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Annual Report of the Institute of Space and Astronautical Science 2022

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ON THE COVER

Successful launch of S-520-32

Shown in the cover is an image of S-520-32 immediately after its launch. It was launched at 23:20:00 (JST), midnight local time, on 11 Aug 2022, and the plume of the rocket motor glowed a pale orange. The rocket soared through the darkness ahead of the plume, leaving the launcher standing in a cloud of smoke. As the objective of S-520-32 is "Observation of the vertical and horizontal structure of electron density in the ionospheric E and F region during MS-TID (Medium Scale – Traveling Ionospheric Disturbance)", many antennas and sensors are mounted in the payload section. The upper right image shows the payload section with a half nose-cone, while the lower image shows the payload section with an extended NEI antenna after a spin timer test. From the top of the payload section, a VAS sensor (black one), NEI antenna, IOG, GNSS antennas (red circular ones), MAS, EFD, and other electronic equipment including their processing units, are mounted, and they can measure electron density in the ionosphere using various approaches.

ON THE BACK COVER

Optical microscopic image of Ryugu particle A0241.

・An optical microscopic image of A0241, which was recovered from "Tamatebako" point on the surface of the asteroid Ryugu, measures 2.12 mm along its major axis and weighs 2.6 mg. As shown in the micrograph, it is occupied by a black matrix and contains shiny fine mineral grains on its surface. Its infrared spectrum reveals that it mainly consists of hydrous minerals and contains carbonate and/or organic material. This particle was allocated to the researcher selected in the second announcement of opportunity for Ryugu samples announced in June 2022.

Photo: Scientific balloon experiment B22-07

A Message from the Director General

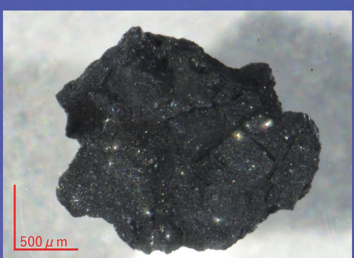
Since fiscal year 2022, we are returning to full-fledged space science with the CubeSats OMOTENASHI and EQUULEUS, launched on NASA's ARTEMIS-1 rocket in November 2022, ESA's Jupiter Icy Moons Explorer (JUICE), launched in April 2023 with JAXA's contribution through science instruments, Smart Lander for 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

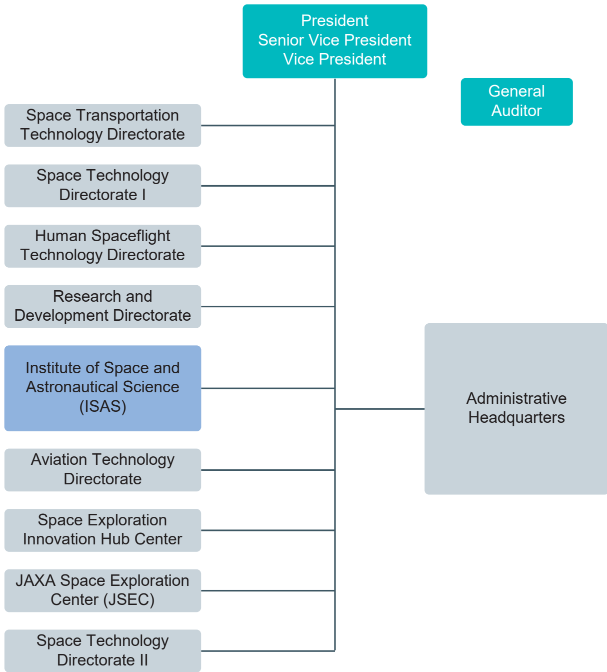


A snapshot of researchers from Institut d'Astrophysique Spatiale (IAS) in France with the Astromaterials Science Research Group (ASRG) curation staff in front of the infrared microscope "MicrOmega."
This is a snapshot of Prof. Jean-Pierre Bibring (right in the back row) and Prof. Cedric Pilorget (center in the back row) with the Astromaterials Science Research Group (ASRG) curation staff in front of the infrared microscope "MicrOmega", which was provided by IAS in France and utilized for the initial description of Ryugu samples. It was taken at the end of May 2022 when they visited the Extraterrestrial Sample Curation Center (ESCuC) at ISAS/JAXA. ASRG curation staff used to analyze Ryugu samples with the MicrOmega in cooperation with IAS staff who were connected online using a video teleconference system. The display behind them shows an infrared microscopic image of Ryugu samples analyzed using the MicrOmega.

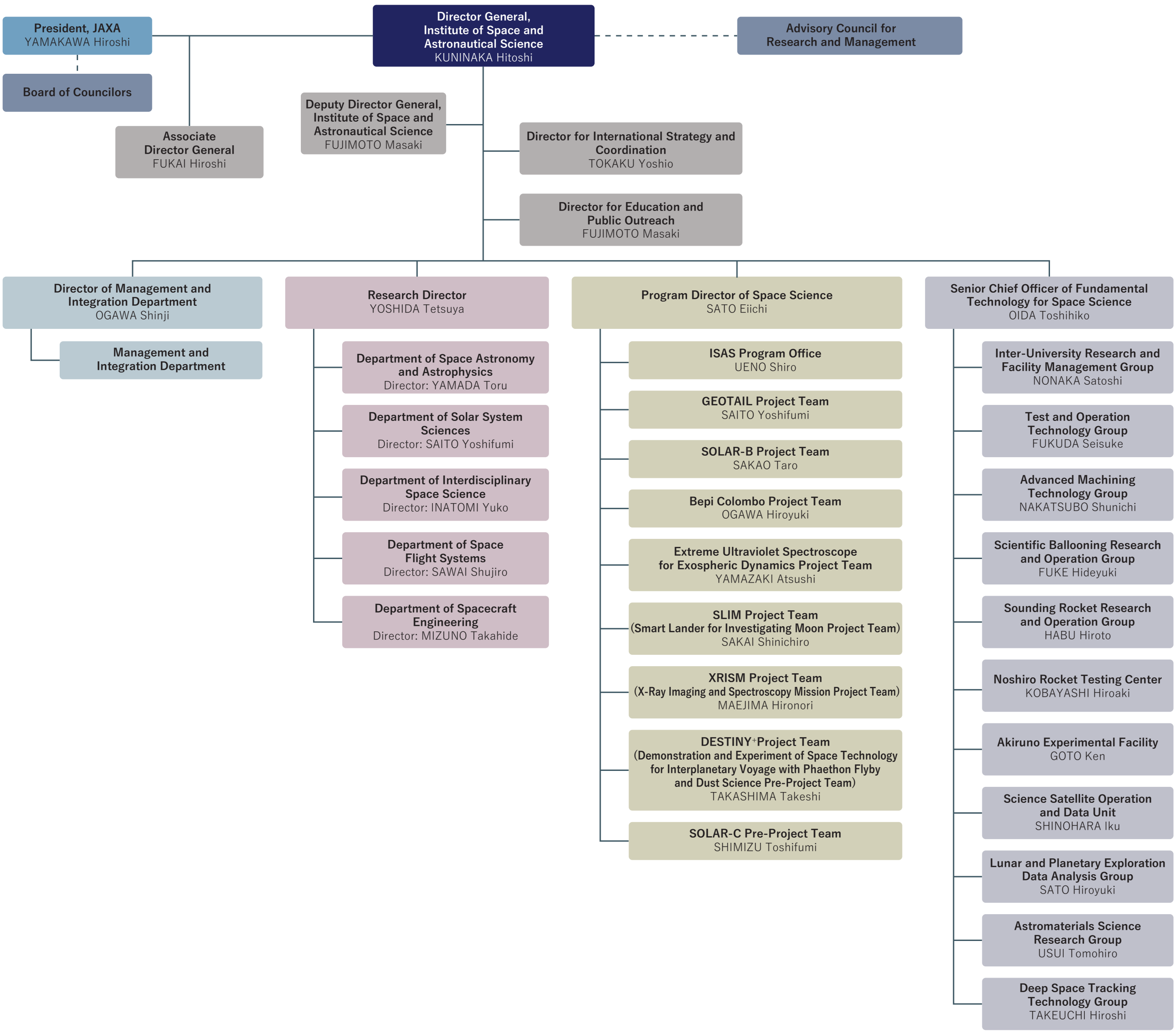
ISAS at a Glance

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)



ISAS at a Glance

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.

ISAS at a Glance

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

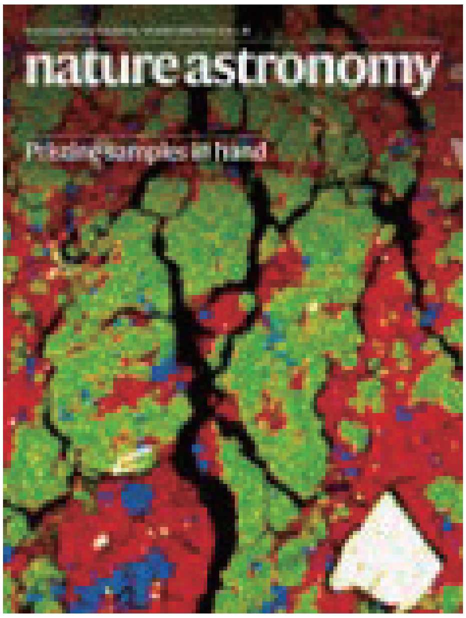
The Sagamihara Campus International Guest House provides accommodations for collaborative researchers, etc., who come from all over Japan and overseas to conduct research using the facilities of ISAS.

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.

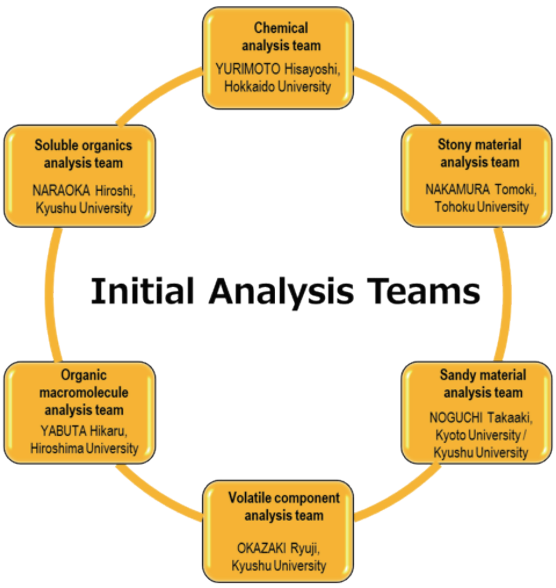
In FY2022, initial analysis (including destructive analysis) was conducted by domestic and overseas universities and institutions that have strengths in their respective analytical technologies, based on the sample catalog of the asteroid Ryugu and analysis conducted using non-destructive methods developed 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.

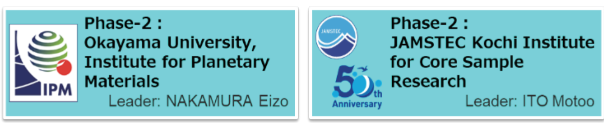


Ryugu sample analysis paper featured on the cover of *Nature Astronomy,* Published October 13, 2022.

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



Phase-2 Curation Institutions



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.

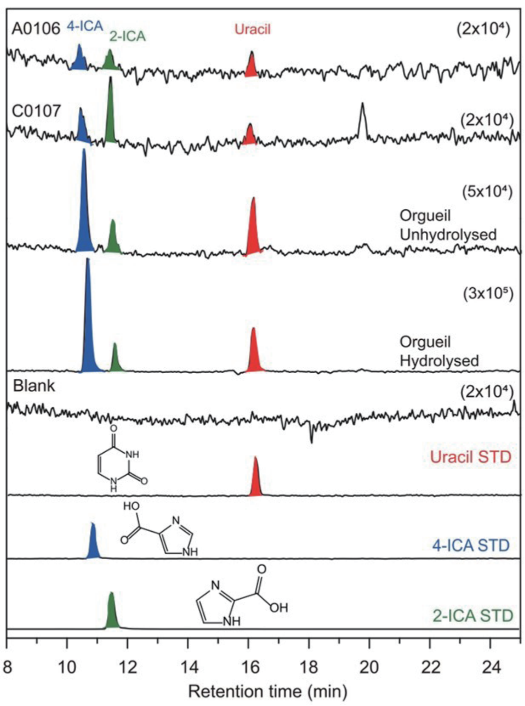


Figure 1. Uracil, a nucleic acid base detected from Ryugu samples (Oba et al., 2023). Uracil is one of the constituents of RNA and an organic molecule that is necessary for the birth of primitive life.

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.

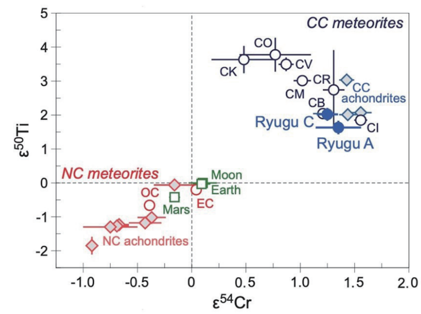


Figure 1. ^{54}Cr-^{50}Ti isotopic diagram showing Ryugu and meteorite data by high mass resolution isotopic analyses. Ryugu A and C samples are plotted in the range of carbonaceous chondrites, especially close to CI chondrites.

- 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.

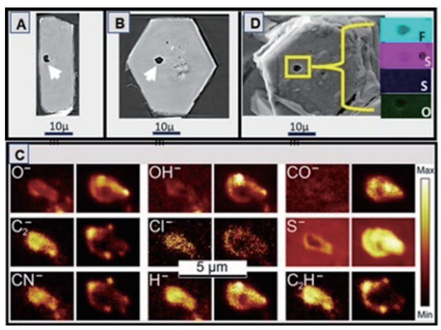


Figure 1. Fluid inclusion found in pyrrhotite of the Ryugu samples. It was determined that the fluid is carbonated water containing salts and organic matter.

- 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.

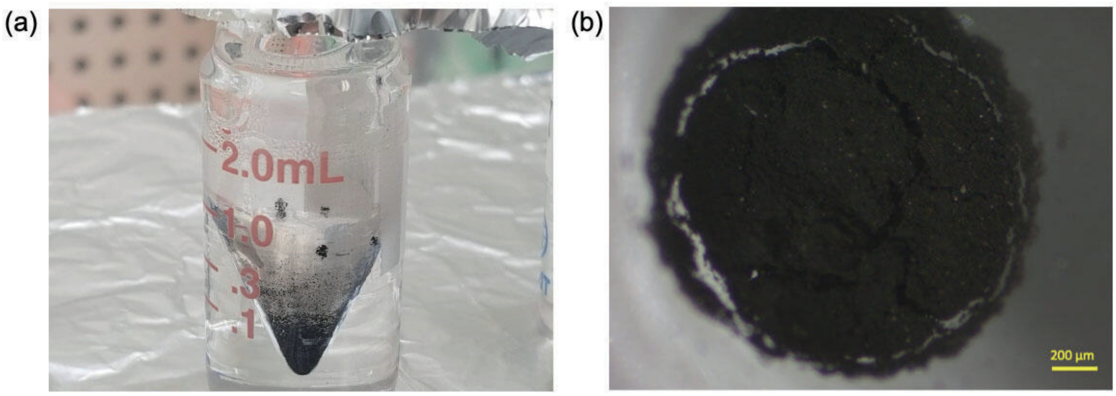


Figure 1. Images of insoluble carbonaceous residues isolated from the intact Ryugu aggregates (A0106) by HF/HCl treatment. (A) The Ryugu carbonaceous residue in a mini glass vial. (B) An overhead image of the Ryugu carbonaceous residue aliquots transferred in another mini vial.

- 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.

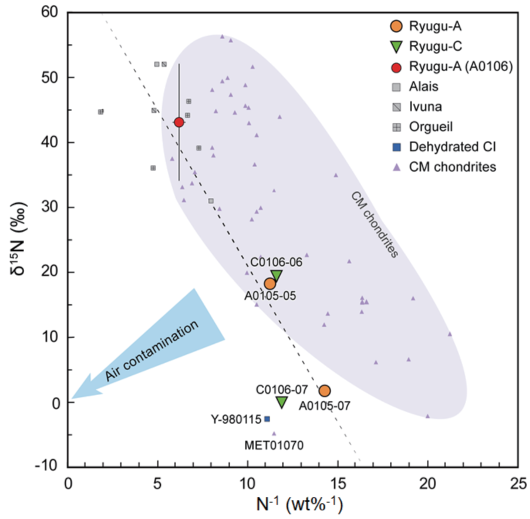


Figure 1. The Nitrogen isotope composition of the Ryugu sample grains (vertical axis, measured as the difference from Earth's atmosphere in parts per thousand) vs. the inverse nitrogen abundance (weight ratio: horizontal axis). The Ryugu grains (orange circles, green inverted triangles, red circle) each 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)

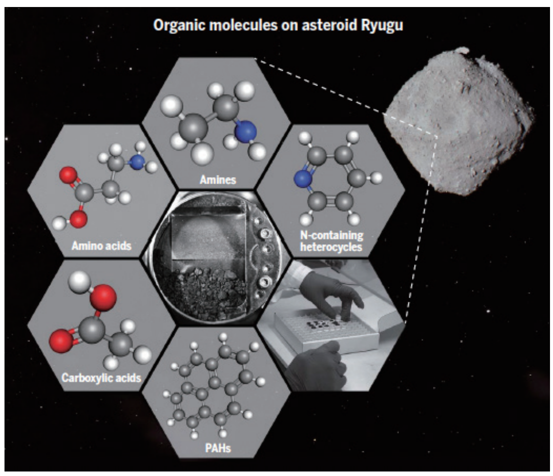


Figure 1. Various kinds of organic molecules found in Ryugu samples. 20,000 organic molecules, including amino acids, the building blocks of life, were detected from them.

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.

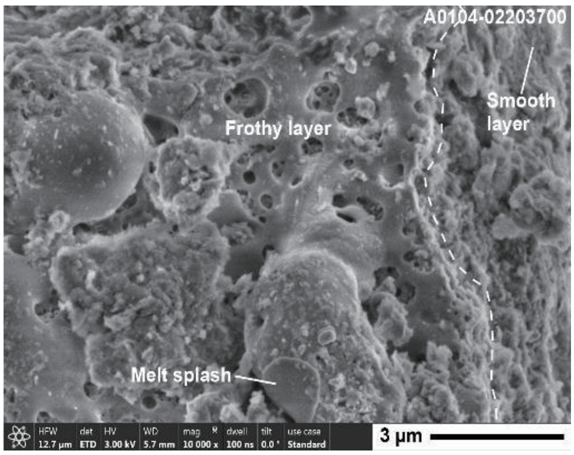


Figure 1. Space weathering of a Ryugu grain. The smooth layer on the right side of the dotted line has been subjected to space weathering from solar wind irradiation. The frothy layer visible on the left side has experienced space weathering from micrometeoroid impacts and contains deposits of thin layers 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 (^3He) 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.

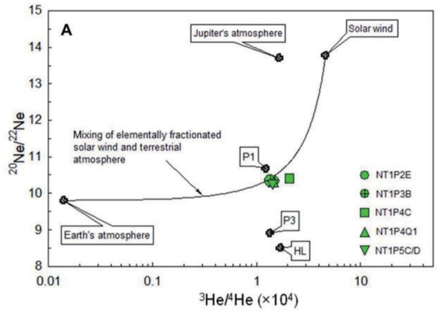


Figure 1. Helium and neon isotopic diagram showing data of gaseous components recovered from the Hayabusa2-sampler container. The container gas is plotted on the mixing line between solar wind and Earth's atmosphere, indicating the spacecraft succeeded in returning the first gas samples from the extraterrestrial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

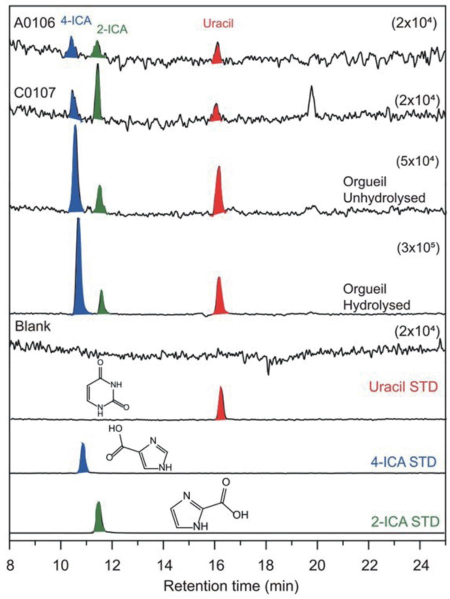


Figure 1. Uracil and its structural isomers detected from Ryugu samples. Uracil is one of the four nucleobases making up the RNA of all life on Earth.

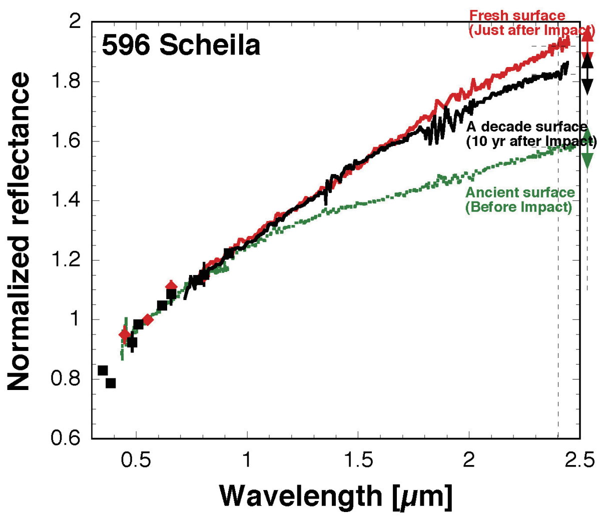
- Oba et al. Uracil in the carbonaceous asteroid (162173) Ryugu, Nature Communications volume 14, Article number: 1292 (2023). doi: 10.1038/s41467-023-36904-3

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

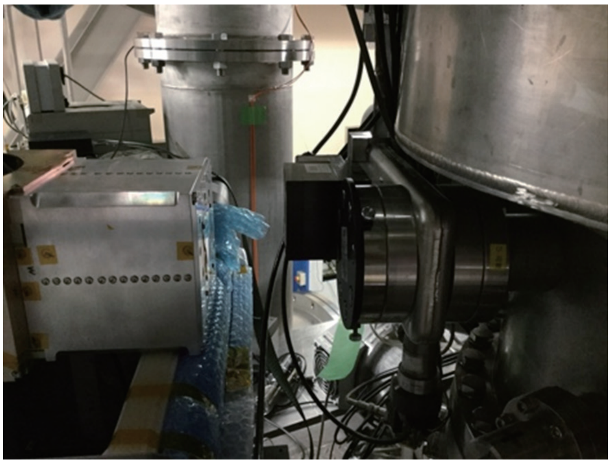
- New physics experiments opened up by a state-of-the-art space observation instrument -

WATANABE Shin
Department of Space Astronomy and Astrophysics

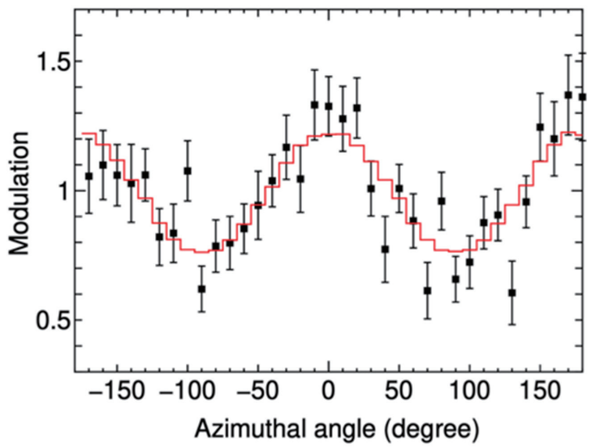
An unanticipated polarization of high-energy X-rays emitted when highly charged ions capture high-energy electrons has been discovered experimentally for the first time. The measurement used a high-energy X-ray polarization detector that was originally developed for high sensitivity space observations 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)>

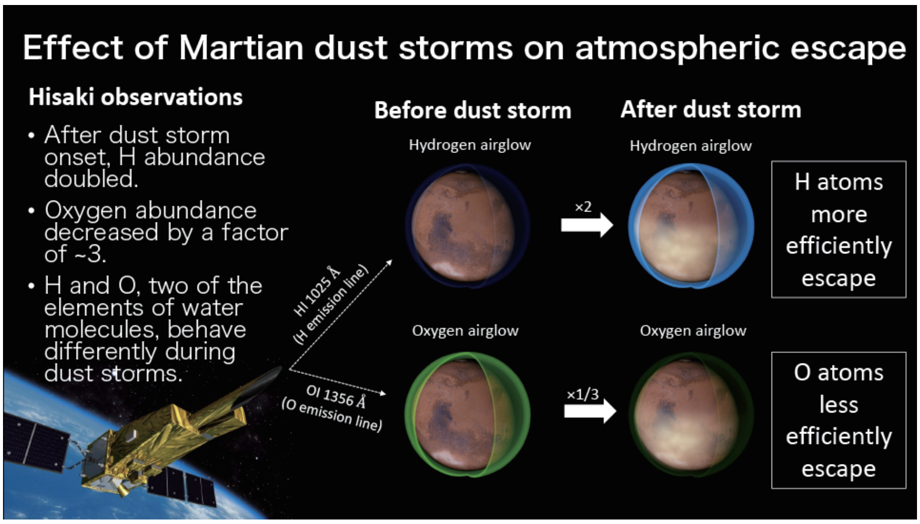
MASUNAGA Kei
Department of Solar System Sciences

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.

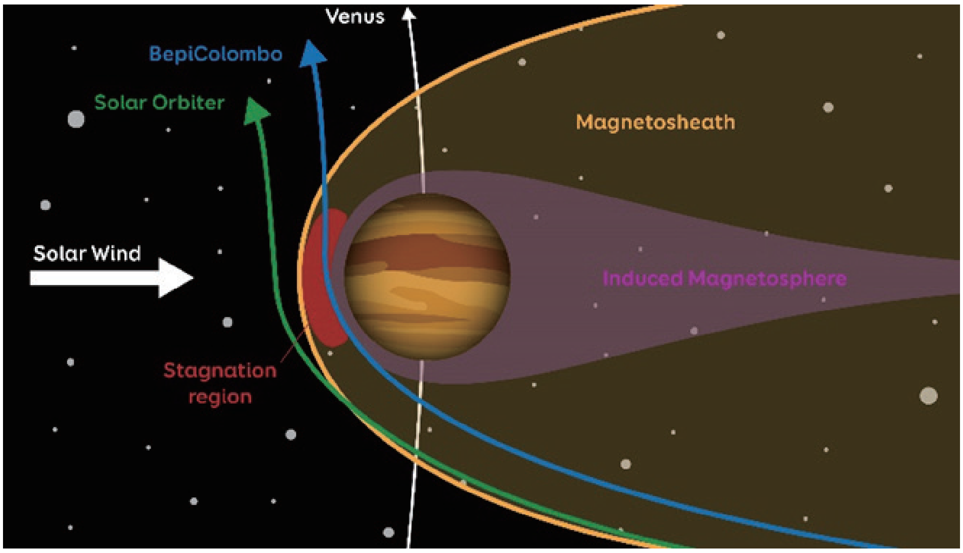


Illustration of the Venusian plasma environment and trajectory of BepiColombo
(©Thibaut Roger/Europlanet)

-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.

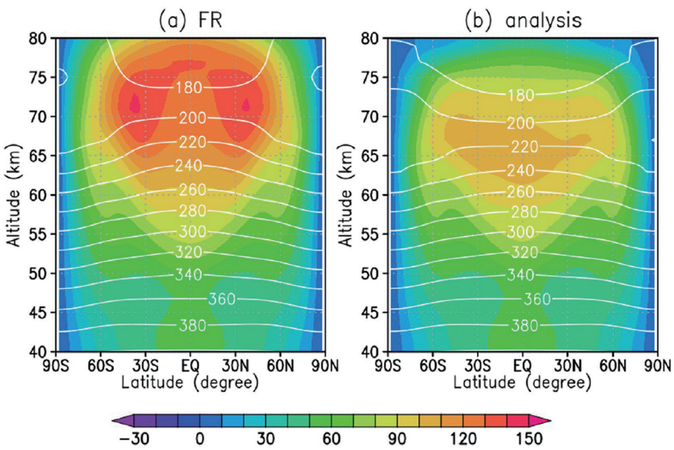


Figure 1. Latitudinal and vertical distributions of zonal-mean zonal wind (color, m/s) and temperature (contour, K) averaged over two Earth months: (a) free run and (b) analysis. (Fujisawa et al., 2022)

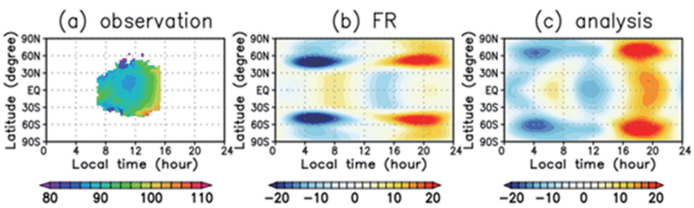


Figure 2. Local time and latitudinal distributions of zonal winds (m/s) associated with thermal tides at the cloud-top level. (a) observation, (b) free run, and (c) analysis. Taken from Figure 1 in Fujisawa et al. (2022) by deleting d-f for latitudinal winds.

-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.

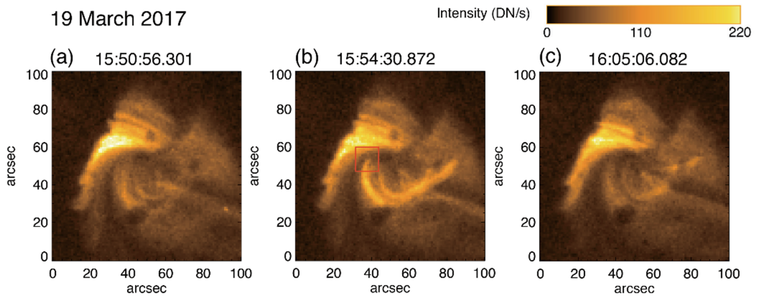


Figure 1. Soft X-ray images from Hinode X-ray telescope, acquired before, during, and after the loop-like microflare. The upper end of loop-like transient brightening (marked by the red rectangle) was successfully captured by IRIS slit jaw imager, ALMA, and Hinode Solar optical telescope's spectro-polarimeter.

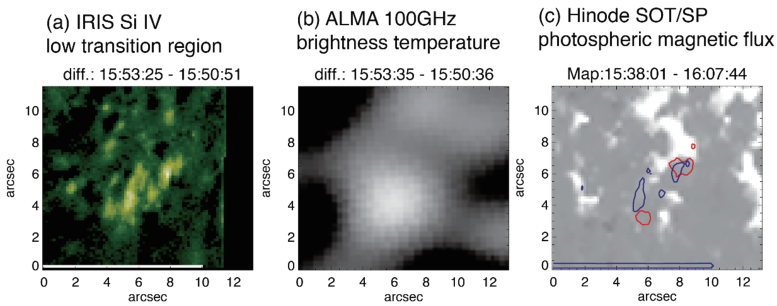


Figure 3. a) and b): Transient counterparts detected in Si IV (IRIS) and millimeter wave (ALMA). The image before the start of the brightening was subtracted to show transient counterparts. c): the magnetic flux distribution at the photosphere (Hinode Solar Optical Telescope's spectro-polarimeter) with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

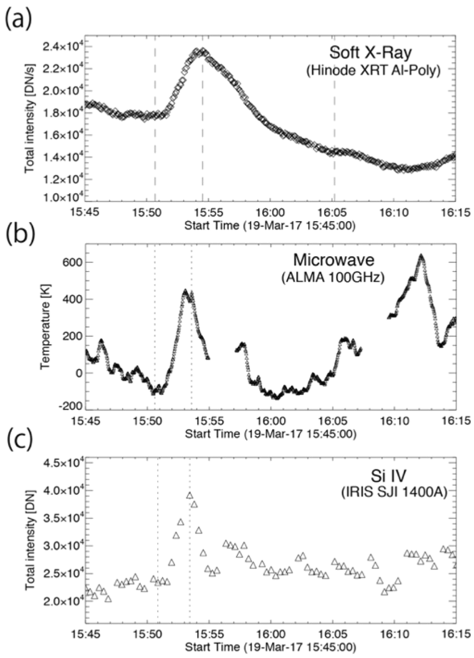


Figure 2. Temporal profiles of a) soft X-ray loop intensity (Hinode X-ray Telescope), b) millimeter wave (brightness temperature) by ALMA, and c) Si IV spectral line intensity (IRIS). Soft X-ray intensity and ALMA brightness temperature were used to derive the amount of the thermal energy produced in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

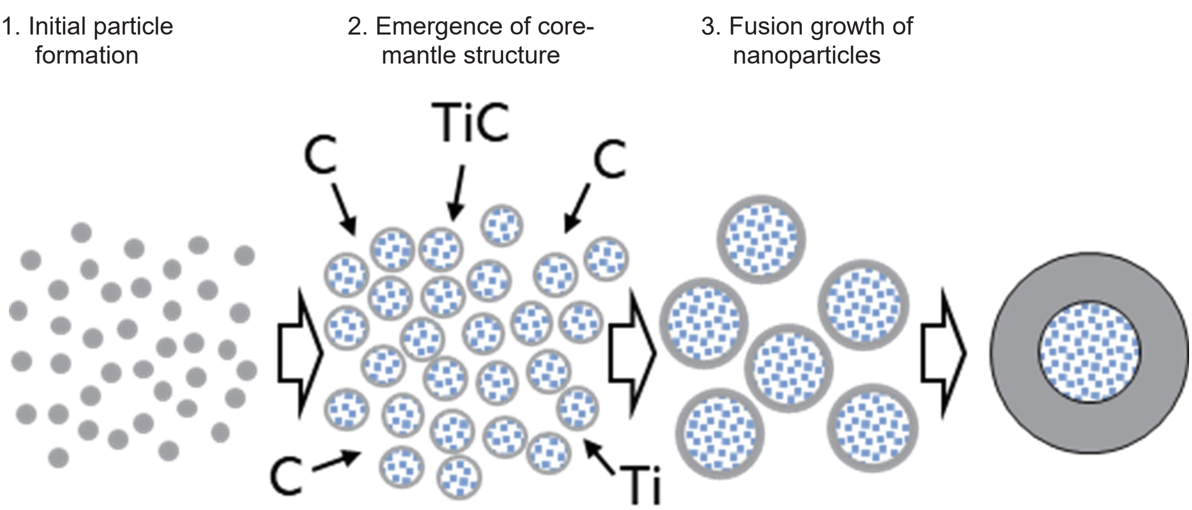


Figure 1. Schematic diagram of core-mantle particle formation process. Gray: carbon (C); light blue: titanium carbide (TiC).

-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

NAKAHIRA Satoshi
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.

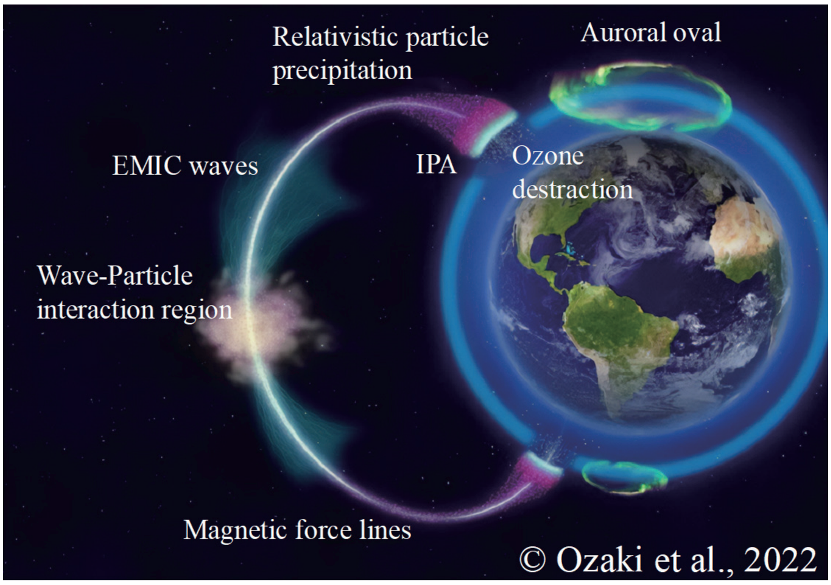


Illustration of the mechanism of ozone phenomena obtained from this study.

[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.

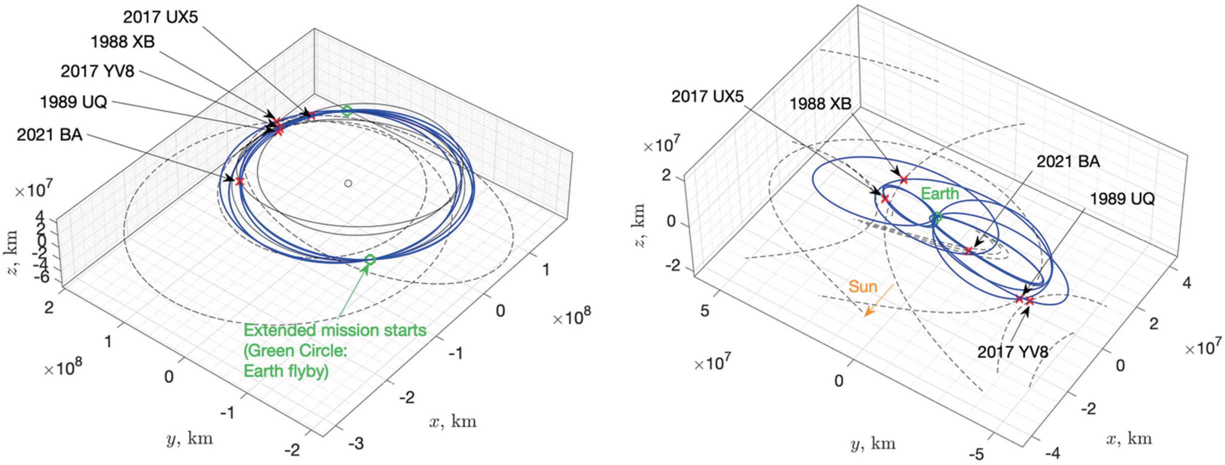


Figure 1. Overview of asteroid flyby cycler trajectories (left: Sun-centered and ecliptic plane centered inertial frame, right: Earth-centered and Sun-Earth line fixed rotational frame)

-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

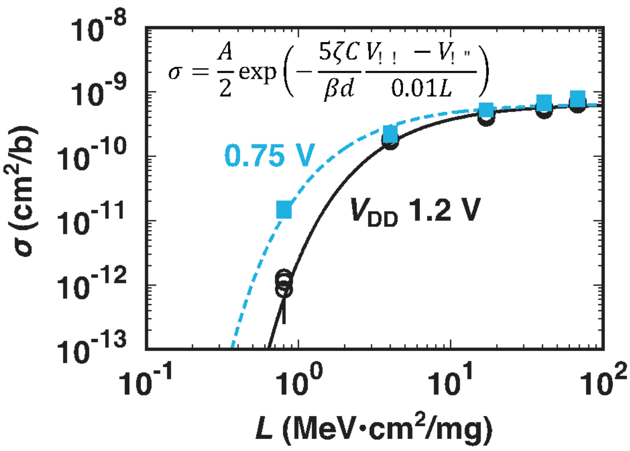
KOBAYASHI Daisuke
Department of Spacecraft Engineering

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.

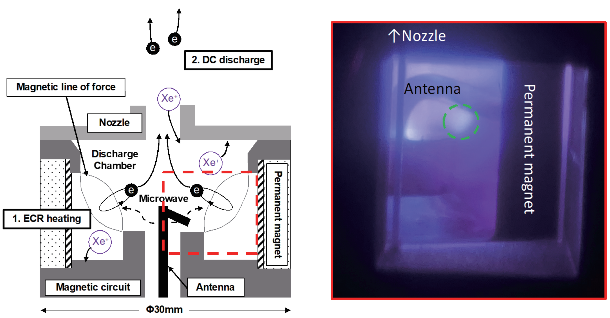


Figure 1. Schematic diagram of microwave discharge cathode (left) and photograph of the internal plasma (right).

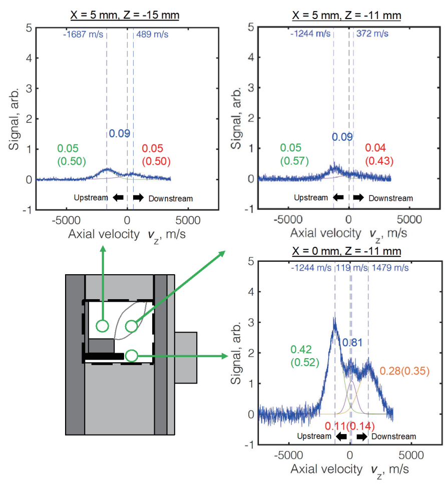


Figure 2. Axial ion velocity distributions inside the microwave discharge cathode.

-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

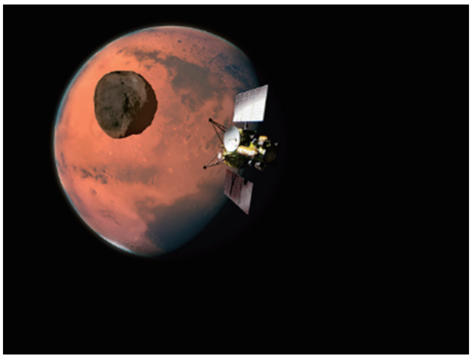


Image 2. Artist's concept of MMX, Phobos, and Mars

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)

Space Science Roadmap

Goals and Basic Framework

The goals of space science are to expand our knowledge of human life in regard to the origins of the earth and the solar system, origins of cosmic space, time and matter, and the possibility of extra-terrestrial life, while simultaneously giving rise to technological revolutions that will cause a paradigm shift in space engineering. Space projects are a primary means to enable space science to achieve these goals.

Space science projects are presently categorized into four classes: strategic large missions (L-class), competitively-chosen Medium-size focused missions (M-class), strategic participation in foreign-agency flagship missions (S-class), and small missions conducted with universities or other organizations using matching-funds and project-like schemes.

Strategic Large Missions Under Development

XRISM (X-Ray Imaging and Spectroscopy Mission) entered Phase C (final design phase) in FY2019, and its Critical Design Review was completed in April 2022. Its development was completed with PQR in March 2023.

MMX (Martian Moons eXploration) is a Martian moon sample return mission. The mission's Phase A study was executed as a candidate for L-class Mission 1, and it passed its System Definition Review in December 2019. Its Phase B study has now started as a JAXA project.

LiteBIRD (cosmic microwave background B-mode observation) was selected as a candidate for L-class Mission 2 in 2019, and its Pre-Phase A2 study is continuing. Its replanning in cooperation with CNES and KEK is now in progress after it failed to be selected as one of NASA's Missions of Opportunity (MoO). The International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles (QUP) was established in KEK in 2021.

Competitively-Chosen Medium-Size Focused Missions Under Development

SLIM (Smart Lander for Investigating Moon) was selected as M-class Mission 1 and will be launched by an H3 rocket together with XRISM. It moved to Phase C and its Critical Design Review was executed in March 2021. Its development is proceeding smoothly. Its development was completed with PQR in February 2023.

DESTINY$^+$ (Demonstration and Experiment of Space Technology for INterplanetary voYage with Phaethon fLyby and dUst Science), the M-class Mission 2 candidate, is a flyby mission to the meteor-shower parent body, Phaethon. It entered Phase A from April 2020, and it passed its System Requirement Review and its System Definition Review in March 2021. It is currently in Phase B.

JASMINE (Japan Astrometry Satellite Mission for INfrared Exploration) is an infrared astrometry mission dedicated to the astrometry of stars in the Galactic bulge. It was selected as M-class Mission 3 in 2019. Its replanning is now underway in cooperation with NAO after it failed to be selected as one of NASA's Missions of Opportunity (MoO).

Solar-C EUVST (Extreme UV Solar Telescope mission) was selected as M-class Mission 4, and its Pre-Phase A2 study is currently underway. It was selected as one of NASA's Missions of Opportunity (MoO) in December 2020. It finished its MDR in July 2022.

HiZ-GUNDAM (High-Z Gamma-ray bursts for Unraveling the Dark Ages Mission) was selected as a candidate for the mission concept of M-Class Missions 4 or 5, and its Pre-Phase A2 study is continuing.

SILVIA (Space Interferometer Laboratory Voyaging towards Innovative Applications) was selected as a candidate for M-Class 5 or 6, and its Pre-Phase A2 study is continuing.

Strategic Participation in Foreign-Agency Flagship Missions Under Development

JUICE (JUpiter ICy moons Explorer) is ESA's Cosmic Vision L1 mission. Japan's contribution to JUICE has continued though the development of the flight system. Nancy Grace Roman Space Telescope (former WFIRST) is NASA's mission planned for launch in 2025. Japan's contribution to Roman continued during the Pre-Phase A2 study and has entered Phase A.

Hera is ESA's mission constituting AIDA, the International Planetary Defense Mission with NASA's DART mission. Ja- pan's contribution to Hera continued during the

Pre-Phase A2 study and entered Phase A in 2021.

WSO-UV is a Russian mission planned for launch in 2025. Japan's contribution to the mission continued during the Pre- Phase A2 study and entered Phase A in 2021. However this project is now in hold since February 2022, due to the deteriorating Ukraine-Russian situation.

Comet Interceptor is ESA's Cosmic Vision F1 planned for launch in 2028. Japan's contribution to Comet Interceptor started with the Pre-Phase A2 study in 2020.

Dragonfly is NASA's New Frontiers 4 planned for launch in 2027.

Athena is ESA's Cosmic Vision L2 planned for launch in the late 2020's. Japan's contribution to Athena is continuing with the Pre-Phase A2 study.

Missions in Operation

The BepiColombo / MMO (Mercury Magnetospheric Orbiter) was launched in October 2018, and finished its checks early during FY2019.

Hayabusa2 was launched in December 2014, arrived at Ryugu in June 2018, touched down twice, operated its SCI (impactor) to make an artificial crater, then departed Ryugu in November 2019 and returned to the earth. From November 2020, the earth return operation was executed, and the capsule was retrieved in Woomera, Australia in December 2020. The samples from the capsule were undergoing initial analysis in the curation facility while the explorer itself has started an extended mission.

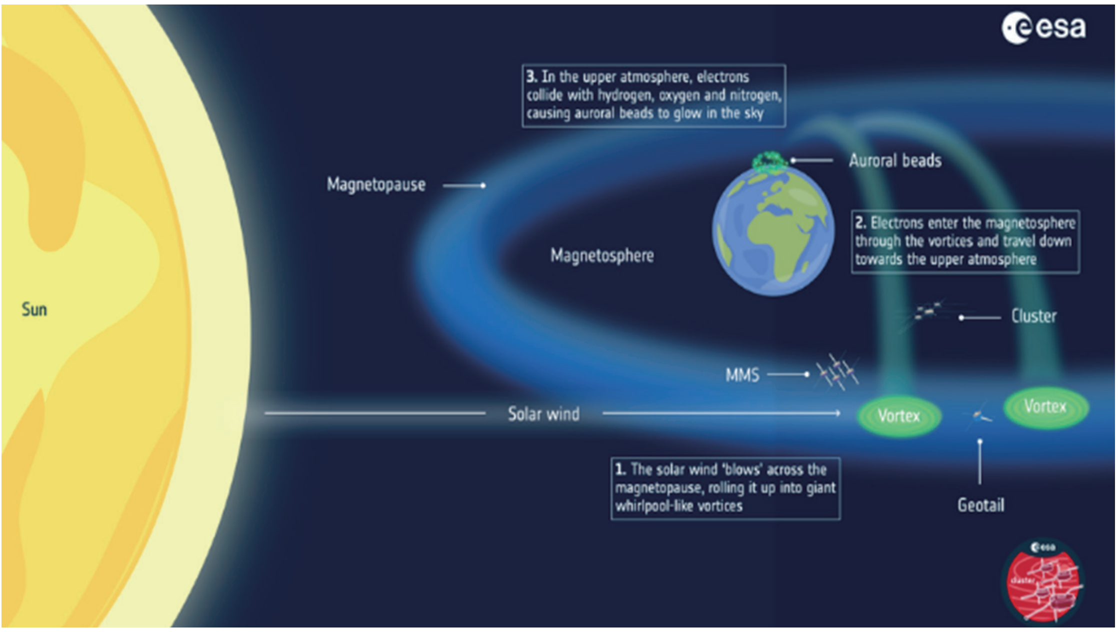
The five spacecraft in orbit, the Geospace explorer Arase, the planetary spectroscopy mission Hisaki, the Venus climate explorer, Akatsuki, the solar observatory Hinode, and the Geo-magnetosphere explorer, GEOTAIL, all conducted their observations safely and successfully. GEOTAIL terminated its operation in November 2022, after its 30 years operation.

Small Missions Conducted through Matching Funds with External Organizations

In fiscal year 2021, ISAS selected two additional projects: FOXI-4 and GEO-X (GEOspace X-ray Imager), the latter is conditional on determining the launcher.

In addition, the following projects were continued: DUST (dust nucleation sounding rocket experiments), GAPS (General Anti-Particle Spectrometer balloon experiment), small solar program SUNRISE-3 and CLASP2 (balloon and sounding rocket experiments, respectively), Phenix-2 (droplet group combustion research), XL-Caliber (balloon experiment), and wide-field near UV transient survey in a 6U CubeSat (cubsat).

Earth Magnetosphere Observation with GEOTAIL



Schematic summarizing multi-spacecraft observations by GEOTAIL, MMS, and Cluster in the magnetosphere and auroral bead observations by the DMSP satellite, and the connection between the solar wind, giant plasma vortices along the flank magnetopause, and auroral beads in the upper atmosphere (figure from ESA: https://www.esa.int/Science_Exploration/Space_Science/Magnetic_vortices_explain_mysterious_auroral_beads) [1].

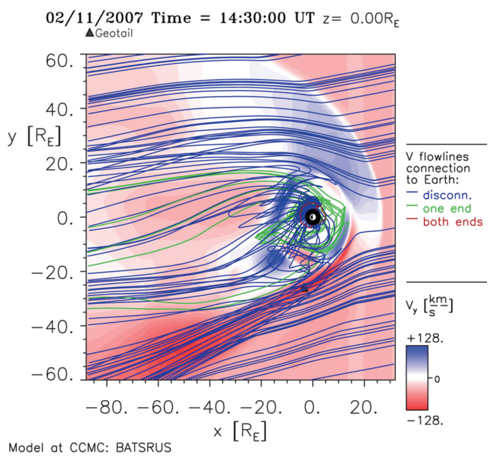
After the joint U.S.-Japan satellite GEOTAIL was launched in 1992, it remained in operation continuously for more than two solar cycles. The major purpose of GEOTAIL was direct observation of plasma in Earth's magnetotail.

One of GEOTAIL's two onboard data recorders failed at the end of December 2012, and on 28 June 2022, it was found that GEOTAIL's other data recorder, the only one that remained operational, had also failed. As sufficient observation data could no longer be obtained as a result of the failure of both onboard data recorders, we decided to end GEOTAIL operation, and the onboard transmitter was powered off on 28 November 2022.

The "Symposium on the Future of Heliospheric Science: From Geotail and Beyond" was held for four days from March 28 to 31, 2023, at Koshiba Hall of the Hongo Campus of the University of Tokyo in order to summarize the achievements of GEOTAIL over the past 30 years and to discuss the future of Heliospheric system exploration. The symposium was co-hosted by ISAS and the Heliospheric Science Center at Nagoya University and attracted more than 100 registered participants, both in person and online.

Japanese researchers from the GEOTAIL project have been deeply involved in NASA's Magnetospheric Multiscale (MMS) mission by designing, fabricating, and performing initial tests of 16 fast plasma investigation–dual ion spectrometer (FPI-DIS) sensors. From July 2015, the GEOTAIL operation time in Japan had been increasing for collaboration with MMS. Until the end of GEOTAIL operation, GEOTAIL provided opportunities to make simultaneous multiscale plasma measurements by carrying out coordinated observations with MMS, ARASE and THEMIS/ ARTEMIS.

One of the main results was obtained by combining simultaneous observations by GEOTAIL and ESA's Cluster spacecraft in the magnetosphere and a global magnetohydrodynamic simulation of solar wind-magnetosphere interaction designed for the observed event. The study demonstrated that under observed low solar wind Mach number conditions, which were due to unusually low solar wind density, the magnetosphere was highly deformed with significant dawn-dusk asymmetries, as shown in the figure below [2]. The results may also provide insight into our understanding of other space environments surrounding Mercury and exoplanets, where the Mach number of upstream stellar wind can be low, and Jovian or Saturnian satellites, around which upstream plasma flows usually have a low Mach number.
([1] *Frontiers in Astronomy and Space Sciences*, February 2022, and [2] *Earth Planets Space,* December 2022)



Structure in the equatorial plane of Earth's magnetosphere simulated by a global magnetohydrodynamic simulation with solar wind conditions set by observations on 11 February 2007, when GEOTAIL was located at the dawn-side magnetopause [2]. The lines show plasma flowlines, with the dawn-dusk component of the velocity (Vy) in color. The black triangle (▲) shows the GEOTAIL location.

Small Satellite INDEX (Reimei)

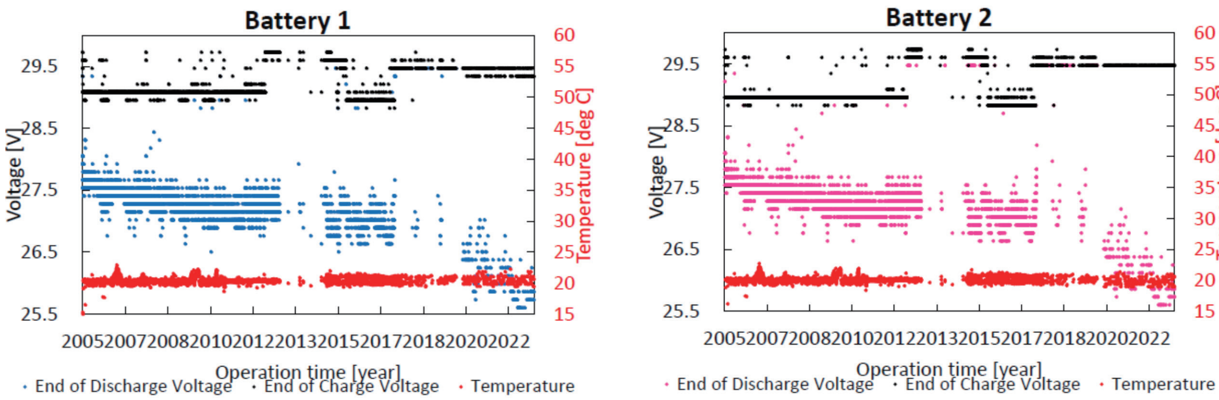
The small scientific satellite 'Reimei' is a piggy-back satellite with a mass of 72 kg that was launched in 2005. It has remained in orbit for 16 years. Its scientific purpose is observation of the fine structure of aurora phenomena by means of three-spectral imagers and particle energy analyzers. Meanwhile, its engineering purpose is to demonstrate small satellite technologies.

Reimei's aurora observation mission was terminated in 2014, and today the life cycle performance of batteries in space is one of the satellite's most important missions.

The batteries are charged by the CC-CV method. A constant current is provided at the initial constant-current phase of charging. After the battery voltage reaches a specific voltage, it is maintained by the power supply circuit to recover voltage loss resulting from internal battery impedance. Even today, the batteries continue to maintain a healthy condition. However, recently the end of discharge voltage has dropped drastically due to the long period the satellite has been in operation.

Currently, we are focusing our efforts on clarifying the internal condition of the batteries. Recently, the development of metallic lithium inside cells has been recognized as one of the phenomena fatal to battery operation. The development up of lithium metal inside the cells of the Reimei batteries has also been monitored. The information will be utilized for safer passivation of the satellite in the future. The in-orbit information of the Reimei batteries was shared with universities and national laboratories.

One of the efforts we are focusing on is our collaboration with Deutsches Zentrum für Luft und Raumfahrt (DLR). DLR has a technique for simulating the internal condition of lithium-ion secondary cells. DLR's researchers performed electro-chemical simulations of the Reimei batteries based on their initial parameters in the development phase, including thermochemical parameters and the degradation phenomena of separators and electrolytes.



End of Discharge Voltage over 17 years of Reimei operation.
The discharge voltage has been falling drastically.

Solar Observation with Hinode (SOLAR-B)

The Hinode satellite (formerly called SOLAR-B) was designed to make observations that will improve our understanding of space weather in the solar system. Specifically, we are observing the solar processes of magnetic field generation, energy transfer from the photosphere to the corona and how this transfer affects the heating and structuring of the chromosphere and the corona, and eruptive phenomena. Hinode is a follow-up to the YOHKOH satellite (operated from 1991–2001), which revealed that the high-temperature corona is highly structured and dynamic and that rapid heating and mass acceleration are common. Hinode is designed to address the fundamental question of how magnetic fields interact with the ionized atmosphere to produce dynamic behaviors. It accurately measures the magnetic fields at the photosphere with simultaneous X-ray and extreme ultraviolet (EUV) measurements of coronal behavior.

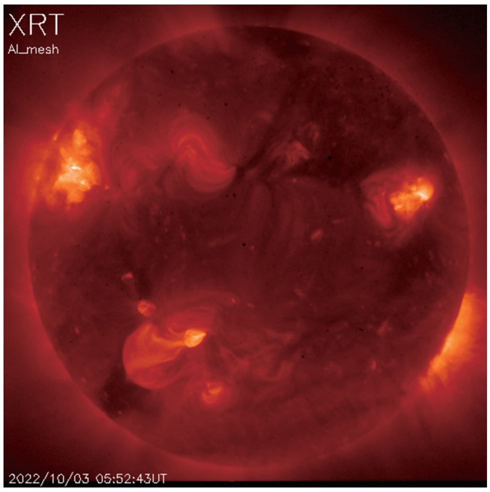
Hinode was launched in September 2006 and has been continuously operated as an on-orbit solar observatory for over 16 years. The observatory can be used by the global research community and 29 new observation proposals were delivered to the Hinode operations team in JFY2022. In addition to regular closely coordinated observations with NASA's Interface Region Imaging Spectrograph (IRIS) satellite, the Hinode team has coordinated its observations with NASA's Parker Solar Probe every three months when the explorer makes a close approach to the Sun and supported observations of ESA's Solar Orbiter. All data acquired by Hinode is made fully available to the international research community immediately after observations.

In JFY2022, 65 articles were published in refereed journals based on Hinode observations, resulting in a cumulative total of 1,712 published papers to date (as of March 2023). This record shows that Hinode has been one of the most productive missions at ISAS.

A review article entitled "Achievements of Hinode in the first eleven years" (Hinode Review Team, 2018, Publications of the Astronomical Society of Japan, 71, R1) was recognized as one of "the most read articles" among the articles published in 2018-2019 by the publisher Oxford University Press.

Based on a mission review in 2020 for further extension of the operations, JAXA has confirmed the continuation of Hinode operations until March 2024. Hinode operations are supported by NASA (operation of onboard instruments and ground tracking support), ESA, the Norwegian Space Center (ground tracking support in polar regions and data center in Europe) and the U.K. Space Agency (UKSA) (operation of EUV imaging spectrometer).

The Hinode mission on orbit.



A full-disk soft X-ray image from the X-Ray Telescopeonboard Hinode taken on 3 October 2022, showing increasing solar activity towards cycle 25 activity maximum.

Venus Meteorology Observations by Akatsuki (PLANET-C)

Akatsuki, in the Venus orbit since December 2015, has continued to conduct observations of the Venusian atmosphere (its motions and conditions). One of the primary objectives of Akatsuki is to understand the mechanism of super-rotation, a very rapid westward wind encircling Venus at a speed of up to 100 m/s. Recently, quantitative and statistical analysis of high-precision cloud-tracked wind measurements from Akatsuki data has revealed that the super-rotation in the equator and the low-latitudes is maintained primarily by thermal tides in the atmosphere. As of this writing, the spacecraft itself is in good condition, and on-board instruments (UVI, LIR and LAC as well as the ultra-stable oscillator for radio science) are operating normally. IR1 and IR2, on the other hand, have been non-operational since December 2016, though intense data analysis efforts are being made by the science members.

Akatsuki's IR1 and IR2 (now inactive) revealed an intriguing sharp discontinuity in the lower clouds that propagates to the west faster than the winds while altering the clouds' properties and suffering little distortion for weeks. NASA's IRF telescope has also observed a similar feature on Venus in near infrared images (Figure 1). Results from numerical simulations combined with its absence in observations of the upper clouds show that this is an atmospheric wave generated below the clouds that is probably pumping energy to the super rotating upper clouds.

The results, published in *Scientific Reports* in FY2022, show a pioneering and fully-staged example of the 'data assimilation' studies that the Akatsuki project has aimed to perform to integrate continuous observational data of the Venusian cloud top with numerical models. The assimilation of wind speed data has improved the reproducibility of the super-rotation structure, and has also made it possible to obtain a structure of thermal tidal waves and the associated angular momentum transport effects that more closely resembles the real atmosphere. The 'data assimilation' method, which has become commonplace in terrestrial meteorological studies, has been applied in Venusian meteorological studies for the first time to demonstrate its usefulness. Improvements to the method and the accumulation of data are expected to contribute to a deeper understanding of the nature of Venusian meteorology and how it differs from terrestrial meteorology. The method also provides important guidance on what should be measured and how to measure it in future atmospheric planetary / satellite missions [Also see p.16].

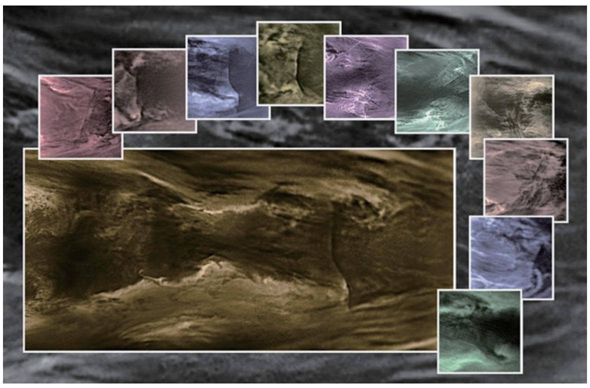


Figure 1. The disruption and its morphological changes observed from March to October 2016 (Akatsuki) and from November 2018 to January 2019 (IRTF).

Solar Power Sail Demonstration with IKAROS

IKAROS, a small solar power sail demonstrator that launched on May 21, 2010, fully succeeded in demonstrating solar sail and solar power sail technology for the first time. Since 2012, it has alternated between hibernation and recovery, as it has nearly exhausted its fuel supply and cannot control its attitude. However, we continue the IKAROS operation to obtain valuable data for the development and operation of new solar power sail spacecraft. In particular, camera images of the sail membrane and data on power generation by the thin-film solar cells will be useful for evaluating the long-term performance of the solar power sail.

Achievements:

- In order to release the IKAROS data held by the ISAS Orbit Determination Group, we have converted the data from ISAS's proprietary format to the international standard formats, CCSDS OEM and CCSDS TDM.
- Doppler and range data during the normal operation period (May 2010 - November 2011)
- Tracking data during the search phase (December 2011 - September 2015)
- Trajectory history of the normal operation and search phases.

Outcomes:

- Total number of papers: 110.
- The orbital data of the world's first solar sail mission can now be shared with researchers around the world.

Extreme-Ultraviolet Spectroscopic Observation by Hisaki (SPRINT-A)

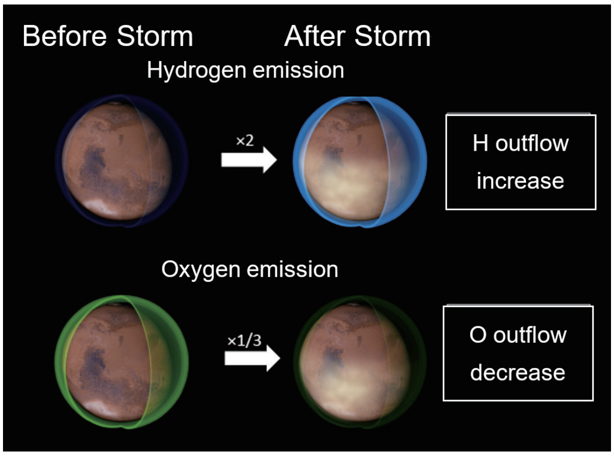
The extreme-ultraviolet (EUV) spectroscopic observatory Hisaki (formerly called SPRINT-A: Spectroscopic Planet Observatory for Recognition of Interaction of Atmosphere), which was launched on September 14, 2013, is a unique space telescope specializing in observations of planetary atmospheres, ionospheres, and magnetospheres from low Earth orbit. Its primary instrument is the EUV spectroscopic system, which has the highest time resolution and the longest observation duration in history. The EUV system is especially useful for understanding energy and plasma transportation in Jupiter's magnetosphere and the atmospheric evolution of the terrestrial planets.

Hisaki's long-term planetary observations of the Jovian magnetosphere and Venusian/Martian ionospheres are continuously performed to provide unique and important data sets of EUV spectra.

This year's continuous monitoring observations have focused on Jupiter and Mars. The extreme ultraviolet spectral data accumulated over a long period provides valuable observational data for solar system scientific research.

We will maintain our international collaborative research on the studies of Jupiter magnetospheric physics and atmospheric escape from the Earth-like planets. The international partnership will become a basis for participating in the international scientific strategy for the actual exploration of Jupiter to be promoted in the near future.

Observations of the Martian upper atmosphere over a period of one month have shown that hydrogen gas increases and oxygen gas temporarily decreases in the upper atmosphere during large-scale dust storms. The results indicate that hydrogen gas outflow is enhanced while oxygen gas outflow is suppressed during dust storms, and suggest that dust storms play a role in conserving oxygen and oxidising the Martian atmosphere. In other words, ancient Mars had a more reductive atmosphere than today, suggesting that it may have been an environment conducive to life (Masunaga et al., 2022, *Nat. Commun*.). Samples returned from the Martian satellite Phobos in the future by the Martian Moons eXploration (MMX) mission are expected to contain atmospheric components that have been outgassed from Mars. The results of this study are expected to provide important insights for the analysis of the returned samples.



Schematic image of the increase and decrease in hydrogen and oxygen gases before and after a dust storm.

Asteroid Exploration: Hayabusa2 and Hayabusa2 Extended Mission (Hayabusa2#)

Hayabusa2 is a mission to explore and obtain samples from the C-type asteroid Ryugu. The purposes of the mission are to reveal the origins of Earth, the sea, and life by studying the interaction between minerals, water, and organic matters in the primitive solar system, and to develop technology for deep space round-trip exploration as demonstrated by HAYABUSA. In particular, we aim to lead the world in this field by taking on the new challenge of creating an artificial crater on the asteroid and collecting samples near the crater.

Hayabusa2 was launched on December 3, 2014, and arrived at the asteroid in June 2018. It stayed near the asteroid for about one year and five months, and performed observations with remote sensing equipment, observations with a lander and rovers, artificial crater generation, and sampling via two touchdowns. Hayabusa2 left Ryugu in November 2019, and the reentry capsule returned to Earth on December 6, 2020.

Approximately 5.4 g of samples were obtained from Ryugu, and the curation work and ensuing initial analysis work were carried out. Analyses were also carried out on the scientific data acquired during Hayabusa2's stay on Ryugu.

Hayabusa2 left Earth after releasing the capsule and continued its mission as an extended mission (Hayabusa2#). The extended mission aims to perform flyby exploration of asteroid 2001 CC21 and rendezvous exploration of asteroid 1998 KY26.

The following results were achieved in FY2022:

Results:

(1) The project completion review was conducted in April 2022, and activities were shifted to the extended mission (ISAS project team) in July of the same year.

(2) The spacecraft continued cruise operations toward the asteroid 2001 CC21 to make a flyby in 2026. During FY2022, orbit control by the ion engine was performed from May to November as planned. In addition, zodiacal light observations and transit observations of exoplanets were carried out as planned using the onboard camera during the long ballistic cruise operation period, and good observation data were obtained. Besides in-space operations, preparation and development for updating the AOCS onboard software are in progress in order to respond to possible future contingency cases. In addition, a preliminary in-house study regarding the flyby operation of asteroid 2001 CC21 is in progress.

(3) The Hayabusa2 sample analysis team participated in the OSIRIS-REx sample analysis rehearsal and shared and discussed lessons learned from Ryugu analysis at the OSIRIS-REx sample analysis meeting. The physical properties analysis team has newly joined the Bennu analysis team.

(4) The OSIRIS-REx return sample clean room (CR) was newly constructed, a liquid nitrogen cold evaporator was installed, and nitrogen gas supply to the CR was commenced.

(5) The development of various higher-order processing products using ONC and TIR data (ONC highest-resolution distribution map, global mosaic using high-resolution images, and satellite orbit and attitude data with improved accuracy) was started and partially completed. As a technical validation for the development of the Hayabusa2 data distribution system, an implementation test of the NIRS3 data retrieval, display, and distribution function was conducted.

Effects:

(1) Number of published papers in FY2022: 47
Cumulative number of peer-reviewed papers: 298

(2) We continued to monitor the status of each component of the spacecraft that has exceeded its design life, and continued to evaluate performance changes such as deterioration. The knowledge obtained was shared with other projects under development, contributing to future missions. In addition, JAXA provides opportunities for human resource development both within and outside of JAXA by actively accepting the participation of young and new members in the operation team activities, such as training for new members, students and young staff on operation duty, and participation of young members on the team.

(3) For the Bennu sample analysis activity, the knowledge and experience gained from Ryugu analysis were shared through the OSIRIS-REx sample analysis conference and Ryugu analysis papers (See the references).

(4) At the Goldschmidt Conference (Hawaii, 2022/7/11-15), members of both the Hayabusa2# and OSIRIS-REx missions jointly organized a session to discuss return sample analysis in the analytical community.

(5) The status of the return sample receiving facility was disclosed at the ISAS open campus event.

(6) The types and precision of higher-order processing products to be installed in the data distribution system in the future were improved, which will enable more precise measurements and scientific verification in future scientific research.

Geospace Exploration with Arase (ERG)

The geospace explorer Arase (Exploration of Energization and Radiation in Geospace (ERG)) was developed as the second small science satellite by ISAS/JAXA in collaboration with institutions in Japan and Taiwan. The Arase satellite was successfully launched by the second Epsilon rocket on December 20, 2016, from the Uchinoura Space Center (USC) in the southern part of Kyushu.

The ERG's science program is intended to address the generation and loss mechanisms of high-energy electrons in Earth's radiation belts. This problem is a critical issue in understanding the dynamic variation of geospace. This program's essential task is using the Arase satellite to conduct detailed in-situ measurements of particles and electromagnetic fields in the radiation belts while monitoring the global variation of geospace by ground-based measurements. These ground-based measurements involve a network of radar facilities, aurora cameras, magnetometers, etc. We also prepared joint strategic observations with the NASA Van Allen Probes. These systematic observations shed light on the scientific mysteries of the radiation belts. The experimental results are also expected to contribute to improvements in space-weather forecasting.

Arase is designed as a spin-stabilized satellite with a spin rate of approximately 7.5 rpm. Given its perigee altitude of approximately 400 km, apogee altitude of approximately 32,000 km, and inclination of approximately 31 degrees, Arase's orbit allows it to cover all of Earth's outer radiation belt. The orbital period is about 570 minutes. The satellite system and all onboard mission instruments are in good condition even after over six years in space. All mission instruments achieved their expected performance as designed and have continued observations. Arase provides data from comprehensive observations of the radiation belts.

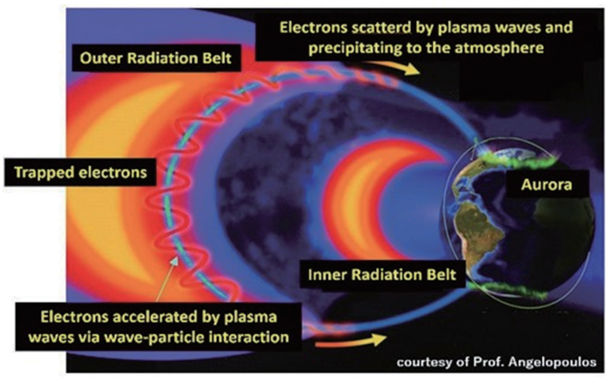
Each instrument team and the ERG science center operate the data pipeline processing of the acquired data and the data calibration. The processed data products are released from the ERG science center via a web interface. The ERG science center is managed through inter-institution collaboration between the Nagoya University Institute for Space-Earth Environmental Research (ISEE) and ISAS. Coordination of observation planning and science data management by the ERG science center facilitates smoother and easier joint research with multiple data sets by providing a unified contact point for all data resources. After evaluation by the ERG science team, the processed science data products will be open to the public. The ERG science center developed relevant data analysis software. It was made available as a plug-in package for SPEDAS, the standard data analysis software used in the solar-terrestrial physics and community. Processed higher-level science datasets will also be released to the research community.

The primary mission period began on March 24, 2017, and was completed on October 16, 2018. The primary mission period corresponds to the declining phase of Solar Cycle 24. Arase successfully observed a dozen geospace storms. Most importantly, all instruments have provided scientific data from both normal and burst observations of these storms. We have conducted joint strategic observations with ground-based measurements to reveal the causes and consequences of wave-particle interactions and magnetosphere-ionosphere couplings. We have collaborated with radar facilities, aurora cameras, riometers, VLF observations, standard radio networks (e.g., EISCAT, Super DARN, and PANSY), and magnetometers. Arase has proven itself as a member of the international fleet of geospace satellites and has contributed to comprehensive observations of geospace plasma dynamics.

A total of 512 burst-mode observations of plasma waves have also been completed simultaneously with the Van Allen Probes, providing simultaneous waveform data at different magnetic latitudes along the same field lines by the end of the mission termination of Van Allen Probes in late 2019. Collaborative observations with other satellites like THEMIS and MMS have also been carried out. The collaboration with AFRL DSX (Demonstration and Science Experiments) was successfully completed, and 50 burst-mode cooperative observations had been performed for the DSX active experiments by May 2021.

Over 250 scientific papers have been published in international refereed journals since the start of the Arase observations, including articles in Nature, Nature Communication, Scientific Reports, special issues of Geophysical Research Letters, and Journal of Geophysical Research. These publications show that Arase reveals a novel aspect of geospace and how wave-particle interactions contribute to the dynamic variation of the radiation belts.

Now, we are in the extended mission phase that will continue until the end of March 2023. The extended mission period can cover the whole Solar Cycle 25 so that Arase can observe dynamical variations of the radiation belts and geospace under various solar wind conditions. If the extended mission completes, it will be the first achievement of surveying the deep inside of the Earth's outer radiation belt over the 11-year (one solar cycle). Solar activity is currently in the ascending phase of Solar Cycle 25 after the solar minimum of Solar Cycle 24 and has already exceeded the maximum number of sunspots in Solar Cycle 24. We expect coming observation results toward the solar maximum period.



Contribution of wave-particle interactions to the radiation belts.

Mercury Exploration with BepiColombo/MMO

Despite having a size between that of the Moon and Mars, Mercury unexpectedly has an intrinsic magnetic field. This was discovered by the Mariner 10 spacecraft during three flybys and was confirmed by NASA's Mercury orbiter, MESSENGER, which completed its mission in May 2015 as planned by deorbiting into Mercury.

BepiColombo is an ESA–JAXA joint mission to Mercury that aims to understand the process of planetary formation and evolution and to identify the similarities and differences between the magnetospheres of Mercury and Earth. The MESSENGER observations raised many new questions, and BepiColombo hopes to answer them.

The baseline mission consists of two spacecraft: the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (MMO), Mio. The two orbiters and the Mercury Transfer Module (MTM) will be combined in a stacked configuration, which will be called the Mercury Cruise System (MCS). JAXA is responsible for the development and operation of Mio, while ESA is responsible for the development and operation of the MPO, as well as the launch, cruising, and insertion of the two spacecraft into their dedicated orbits. The main objectives of Mio are to study Mercury's magnetic field and the plasma environment around Mercury, including the solar wind–magnetosphere interaction, mainly by using in-situ measurements, while the main objective of the MPO is to study planet Mercury itself, mainly by using remote sensing.

In FY2022, the second Mercury swing-by was performed on 23 June 2023 (JST), and scientific observations of Mercury's magnetosphere were performed. Mio successfully observed clear variations of magnetospheric plasmas that compare to the results from the first Mercury swing-by. We have also carried out several scientific observations during the interplanetary cruise, especially detecting solar energetic particle (SEP) events and coronal mass ejection (CME) events, and we prepared scientific observation plans to be carried out during the third Mercury swing-by and interplanetary cruise in FY2023.

In preparation for arrival at Mercury in 2025, we built a Mio spacecraft simulator and observation planning/verification tool. In particular, we performed numerous simulations and exercises regarding the critical separation and extension operations.

37 peer-reviewed papers related to the BepiColombo project were published in FY2022.

Image of Mercury taken by the monitoring camera onboard the BepiColombo spacecraft during the second Mercury swing-by on 23 June 2022 (credit: ESA/BepiColombo/MTM).

SLS CubeSats: OMOTENASHI and EQUULEUS

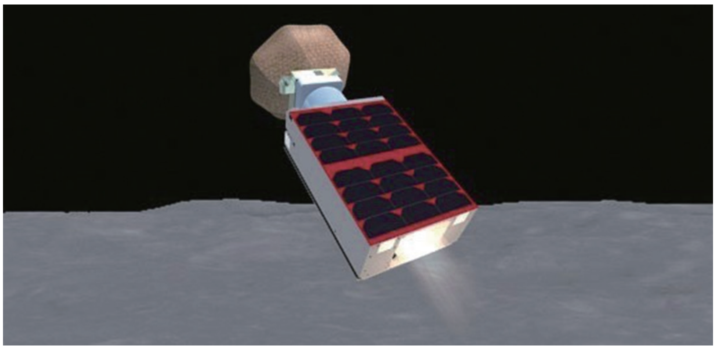
OMOTENASHI (Outstanding MOon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor) and EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) are 6U, 14-kg CubeSats that was launched by NASA's Space Launch System (SLS) in Nov. 2022.

OMOTENASHI was planned to demonstrate technologies for the world's smallest moon lander, such as a small solid rocket motor, shock absorption mechanism, and observe the radiation environment. However, because of an anomaly of the propulsion system in orbit, the lunar landing experiment was abandoned. The radiation environment was successfully measured by commercial portable dose meters.

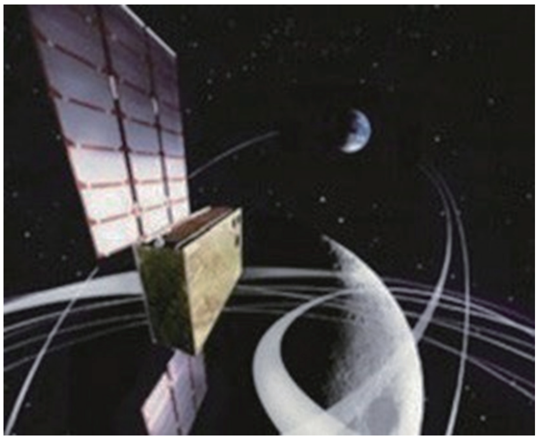
EQUULEUS has four missions. The primary, engineering mission is the demonstration of the trajectory control techniques within the Sun-Earth-Moon region by a nanospacecraft during the flight to the Earth-Moon Lagrange point L2. A water resistojet propulsion system has been newly developed for trajectory control. The other, scientific missions are to observe Earth's plasmasphere, lunar impact flashes and the lunar dust environment. Those observations will be conducted by three instruments, namely, PHOENIX, DELPHINUS and CLOTH.

After being inserted into a lunar transfer orbit by SLS Artemis-1 on November 16, 2022, EQUULEUS completed checkout operations and successfully performed a delta-V maneuver and subsequent trajectory correction maneuver. This enabled a precise lunar flyby as planned and successful insertion into the orbit toward EML2, which will take advantage of multiple lunar gravity assists and the gravity of the Sun. With this successful orbit control, EQUULEUS became the first spacecraft in the world to successfully control its orbit beyond low Earth orbit using water propulsion. Checkout operation for the three science instruments is being conducted.

Small, light-weight and low-cost technologies developed for both spacecraft will contribute to future space science and human exploration, and will promote the participation of universities, industry, and even individuals in future space exploration.



Artist's concept of OMOTENASHI deceleration maneuver and the separation with a solid-fuel motor.



Artist's concept of EQUULEUS observation from L2.

The Smart Lander for Investigating Moon (SLIM)

The Smart Lander for Investigating Moon (SLIM) is a project aimed at demonstrating the possibility of precise “pinpoint” landings on the lunar surface using a small and lightweight spacecraft. Pinpoint landings with accuracies of 100 m are required for future Moon exploration. Moreover, since conventional ground-based navigation systems cannot achieve this level of accuracy, it is necessary to develop an autonomous onboard navigation system. A novel image-based onboard navigation system has been developed and will be demonstrated during the SLIM mission, together with several other technologies.

In April 2016, JAXA authorized the SLIM project and the formation of a specific project team. As a continuous investigation from FY2017, suitable system configuration was discussed to adapt to the situation after the HITOMI (ASTRO-H) anomaly. Ultimately, JAXA and the SLIM project team decided to launch SLIM using an H-IIA rocket, together with the XRISM (X-Ray Imaging and Spectroscopy Mission) satellite.

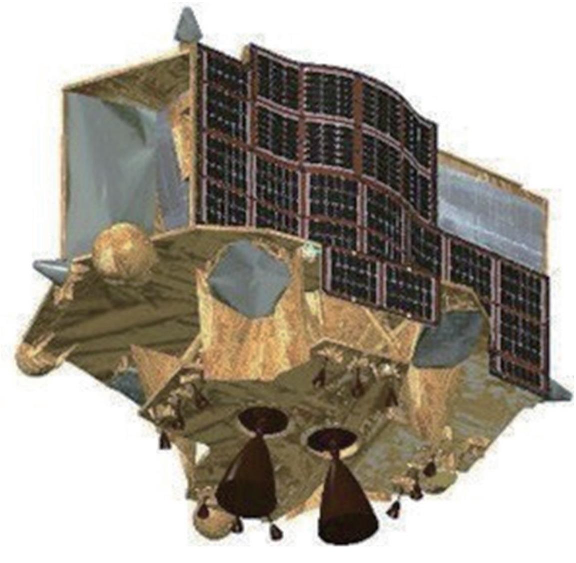
In FY2018, a preliminary design study (contemplating certain modifications in response to the launcher change) was conducted, followed by a preliminary design review. This last process included component vendors, system design, and JAXA’s engineering peer reviews. Finally, at the end of FY2018, approval was given for the SLIM project to commence the detailed design phase (Phase-C).

In FY2019-FY2020, a detailed design study and several engineering model tests were conducted. The results of these activities were reflected in the spacecraft system design, which was reviewed in the critical design review process. Finally, approval was given to commence system assembly, integration and the test phase (Phase-D).

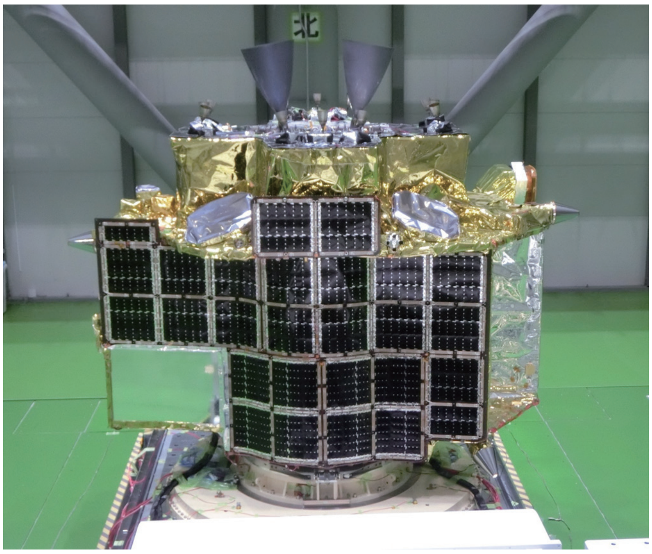
In FY2021, assembly and integration were proceeded with, and a series of system tests for a flight model was commenced.

In FY2022, a series of system tests with a flight model, such as a mechanical environment test, thermal vacuum test or several functional tests, was completed. The design and evaluation results were confirmed in the post-qualification review, which concluded that the spacecraft is ready to commence launch site operation. After this review, the SLIM spacecraft was shipped to Tanegashima Space Center.

Pinpoint landing technology is key for the next generation of lunar landers, since it will allow access to specific places on the Moon that are scientifically valuable as well as important exploration targets. Thus, SLIM is a precursor for future national and international landing missions on the Moon, Mars, other planets as well as astronomical bodies.

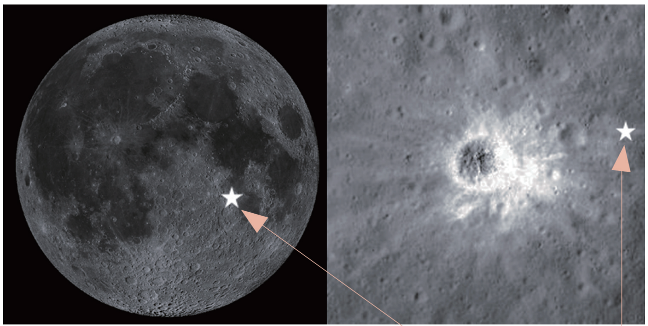


Appearance of the SLIM spacecraft



The SLIM spacecraft in a mechanical environment test

Expected view of the SLIM on the landing site



Location of the target landing site (13.3 degS / 25.2 degE).

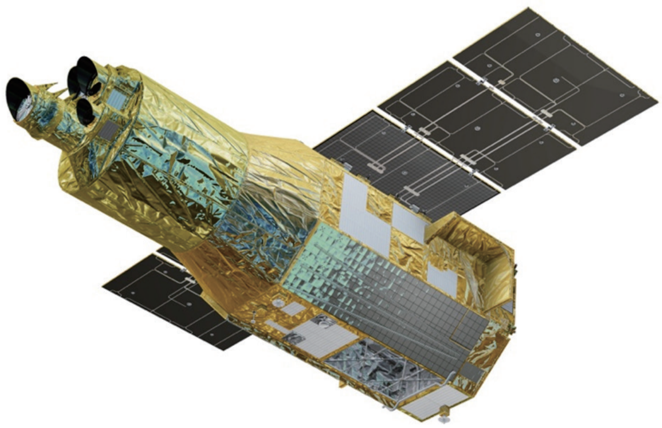
X-Ray Imaging and Spectroscopy Mission (XRISM)

The X-ray Imaging and Spectroscopy Mission (XRISM) has been proposed in order to achieve the scientific objectives targeted at the time of launching ASTRO-H (HITOMI). The XRISM will recover the science that ASTRO-H was aiming for in the shortest time possible by focusing on the main scientific goal of “Revealing material circulation and energy transfer in cosmic plasma and elucidating the evolution of cosmic structures and objects”.

XRISM will perform high-resolution X-ray spectroscopic observations of the hot gas plasma wind that blows through the galaxies in the universe. These observations will enable us to determine flows of mass and energy, revealing the composition and evolution of celestial objects. The high spectral resolution realized by the XRISM will not offer mere refinement; rather, it will enable qualitative leaps in astrophysics and plasma physics. Four scientific objectives required for XRISM are to investigate (1) structure formation of the universe and the evolution of clusters of galaxies; (2) circulation history of baryonic matter in the universe; (3) transport and circulation of energy in the universe; and (4) new science with unprecedented high resolution X-ray spectroscopy. In order to achieve these scientific objectives, the XRISM will carry a 6×6 pixel X-ray microcalorimeter (Resolve SXS) on the focal plane of an X- ray mirror assembly, together with an aligned X-ray CCD camera (Xtend SXI) covering the same energy band and a wider field of view.

In 2022, the Spacecraft system PFT was completed and the launch site activity was subsequently commenced. The tracking and control team has been formed, and the operation training and rehearsal are ongoing. In order to maximize the output from the PV phase observations, the team invited XRISM Guest Scientists by way of public invitation. With the guest scientists, each PV target team proceeds with preparation for PV observations and data analysis.

The XRISM is a collaboration between JAXA and NASA, with contributions from ESA.



Graphic rendering of the X-ray Imaging and Spectroscopy Mission on orbit.

Demonstration and Experiment of Space Technology for INterplanetary voYage with Phaethon fLyby and dUst Science (DESTINY$^+$)

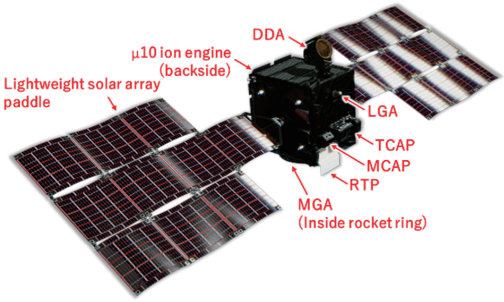
DESTINY$^+$ (Demonstration and Experiment of Space Technology for INterplanetary voYage with Phaethon fLyby and dUst Science) is the ISAS M-Class small program mission jointly proposed by the engineering and science communities. The mission has the following two engineering mission objectives: [E1] Development of space transportation technology using electric propulsion and extension of the range of applications of electric propulsion; and [E2] Acquisition of advanced flyby exploration technology and expansion of opportunities for small body exploration in the solar system. In addition, DESTINY$^+$ has the following two scientific mission objectives: [S1] Elucidation of the physical (velocity, direction of arrival and mass distribution) and chemical properties of dust reaching Earth; and [S2] Investigation of asteroid (3200) Phaethon, which is the parent body of the Geminids meteor shower, as a specific source of dust coming to Earth.

DESTINY$^+$ will be put into an elliptical orbit around Earth by an Epsilon S launch vehicle, after which electric propulsion will be used to raise the orbit to reach the Moon. At this point, it will escape Earth’s gravitational sphere of influence via multiple lunar gravity assists, approach asteroid Phaethon after cruising in deep space using electric propulsion and conduct a flyby observation. After the Phaethon flyby, DESTINY$^+$ may head for a subsequent exploration target as part of an extended mission.

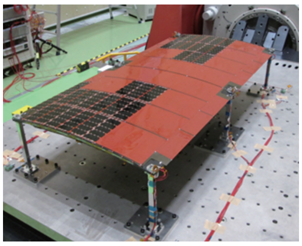
JAXA plans to develop scientific instruments to observe an active asteroid, Phaethon, during its flyby, whereas DLR will provide the DESTINY$^+$ Dust Analyzer (DDA), which belongs to a field in which Germany has had the world’s leading expertise for decades. Since the establishment of the Implementation Arrangement (IA), DLR and JAXA have been conducting joint feasibility studies. An international observation campaign was conducted for Phaethon during its last close encounter with Earth in December 2017. Photometric, spectroscopic and polarimetric observations of Phaethon were successfully performed with ground-based and space telescopes. In 2019, occultation observations were conducted in Japan and the US as well to determine its shape and size.

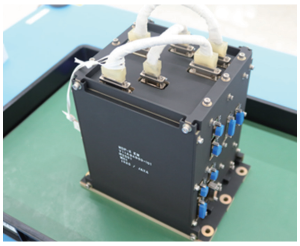
We completed the preliminary design reviews (PDRs) of the spacecraft system and all subsystems and moved on to the detailed design phase in FY2022. Engineering models (EMs) of some onboard components shown below have been developed and tested. Based on the results of the basic design, constraints on the spacecraft system and ground stations were identified, and a detailed study of the trajectory design and operation plan has been conducted. In addition to Phaethon, we have been considering other flyby targets from the viewpoints of both the scientific significance of the observations and the feasibility of the trajectory design. A communication test was performed with the telemetry command simulator of DDA connected to the mission data processor. Proton irradiation tests of the imaging sensors for TCAP and MCAP were conducted to investigate the effects of degradation on the optical navigation and observations. The spacecraft launch is scheduled for FY2024.

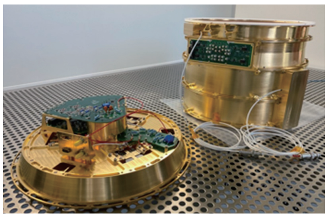
Related organizations for this mission include Chiba Institute of Technology Planetary Exploration Research Center (Chitech/PERC, Japan), Universität Stuttgart Institut für Raumfahrtsysteme (Uni Stuttgart/IRS, Germany) and DLR (Germany).

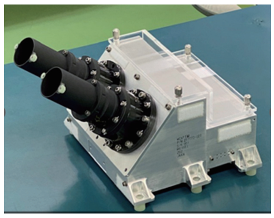


Dimensions	Body: 1.3 x 1.08 x 1.33 m, Wingspan: 9.12 m
Mass	480 kg (incl. 70.2 kg Xenon and 1.53 kg Hydrazine)
Launcher	Epsilon S rocket + Kickstage
Mission period	6.2 years
Communication	X-band medium gain and low gain antennas
Solar array	4.7 kW, 100 W/kg (BOL), 2.7 kW (EOL)
Propulsion	RCS + Ion thrusters (40 mN, 4 km/s, Isp 3000 s)
Thermal control	Loop heat pipes to transport heat from ion thrusters

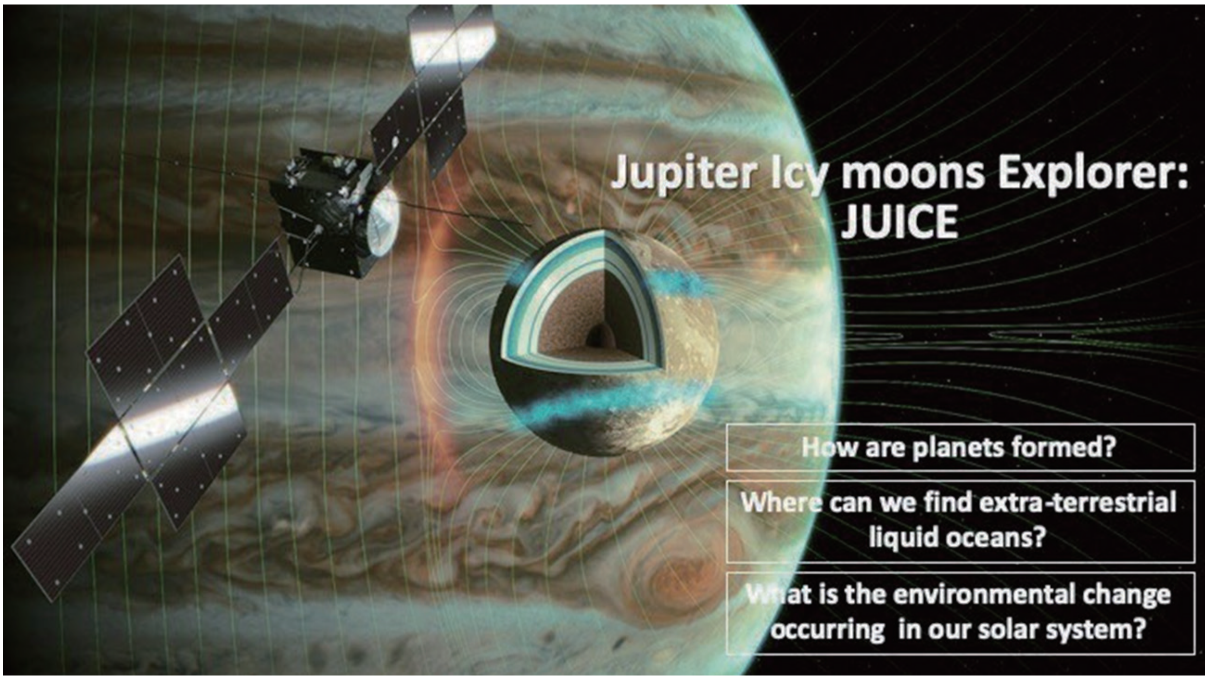

Solar Array Paddle EM


Mission data processor EM


DESTINY+ Dust Analyzer EM


MCAP EM

Jupiter Icy Moons Explorer (JUICE)



In 2034, JUICE will visit Ganymede, in order to answer the questions “How are planets formed?” “Where can we find extra-terrestrial liquid oceans?” “What is the environmental change occurring in our solar system?”

JUICE is an ESA L-Class mission to explore Jupiter's icy moons. The scientific objectives of JUICE are to understand (1)the emergence of habitable worlds around gas giants and (2) the Jupiter system as an archetype for gas giants. The JUICE mission was adopted in November 2014, and JUICE was successfully launched in April 2023 by an Arian-5 rocket. After eight years of interplanetary transfer and Earth-Earth-Venus-Earth-Earth gravity assists, JUICE will be inserted into an orbit around Jupiter in 2031, and make observations of all three Jupiter icy moons that potentially have subsurface oceans under their icy crust. After insertion into the Ganymede orbit in 2034, JUICE will make detailed observation of the largest icy moon in the solar system.

ISAS is participating in three science instruments: Radio and Plasma Wave Investigations (RPWI), Ganymede Laser Altimeter (GALA), and Particle Environment Package/ Jovian Neutral Analyzer (PEP/JNA)—by providing hardware and two instrument groups— Jovis, Amorum ac Natorum Undique Scrutator (JANUS) and JUICE magnetometer (J-MAG)—as science co-investigators (Co-Is). JUICE is the first mission in which ISAS/JAXA is participating as a junior partner by providing part of the science instrument payload for a foreign large science mission. Considering all the data to be obtained by the five instruments through which Japan will participate, the Japanese team will contribute to major scientific objectives related to the planet Jupiter (JANUS), Jupiter's magnetosphere (PEP/JNA, RPWI, and J-MAG), and the icy moons (GALA, J-MAG, and JANUS).

For the three instruments (RPWI, PEP/JNA, and GALA) for which ISAS/JAXA developed and provided part of the hardware, the three teams responsible for the instruments, RPWI-JAPAN, PEP/JNA-JAPAN and GALA-JAPAN, had completed the shipment of the flight models and flight spare models of all the instruments to Europe by the end of 2022. After the shipment, the three teams provided support for the instrument test conducted in Europe in preparation for the launch in April 2023. Also, as science Co-Is, two teams JANUS-Japan and J-MAG-Japan, are participating in JUICE and they contributed to the development of the observation plan and the instrument calibration method, respectively.

JUICE is a long-term mission that will continue for approximately 25 years. To make Japan's participation in JUICE successful, it is very important to plan for project continuity as the project team makeup changes over time.

Related organizations for this mission include ESA (Europe), Deutsches Zentrum für Luft- und Raumfahrt (DLR, Germany: GALA), Swedish National Space Agency (SNSA: RPWI, PEP/JNA), Institutet för Rymdfysik Uppsala (IRF Uppsala, Sweden: RPWI), IRF Kiruna (Sweden: PEP/JNA), Imperial College London (UK: J-MAG), and the National Institute for Astrophysics (INAF- OAC, Italy: JANUS).

Martian Moons eXploration (MMX)

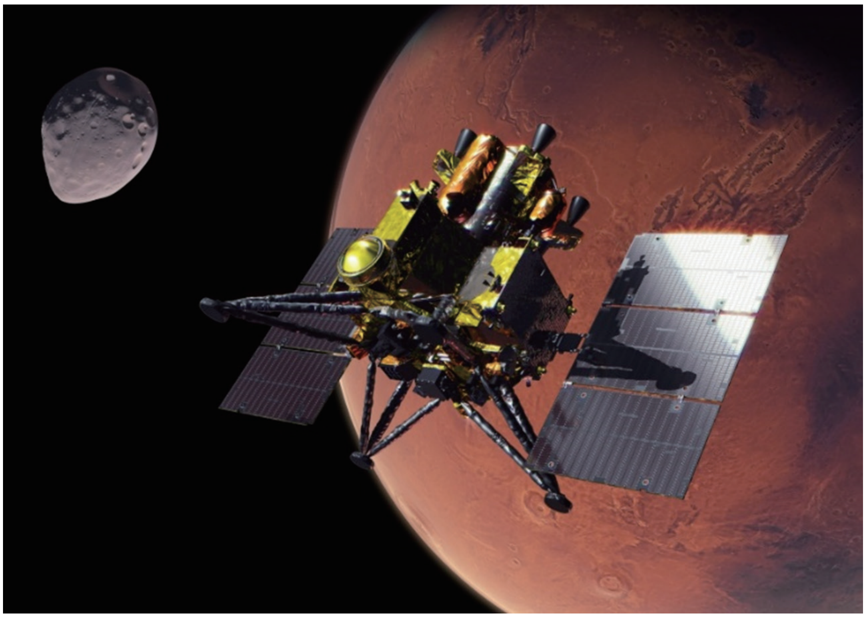


Image of the MMX spacecraft. One possible MMX spacecraft configuration with a launch mass of 4,000 kg. The spacecraft consists of three main modules: return, exploration, and propulsion. The nominal mission duration will be five years.

The Martian Moons eXploration (MMX) mission is the world's first sample return mission from one of the Martian moons. In order to contribute to the elucidation of the "migration of organic matter and water, and their supply to celestial bodies" in the primitive solar system, MMX will analyze hydrous minerals, water, and organic matter, etc. contained in the Martian satellite to clarify the existence of water and organic matter, and to elucidate the origin of Martian satellites. While inheriting the exploration technology that Japan has cultivated, MMX will promote the investigation of Martian satellites as a candidate for the future base of manned exploration on Mars itself. MMX is currently in the development phase as the first Strategic Large Mission (L-Class) and will be launched in FY 2024.

The achievements of our activities in FY2022 are as follows:

1) In FY2022, based on the results of a series of manufacturer reviews in a hierarchical manner, the JAXA Comprehensive Detailed Design Review (Comprehensive CDR) was conducted twice, in June and December 2022. The system and operational design for proceeding with manufacturing and testing were presented, and conformity to the comprehensive system requirements was confirmed. Remaining critical issues were also identified, and it was indicated that they would be addressed appropriately. Therefore, it was determined that the transition to the primary engagement test and manufacturing and testing phase was feasible.
2) In parallel with the critical design, various test models and certain flight models were fabricated, and system-level tests (EMIC test, etc.) were conducted using these models.
3) In line with development progress, agreements with international cooperation partners were concluded and revised (IA revision with DLR: June).
4) Number of peer-reviewed papers in FY2022: 4. Cumulative number of peer-reviewed papers: 60.
5) A self-assessment of the MMX project concluded that it is making steady progress in its operations toward the launch of the MMX spacecraft in FY2024, with the aim of realizing the first sample return from the Martian sphere in FY2029.

[EMIC: Electric and Mechanical Integration Test]

An EMIC test was conducted in Japan at Mitsubishi Electric's Kamakura Works to confirm that the spacecraft bus system and each piece of mission equipment (engineering model (EM) or flight model (FM)) are connected and satisfy each other's mechanical, electrical, and communication interface specifications, in order to reduce the risk of interface inconsistencies during the subsequent assembly phase.

Hera – binary asteroid exploration

Hera is an ESA asteroid rendezvous mission to the near-Earth binary asteroid system of S-type (65803) Didymos and its moon Dimorphos for the purposes of planetary defense and science. JAXA contributes to Hera with the heritage of Hayabusa2, by procuring the TIRI instrument, a thermal infrared imager with a filter wheel, to investigate the thermophysical properties and composition of the binary asteroid, as well as enhance asteroid science, such as the geology, impact phenomena, and dynamics of asteroids.

The primary objective of the Hera mission is technical demonstration for planetary defense, to avoid asteroid impacts with Earth, which would be hazardous to human civilization, by asteroid deflection using a kinetic impactor. Planetary science is also a significantly important objective for understanding the planetary formation and early evolution processes by achieving this mission.

Hera and the NASA Double Asteroid Re-direction Test (DART) mission consist of the first international planetary defense mission called Asteroid Impact and Deflection Assessment (AIDA). After the impact of the DART kinetic impactor on Dimorphos on 26 September 2022, which successfully changed its trajectory (the rotation period around Didymos changed from 11h55m to 11h23m, a 32-minute reduction), Hera will be launched in October 2024 and rendezvous with the asteroid binary system in January 2027 for observations over half a year.

The mission purposes, the scientific objectives, the introduction of onboard instruments, including TIRI, and the concept of operations for the Hera mission were outlined in a paper by P. Michel et al. [1].

The TIRI team is comprised of the Science Organizing Committee (SOC) members for the Thermophysical Model for Planetary Science (TherMoPS), and its fourth meeting is scheduled in April 2023.

The Hera mission has been conducted as a strategic international collaborative mission and approved as an ISAS project. The status of the development of the TIRI instrument is shown below.

In April 2022, the preliminary design review (PDR) was conducted by ISAS/JAXA, and it was confirmed that the instrument would move on to Phase C (Detailed Design Phase).

In February 2023, the design review for TIRI electronics was conducted to confirm the commencement of the manufacture and testing of TIRI PFM electronics.

In March 2023, the function and performance tests of TIRI using the EM1 (function test unit) and the EM2 (EQM) were performed with the payload interface checker (PIFC) provided by ESA/OHB, checking all the TM/TC functions. Several action items were identified, which have already been corrected for the PFM FPGA.

[1] P. Michel et al., (2022), The ESA Hera mission: Detailed characterization of the DART impact outcome and of the binary asteroid (65803) Didymos. Planet. Sci. J., 3, 160.

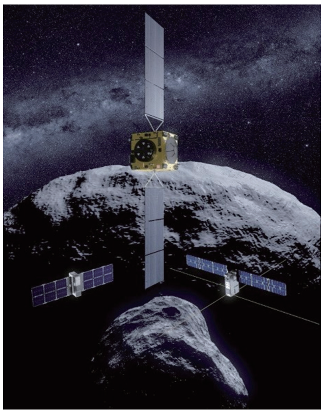


Figure1. Artist's illustration of the Hera and the CubeSats at the Didymos binary system (credit: ESA).

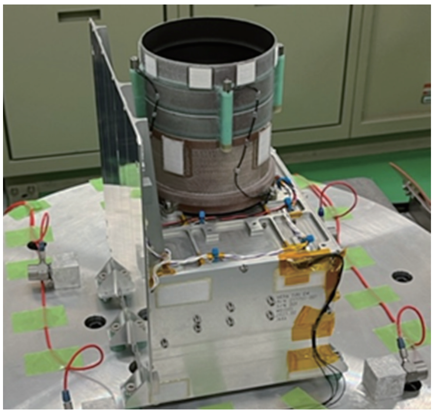


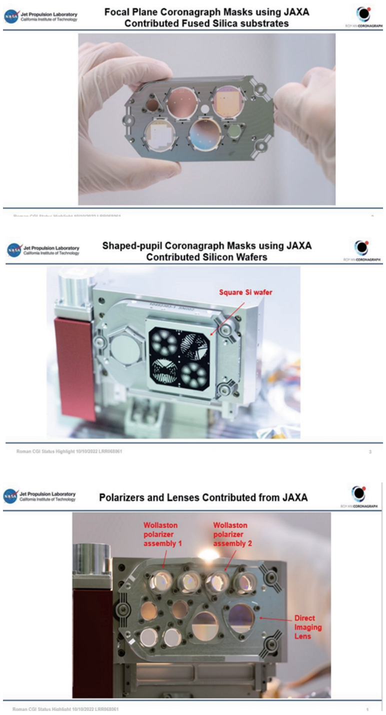
Figure 2. TIRI EM set for the component vibration test.

Roman Pre-Project (Roman)

The Nancy Grace Roman Space Telescope, which is NASA's future flagship mission in astrophysics, is planned to be launched in 2026. The telescope has a primary mirror that is 2.4 m in diameter and is equipped with a NIR Wide Field Imager, which is designed to unravel the secrets of dark energy and dark matter, search for and capture images of exoplanets, and explore many topics in infrared astrophysics. It also carries a Coronagraph Instrument (CGI) for technical demonstration of high contrast observations in space. The ISAS Roman pre-project represents the Japanese contribution for Roman, including (i) providing the CGI polarization module optics and mask substrates, (ii) receiving and transferring scientific data via the JAXA ground station, (iii) synergistic observations with the Subaru Telescope, (iv) and microlensing synergistic observations.

In 2022, following the successful System Requirement Review and System Definition Review, the ISAS Roman Project was formulated to carry out the program. By March 2023, the industry Preliminary Design Review for the Ground System had been conducted.

Artist concept of Roman Telescope (NASA).



The CGI Optics provided by JAXA were mounted on the holders in CGI.

Lite (Light) Satellite for Studies of B-Mode Polarization and Inflation from Cosmic Background Radiation Detection (LiteBIRD)

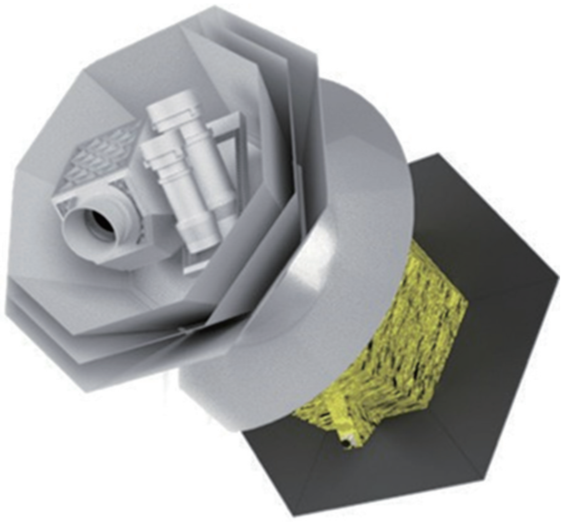
LiteBIRD aims to verify the inflation theory describing the expansion of the universe before the “hot big bang.” It is the second of a series of strategic large-class missions of JAXA, aiming at a launch in the late 2020s. According to the inflation model of cosmology, the universe experienced an extremely accelerated expansion before becoming a “fireball.” The model further postulates that quantum fluctuations are associated with inflation generated primordial gravitational waves. LiteBIRD aims to verify all representative inflation models through detailed analysis of primordial gravitational waves. For this purpose, an all-sky survey will be performed from Sun–Earth Lagrangian point L2 to precisely observe the spiral polarization distribution (B-mode polarization) produced by the primordial gravitational waves in the cosmic microwave background (CMB). During observations, any B-mode polarization caused by sources other than CMB needs to be carefully eliminated. For this purpose, LiteBIRD covers 34–448 GHz in 15 bands, which are shared between a low-frequency telescope (LFT) and medium/high-frequency telescopes (MHFT) with overlap. The LFT adopts a single reflective telescope, while the MHFT consists of two refractive telescopes. 1/f noise is reduced by using a polarization modulator with a rotating half-wave plate at 46 rpm (LFT) and 39/61 rpm (MHFT). We use transition edge sensor (TES) bolometers as detectors, which will be read with superconducting quantum interference devices (SQUID). The LFT and MHFT, including detectors and optical systems, are actively cooled down to 0.1–4 K.

LiteBIRD is based on a wide range of collaboration. In Europe, France, Italy, the UK, Germany, the Netherlands, Norway, Spain, and Belgium participate in LiteBIRD, and CNES takes the lead in developing the MHFT and sub-Kelvin Adia- batic Demagnetization Refrigerator (ADR). It is expected that ESA will also contribute to LiteBIRD and will provide the pulse-tube cooler and service-module components. Canada is responsible for the room-temperature electronics for LFT and MHFT. For domestic collaboration, the International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles (QUP), newly established within KEK, develops the focal plane detectors using technology developed in the US. Another institute of KEK, IPNS, is in charge of cryogenic tests of the LFT on the ground. IPMU of Tokyo University develops the polarization modulation unit of the LFT. Okayama University leads the systematic error analysis for LiteBIRD.

JAXA has concluded research agreements with the partner agencies to advance the LiteBIRD collaboration. Specifically, a JAXA-CNES agreement was concluded in 2021, and a trilateral agreement among KEK QUP, KEK IPNS and JAXA, a JAXA-IPMU Tokyo Univ. agreement, and a JAXA-Okayama Univ. agreement were concluded in 2022.

Telescopes on board LiteBIRD need to have very high sensitivity and to enable high-precision measurements of CMB polarization. For this purpose, both the LFT and MHFT are cooled down to 5K, and the focal plane detectors to 0.1K. The development of such telescopes is challenging, and conceptual studies and technical development of mission instruments are being undertaken vigorously in each participating country. At JAXA, the following studies were performed in FY2022. Structural and thermal design of the payload module (PLM) was optimized to satisfy the requirements for both the eigen frequency and the heat-load to the 4K Joule-Thomson cooler. This optimization also includes that of the V-groove. The optical design of the LFT was updated and its weight was reduced. We conducted preliminary tests of the alignment measurements, which are applicable at low temperature. The framework of Technology Front-loading was used to develop the driver for 2K JT cooler and the active control system of micro-vibrations of the mechanical coolers.

LiteBIRD successfully passed the pre-phase A2 exit review of ISAS in May 2019 and was selected as the second of the strategic L-Class missions of JAXA. The next major milestone is the mission definition review of ISAS, and various preparatory activities are well under way.



Artist’s impression of LiteBIRD.

Japan Astrometry Satellite Mission for INfrared Exploration (JASMINE)

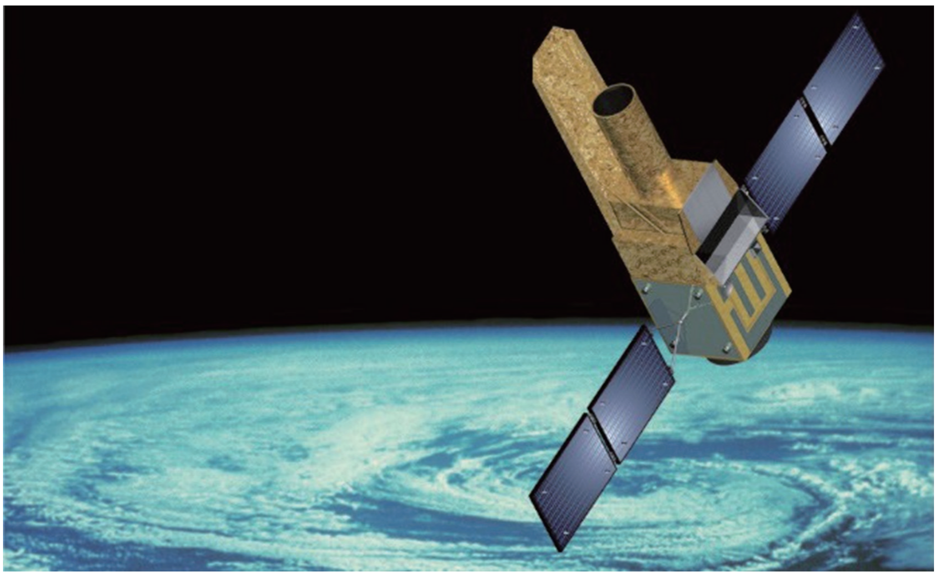
Japan Astrometry Satellite Mission for INfrared Exploration (JASMINE) is a satellite for ultra-high precision astrometry and exoplanet exploration using the transit method.

JASMINE will create a star catalog that includes astrometric parameters such as annual parallaxes and proper motions of approximately 100,000 stars by observing the stars hundreds of thousands of times over a period of three years. The scientific payload of the mission consists of the infrared telescope subsystem and the infrared detector subsystem. Whereas the European Space Agency's Gaia mission (launched in 2013, the final catalog is expected around 2028) could not observe the direction of the Galactic center at visible wavelength, JASMINE will be the first to measure high-precision distance and motion information of stars in the dust- and gas-obscured central bulge at near-infrared wavelength. The success of JASMINE is tied to the European Space Agency's GaiaNIR mission, an infrared all-sky astrometric satellite, which is planned for launch around 2045.

The ability of JASMINE to make repeated observations in the near-infrared wavelength range will also be utilized to search for exoplanets. By continuously observing mid-M dwarfs, which are smaller than the Sun, for long periods, and detecting slight changes in their brightness, JASMINE aims to discover terrestrial planets with orbits that could be suitable for life. Mid-M dwarfs have a radius of about 0.2 times that of the Sun and a surface temperature of about 3000K. They are abundant in the vicinity of the solar system and have relatively large amplitude of light curves in transit observations. In this field of observation, JASMINE has a significant advantage over NASA's Transiting Exoplanet Survey Satellite (TESS, launched in 2018), since JASMINE has a larger aperture and operates in the near-infrared wavelength range. Detailed spectroscopy of the atmospheres of the terrestrial planets discovered by JASMINE using a large space telescope will open a new era in the search for signatures of life on exoplanets.

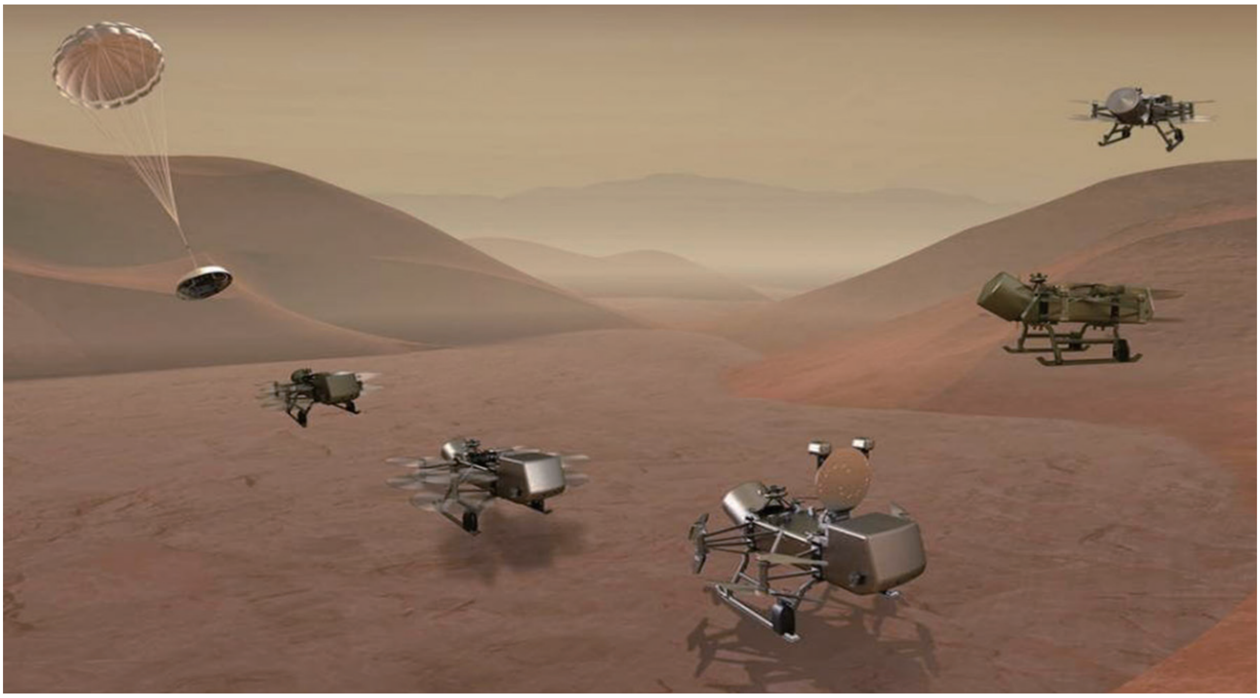
The achievements of our activities in FY2022 are as follows:

1) A feasibility study was conducted for the telescope and structure to ensure stable optical performance in orbit. Optical and thermal structural designs were performed, feasible assembly procedures were established, and conditions for ground verification tests were set.
2) A conceptual study of the detector subsystem, thermal structure cooling system, and drive electronics, was conducted to meet the requirements for JASMINE. As part of the Technology Frontloading activities, an infrared sensor chip was developed by adapting a sensor chip developed for ground-based telescopes for space applications.
3) A numerical simulation was constructed with the help of volunteers from the research community to show that the required accuracy for the derivation of astrometric parameters can be achieved under realistic errors. The simulation reflects the optical design, the mathematical model of the thermal structure, the actual data from the sensor chip, and the satellite-induced errors, etc.
4) As a "comprehensive check" by the team, a systematic study was conducted using the observation simulation software to optimize the specifications of the telescope. As a result, the telescope aperture was reduced from 40 cm to 36 cm, and the cut-on wavelength was shifted from 1.1 microns to 1.0 microns, resulting in an observation wavelength range of 1.0-1.6 microns.
5) Through coordination with domestic and overseas universities and research institutes, as well as candidate companies to take charge of development, the establishment of the development framework was promoted.
6) A session entitled "Near-Infrared Time-Series Astrometry and Photometry Science opened up by JASMINE" was held at Niigata University (a hybrid meeting) for 1.5 days during the Autumn Annual Meeting 2022 of the Astronomical Society of Japan. Discussions were held on how to make the observational data collected with JASMINE more useful for scientific studies.



The JASMINE satellite on orbit (artist's illustration)

Dragonfly

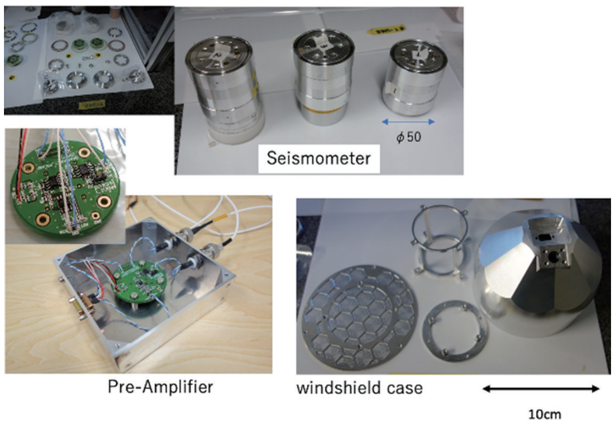


[Image of the DragonFly spacecraft] The drone has a total length of approximately four meters and weighs around 800 kg. It is equipped with more than 10 instruments for observation of material analysis, atmosphere observation, and internal structure exploration.

Dragonfly is a mission selected as part of NASA's fourth New Frontiers program. It involves a drone-like probe that will perform powered flight and repeated landings to observe the atmosphere, surface, and subsurface of Saturn's moon Titan. The probe includes a weather and geophysical observation package called "DraGMet", and JAXA is responsible for the development of a portion of the seismometer subsystem. The seismometer development team was approved as a project at the Institute of Space Science in July 2022 and commenced full-scale activities. The currently scheduled launch is in FY2027, with an estimated arrival at Titan in 2034. The mission is expected to operate for approximately three years after arrival.

The achievements of our activities in FY2022 are as follows:

1) By August 2022, evaluation tests using the prototype seismometer had been conducted at APL for specification verification and operation confirmation. It was confirmed that the seismometer possesses the necessary performance for scientific observations.
2) Towards the launch in FY2027, the equipment's preliminary design (APL) was completed in August 2022, and the system's preliminary design (NASA) was completed in February 2023. Preparations for the Phase-C transition are currently underway.
3) For the JAXA-developed components, the Mission Definition Review (MDR), System Requirement Review (SRR), and System Definition Review (SDR) were conducted and approved in April 2022. The Preliminary Design Review (PDR) at JAXA began in February 2023 and is planned to be completed in the first half of FY2023, followed by the transition to the Engineering Model (EM) manufacturing and testing phase.
4) In parallel with the instrument development, a science team has been organized to study the science and observational methods that can be obtained through shallow and deep structure exploration.
5) Number of presentations at domestic and international conferences:5
6) Steady progress has been made in the development of reliable testing under cryogenic high pressure environments (-180℃,1.5atm).
7) The scientific activities have been expanded through presentations at academic conferences.



The seismic instrument package under development by JAXA consists of a seismometer, preamplifier circuits, and a wind shield case.

SOLAR-C

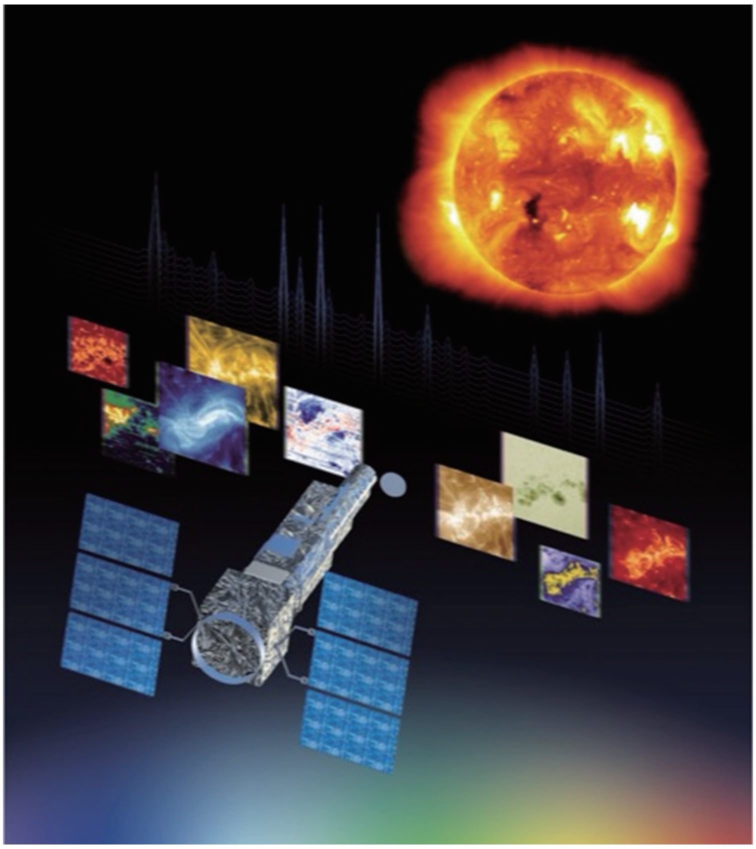


Image of the SOLAR-C spacecraft. The SOLAR-C spacecraft configuration with a launch mass of about 600 kg. The EUV High-throughput Spectroscopic Telescope (EUVST) mounted on the spacecraft bus module will provide spatial mapping of the spectroscopy for plasma diagnostics of our Sun.

As a fundamental step towards answering how the plasma universe is created and evolves, and how the Sun influences Earth and other planets in our solar system, the SOLAR-C mission is designed to comprehensively understand how mass and energy are transferred throughout the solar atmosphere and to explore fundamental physical processes occurring commonly in the plasma universe. The primary scientific objectives are to understand how fundamental processes lead to the formation of the solar atmosphere and solar wind, and to understand how the solar atmosphere becomes unstable, releasing the energy that drives solar flares and eruptions that may propagate disturbance to the interplanetary space. To achieve these objectives, the mission carries the EUV High-throughput Spectroscopic Telescope (EUVST), which seamlessly observes all the temperature regimes of the solar atmosphere from the chromosphere to the corona simultaneously, resolves elemental structures of the solar atmosphere with high spatial resolution and cadence to track their evolution, and observes spectroscopic information on the dynamics of elementary processes taking place in the solar atmosphere. The SOLAR-C, as the fourth mission in a series of competitively chosen M-Class missions, is an international JAXA-led mission with participation by the US and European countries and will be launched in FY 2028.

The achievements of our activities in FY2022 are as follows:

1) Mission Definition Review (MDR, July 2022) and Project Preparation Review (September 2022) were completed, followed by the launch of the SOLAR-C Pre-Project Team in November 2022.
2) Following system Requirement Review (SRR, December 2022), the mission is currently in the planning phase.
3) Technical studies for EUVST are in progress, including coordination of interfaces with foreign partners and the spacecraft system and the development of a bread-board model for verifying performance of a primary mirror tip-tilt and scanning mechanism.
4) In line with the progress of the development, the scheme for international collaboration has been established. Agreements regarding hardware development with NASA, ESA, ASI, CNES, and DLR are either established or under preparation. The International Steering Committee (ISC) and the Science Working Group (SWG) have commenced their activities with clarification of their charters.
5) Number of peer-reviewed papers in FY2022: 0 Cumulative number of peer-reviewed papers: 10
6) A self-assessment by the SOLAR-C Pre-project Team concluded that it is making steady progress toward realizing the launch in FY2028 and good progress has been made with respect to the international scheme for the hardware development and conceptual design studies.

Comet Interceptor

Comet Interceptor is a long-period comet exploration mission led by the European Space Agency (ESA), which aims to be the first spacecraft to directly explore long-period comets, a category of comets that is considered most primitive. The mission consists of a mother-spacecraft and two ultra-small daughter-spacecraft mounted on it to perform simultaneous multi-point flyby observations. Japan will provide one of the three spacecraft and conduct observations using two visible cameras (the narrow- and wide-angle cameras), the hydrogen imager, and the plasma suite (ion mass spectrometer and magnetometer), jointly with two European spacecraft.

The imaging and spectroscopy of the nucleus surface and coma from multiple angles will investigate the shape, structure, and composition of the target. The first-ever simultaneous multi-point observations of cometary plasma will reveal dynamic interaction with the solar wind. As a result, the mission will provide unique and important knowledge addressing the two major themes of the solar system science community: (1) understanding of the formation of a habitable environment for life in the solar system and (2) discovery of the universal laws governing cosmic gases. The mission also aims to enhance the small and ultra-small spacecraft technologies that Japan has cultivated to date by implementing and demonstrating a short-term, low-cost, and efficient spacecraft development method in cooperation with the spacecraft system developer.

Comet Interceptor is currently in the development preparation phase aiming for launch in FY2028.

The achievements of our activities in FY2022 are as follows:

1) The Mission Definition Review (MDR), System Requirements Review (SRR), and ISAS project preparation review were conducted from May to July 2022, and a pre-project team was formulated.
2) The pre-project team conducted an RFP for the development of the ultra-small spacecraft bus system and selected a contractor. The team conducted a preparatory study for the System Definition Review (SDR) scheduled for the next fiscal year.
3) Steady progress was made in the study of spacecraft development toward the realization of the first-ever exploration of a long-period comet.

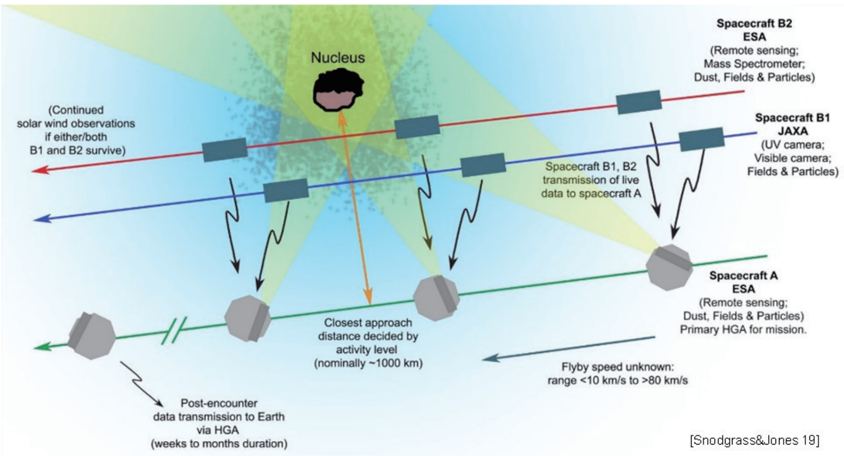


Image of simultaneous multi-point flyby observation by three spacecraft.

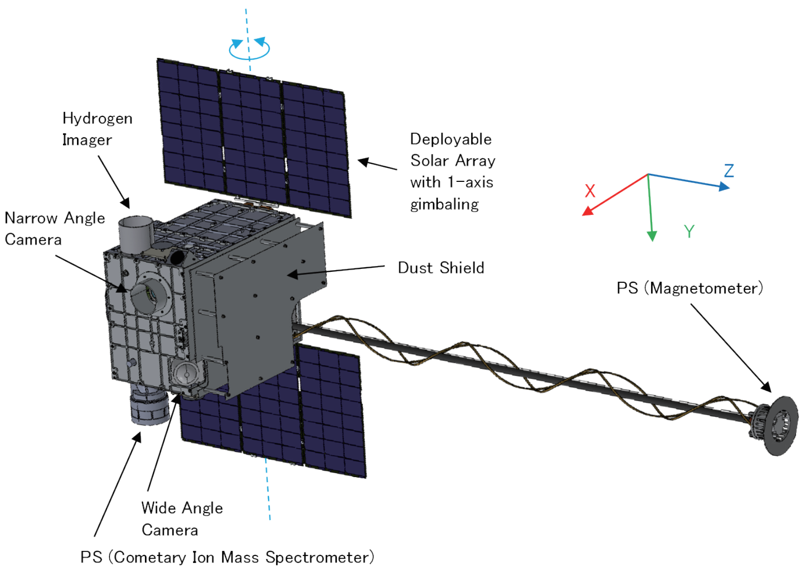


Image of the ultra-small probe under study.

Cryo-Chain Core Technology Program (CC-CTP)

The CC-CTP is an international project aimed at demonstrating a detector cooling system, including a cryostat and active coolers, to reach temperatures as low as 50 mK. The European CC-CTP partners are financially supported by ESA, with CNES (France) and the French Alternative Energies and Atomic Energy Commission (CEA) leading the effort.

The CC-CTP will establish the system step-by-step. JAXA has provided 2K and 4K Joule-Thomson (JT) coolers, Stirling coolers for pre-cooling, and driving electronics. In 2017 and 2018, a combined test of JAXA coolers, a European pulse-tube cooler, sorption cooler, and adiabatic demagnetization refrigerator (ADR) was performed, and production of 50 mK was successfully achieved without cryogen. It was the first cooling chain for space use that combined Japanese and European spacecraft cooling technology. In 2021, we collaborated with CNES/CEA for the next step with a cryogenic radiation sensor, to confirm the performance of the cooling system. JAXA coolers were confirmed to fulfill the requirements, and we designed the I/F and discussed the assembly procedures, and participated in the detailed design review for this project.

This system will also be tested as the demonstration model for Athena X-IFU (X-ray integral field unit). A 4K Joule-Thomson cooler that was not used in the test was sent back to Japan and had its performance checked.

To improve the robustness of this system, we investigated and specified the cause of the aging effect inside cooler compressors, and updated designs and procedures to overcome the aging, which will allow us to design compressors with a 10-year lifetime. Based on the new design made in 2020, we have started the fabrication of new compressors and produced two compressors in 2022. The characteristics were evaluated.

International Top Young Fellowship

Since FY2009, ISAS has offered the JAXA International Top Young Fellowship (ITYF) program as part of its initiatives to make Japan a leading member of the most advanced space science community. The program calls for the participation of young and promising researchers from across the world, and successful applicants are invited to Japan for a predetermined assignment term. It is a popular program, with the open call applicants significantly outnumbering the available places every year. Fellows invited through this program stay Japan on a three-year term, which can be extended to five years after review. The program was recognized in the FY2012 JAXA international external evaluation as "highly effective in promoting ISAS's presence and in contributing to the advancement of space science."

A total of 19 fellows have participated in the program so far. ITYF fellows are encouraged to become involved in other projects as well as to pursue their own studies. These opportunities are expected to have a synergistic effect through interactions between the fellows and Japanese researchers at ISAS. Much as previous fellows have contributed to remarkable outcomes in the projects in which they were involved, our current fellows are not only making proactive contributions to ongoing projects but are also actively engaged in forming future projects.

ITYF Fellows (as of March 2023)

Name	Former Affiliation	Research Theme	Term
James O'DONOGHUE	NASA Goddard Space Flight Center	*Ground-based observations of Gas Giant ionospheres*	May 2019-
HYODO Ryuki	Tokyo Institute of Technology	*Formation of small bodies, planetesimals, and planets: Bridging theoretical studies and JAXA's planetary explorations*	October 2019-

James O'DONOGHUE
ITYF, Department of Solar System Sciences

In FY2022 I published a Review article on what we have learned, are learning and will learn in the study of giant planet upper atmospheres. This timely article was designed to coincide with remarkable new data of the giant planets (Jupiter, Saturn, Uranus and Neptune) being obtained by the JWST telescope, which was several months into its mission when the article was published. I am a contributing member of the JWST Early Release Science team, and our global team is heavily invested in the mission and its solar system data from Jupiter and Saturn which came down during the year, so has been busy analysing this new, unique data set. This investment in time will pay off for our team during 2023-2024, when exciting new results will be published that transform what we know about the giant planets. For example, we have seen 1000-km sized density waves in Jupiter's upper atmosphere for the first time: this Jupiter study, on which I am a second author, was submitted to Nature Astronomy by invitation at the end of FY2022.

I have completed a study of ground-based data from the Keck telescope in Hawaii, in which we reveal a giant planetary scale 'heat wave' was seen rolling away from the aurora of Jupiter at about 500m/s following what we thought (at the time) was a compression of the Jovian magnetosphere by a dense region of solar wind. This was presented at EPSC in FY2022 and had an associated press release with numerous articles in international media outlets. Following the release, scientists from the Juno spacecraft found supporting evidence that the magnetosphere was compressed in their in-situ data taken at the same time by the spacecraft, which has now been added to our study to solidify our conclusions. The study is important as it shows, definitively and for the first time, that the solar wind can drive large planetary-scale heat waves to emanate from the auroral region of Jupiter and propagate around the planet. This means that the Jovian upper atmosphere can be periodically globally heated owing to the conditions of the solar wind, which is a surprising example of star-planet coupling.

Published Research in FY 2022:

Author	Title	Journal / Conference	DOI
J. O'Donoghue *et al.*	What the Upper Atmospheres of Giant Planets Reveal	*Remote Sensing*	https://doi.org/10.3390/rs14246326
J. O'Donoghue *et al.*	A planetary-scale heat wave in Jupiter's mid-latitude upper atmosphere	*Europlanet Science Congress 2022*	https://doi.org/10.5194/epsc2022-373
L. Moore *et al.*	Ionospheric temperature variability above Jupiter's Great Red Spot	*Europlanet Science Congress 2022*	https://doi.org/10.5194/epsc2022-564

HYODO Ryuki
ITYF, Department of Solar System Sciences

This year, I have conducted research on (1) planetesimal formation, (2) Ryugu formation, and (3) Martian moon formation. These studies are crucial for bridging the gap between data obtained from planetary explorations and theoretical studies of planet formation.

Regarding (1), planetesimals are fundamental building blocks of all planets and small celestial bodies. The formation process of planetesimals is still poorly understood, and as a result, a key mechanism for the formation of all planetary bodies remains elusive. In my research, I have proposed a new mechanism called the “no-drift mechanism” to explain the formation of planetesimals. Moving on to (2), Ryugu is the target of JAXA’s Hayabusa2 mission. In my investigation, I have focused on determining the origin of Ryugu. Specifically, I have examined the conditions under which impact fragments can give rise to the formation of Ryugu. Additionally, I have studied the evolutionary changes in Ryugu’s shape over time.

Finally, with respect to (3), the Martian moons Phobos and Deimos are the subjects of JAXA’s MMX mission. I have re-evaluated the possibility that Phobos and Deimos were formed from a single moon that split due to a collision with a meteoroid, as recently reported in Nature Astronomy. Based on my analysis, I have demonstrated that Phobos and Deimos are unlikely to have been formed through this process.

Published Research in FY 2022:

Author	Title	Journal	DOI
R. Hyodo *et al.*	Formation of Moons and Equatorial Ridge around Top-shaped Asteroids after Surface Landslide	*The Astrophysical Journal Letters*	https://doi.org/10.3847/2041-8213/ac922d
R. Hyodo *et al.*	Challenges in Forming Phobos and Deimos Directly from a Splitting of an Ancestral Single Moon	*The Planetary Science Journal*	https://doi.org/10.3847/PSJ/ac88d2
Y. Liang *et al.*	Giga-year dynamical evolution of particles around Mars	*Icarus*	https://doi.org/10.1016/j.icarus.2022.115335
N. Ozaki *et al.*	Asteroid Flyby Cycler Trajectory Design Using Deep Neural Networks	*Journal of Guidance, Control, and Dynamics*	https://doi.org/10.2514/1.G006487
A. Okuya *et al.*	Modelling the evolution of silicate/volatile accretion discs around white dwarfs	*Monthly Notices of the Royal Astronomical Society*	https://doi.org/10.1093/mnras/stac3522
T. Nakamura, *et al*	Formation and evolution of carbonaceous asteroid Ryugu: Direct evidence from returned samples	*Science*	https://doi.org/10.1126/science.abn8671
G. Madeira *et al.*	Dynamical origin of Dimorphos from fast spinning Didymos	*Icarus*	https://doi.org/10.1016/j.icarus.2023.115428

Graduate Education

At ISAS, academic staff appointed by universities as professors, associate professors, and assistant professors provide education for students at ISAS through requests by universities for experimental and theoretical research and innovative R&D.

ISAS provides comprehensive guidance on space science and space engineering research to students, as well as direct involvement in preliminary research and large research projects that are difficult to conduct at universities. Through these means, opportunities to acquire deep knowledge and planning skills for space science projects contribute to the development of human resources by fostering personnel who will lead future space science and aerospace research, engage in R&D with space equipment manufacturers and companies utilizing space infrastructure for their clients, and organizing projects in a wide range of social fields.

The Director General of ISAS defined and established the Graduate Education Committee as an organization to promote graduate education at ISAS. This committee reviews important program elements, including basic policies and guidelines related to cooperation with graduate education, cooperation with the Graduate University for Advanced Studies (known as SOKENDAI in Japan) and the University of Tokyo, and other issues related to affiliations with graduate schools.

ISAS staff engaged in graduate education (As of March 31,2023):

School or Program	Professors	Associate professors	Assistant professors	Total
The Graduate University for Advanced Studies (SOKENDAI)	24	38	14	76
School of Science / The Graduate School at the University of Tokyo	9	4	6	19
School of Engineering / The Graduate School at the University of Tokyo	10	4	7	21

In FY2018, the acceptance of students was enhanced under a new ISAS cooperation system after having reviewed the past system. The new system has been divided into 2 main categories based on the acceptance purpose, and upon taking into account the differences in training content and acceptance period and so on, each of them was categorized into 2 programs: Graduate Student Education/Research Guidance Program (Cooperative Graduate School System and Commissioned Guidance Student System) and Student Training Program (Skill Acquisition Program and Internships). Conditions common to each program such as handling of expenses, insurance and damage compensation as well as handling of intellectual property were clearly defined. It was also determined that agreements will be concluded for each system to fulfill the responsibility of accepting students. To provide proper guidance to the students, qualifications for JAXA employees were established, safety of students were ensured, and responsibilities of JAXA employees who provide training and guidance were specified.

Major features of ISAS cooperation for graduate education are described below.

a. Department of Space Astronautical Science, School of Physical Sciences, SOKENDAI

SOKENDAI was established in 1988 and was the first Japanese university to offer only graduate degrees. ISAS has cooperated with SOKENDAI since April 2003. ISAS established the SOKENDAI Department of Astronautical Science in what was then the School of Mathematical and Physical Science. The school was reorganized in April 2004, and the Department of Astronautical Science was placed in the School of Physical Sciences. Academic staff from ISAS also teach at SOKENDAI, instructing students in 5-year doctoral programs and other courses. SOKENDAI is scheduled to be reorganized in 2023.

SOKENDAI Department of Space Science Admissions in FY2022:

<table>
<tr><th>Admission month</th><th>Admission capacity</th><th>Applicants</th><th>Accepted applicants</th></tr>
<tr><td>October</td><td rowspan="2">5*</td><td>0</td><td>0</td></tr>
<tr><td>April</td><td>4</td><td>4</td></tr>
</table>

*Of which 3 were admitted to secondary doctoral courses.

b. Interdisciplinary Studies (Graduate School of Science/ Engineering) at the University of Tokyo's Graduate School of Science and Engineering

Interdisciplinary studies at the University of Tokyo's Graduate School of Science and Engineering originated from acceptance of graduate students from the University of Tokyo when ISAS was the National Aerospace Laboratory of Japan. Academic staff at ISAS are university instructors in eight departments at the University of Tokyo: the departments of Physics, Astronomy, Earth and Planetary Science, and Chemistry at the Graduate School of Science and the departments of Aeronautics and Astronautics, Electrical Engineering, Materials Engineering, and Chemical System Engineering at the Graduate School of Engineering. They accept, teach, and train master's and doctoral degree students.

c. Graduate student education and research guidance system

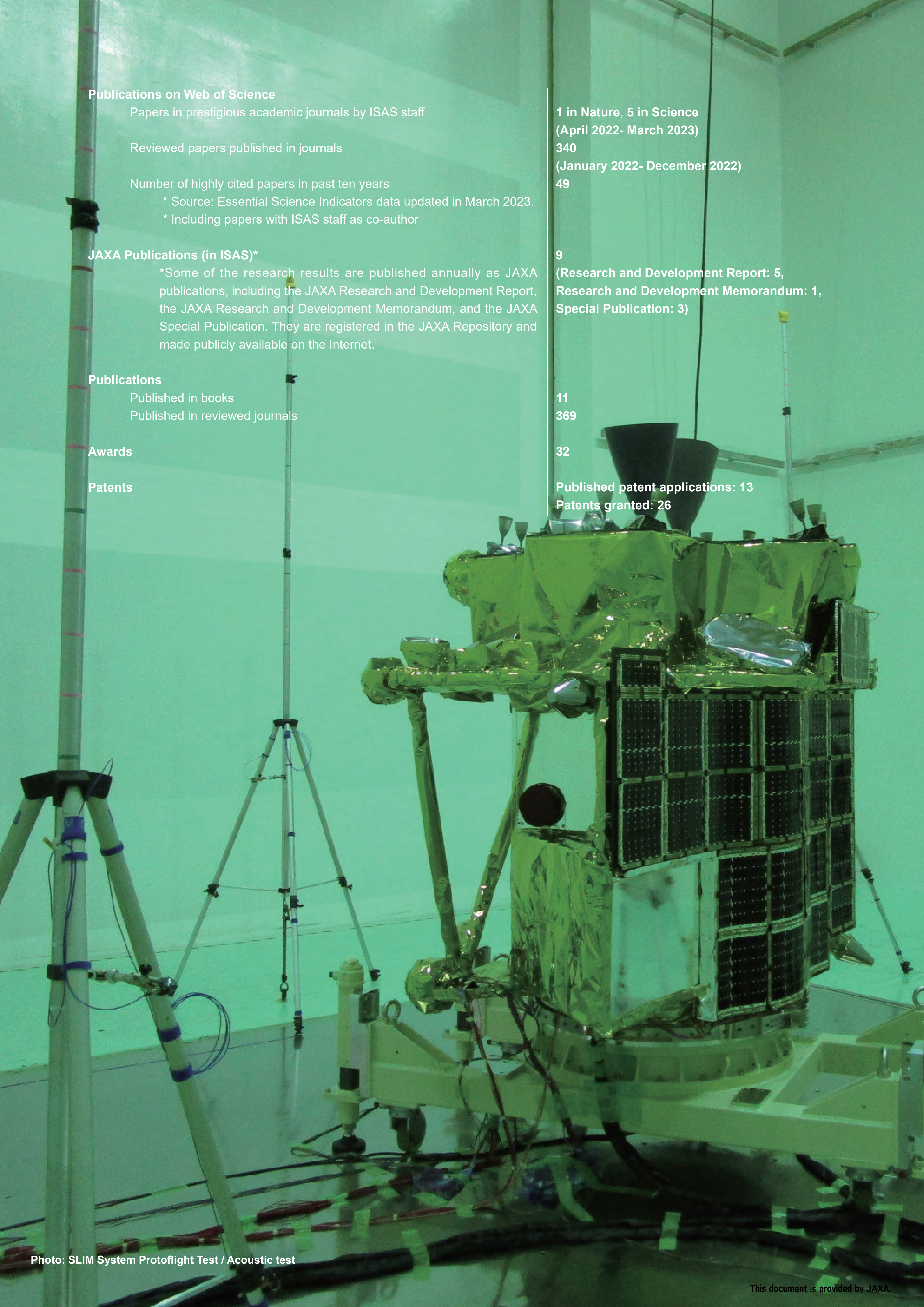
In the Special Inter-Institutional Research Fellows system, ISAS accepts students from national, public, and private universities throughout Japan who need advice on their university-sponsored research and provides education and guidance on specific research themes for limited periods. These activities are part of ISAS cooperation with graduate education as an inter-university research system. The universities to which the students belong regard these activities as "education at research institutions" as defined in Japanese graduate school guidelines, and they issue credits, review dissertations, and confer degrees.

d. Cooperative Graduate School System

The Cooperative Graduate School System is based on agreements between JAXA and specific universities. In the system, JAXA staff are appointed as visiting professors by universities, and they accept, teach, and train master and doctoral students under commission. In 2020, ISAS was cooperating with 12 schools in 11 universities and accepts, teaches, and trains master's and doctoral degree students.

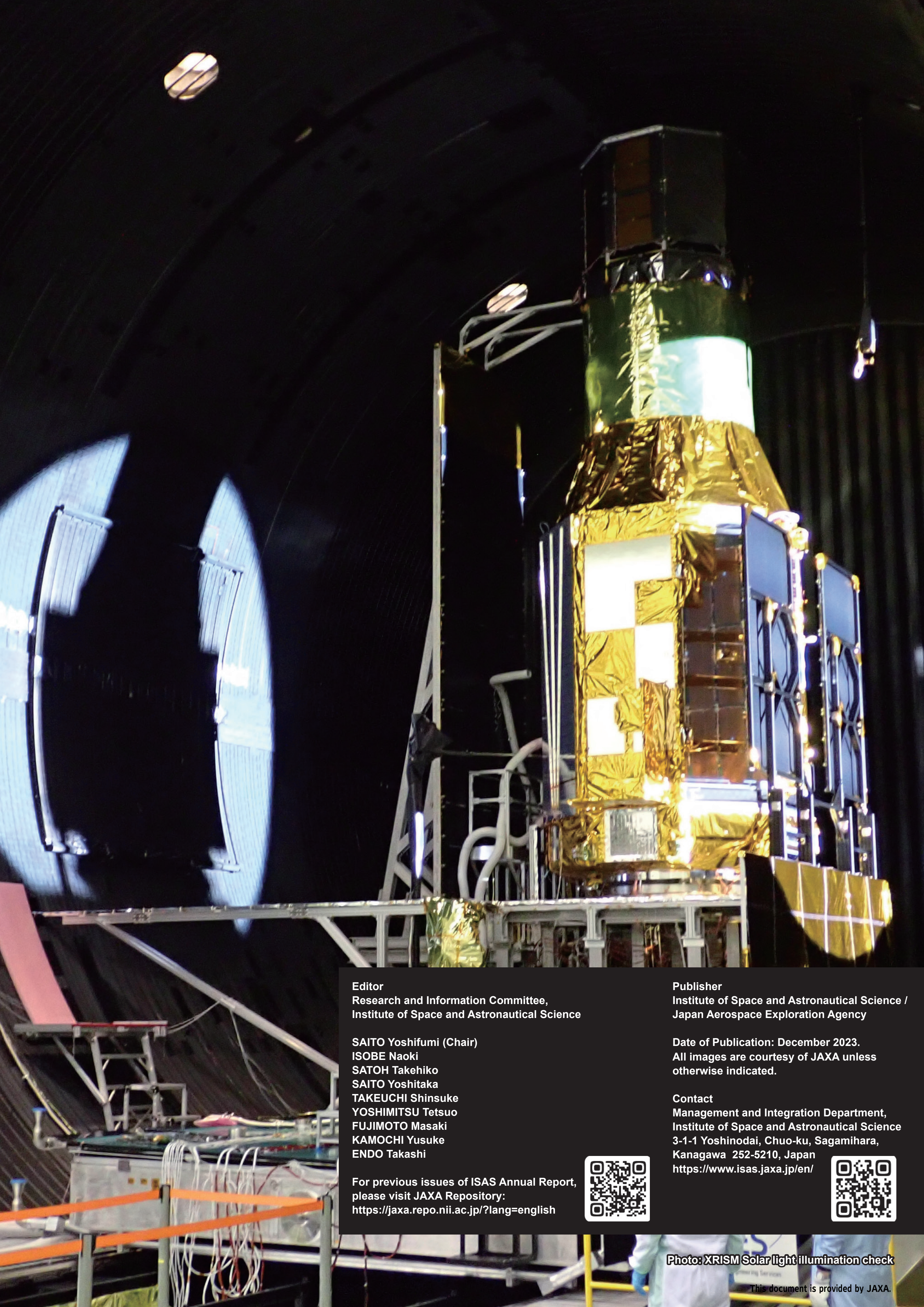
e. Commissioned Guidance Student System

To accept individual students to whom the Cooperative Graduate School System does not apply, JAXA will, based on agreements between JAXA and specific universities, appoint staff as the universities' visiting professors who will teach graduate school students on a specific theme.



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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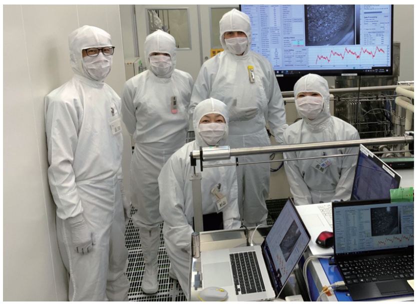

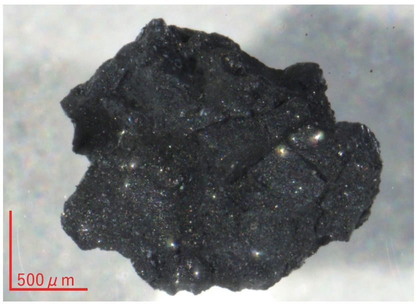

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2022

Institute of Space and Astronautical Science,
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