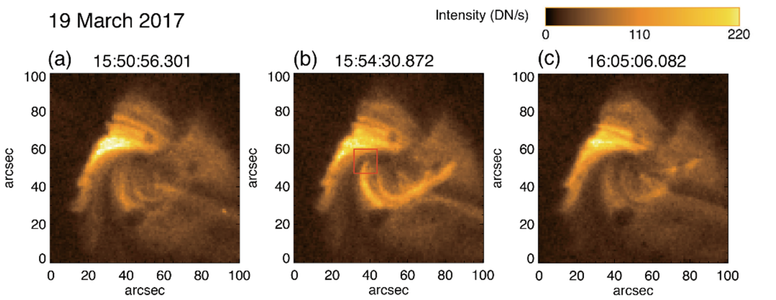


Figure 1. Soft X-ray images from Hinode X-ray telescope, acquired before, during, and after the loop-like microflare. The upper end of loop-like transient brightening (marked by the red rectangle) was successfully captured by IRIS slit jaw imager, ALMA, and Hinode Solar optical telescope's spectro-polarimeter.

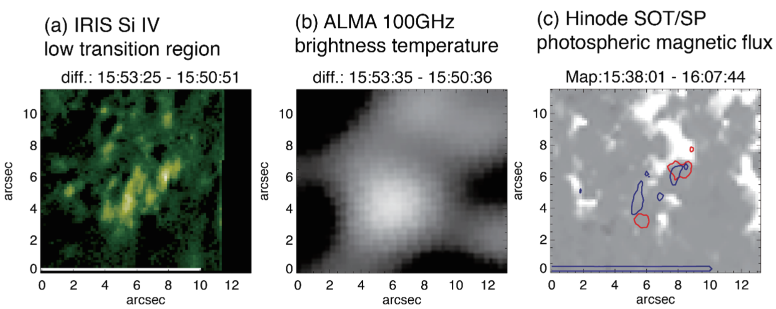


Figure 3. a) and b): Transient counterparts detected in Si IV (IRIS) and millimeter wave (ALMA). The image before the start of the brightening was subtracted to show transient counterparts. c): the magnetic flux distribution at the photosphere (Hinode Solar Optical Telescope's spectro-polarimeter) with contours showing the location of the transient counterparts in Si IV at two times during the event.

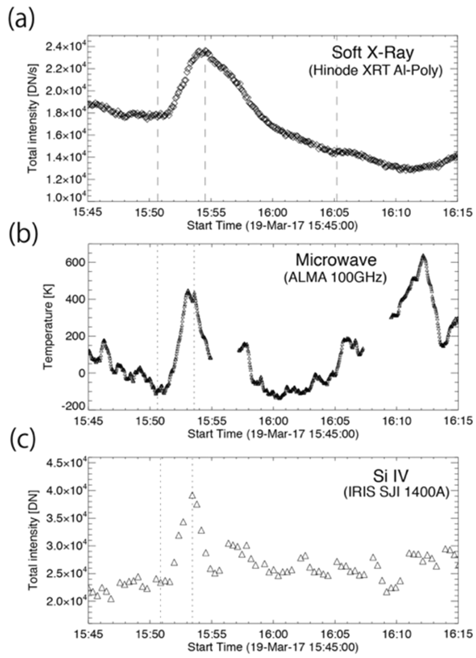


Figure 2. Temporal profiles of a) soft X-ray loop intensity (Hinode X-ray Telescope), b) millimeter wave (brightness temperature) by ALMA, and c) Si IV spectral line intensity (IRIS). Soft X-ray intensity and ALMA brightness temperature were used to derive the amount of the thermal energy produced in the corona and given to the foot.

-Shimizu, T., Abe, M., and Shimojo, M., Simultaneous ALMA-Hinode-IRIS Observations on Footpoint Signatures of a Soft X-Ray Loop-like Microflare, *The Astrophysical Journal,* 922, 113 (2021), doi:10.3847/1538-4357/ac27a4)

Nano Phenomena are Key to Formation of Carbonaceous Dust

<Small-scale program "DUST (Determining Unknown yet Significant Traits)">

INATOMI Yuko
Department of Interdisciplinary Space Science

Outer space contains large quantities of nanoparticles, called dust, less than 100 nm in diameter, which eventually become the material for planetary systems. However, the formation process of cosmic dust has not been theoretically explained in terms of particle size, structure, and other characteristics. Therefore, an international research team led by Hokkaido University investigated why a core-mantle structure with titanium carbide nanocrystals appears in carbonaceous dust.

The research team conducted a sounding rocket experiment in June 2019 in cooperation with Japan and Europe. In this experiment, titanium and carbon were vaporized at high temperatures to reproduce the conditions for cosmic dust formation under a microgravity environment for a few minutes. The formation of nanometer-sized particles via nucleation was observed in real time as the gas cooled, and the recovered experimental samples were analyzed in nanoscale detail using transmission electron microscopy.

By applying the experimental results and estimates of the gas environment emitted by the dying star to the theory of nanoparticle nucleation and crystal growth, the team found that a three-step process occurs in the formation of core-mantle particles, as shown in Figure 1. Atoms and molecules diffuse faster in nanoparticles than in the interior of macroscopic solids. In addition, around the dying star, the number density of carbon atoms is much higher than that of titanium atoms. Therefore, titanium atoms on the particle surface are quickly incorporated into the core as titanium carbide while carbon atoms continue to stack up around the core to maintain the mantle.

Previous studies on the formation of cosmic dust have assumed that the physical properties of nanoparticles are the same as those of macroscopic solids. The results of this research will lead to the establishment of a theoretical method to explain the characteristics of cosmic dust. It also provides a new interpretation of the formation process of particles found in meteorites that were used as materials in the formation of the solar system and dust detected by astronomical observations, focusing on the nucleation and rapid diffusion of the constituent elements and the fusion of particles with each other, which are nano phenomena.

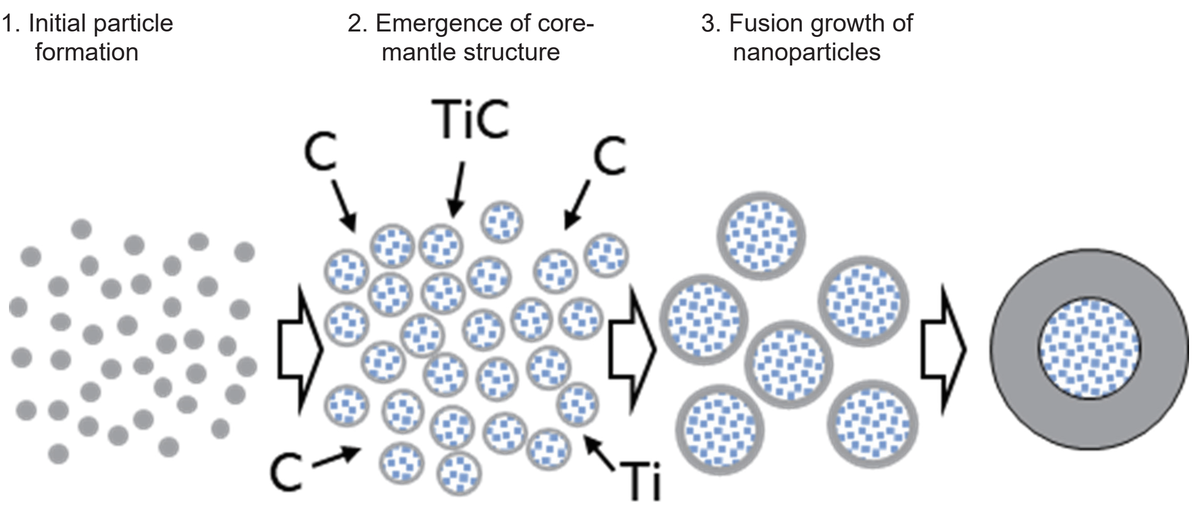


Figure 1. Schematic diagram of core-mantle particle formation process. Gray: carbon (C); light blue: titanium carbide (TiC).

-Kimura, Y., et al., Nucleation experiments on a titanium-carbon system imply nonclassical formation of presolar grain, *Science Advances 9,* eadd8295 (2023), doi:10.1126/sciadv.add8295

Extreme loss of mesospheric ozone levels occurring directly below the isolated proton aurora

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Science satellite Operation and Data Archive Unit

Radiation belt electrons, electromagnetic waves, and auroras are key phenomena in understanding ozone variations caused by radiation belt electrons. By measuring electromagnetic waves, we can determine "when" the atmospheric fallout began, and by measuring auroras, we can determine "where" the fallout occurred. Simultaneous observations of ozone fluctuations directly below the aurora and electrons in the radiation belt directly above the aurora can tell us "how" and "what part of" the atmosphere was affected. To understand these phenomena, researchers from a wide range of research fields came together to conduct an integrated observational study.

As in the previous studies, the generation of the isolated proton aurora was triggered by the generation of electromagnetic waves below 1 Hz, and radiation belt electrons were detected by the MAXI/RBM on the International Space Station (ISS) and POES satellites passing directly over the isolated proton aurora. The SABER instrument (TIMED satellite), which probes atmospheric composition, detected a clear decrease in mesospheric ozone in the mesosphere just below the aurora. It was found that only 1.5 hours after the onset of the isolated proton aurora, ozone in the mesosphere directly below the isolated proton aurora was reduced by 10-60%. The spatial size of the isolated proton aurora is approximately 400 km in the north-south direction, and the ozone decreases rapidly only in the spatially limited region directly below the isolated proton aurora. This result is the first observational evidence that radiation belt electron fallout from space around Earth has a direct, immediate, and localized effect on atmospheric variations in the mesosphere.

The MAXI onboard the ISS used in this research is an astronomical instrument, but through a publicly solicited research program conducted by ISAS, data from an auxiliary instrument called the Radiation Belt Monitor (RBM) was made available to the public through DARTS[1] after being prepared for easy use in other fields, such as geophysics. DARTS has been working on data development to make it easier to conduct research that combines various types of data.

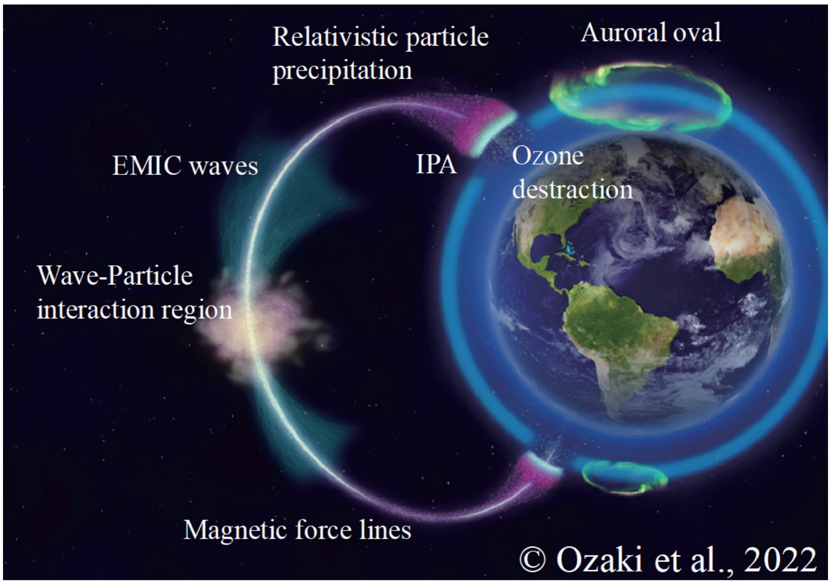

Illustration of the mechanism of ozone phenomena obtained from this study.

[1] https://darts.isas.jaxa.jp/

Ozaki, M., et al., Localized mesospheric ozone destruction corresponding to isolated proton aurora coming from Earth's radiation belt, *Scientific Reports,* 16300 (2022), doi:10.1038/s41598-022-20548-2)

Flyby Cycler Trajectory for Multiple Asteroid Exploration - Trajectory Design Approach by Machine Learning

OZAKI Naoya
Department of Spacecraft Engineering / DESTINY+ Project Team

More than one million small bodies have been discovered in the solar system so far. The frequency of JAXA's sample return missions is about once every 10 years, so it would take too long to obtain statistical information on such small bodies. One of the mission design solutions is utilizing a concept known as "asteroid flyby cycler" trajectories (Fig. 1). An asteroid flyby cycler is an orbit that alternately flybys Earth and asteroids, such as Earth → asteroid #1 → Earth → asteroid #2 → Earth → .... The asteroid flyby cycler trajectory design problem belongs to a class of global trajectory optimization problems associated with multiple flybys, in which two types of optimization problems are nested: a combinatorial optimization problem in determining the sequence of flybys and a trajectory optimization problem for a given flyby sequence. In particular, as the number of flyby targets increases, the computation time for the optimization problem increases exponentially, making it difficult to complete the computation in a realistic amount of time. Traditionally, evolutionary computation methods have been used to solve such global trajectory optimization problems. Evolutionary computation tends to require a large amount of computation time because it does not take advantage of the "experience" of experts, such as "a small body with some specific orbital elements would be easy to access". Therefore, the authors proposed a machine learning approach to model "experience" as a surrogate model and perform a global search utilizing the surrogate model. Given that one of the bottlenecks of machine learning approaches is the computational time required to generate a large trajectory database, we have established an efficient database generation method that can generate 10 times more data in the same computation time by introducing pseudo-asteroids that satisfy the optimality condition (= Karush-Kuhn-Tucker condition). The proposed method was applied to the extended mission after the Phaethon flyby of DESTINY+, demonstrating the applicability to the actual mission.

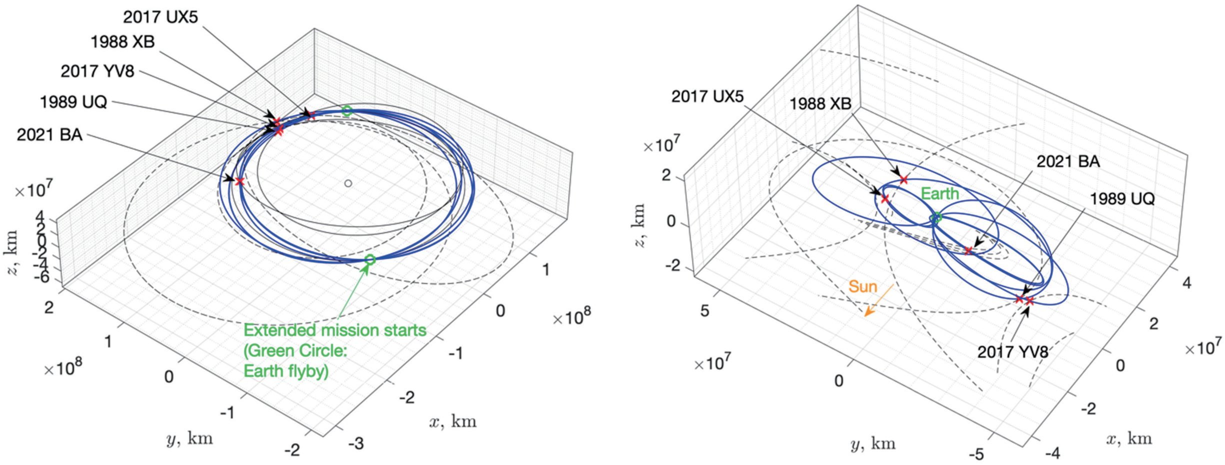

Figure 1. Overview of asteroid flyby cycler trajectories (left: Sun-centered and ecliptic plane centered inertial frame, right: Earth-centered and Sun-Earth line fixed rotational frame)

-Ozaki, N., et al., Asteroid Flyby Cycler Trajectory Design Using Deep Neural Networks, *Journal of Guidance,* Control, and Dynamics, Vol.45(8),(2022), doi:10.2514/1.G006487

A "magic equation" might solve a problem: "Computers being startled"~ IEEE NSREC Outstanding Conference Paper Award

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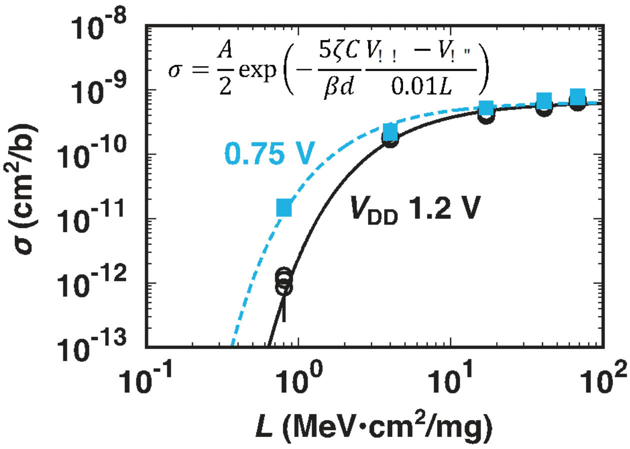
Department of Spacecraft Engineering

Computer chips must be protected from bombardments of cosmic rays for their trouble-free operation in artificial satellites and space probes. To this end, the development of countermeasures requires a priori information regarding the area of computer chips that is sensitive to cosmic rays. We have found that an equation provides the sensitive area, despite being simple in form like the equations learned in high-school math textbooks. This equation was presented at the 2021 IEEE Nuclear and Space Radiation Effects Conference (NSREC) and selected as the recipient of the Outstanding Conference Paper Award after a rigorous two-stage nomination-and-selection process by the award committee.

Computer chips used in spacecraft require high reliability for trouble-free operation in space. Ensuring cosmic-ray reliability is particularly important. In general, computer chips are sensitive to cosmic rays, sometimes so sensitive as to fail even by the single strike of a cosmic ray.

To make the best countermeasures requires a priori information on the size of the sensitive area. Obtaining this information is burdensome because it requires high-cost experiments using cyclotron accelerators and/or high-cost simulations, which may consume a few months for computation time. Thus, it would be like magic to identify the size of the sensitive area without any bombardments of cosmic rays.

We have developed an equation as a step towards making the magic come true. As shown in the figure, the equation describes how the sensitive area σ evolves as a function of strength of cosmic-ray denoted by L. The equation has many parameters other than σ and L, but they are dominated by the properties of computer chips. Thus, they have the potential to be determined based on the design of a target computer chip (precisely, an SRAM chip) or from the property of the physics of cosmic ray effects. The proposed equation is a simple exponential function, i.e., $y = e^x$., which is as simple as equations learned in high-school math textbooks. We have shown that such a simple equation successfully provides sensitive areas, the measurement of which usually consumes more than two days in a cyclotron test.



Equation results (lines) and experimental results (symbols). This figure was taken from the paper under the license of CCBY4.0. Two voltage conditions (V_{DD}) are compared. Note that the equation is slightly different from the original one reported in the paper. The factor of five is inserted, as suggested in our recent paper: Kobayashi D. et al., Threshold and characteristic LETs in SRAM SEU cross section curves, *IEEE Transactions on Nuclear Science*, Vol. 70(4), pp.707–713,(2023), doi: 10.1109/TNS.2023.3244181.

-Kobayashi D., et al., An SRAM SEU cross section curve physics model, *IEEE Transactions on Nuclear Science*, Vol. 69(3), pp.232–240, (2022), doi:10.1109/TNS.2021.3129185

Succeeded in observing the internal plasma of the ion thruster cathode

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This paper was ranked as the 2nd Most-Read Article of 2022 in the American Institute of Physics/Journal of Applied Physics. This paper was also selected as a “featured article” and “Scilight (science highlight)”.

An ion thruster is one of the forms of electric propulsion and consists of two major components, namely an ion source and a neutralizer cathode. The cathode emits electrons to neutralize the ion beam accelerated by the ion source. Our laboratory previously developed a microwave discharge cathode as the neutralizer cathode of the microwave gridded ion thruster μ10, which was the main propulsion system for the asteroid sample return mission Hayabusa and its successor Hayabusa2. Although the Hayabusa mission was a success, it was observed that the cathode degraded faster than it did in the ground endurance test. Therefore, it is necessary to clarify the deterioration mechanism and extend the lifetime.

To determine the operation and degradation mechanisms of the cathode, it is important to clarify the plasma parameters both outside and inside the cathode. However, the parameters inside the cathode have not been well investigated. It is difficult to experimentally measure the plasma parameters inside the cathode using mechanical probes without significantly affecting the internal plasma. However, by the optical approach, it is also difficult to measure plasma parameters inside a cathode without affecting its performance. To investigate the actual condition of the Hayabusa2 onboard cathode, we needed to develop a cathode with an optical window that has equivalent characteristics to those of the flight model. By conducting a careful study of the microwave power, electron current and flow of ions, we realized a visualizable cathode.

As shown in Figure 1, high intensity plasma was observed especially at the bent inner root of the antenna and at the edge of the magnetic circuit the first time.

In addition, we measured ion density and velocity distributions by laser-induced fluorescence spectroscopy. Figure 2 shows multimodal (multiple peaks in the range of velocities) characteristics in the cathode. Therefore, we investigated the relationship between the ion acoustic wave and the multimodal characteristics. As a result, the ion oscillation model well matched the measured multimodal characteristics. It was suggested that the ion energy is increased due to ion oscillation, and increased ion energy has possibility for faster deterioration.

The development of a microwave discharge cathode with an optical window for visual observations can provide important knowledge to clarify problems such as the deterioration mechanism and improve thruster performance for future explorations.

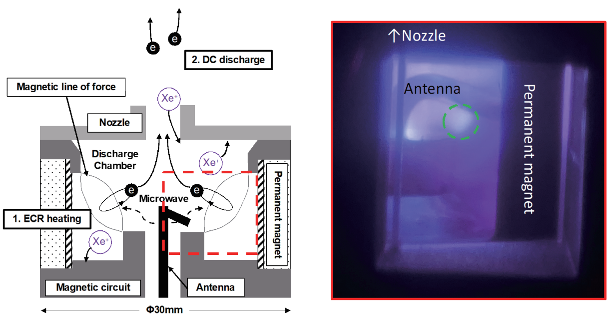


Figure 1. Schematic diagram of microwave discharge cathode (left) and photograph of the internal plasma (right).

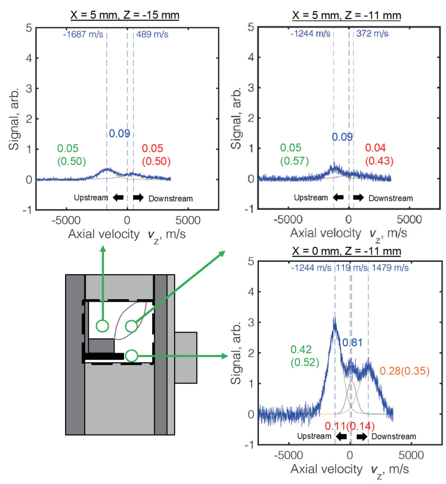


Figure 2. Axial ion velocity distributions inside the microwave discharge cathode.

-Morishita, T., et al., Plasma parameters measured inside and outside a microwave-discharge-based plasma cathode using laser-induced fluorescence spectroscopy. *Journal of Applied Physics*, 131 (1), 013301, (2022), doi:10.1063/5.0071294

Furthering International Collaborations
<Hayabusa2 Sample Analysis and MMX (Martian Moons eXploration)>

International Strategy and Coordination

Artemis I is the first in a series of US-led international space exploration Artemis programs intended to demonstrate the uncrewed flight of the manned probe Orion. It was joined by 10 small satellites known as CubeSats, two of which are OMOTENASHI and EQUULEUS, which were proposed and adopted by JAXA in 2016.

In July 2021, a memorandum of understanding (MOU) was signed between NASA and JAXA for the launch of these CubeSats. After facing many delays, Artemis I was launched from NASA Kennedy Space Center in November 2022.

The CubeSats were successfully deployed into deep space. OMOTENASHI gave up on landing on the moon due to anomalies after separation. Although it was a hard lesson in terms of the difficulty of exploration with a small satellite, JAXA was able to participate substantially at the dawn of this international space exploration program.

In early August, we visited government and university-related organizations in three Australian cities and reported on the results of the return and recovery of Hayabusa2. In the Mars Moon eXploration (MMX) program, which has a scheduled launch in 2024, we asked for Australia's cooperation in collecting capsules in Woomera, as well as obtaining Australian science cooperation.

As a result of further coordination, during the Japan-Australia Leaders' Meeting held in Perth, Australia in October 2022, the leaders expressed their preliminary approval for the landing of the MMX (Martian Moons eXploration) capsule in Australia in a joint statement. It is expected that the cooperative relationship with Australia, which was formed with the "Hayabusa" series, will be further developed and strengthened.

Image 1. Artemis I Launch at NASA Kennedy Space Center

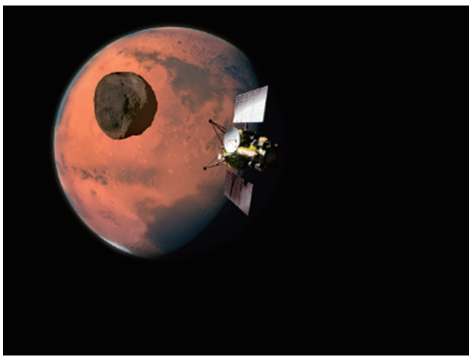


Image 2. Artist's concept of MMX, Phobos, and Mars

Human Resource Development Opportunities at ISAS: ISAS accepts a diverse range of human resources

Management and Integration Department

The Institute of Space and Astronautical Science (ISAS) has been working to develop human resources in accordance with JAXA's Human Resource Development Policy and ISAS's Basic Policy on Human Resource Development. ISAS is actively promoting the development of human resources by utilizing its unique on-site environment. In FY2022, we accepted diverse human resources for human resource development opportunities by utilizing projects and experimental opportunities, such as sounding rocket experiments, atmospheric balloon experiments, and SLS-equipped Cubesats.

■Human resource development using small-scale experimental opportunities (Sounding rocket / Scientific balloon experiments)

Sounding rocket experiments and scientific balloon experiments are, despite their small scale, characterized by the ability to experience the cycle of systematic and project-like activities in a short period, and trainees are accepted every year. In this regard, ISAS students and young staff from Tanegashima Space Center (TNSC) participated as trainees in a sounding rocket experiment. Additionally, newly-hired JAXA employees were accepted for a balloon experiment in Taiki Town, and staff at Sagamihara Campus participated in a scientific balloon experiment in Australia to be conducted from FY2022 to FY2023.

The training was not passive like an observation tour, but focused on the participants' independence, with them being assigned to actual work groups and engaging in actual on-site work together with engineers and staff. Through their involvement in space science projects, the participants were able to improve their basic understanding of the knowledge, techniques, and approaches required for project execution, as well as learn aspects of project management required for smooth execution as system personnel.

■Practical human resource development through the development and operation of Cubesats (OMOTENASHI/ EQUULEUS)

In the development and operation of the Cubesats OMOTENASHI and EQUULEUS, launched by NASA's SLS in FY2022, young personnel were mainly responsible for a series of project cycles up to operation. In consideration of the fact that the opportunity for actual operation by the staff is one of the most valuable on-site opportunities at JAXA, trainees were accepted in the form of an open invitation, and many young members from throughout JAXA were involved in the actual operation (sending commands, etc.). This unique on-site experience improved the participants' understanding of the fundamentals of satellite operation and led them to obtain feedback on their own duties from various perspectives, providing them with a valuable opportunity to gain a wide range of knowledge, both administrative and technical.

■Future developments

In addition to the opportunities listed above, ISAS provides many other opportunities for human resource development, including Hayabusa2 operations, in-house development opportunities at the Advanced Machining shop, and geological mapping opportunities in the Lunar and Planetary Exploration Data Analysis Group.

In addition to creating new opportunities for human resource development, ISAS will make maximum use of the ISAS site in the next fiscal year and beyond to contribute to the development of human resources for a wide range of space fields, including space science.

Participants were involved in the actual operation of the spacecraft.

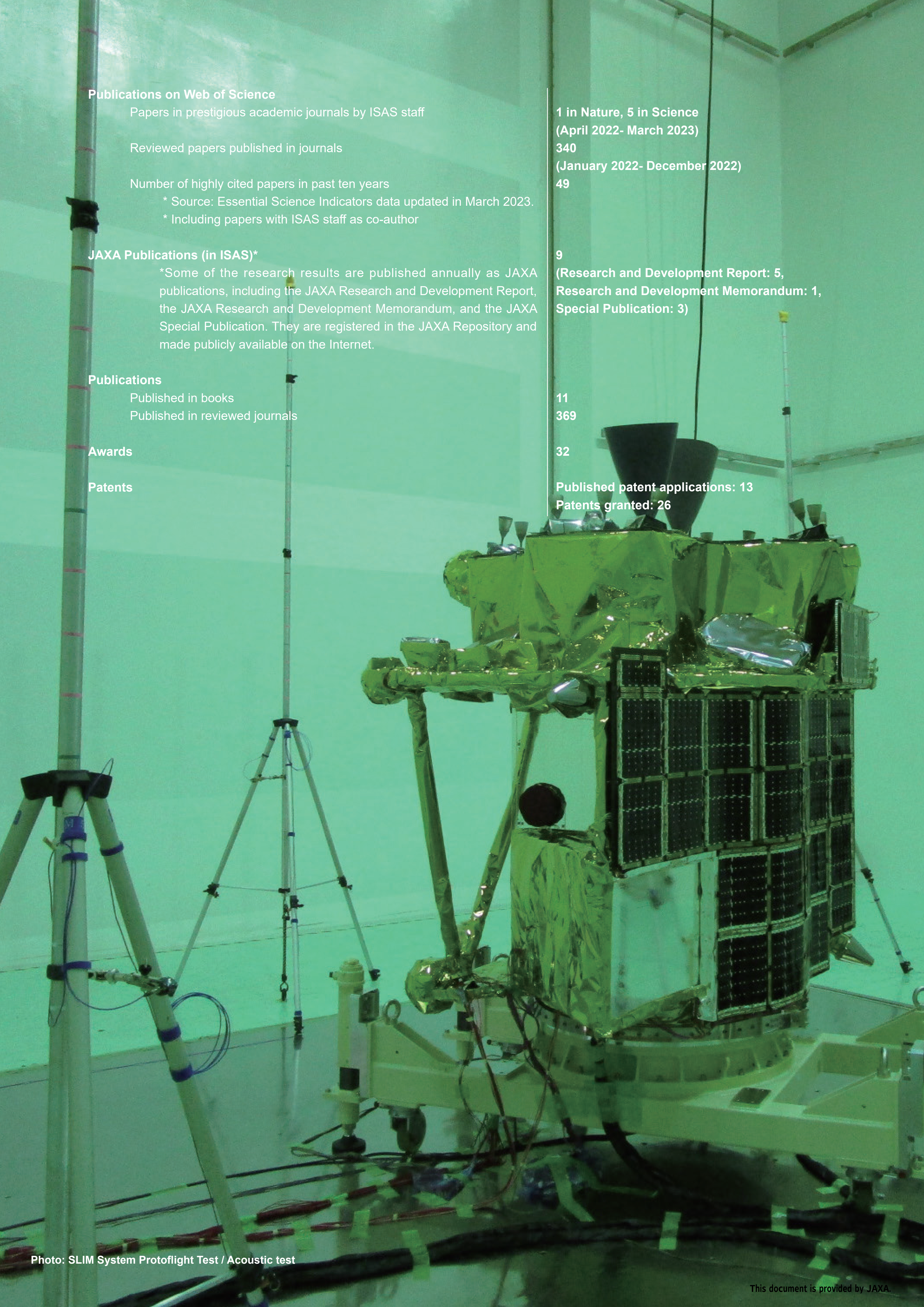
New initiatives for outreach at ISAS and JAXA Sagamihara Campus

Education and Public Outreach, and Management and Integration Department, ISAS

As a cross-departmental outreach initiative at JAXA Sagamihara Campus, "Friendraising" was launched in fiscal year 2022. The first phase of the project was a crowdfunding campaign, to make people feel the universe is more accessible, or to enhance the space experience and focus on interactive content. A traveling exhibition of the Hayabusa2 re-entry capsule, which started in fiscal year 2021, was continued, and replicas of the Ryugu samples were distributed to exhibition facilities throughout Japan in 2022. During President Biden's visit to Japan, actual Ryugu samples were displayed at an exhibition on Japan-U.S. Space Cooperation, contributing to the strengthening of Japan-U.S. cooperation in the future. From a long-term standpoint, as both an objective and action item in accordance with the Act on Promotion of Women's Participation and Advancement, we held our first online individual career counseling event for female students who are interested in space science.

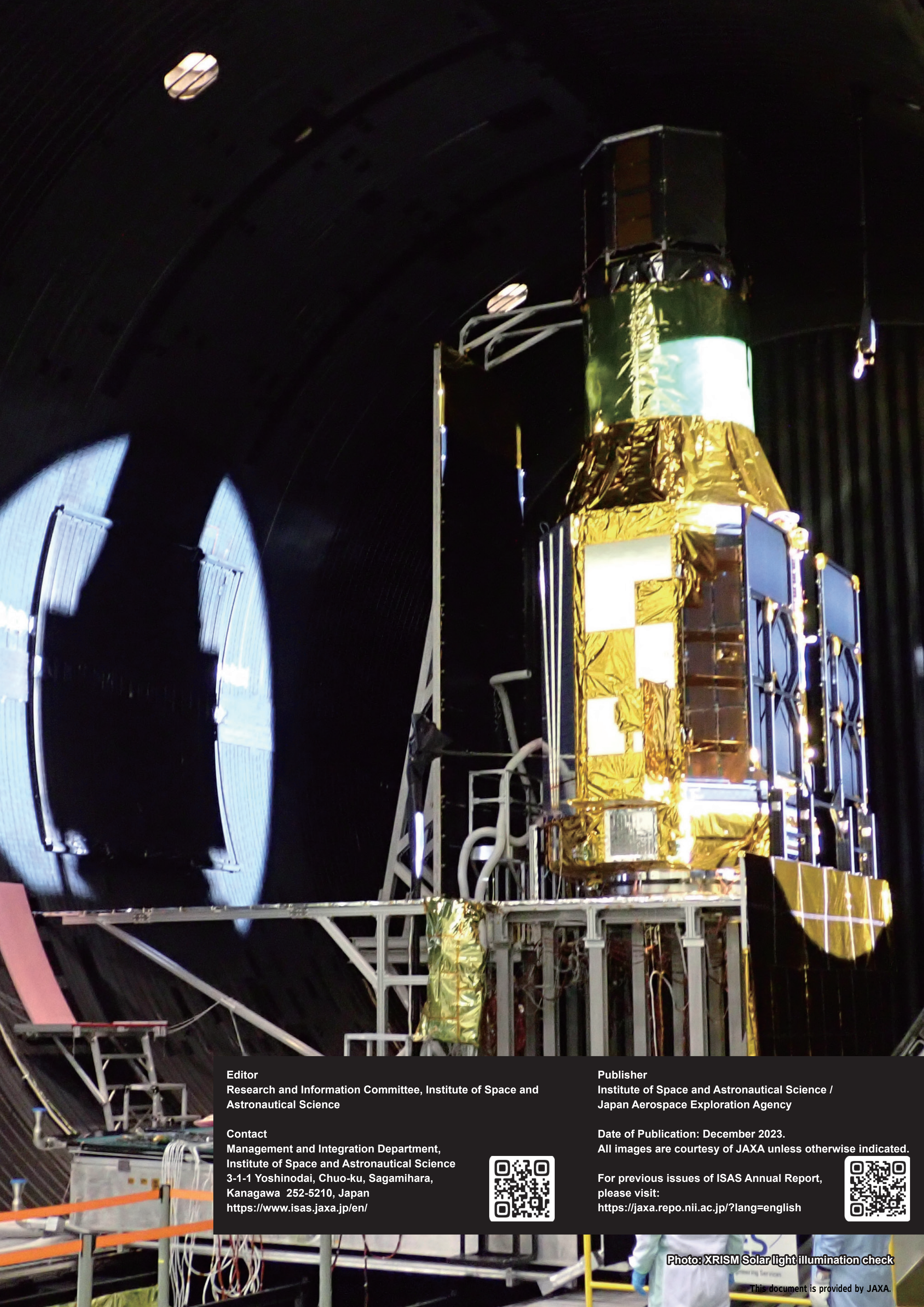
- The friendraising activity was launched in fiscal year 2022 to foster and expand support for the field of space science and exploration at Sagamihara Campus. As the first phase of the project, we launched a crowdfunding campaign aimed at enhancing the space experience and interactive content under the theme of "Bringing the universe closer to us", and received donations from approximately 430 people. Through the exchange of messages of support and gifts, including small-group social events with executives and staff, facility tours, and limited-edition merchandise to enhance a sense of camaraderie, we were able to have more opportunities to interact with the public than ever before. In the future, we will further enhance the space experience and interactive content, which was the objective of this crowdfunding campaign.
- In September 2021, the traveling exhibition of the Hayabusa2 re-entry capsule started in Japan, and was well received and became popular. In fiscal year 2022, we solicited the venue or cooperating organizations to continue the traveling exhibition across Japan. In addition, an enlarged replica of the third largest Ryugu sample brought back to Earth was made and distributed to facilities throughout Japan in order to be displayed sequentially in all 47 prefectures in Japan, starting just before HAYABUSA Day, June 13 (the day was named in recognition of the HAYABUSA's return to Earth in 2010), in 2022.
- In May 2022, Mr. KISHIDA Fumio, Prime Minister of Japan, and Mr. Joseph R. Biden, Jr., President of the United States of America, visited an Exhibition on Japan-U.S. Space Cooperation to see the actual Ryugu samples. The samples to be collected by NASA's OSIRIS-REx sample return mission in the U.S. and the Ryugu samples are scheduled to be mutually exchanged, and a comparison of the two samples is expected to lead to world-first discoveries, which is one form of deepening and strengthening Japan-U.S. cooperation.
- In October 2022, individual career counseling sessions for female students were held online, as a pre-evening event for the campus' annual open day. Sixteen JAXA researchers and other staff members served as advisors to provide individual counseling, mainly to female junior high school, high school and university students, on their career choices. Since it was held online for the first time, the geographic scope of the participants was broad, ranging from Aomori Prefecture in the north, to Kagoshima Prefecture in the south of Japan. A total of 27 people participated, including five junior high school students, ten high school / technical college students, five university students and graduate students, and 7 parents. In response to a questionnaire asking whether the session was at all helpful in choosing their career path, 75% of the respondents answered, "Very helpful" and 25% answered "Helpful".

Exhibition on Japan-U.S. Space Cooperation
(Photo: Cabinet Public Affairs Office)



Publications on Web of Science	
Papers in prestigious academic journals by ISAS staff	**1 in Nature, 5 in Science (April 2022- March 2023)**
Reviewed papers published in journals	**340 (January 2022- December 2022)**
Number of highly cited papers in past ten years * Source: Essential Science Indicators data updated in March 2023. * Including papers with ISAS staff as co-author	**49**
JAXA Publications (in ISAS)* *Some of the research results are published annually as JAXA publications, including the JAXA Research and Development Report, the JAXA Research and Development Memorandum, and the JAXA Special Publication. They are registered in the JAXA Repository and made publicly available on the Internet.	**9 (Research and Development Report: 5, Research and Development Memorandum: 1, Special Publication: 3)**
Publications	
Published in books	**11**
Published in reviewed journals	**369**
Awards	**32**
Patents	**Published patent applications: 13 Patents granted: 26**

Photo: SLIM System Protoflight Test / Acoustic test



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