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Annual Report of the Institute of Space and Astronautical Science 2021

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Annual Report of the Institute of Space and Astronautical Science

Fiscal Year 2021
(Apr 2021 – Mar 2022)

Message from the Director General

October 2022

In 2021, it is undeniable that the COVID-19 pandemic severely restricted our research activities. Despite this disadvantage, we achieved significant results in space science. In particular, we made efforts to maximize and integrate the achievements of an individual space project by using multiple spacecraft and methods to produce multifaceted and comprehensive results.

First and foremost, many scientific achievements of the Asteroid Explorer Hayabusa2 were published in prestigious journals such as Science and Nature. Discussions progressed by comparing image data from cameras mounted on the spacecraft and probes with non-destructive observation of the collected Ryugu samples. Scientific knowledge has expanded as a result of the transition from macroscopic to microscopic analytical techniques. In the next fiscal year, we anticipate even further and incomparable progress in those techniques in resolution of Nano and Angstrom, through destructive analysis of Ryugu samples. Beyond that, if we add analysis data from Hayabusa's Itokawa samples and NASA's OSIRIS-Rex's Bennu samples, we will be thrilled with the multifaceted growth of asteroid science.

In July, a rotating detonation engine (RDE), developed in a project led by Nagoya University, was successfully operated in outer space onboard the sounding rocket S-520-31. Facing the difficulty of transmitting large amount of data through a telemeter, a Reentry and Recovery module with deployable Aeroshell Technology for Sounding rocket (RATS) experiment was performed, and a memory chip containing detailed image data was recovered from the ocean and brought back for analysis. In November, we launched the SS-520-3 sounding rocket from Svalbard Norway, and successfully observed plasma flowing into space from the high-latitude ionosphere. Coincidentally, this was a magnetic storm generated by the reach of a coronal mass ejection (CME) accompanying a solar flare, which was observed by the solar observation satellite HINODE. We would like to express our sincere gratitude to the Norwegian Space Agency (NOSA), Norwegian government agencies, and the Embassy of Japan in Norway, as well as Japan's government and all those involved around the world for supporting the activities of our team during the COVID-19 pandemic.

In April, the Venus Climate Orbiter AKATSUKI and the ESA/JAXA Mercury Exploration Mission BepiColombo had the opportunity to pass simultaneously on the far side of the Sun as seen from the Earth as solar conjunction. At this time, the communication radio waves are affected and disturbed by the plasma emitted from the Sun. The solar observation satellite HINODE performed coordinated observation of the surface of the Sun and obtained a unique data set for corona research. In August, during the second Venus flyby by BepiColombo, joint observations of Venus were performed with AKATSUKI, the Mercury magnetosphere orbiter MIO, and the spectroscopic planetary observation satellite HISAKI.

Even during restrictions on activities due to the COVID-19 pandemic, we have been delivering our news, activities and achievements by utilizing many media tools, such as ISAS News, Cosmos blog, ISAS official Twitter, ISAS Research information portal ISAS GATE, JAXA Space and Astronautical Science Podcast, and many opportunities such as the JAXA Sagamihara Campus online special open days, Hayabusa2 Return Capsule Exhibitions, an opening ceremony for the Misasa deep space tracking station, various space science symposiums, and dialogues at various academic societies, both in Japanese and English. We expect to resume our face-to-face outreach next year.

As described so far, we are now in the process of creating multifaceted and comprehensive results utilizing multiple measures, as a result of both the Deep Space Exploration Fleet and Wavelength-integrated Astronomical Observation Network concepts that I have been advocating. These concepts will allow us to reveal more about the Universe by integrating data from multiple spacecraft and projects both inside and outside ISAS, and from ground observation network. However, we do not intend to stop there. Fortunately, Japan’s government has approved the further expansion of the special budget for Technology Frontloading, which will accelerate research and development of important technologies that are directly linked to the creation of our future missions. Encouraged by the enthusiastic support from all over the world, we will continue to push forward with the promotion of space science even under the constraints of limited budgets, personnel, and time.

This annual report summarizes our activities for fiscal year 2021. We deeply appreciate your recognition of ISAS’s achievements, continued support, and encouragement.

KUNINAKA Hitoshi
Director General of ISAS/JAXA

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ON THE COVER

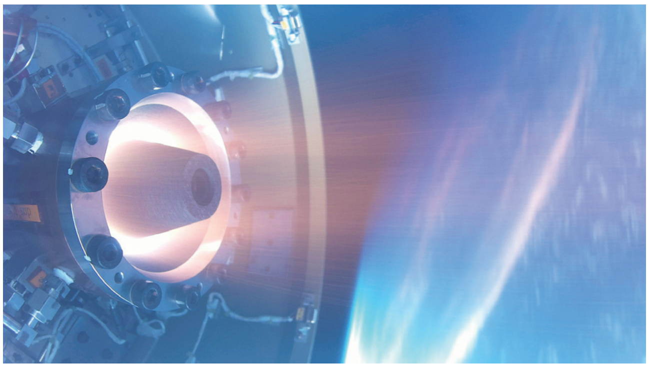
Launch of sounding rocket "SS-520-3" in Svalbard, Norway

On November 4, 2021, in Svalbard, Norway, JAXA and related organizations conducted an SS-520-3 sounding rocket campaign with the purpose of elucidating the plasma acceleration/heating mechanism responsible for the ion outflow/upflow in the ionospheric cusp region. Being able to tackle such an important science topic was made possible by a combination of high time resolution in-situ rocket measurements and ground-based optical and radar observations. A total of nine science instruments were installed on the rocket: digital fluxgate magnetometer (DFG), low frequency analyzer system (LFAS), thermal ion spectrum analyzer (TSA), low energy particle experiment (LEP), ion mass spectrometer (IMS), fast Langmuir probe (FLP), needle Langmuir probe (NLP), plasma and wave monitor (PWM), and sun aspect sensor (SAS).

In this campaign, the rocket equipped with these instruments was launched at 11:09:25 CET from the SvalRak launch facility at Ny-Ålesund in Svalbard after confirming that the rocket would traverse a region of the ion upflow.

It was fortunate that there were relatively active geomagnetic conditions in early November, enabling the rocket to be launched on the second day of the launch window while the science conditions were satisfied. A series of time sequences was performed as planned. The probes and antennae of the instruments were sequentially deployed starting from 92 seconds after launch, and the high voltage power supply for the electron/ion analyzers and ion mass spectrometer came on from 180 seconds after launch. In this way, the onboard instruments started their measurements at the predetermined time, and subsequently continued to obtain data on electrons, ions, electric and magnetic fields, and plasma waves. The flight trajectory of the SS-520-3 rocket was almost the same as planned, and the rocket reached a maximum altitude of 756 km at 490 seconds. At 950 seconds, the rocket splashed down within the predicted impact area in the south-southwest direction.

BACK COVER



Rotating detonation engine combustion with the blue earth in the background

his image shows the combustion of the rotating detonation engine (RDE) from the experiments conducted by S-520-31. The RDE is installed at the rear end of the experimental section, and is exposed to outer space by the separation of the S-520 first stage solid rocket motor. The RDE consists of an outer cylinder and an inner truncated cone, shown at about 1/4 from the left edge of the image. The slightly curved part vertically crossing the center of the image is the separation plane from the first stage, and the right half of the image is the earth at dawn. Supersonic combustion (detonation) takes place in the space between the cylinder and truncated cone of the RDE, and the shock wave caused by the expansion of the combustion gas rotates in the doughnut-shaped space and is emitted to the rear (right side of the image). The internal and rear combustion gases are substantially uniform on the circumference, and this indicates that combustion is stable. Please refer to the highlights for details of the experiments.

Scientific Highlights in FY 2021

Pebbles flying over Ryugu and returned grains

【Asteroid Explorer Hayabusa2】

The analysis of returned samples is distinct from the analysis of meteorites because of the presence of geological information about the asteroid. However, can we expect to obtain valuable information that will lead to an understanding of the entire asteroid from samples gathered from limited areas? In light of this concern, the team decided to run a full information analysis in which observations of the asteroid on different length scales from the global appearance of the asteroid down to the millimeter sized particles in the returned samples were analyzed and compared. In this study, we combined the results of multi-scale observations of Ryugu surface particles by CAM-H during the spacecraft touchdowns, the observations made by the MINERVA-II Rover-1A, 1B at multiple locations across the asteroid, and the returned samples in the clean chamber. We found that the returned samples well represent Ryugu surface particles and that there are characteristic flat and elongated particles on the asteroid. In addition, we found that the sampler system correctly operated to collect and return 5 grams of samples. In this work, CAM-H, which was developed by generous donations, played a particularly important role.

At the point of touchdown to collect samples, the CAM-H images show that many centimeter- and millimeter-sized particles were ejected from the lower part of the sampler horn immediately after the spacecraft fired a projectile. Some of the particles were ejected toward CAM-H (Figure 1), and the ejection angles and velocities of these particles match well with those predicted by ground-based projectile shooting experiments and numerical simulations. This confirms that the projectile was successfully fired on the surface of Ryugu. The quantity of particles in the image also indicates that the collection of 5 grams of samples was due to the projectile shooting onto the surface.

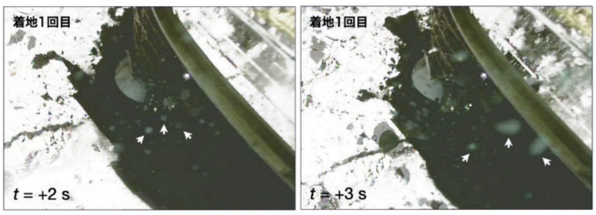


Figure 1. CAM-H images taken 2 and 3 seconds after the first touchdown, showing particles with arrows flying toward CAM-H from the bottom of the sampler horn.

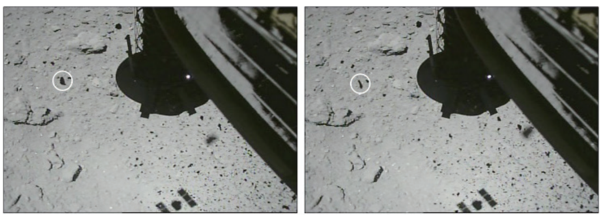


Figure 2. CAM-H images during the ascent of the spacecraft after the first touchdown. The particle in the white circle in the left image was spinning and moved from right to left and showed a flat shape in the image taken one second later (right).

The images taken by CAM-H during the ascent after the two touchdowns show particles flying over the surface of Ryugu, which were raised by the thruster operation for the spacecraft ascent. These particles were sometimes described as looking like “confetti”. We followed each flying particle with multiple images and identified the shapes of 67 particles. We found that there are two types of particles: those with distinct irregularities, and those with few irregularities and smoothness. This is similar to what the spacecraft and the MASCOT lander found in the boulders on the surface of Ryugu. It was also found that there are several flat and elongated particles (17 out of 67 particles) in the “confetti” particles (Figure 2).

The flat particle shape can also be seen in the images taken by the wide-angle optical navigation camera just before touchdown, and the MINERVA-II Rover-1A also found a cracked rock on the surface of Ryugu (Figure 3), where a plate-like grain is about to be chipped off. The flatness seems thus to be one of the representative grain morphologies on the Ryugu surface. We also found that the returned samples also contained flat and elongated particles from the particle observation in the curation chamber (Figure 3). The grain C0002 with a size close to 1 cm is one such particle collected at the second touchdown (Figure 3).

From the image analysis of the entire surface and touchdown sites and the initial description of the returned samples, it is now clear that the Hayabusa2 sampling system worked properly and successfully brought back particles representative of the surface of Ryugu.

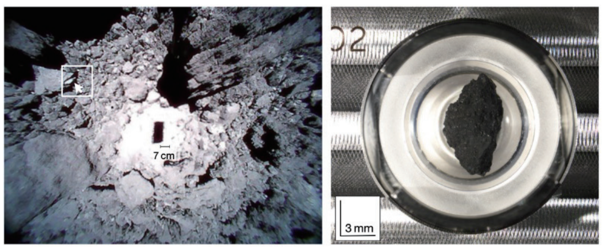


Figure 3. (Left) The surface of Ryugu as photographed by MINERVA-II Rover-1A. The rover's shadow is seen in the center. (right) The 1-cm-sized particle C0002 collected during the second touchdown

- Tachibana S. *et al*. Pebbles and sand on asteroid (162173) Ryugu: In situ observation and particles returned to Earth. *Science* 375, 1011-1016 (2022). doi:10.1126/science.abj8624

The most primitive boulders on asteroid Ryugu

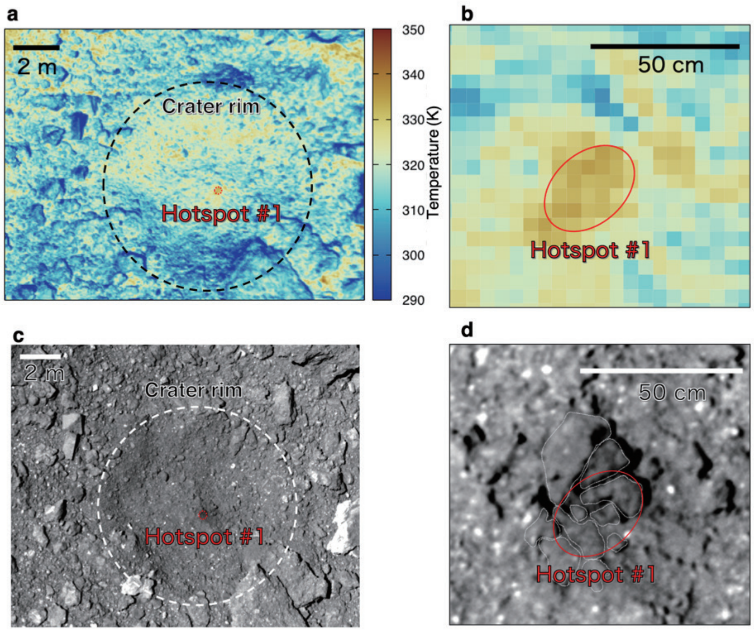
【Asteroid Explorer Hayabusa2】

The mid-infrared camera TIR onboard Hayabusa2 obtained global surface temperature information of the asteroid Ryugu to estimate the thermal inertia of surface materials (materials with lower thermal inertia are more adiabatic and have larger diurnal temperature variations). The globally averaged value was about 300 tiu, which is significantly lower than that of a typical carbonaceous meteorite (up to 1000 tiu). This suggests that the rocks on the Ryugu surface have high porosity (30-50%). However, it is not known where and how the rocks with such high porosity were formed.

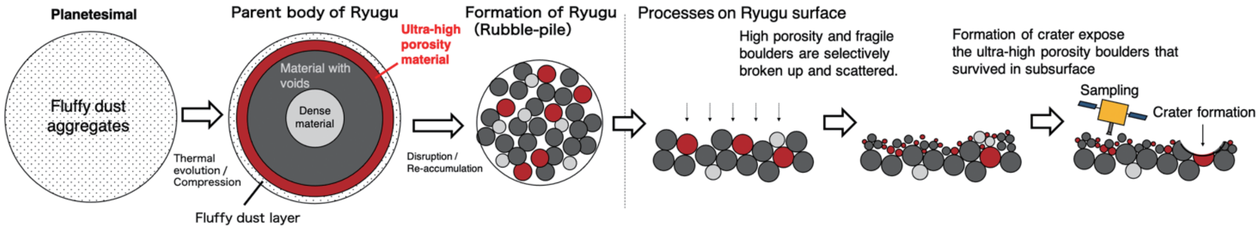
An international research group led by the Japan Aerospace Exploration Agency (JAXA) and Rikkyo University conducted a detailed comparison of high-resolution TIR and the optical navigation camera (ONC) images captured during low-altitude operations, and found rocks with higher temperature (lower thermal inertia) and higher porosity than the surrounding rocks near the center of some small craters. The porosity was estimated to be over 70%. Furthermore, we analyzed various rocks for which images were captured in low-altitude operations and found that the porosity of the Ryugu's boulders is centered around 40 to 50%.

Numerical calculations of the thermal evolution of the parent body using 26Al as a heat source suggest that such a distribution with high porosity rocks can be formed in the parent body. The central part of the body is composed of low porosity sintered material due to the high temperature and pressure. However, near the surface, where the temperature does not increase so much, high porosity material remains. The high porosity rocks discovered in this study are considered to originate from a region that has not undergone thermal alteration of the parent body.

If the most primitive material with high porosity discovered in this study can be found in the collected samples, it will significantly contribute to elucidating the formation and evolutionary history of the Ryugu parent body. In other words, it is expected that the initial stage of the formation process of the solar system, i.e., the collisional destruction and re-accumulation processes leading to the formation of planetesimals and planet formation, will be demonstrated.



The high porosity boulder in TIR (upper) and ONC (lower).



Formation of high porosity boulder in the parent body and surface process on Ryugu.

- Sakatani, N., *et al*., Anomalously porous boulders on (162173) Ryugu as primordial materials from its parent body, *Nature Astronomy* 5, 766-774 (2021). doi:10.1038/s41550-021-01371-7

Evolution of Ryugu's parent body revealed by the remote-sensing observations of the Hayabusa2 spacecraft

【Asteroid Explorer Hayabusa2】

The detailed analyses of the Optical Navigation Camera (ONC) images led by the University of Tokyo and JAXA revealed blue materials with a shallow 0.7-μm absorption on both north and south polar regions of Ryugu. These materials might be fresh and least affected by the solar wind/photon on Ryugu's surface. It is known that the 0.7-μm absorption band is usually very shallow and easily disappeared by the solar wind. The finding of the 0.7-μm absorption band in the fresh materials on Ryugu suggests that the parent body of Ryugu might contain Fe-rich phyllosilicates as indicated by the 0.7-μm absorption band.

To show this, we compare the ONC observations with the model calculation of the solar wind and surface temperature using the shape model and the orbital elements of Ryugu obtained by the previous global observations. We especially focused on the largest boulder "Otohime," which is located in the south pole region, because of its peculiar shape. We found that the three facets of Otohime have different outputs of solar wind irradiation and temperature calculation correlated to the blue-red color variation of the facets. This crucially helped to understand that the color variation on Ryugu is mainly caused by solar wind/photon irradiation, which is called space weathering. This is the first quantitative analysis of space weathering on a real carbonaceous asteroid's surface. Based on this result, Ryugu had originally a blue surface spectrum which is consistent with the spectra of the Polana-Eulalia complex family, suggesting Ryugu might originate from this family. Moreover, this blue spectrum is found to be also similar to the surface spectra of Bennu, an asteroid targeted by NASA with OSIRIS-REx, and Phaethon, an asteroid targeted by JAXA with DESTINY^{+}.

The co-presence of shallow 0.7-μm observed by ONC and 2.7-μm absorptions observed by the near-infrared spectrometer NIRS3 suggests moderate thermal metamorphism up to 300-400˚C after hydration process in the parent body which accreted 2-2.5 Myr after the calcium-aluminum-rich inclusion formation. Compiling this new result and the results from previous studies, Ryugu's parent body might have formed layers of various thermal histories, and have disrupted and re-accumulated by the later catastrophic impact event.

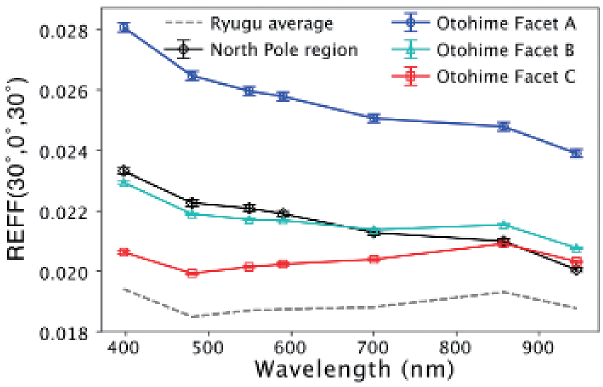


Figure 1. Spectra of the Otohime boulder observed by ONC. The different facets exhibit various spectra due to the space weathering.

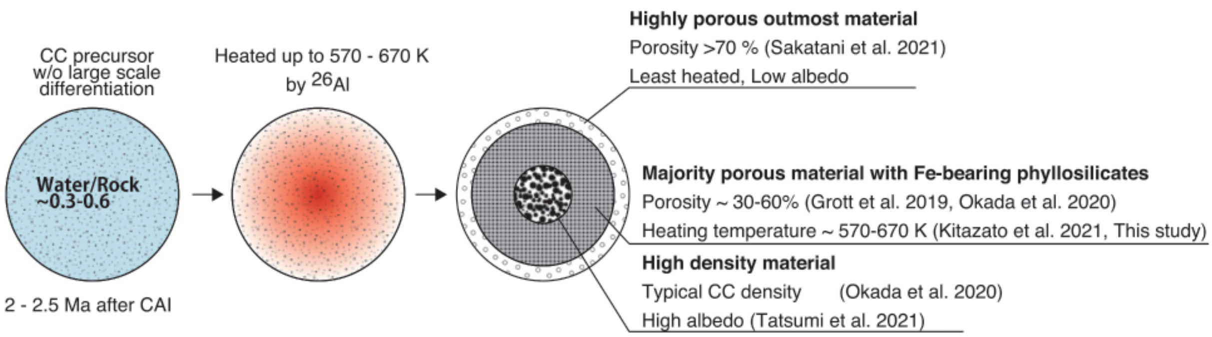


Figure 2. Evolution of Ryugu's parent body revealed by the remote-sensing observations.

- Tatsumi, E., *et al.*, Spectrally blue hydrated parent body of asteroid(16273) Ryugu, *Nature Communications* 12 , 5837 (2021). doi:10.1038/s41467-021-26071-8

Primitive, organics- and water-rich asteroid indicated by initial description for samples returned from C-type asteroid Ryugu

【Asteroid Explorer Hayabusa2】

The samples returned from near-Earth asteroid Ryugu were recovered from the chambers of the sample catcher and analyzed with non-destructive methods for their initial descriptions. In total, 5.4 grams of samples were contained in the catcher. 3.2 grams of samples were recovered from chamber A of the sample catcher, which corresponds to the samples collected by the first touchdown sampling on the asteroid, and 2.0 grams of samples were recovered from chamber C, which corresponds to the samples collected by the second touchdown sampling (Figure 1).

The visible and near infrared reflectance spectra of the bulk samples are comparable to those observed for the global asteroid Ryugu surface by onboard instruments (optical navigation camera (ONC-T) and near infrared spectrometer (NIRS3)) of Hayabusa2, indicating their representativeness of Ryugu's surface materials. Their near infrared spectra show deep adsorption features in 2.7 μm, which corresponds to the presence of O-H, and weak adsorption features in 3.05 μm and 3.4 μm, which corresponds to the presence of N-H and C-H or carbonates (Figure 2), indicating that the Ryugu samples are rich in hydrous minerals and contain organics and/or carbonates. Also, the spectrum of samples from chamber A is comparable to that of chamber C, indicating that there is no difference between the samples from chamber A and chamber C.

After completing the description of the bulk samples, individual Ryugu grains were picked from them. The bulk densities of individual Ryugu grains were calculated from their weights and estimated volumes from their three dimensional sizes to be smaller than any other meteorites and the micro porosity estimated from the bulk density is comparable to that estimated from the thermal inertia obtained from the onboard instruments of Hayabusa2. The optical observation results showed that no high temperature inclusions such as chondrules and calcium- and aluminum-rich inclusions (CAIs) were observed in the returned samples. Together with the optical spectral features and bulk density, Ryugu is most similar to CI chondrites, meteorites closest to the solar elemental abundance, which means it must be one of the most primitive bodies in our solar system (Table 1).

The series of initial description results for the samples returned from Ryugu should be a good reference for the following sample return missions.

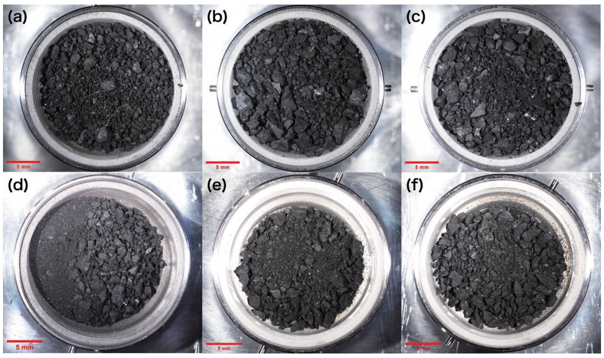


Figure 1. Optical microscopic images of samples recovered from chamber A (a-c) and chamber C (d-f) of the sample catcher of Hayabusa2. The red scale bars in the images are 5 mm long. The samples are composed of black mm-sized grains and sub-mm fine powders.

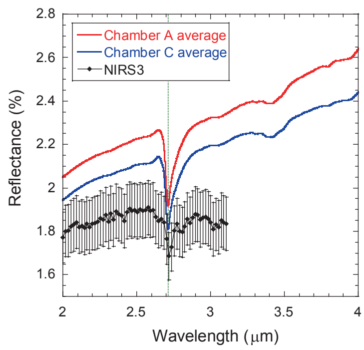


Figure 2. Infrared reflectance spectra of the bulk samples from chamber A (red) and chamber C (blue). The infrared reflectance spectra of the global Ryugu surface observed by onboard instrument NIRS3 of Hayabusa2 is shown as a reference (black).

Table 1. Summary table of Ryugu samples compared with meteorites. Bold characters indicate good matching to Ryugu, normal characters indicate moderate matching, and italic characters indicate poor matching.

	Reflectance at 0.55 μm	*CAIs (vol%)*	*Chondrules (vol%)*	*Bulk density (kg m^{-3})*	*3 μm band adsorption*
Ryugu	~0.02	Not observed	Not observed	1282 ± 231	Yes
CI	0.063	**<0.01**	0	2110	**Yes**
Tagish Lake	**0.02**	**rare**	*<17*	1660	**Yes**
CM	0.065	*1.21*	*20*	2120	**Yes**
CR	-	0.12	*55*	*3100*	**Yes**
CO	*0.10-0.13*	*0.99*	*40*	*2950*	*No*
CV	0.086	*2.98*	*45*	*2950*	*No*

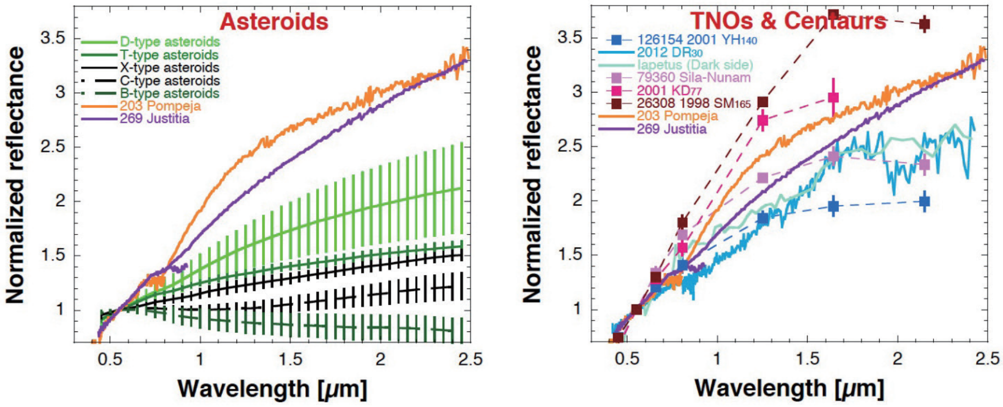
- Yada. T., *et al.*, Preliminary analysis of the Hayabusa2 samples returned from C-type asteroid Ryugu, *Nature Astronomy*, 6. 214-220 (2022). doi:10.1038/s41550-021-01550-6
- C. Pilorget, *et al.*, First compositional analysis of Ryugu samples by the MicrOmega hyperspectral microscope, *Nature Astronomy*, 6. 221-225 (2022). doi:10.1038/s41550-021-01549-z

Discovery of very red bodies in the asteroid belt that resemble trans-Neptunian objects

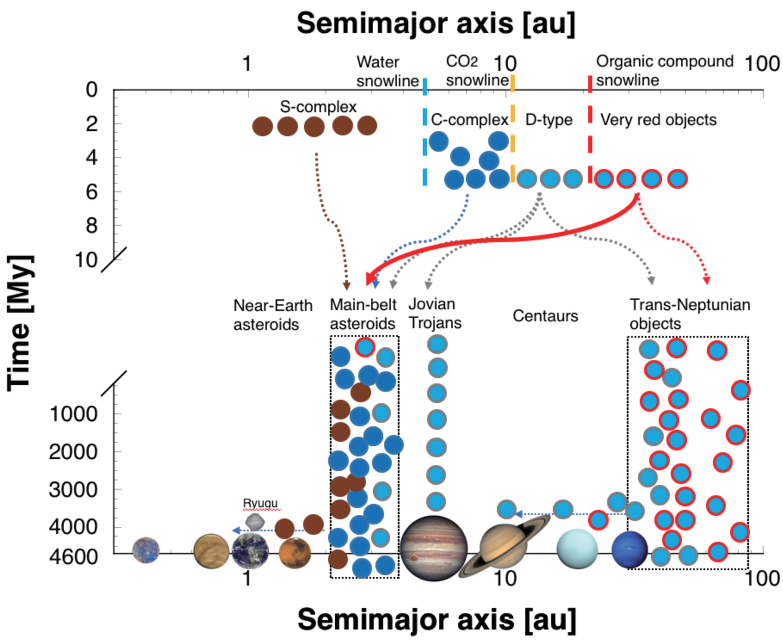
Two asteroids (203 Pompeja and 269 Justitia) have been discovered with a redder spectrum than any other object in the asteroid belt between Mars and Jupiter. The discovery was led by HASEGAWA Sunao, Associate Senior Researcher at ISAS JAXA, with an international team of researchers from MIT, the University of Hawai'i, Seoul National University, Kyoto University and the Laboratoire d'Astrophysique de Marseille.

The spectral slope of these two asteroids is steeper than the D-type asteroids, which were thought to be the reddest objects in the asteroid belt. Rather, their spectra resembles that of trans-Neptunian objects and Centaurs in the outer Solar System that have a very red spectrum.

Spectroscopic observations suggest the presence of complex organic matter on the surface of these asteroids. It is possible that these objects were formed near the outer edge of the Solar System and migrated to the asteroid belt during the early stages of the Solar System's formation. This discovery therefore provides new evidence that planetesimals formed at the outer edge of the Solar System have moved to the asteroid belt within Jupiter's orbit.



203 Pompeja and 269 Justitia spectra. Horizontal axis marks wavelength, while the vertical axis shows the reflectance intensity, normalised to that at a wavelength of 0.55 microns. Longer wavelengths have a higher intensity, which is said to be more "red". If the intensity decreases with lengthening wavelength, the spectra is said to become more "blue" (adapted from Hasegawa *et al*. 2021).



Evolution of the Solar System. Created in reference to Neveu & Vernazza, 2019 and DeMeo & Carry, 2014. (Credit: Astronomical images: NASA, Ryugu image: JAXA).

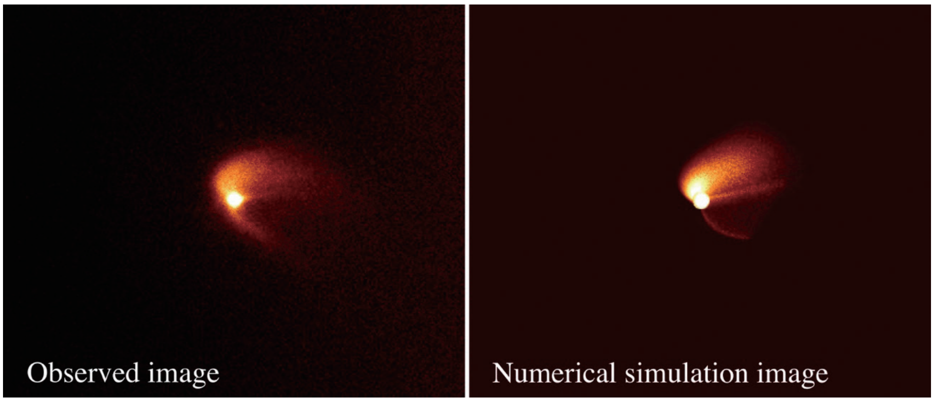
- S. Hasegawa *et al*. Discovery of two TNO-like bodies in the asteroid belt, *Astrophysical Journal Letters* 916, L6 (2021). doi:10.3847/2041-8213/ac0f05

Asteroid with a refreshed surface after losing its top layer discovered in the asteroid belt

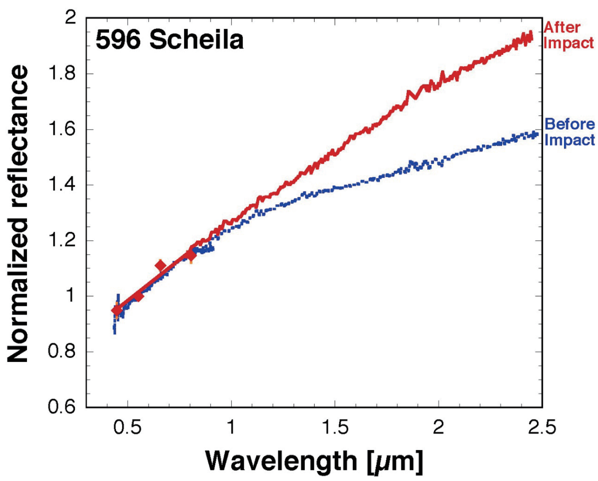
Observations of the near-infrared spectra of the 114 km diameter asteroid 596 Scheila that orbits within the asteroid belt revealed that the asteroid changed its color after an impact event in December 2010. This suggests that the older surface layer of 596 Scheila, which had been exposed to outer space for a long period, had been covered with fresh subsurface material ejected from the impact crater. The asteroid color became redder after the collision, indicating that the near-infrared light from the asteroid shifts towards blue due to prolonged space weathering.

The observations were conducted before and after the impact by an international team of researchers, led by HASEGAWA Sunao, Associate Senior Researcher at ISAS, JAXA, in collaboration with researchers from Massachusetts Institute of Technology, the European Southern Observatory, University of Hawaii, Seoul National University, Kyoto University, Charles University, Kobe University and Laboratoire d'Astrophysique de Marseille.

There are many minor bodies with a red spectrum similar to the fresh surface of 596 Scheila at the trans-Neptunian of the Solar System, which is redder than those typically found in the asteroid belt. The blueing caused by space weathering moreover suggests that the dark and red minor bodies we can currently observe may have once been redder still. Many such dark and red bodies exist in the asteroid belt. These observations therefore suggest that many more minor bodies in the asteroid belt may have originated from the trans-Neptunian of the Solar System than previously thought.



Observation obtained with the Ishigakijima Astronomical Observatory / Murikabushi Telescope and the image of the collision phenomenon reproduced based on the model calculation. The observational image of the collision phenomenon is faithfully reproduced by the model calculation (Research results in Ishiguro *et al*. 2011 ApJ 741, L24. credit: NAOJ).



These plots show the change in the spectrum of 596 Scheila before and after the collision.
The horizontal axis shows the wavelength, while the vertical axis is the reflection intensity, normalized to the reflection at a wavelength of 0.55 microns. It is said to be "red" in that its intensity increases with the longer wavelength of the spectrum. Conversely, as the intensity decreases as the wavelength lengthens, the shape is said to be "blue" (adapted from Hasegawa *et al*. 2022).

- S. Hasegawa *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

Martian Moon Phobos Shows Possibility of Containing "Traces of Martian Life"

— Role of MMX in the Search for Martian Life in the New Era of Mars Exploration —

【Martian Moons eXploration (MMX)】

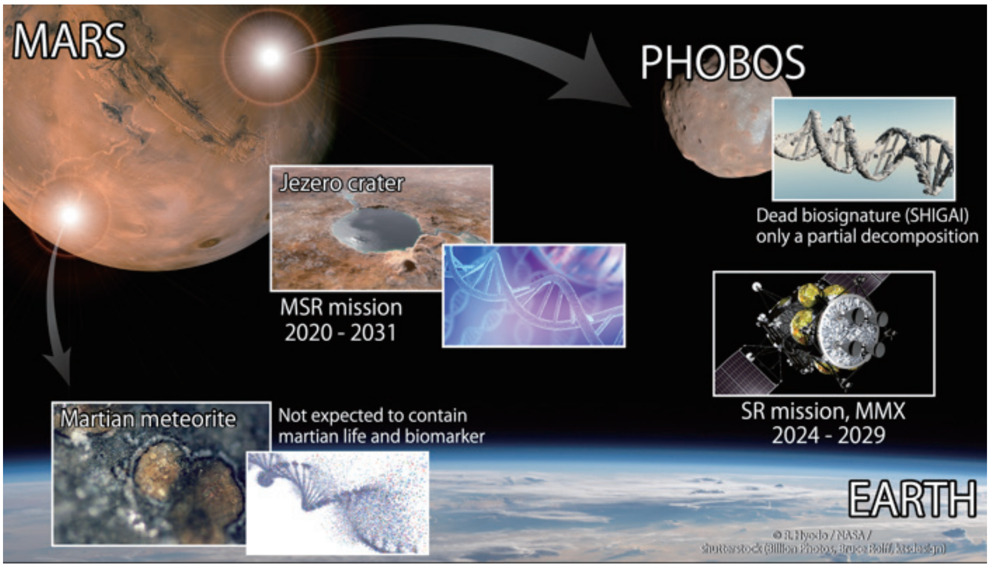
"Does life exist on Mars?" - Humans continue to ask this question of Mars, which is thought to have once had oceans like those of the Earth.

Numerous craters exist on the surface of today's Mars. These craters are evidence of continuous meteorite impacts on Mars. When a meteorite impact occurs, the surface materials of Mars are excavated and scattered as impact debris. The Martian moon, Phobos, orbits close to Mars. Therefore, some of the impact debris can reach Phobos.

JAXA's researchers, Dr HYODO Ryuki and Dr USUI Tomohiro, have studied meteorite impacts on Mars and transport processes of the impact ejecta from Mars to Phobos in detail, using high-resolution impact simulations and particle orbital calculations. They found that some of the Martian materials reach Phobos without experiencing a strong impact shock or complete melting. This indicates that if there is life on Mars, or if there are traces of life such as fossils, they can be transported to Phobos without being damaged or destroyed. If living organisms are transported to Phobos, they are sterilized by cosmic rays on Phobos. Therefore, the traces of life that can be found on the surface of Phobos are "SHIGAI"(Sterilized and Harshly Irradiated Genes, and Ancient Imprints) - the acronym in Japanese means "dead remains" that comply with the requirements of planetary protection policies.

In the 2020-2030s, humanity will embark on a new era of Mars life exploration. The U.S.-European collaboration aims to return samples of Martian materials from the Jezero crater that exists on Mars (Mars Sample Return, MSR). Japan's next flagship mission, the Martian Moons eXploration (MMX), aims to return samples from the Mars moon Phobos. The MSR aims to collect "a large but localized amount of Martian material" from the Jezero crater. The MSR project has the potential to discover even living life, if it exists. The MMX, on the other hand, is expected to collect "a small but diverse amount of Martian materials" excavated from the entire surface of Mars.

The analysis of various Martian materials may finally reveal traces of Martian life, such as ancient fossilized life, dead bodies of recently existing life, DNA fragments, and so on. MSR and MMX will play complementary roles in the search for life on Mars. MSR and MMX will open a new era of Mars life exploration by investigating for traces of Martian life from various perspectives.



The role of MMX in the new era of Mars life exploration. Phobos contains a wide variety of Martian materials delivered as impact ejecta from the entire surface of Mars. Although it will be a small amount, MMX aims to collect such diverse materials. Although it is limited to the Jezero crater, MSR aims to collect a large amount of material. Martian meteorites are those that experienced a strong impact shock when they escaped from Mars. Also, Martian meteorites remain unburned when they entered the Earth's thick atmosphere. Therefore, it is considered that they do not contain any information on Martian life.

- R. Hyodo & T. Usui. Searching for life in Mars and its moons, *Science,* 373(6556), (2021), doi:10.1126/science.abj1512

Discovery of Ion Distribution Producing Radio Waves in Space

【Geospace Explorer ARASE (ERG)】

In space plasma, it is believed that radio waves are generated by the energy exchange between plasma and radio waves (wave-particle interaction), which changes the velocity distribution of ions and electrons in the plasma. However, this is based on theory and computer simulations, and no observational evidence of actual energy transfer has been obtained. The plasma and electromagnetic field measurements onboard ARASE enable us to continuously observe the ion velocity distribution and the waveform of radio waves with high time resolution. Combining data from the instruments, it is possible to precisely determine the angle between the direction of ion velocities perpendicular to the ambient magnetic field and the direction of wave magnetic fields. In this study, we have developed a new data analysis method to estimate the energy transfer between ions and radio waves by identifying the fluctuation of the ion velocity distribution from the phase relationship between radio waves and ions. By directly measuring the energy transfer with the new method, we successfully captured the moment when ions with an energy of several keV generate electromagnetic ion cyclotron waves (EMIC waves), a kind of radio wave in plasmas. Furthermore, we found that the evolution of the ion velocity distribution through the generation of the radio waves forms a bias in the distribution of the ions and that the change of the ion velocity distribution causes the energy transfer from the ions to the radio waves, generating EMIC waves with a descending frequency. This result demonstrates the first observation of the formation of a bias in the ion velocity distribution of ions due to the generation of EMIC waves. Not only EMIC waves but a wide variety of radio waves are also naturally generated in space. The data analysis method developed in this study should be a powerful tool for revealing how the radio waves in space plasma interact with the surrounding plasma and how the radio waves and plasma are modulated via wave-particle interactions.

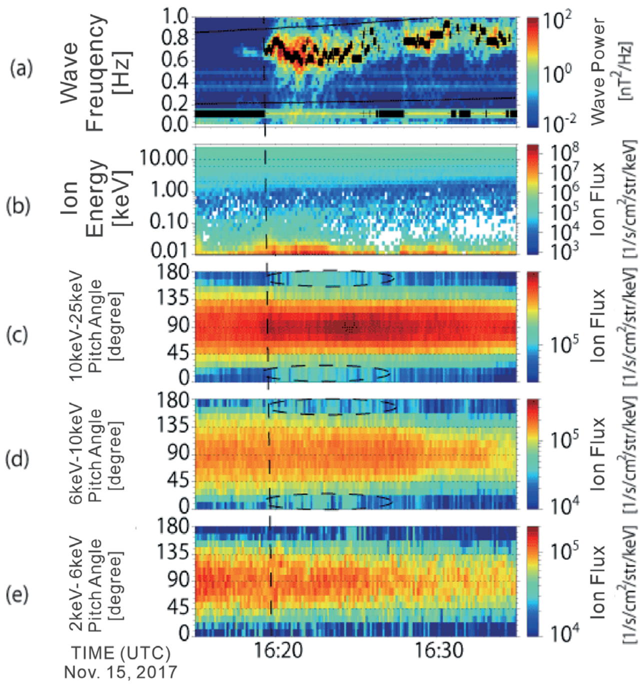


Figure 1. (a) Time variation of the EMIC wave power spectrum. The '+' symbol indicates the frequency at which the wave intensity reaches the maximum value each time. (b) The time variation of the ion energy spectrum of the total ion fluxes and (c), (d), and (e) show the pitch angle distribution of the ion fluxes for each energy. A Pitch angle of 0 degrees indicates the directions along the geomagnetic field.

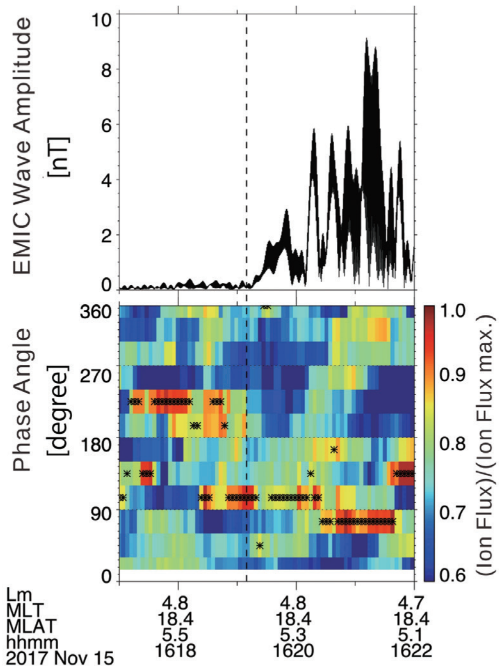


Figure 2. Top: Time variation of the magnetic field wave amplitude of EMIC wave between 0.6 and 0.75 Hz. Bottom: Ion flux distribution in the phase angle direction normalized by the maximum value. Dots indicate the maximum ion flux each time. This clearly shows that the phase angle decreases around the time (vertical dashed line) when the wave grows significantly.

- Shoji, M., Miyoshi, Y., Kistler, L.M. *et al*. Discovery of proton hill in the phase space during interactions between ions and electromagnetic ion cyclotron waves. *Sci Rep* 11, 13480 (2021). DOI:10.1038/s41598-021-92541-0

Depletion of mesospheric ozone due to the pulsating aurora

― ARASE (ERG) reveals the impact of radiation belt electrons on the Earth's atmosphere ―

【Geospace Explorer ARASE (ERG)】

On March 27, 2017, a coordinated observation combining electromagnetic wave and electron observations by ARASE (ERG), optical observations of aurorae deployed in Northern Europe, and the European Incoherent Scattering Radar (EISCAT) was carried out. ARASE observed the emergence of strong chorus waves and the presence of electrons with a wide energy range from a few keV to a few MeV (Figure 1). We performed a computer simulation of the wave-particle interaction using electromagnetic waves and electrons observed by ARASE as the inputs. The simulation result revealed that the chorus waves could scatter electrons with a wide range of energies that spread over more than three orders (from tens keV that generate pulsating aurorae to several MeV of the radiation belts all at once into the atmosphere via the interaction between the chorus waves and electrons in space. At this time, active pulsating aurorae were observed by the optical observations on the ground, and EISCAT identified clearly that the electrons had penetrated the lower region of the mesosphere, near an altitude of 60 km. Further, the energy spectrum of the electrons that precipitated into the atmosphere can be estimated from an inversion calculation based on the EISCAT observations. The result is consistent with the energy spectrum calculated in the simulation of the wave-particle interactions based on the ARASE observations. It demonstrates that the chorus waves and electrons in space cause the pulsating aurora and the ionization of the mesosphere. Next, to investigate how much the precipitation of high-energy electrons in the radiation belts impacts the mesosphere, we also performed an atmospheric chemistry simulation for the region between 20 km to 150 km, using the EISCAT observation as the input. The result demonstrates that high-energy electrons from the radiation belts penetrating the mesosphere can reduce ozone by 10% or greater at about 80 km altitude. (Figure 2) In other words, the chorus waves excited in space can reduce the mesospheric ozone. Since it was pointed out that the variation of the mesospheric ozone possibly affects the climate, our result suggests the possibility that the precipitation of high-energy electrons from space may impact the climate.

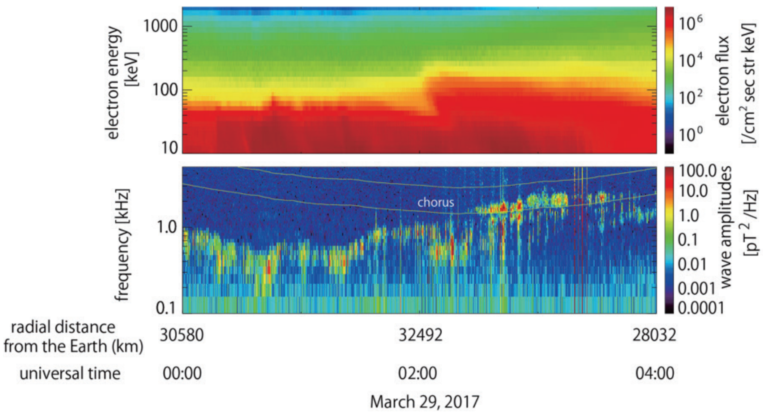


Figure 1. Top: Observation of the chorus waves by the ARASE satellite. The strong plasma waves (yellow and red) visible at hundreds of Hz to kHz are chorus waves. Bottom: Observation of electrons in space with the ARASE. Electrons with tens to keV of energy generate the pulsating aurora. Conversely, electrons with energy of several hundred keV to several MeV are radiation belt electrons.

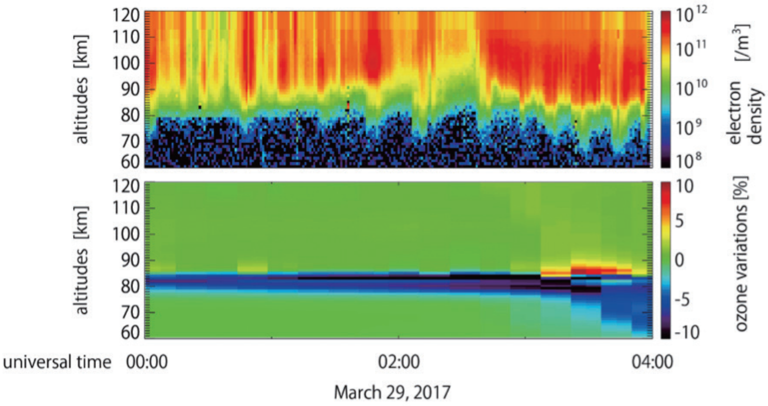


Figure 2. Top: Electron observations between 60 km - 120 km in altitude taken with the EISCAT VHF radar. The redder the color, the more electrons are present, indicating that electrons precipitate from space. Bottom: Change in ozone from an altitude of 60 km to 120 km (Computer Simulation). It can be seen that the abundance of ozone at about 80 km in height is reduced by 10% or more due to the precipitation of electrons from space.

- Miyoshi, Y. *et al.*, Penetration of MeV electrons into the mesosphere accompanying pulsating aurorae, *Sci. Rep.* 11, 13724 (2021), doi:10.1038/s41598-021-92611-3

Energy transfer between plasma particles and waves in geospace

【Geospace Explorer ARASE (ERG)】

The space around the Earth (geospace) is surrounded by a low-density environment of ions and electrons. These plasma particles are known to exist in a variety of states, with low to high energies. However, the origin of this diversity has not previously been known. One important factor is thought to be the interaction between plasma particles and waves. By applying a new analysis method to the observation data collected by the ARASE satellite, we were able to discover a typical example of this; a magnetosonic wave was observed to heat ions as it traveled through space. These heated ions then produced a different plasma wave known as an ion wave (electromagnetic ion cyclotron wave).

We have applied “wave-particle interaction analysis (WPIA)” to in-situ observation data obtained by the ARASE satellite. WPIA can map the motion of ions to that of plasma waves to calculate the quantity of energy transfer between particles and waves.

Figure 1 shows the amount of the energy transported from the plasma waves to low-energy ions calculated through WPIA based on the selected event among the ARASE observations. Figure 1(a) and (b) are the energy transfer rate for the magnetosonic waves and the electromagnetic ion cyclotron waves, respectively. From Figure 1(a), the magnetosonic wave can be seen to be giving a net energy to the ions, although the direction of the energy transport does vary. On the other hand, Figure 1(b) clearly shows energy transport from the ions to the plasma waves. It is therefore clear that there is an overall energy flow moving from the magnetosonic waves to ion heating, then to electromagnetic ion cyclotron waves. Figure 2 schematically shows this energy flow. It has also been shown in theoretical studies that the electromagnetic ion cyclotron waves can scatter high-energy protons which may contribute to produce a proton aurora.

The WPIA method used in this research will also been used in the joint international Jupiter exploration mission, JUICE, between Europe, Japan, and the US. This technique will help clarify the generation / damping process of plasma waves in the upper atmosphere of the Jupiter system. The method will therefore be able to elucidate the energy transport between the different types of plasma waves and particles that exist in the Universe, as well as the reason as to why plasma particles can exist with various energies simultaneously in the same region.

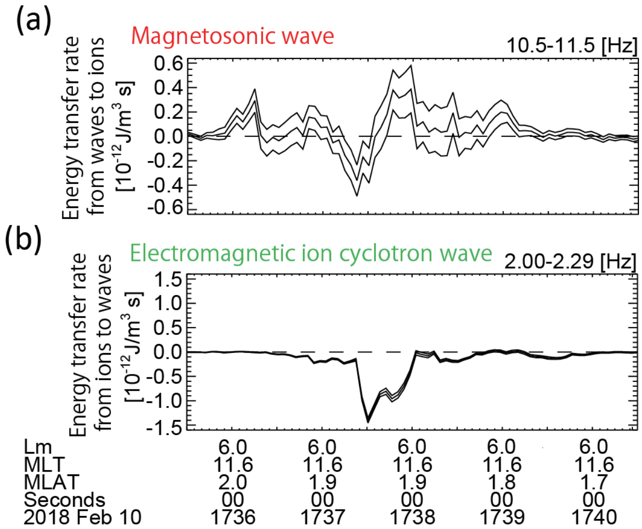


Figure 1. Plot showing the energy transfer rate from plasma waves to ions during the observational events analyzed in this study for (a) magnetosonic waves and (b) electromagnetic ion cyclotron waves. The three lines plotted on each panel show the calculated value (middle line) and the upper and lower confidence intervals.

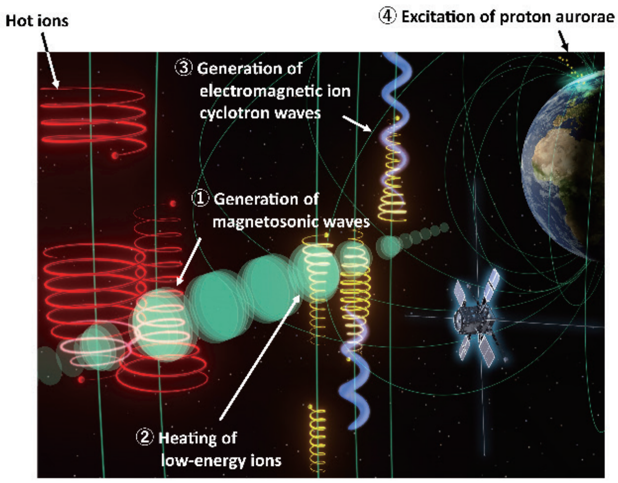


Figure 2. Schematic diagram of the energy flow discovered in this study (Credit: ERG science team)

- K. Asamura *et al.*, Cross-energy couplings from magnetosonic waves to electromagnetic ion cyclotron waves through cold ion heating inside the plasmasphere, *Physical Review Letters*, 127, 245101 (2021). doi:10.1103/PhysRevLett.127.245101

Revealing the Global Structure of Circulation in Venus's Atmosphere

【Venus Climate Orbiter AKATSUKI】

Measuring the wind fields in Venus's atmosphere, such as the super rotation (fast westward wind, reaching a speed of 100 m/s), had only been possible for the sunlit hemisphere or the dayside. The feature tracking, by utilizing inhomogeneous absorption of ultraviolet light, revealed poleward flows of the order of 10 m/s as well as the super rotation (westward). It is not clear if these poleward flows are due to the Hadley circulation (known in the earth's atmosphere) or the dayside part of the thermal tides which are excited by the solar heating of the atmosphere. Since the Hadley circulation can only be measured by globally averaging the equator-to-pole flows, and the thermal tides differ in the day and the night, it is essential to acquire the true global measurements of wind fields.

The Longwave-InfraRed camera (LIR) onboard Japan's Venus Climate Orbiter, AKATSUKI, achieved a breakthrough to this outstanding problem. Like the infrared sensors onboard the geo-stational meteorological satellite "Himawari", the LIR works as a thermography device, measuring the temperature variations at the cloud-top level of Venus both in the day and the night. Unfortunately, the original LIR images are rather noisy and it was difficult to perform the feature tracking until this fantastic work was done. We developed a way to improve the signal-to-noise ratio of the LIR data, by averaging many of them in a coordinate system that moves at the speed of the super rotation. The resultant averaged images exhibit fine-scale structures (of the order of 0.3 K temperature variations) that can be tracked from image to image. Thus the global wind fields at the cloud-top level have successfully been obtained. Our results clearly show the meridional motion in the day is "from equator to pole" but it reverses in the night to "from pole to equator". A striking result is that the day-and-night average of this is almost zero.

The global structure of wind fields caused by the thermal tides has been, for the first time, obtained by removing the super-rotating component. This is dominated by a semi-diurnal component (wavenumber 2 in the full longitude), which may contribute to the maintenance of super rotation by vertically transferring the east-west momentum. However, the null average of the meridional circulation at the cloud-top level may suggest that the poleward flow of the Hadley cell may exist above the cloud top while its return flow may be in the cloud layer (below the cloud top). This speculation is opposite to what was believed but suggests the transport of materials (clouds) from higher latitudes to lower latitudes. Combining these observations with the sophisticated numerical simulations should lead us to a better and deeper understanding of the Venusian atmosphere which may have implications to the exoplanets.

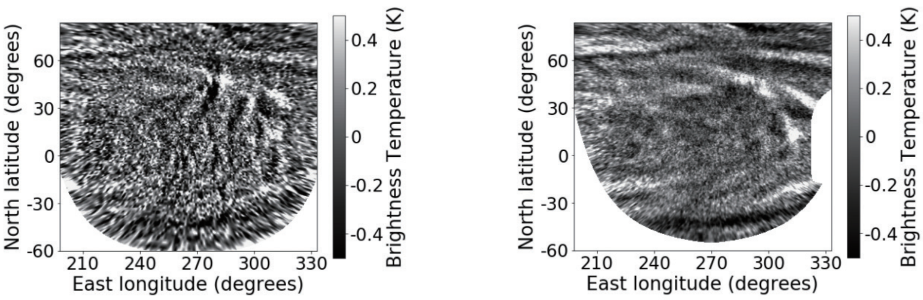


Figure 1. Left) Original LIR image; Right) Fine cloud structure as revealed by averaging multiple images.

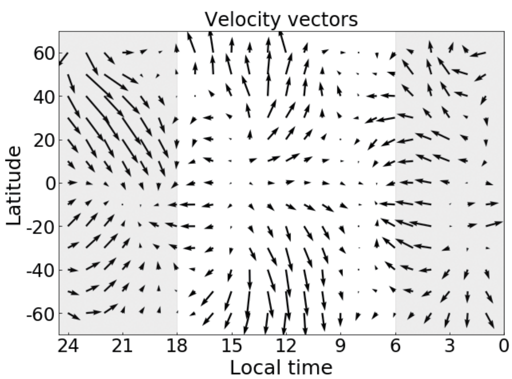


Figure 2. Global structure of wind fields caused by the thermal tides.

- K. Fukuya, *et al*. The nightside cloud-top circulation of the atmosphere of Venus, *Nature* 595, 511-515 (2021). doi:10.1038/s41586-021-03636-7

Global upper-atmospheric heating on Jupiter by the polar aurorae

Jupiter's upper atmosphere has a similar temperature to that of Earth, about 700 Kelvin, but Jupiter only receives 4% the amount of solar heating compared to the Earth. Computer models demonstrate that Jupiter's upper atmosphere should be about 180 Kelvin based on heating from the Sun alone, so where is the missing energy coming from? The source of this extra heat has remained elusive for 50 years, causing scientists to refer to the discrepancy as an "energy crisis" for the planet. In fact, this model–observation gap also exists to some extent at Saturn, Uranus and Neptune as well.

In our new study, published in Nature on 4th August 2021, we reported that Jupiter's intense aurora, the most powerful in the solar system, is the missing energy source responsible for heating the entire planet's upper atmosphere to surprisingly high temperatures (see Figure 1). Aurorae occur when electrically charged particles are caught in a planet's magnetic field. These spiral along invisible lines of force in the magnetic field towards the planet's magnetic poles, striking atoms and molecules in the atmosphere to release light and energy. On Earth, this leads to the colourful light show that forms the aurora Borealis and Australis, also known as the northern and southern lights. At Jupiter, material erupting from its volcanic moon, Io, leads to the most powerful aurora in the Solar System and enormous heating in upper atmosphere over the polar regions of the planet.

On top of this constant global heating, we discovered a heating event on one of the days we observed Jupiter (see Figure 2). A long arc of hot upper atmosphere was found extending around half of the planet, unlike anything we have ever seen before. Previous observations from JAXA's HISAKI satellite have showed that high-pressure solar wind conditions at Jupiter can generate a strong aurora on Jupiter, and it turned out that during our observations, the solar wind was strongly impacting Jupiter with a high-pressure stream of charged particles. The resulting compression of Jupiter's magnetic field is likely to have triggered enhanced heating and sent this global heat wave towards the equator. These observations indicate that Jupiter's upper atmosphere is predominantly heated by the redistribution of auroral energy.

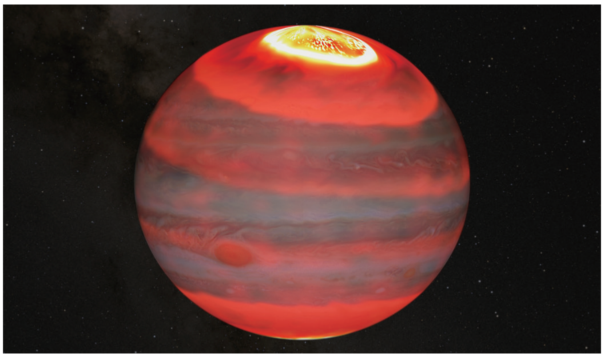


Figure 1. Jupiter is shown in visible light underneath an artistic impression of the Jovian upper atmosphere's infrared glow. The brightness of this upper atmosphere layer corresponds to temperatures, from hot to cold, in this order: white, yellow, bright red and lastly, dark red. The aurorae are the hottest regions and the image shows how heat is carried by winds away from the aurora, causing planet-wide heating *(Credits: J. O'Donoghue (JAXA) / Hubble / NASA /ESA / A. Simon / J. Schmidt)*.

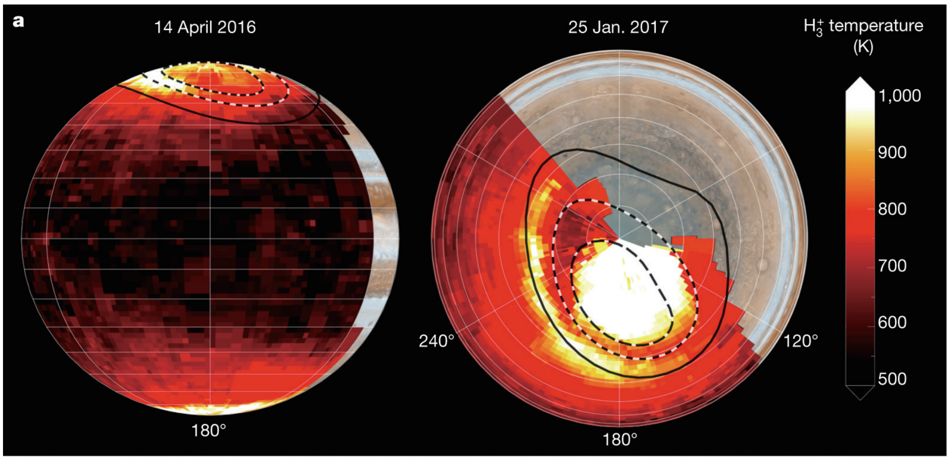


Figure 2. Visible computer-generated globes of Jupiter based on Hubble Space Telescope imagery are shown underneath two H_3^+ temperature maps (H_3^+ is a proxy for upper atmosphere temperature). The map in 2016 shows the aurora heating the planet in ordinary times, whereas in 2017 we see an auroral event additional heating globally, itself likely due to a solar wind compression (Credit: NASA Goddard Space Flight Center and the Space Telescope Science Institute).

- J. O'Donoghue, *et al*. Global upper-atmospheric heating on Jupiter by the polar aurorae, *Nature* 596, 54-57(2021). doi:10.1038/s41586-021-03706-w

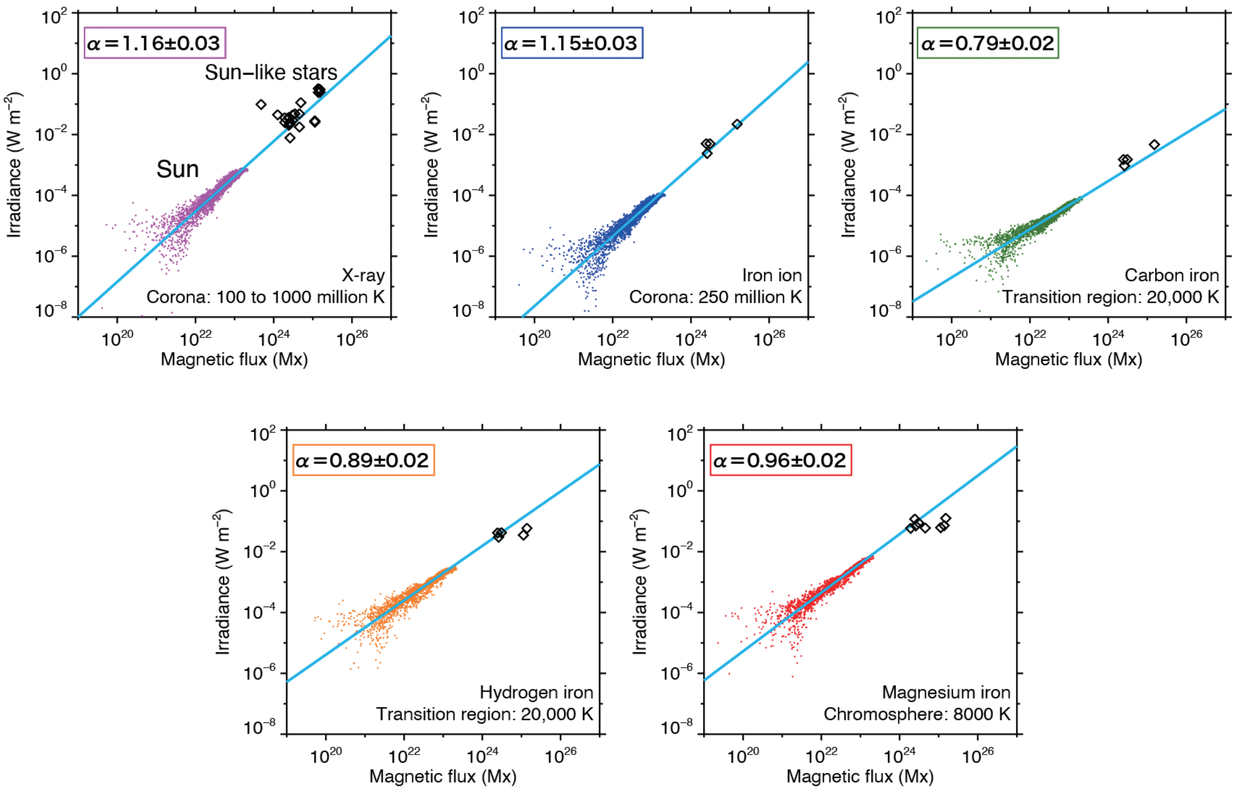
Extremely hot atmospheres of the Sun and stars -Existence of common heating mechanisms revealed-

【Solar Observation Satellite HINODE (SOLAR-B)】

The Sun and stars with properties similar to those of the Sun (called Sun-like stars) have extremely hot atmospheres, such as a corona with a temperature exceeding 1 million K and a chromosphere with a temperature of about 10,000 K. However, how these atmospheres are heated and maintained, and in particular, whether the heating mechanism is common to the Sun and these stars, remains one of the most important outstanding questions.

Using a large amount of solar observation data over 10 years from 2010 to 2020, we compared the magnetic flux on the solar surface with the intensity of spectral lines at various wavelengths (irradiances) to estimate the scaling relationships between the magnetic flux and irradiances. The scalings are described by power laws, where the power-law exponents represent the heating efficiency of the atmospheres. Since the formation temperature of each spectral line varies with wavelength, the heating efficiency of the solar atmospheres at various temperatures can be investigated by estimating the scalings (power-law exponents) at various wavelengths.

We compared the observational data of the Sun-like stars with the solar scalings. Although these stars range in age from about 50 million years to about 4.5 billion years and have a variety of activity levels, it was found that they are all situated at the extensions of the solar scaling laws. The results indicate that the heating mechanism is universal between the Sun and Sun-like stars in all temperature ranges from the corona to the chromosphere, regardless of age or activity.



Comparison of solar and stellar observation data. The colored dots show the increase of the irradiance with the surface magnetic flux. The light blue line shows the scaling (power law) obtains by fitting a straight line to the solar data. The value of the power-law exponent (slope α) for the scaling is noted in the upper-left corner of each panel. In addition, ◇ represents the magnetic flux and irradiance data for solar-type stars with ages ranging from about 50 million to 4.5 billion years

- S. Toriumi & V. S. Airapetian, Universal Scaling Laws for Solar and Stellar Atmospheric Heating, *The Astrophysical Journal*, 927, 179 (2022). doi:10.3847/1538-4357/ac5179

A rogue in the "Cosmic Standard Candle"? The relic of the densest white dwarf has been detected in the remnant of its supernova.

【XMM-Newton X-ray satellite】

A type Ia supernova (SN Ia) is an explosion of a white dwarf. Since a number of observed SNe Ia indicate the uniformity of their peak brightness, they are utilized as cosmic distance indicators. However, the mass and central density of exploding white dwarfs have never been observationally constrained, and thus the physical origin of this uniformity is still poorly understood.

The international research group led by OHSHIRO Yuken (The University of Tokyo), in YAMAGUCHI Hiroya Laboratory at ISAS, has conducted deep observations of the type Ia supernova remnant (SNR) 3C 397 using the XMM-Newton satellite. The team have identified a region containing a large amount of titanium and chromium (Fig. 1(a)). The X-ray spectrum extracted from this region indicates an overabundance of titanium and chromium, in addition to manganese, iron, and nickel (Fig. 1(b)), which are synthesized in the deepest core of the progenitor white dwarf. This is the first time that titanium has been detected from an SN Ia or its remnant. In the SN Ia nucleosynthesis, the abundance ratio of titanium to nickel strongly depends on the central density of the white dwarf. The team has constrained the central density of 3C 397's progenitor to be 5×10^{9} [g cm^{-3}], 2-3 times higher than the values expected by typical SN Ia nucleosynthesis models. The observed amount of titanium and chromium with respect to the other Fe-group elements are substantially larger than the average abundances of the interstellar medium, implying that the progenitor of 3C 397 is a "rogue" of SNe Ia.

This work has suggested that SNe Ia may originate from the variety of white dwarfs with different central densities, providing a clue to understand the origin of the cosmic standard candles.

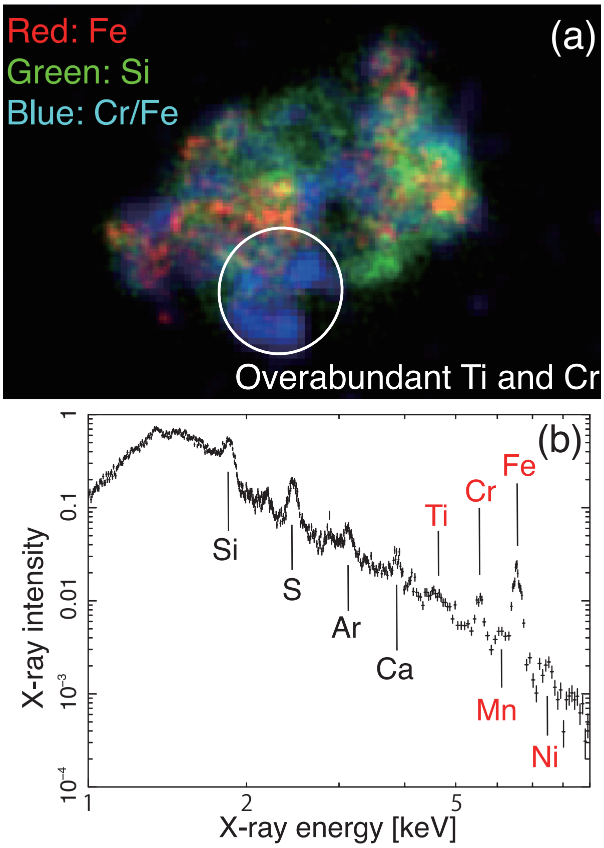


Figure 1. (a) The X-ray image of SNR 3C 397. Red and green show the spatial distribution of iron and of silicon, respectively. The blue shows the relative abundance ratio of chromium to iron. The region with the high Cr/Fe ratio is encircled. (b) The X-ray spectrum extracted from the region indicated in Figure 1a. The strong emission from titanium, chromium, manganese, iron, and nickel are detected.

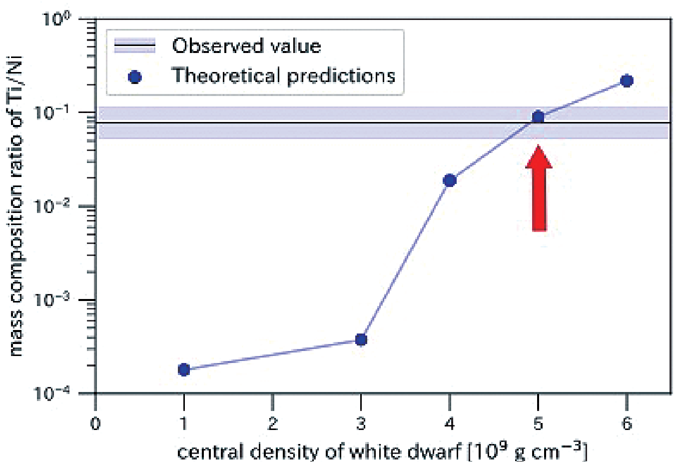


Figure 2. Comparison between the measured mass ratio of titanium/nickel (horizontal band) and the theoretical predictions (solid line) for the central region of the white dwarf. The predicted titanium/nickel ratio drastically increases when the central density exceeds 3×10^{9} [g cm^{-3}]. This comprison constrains the central density of the 3C 397's progenitor to be 5×10^{9} [g cm^{-3}].

- Ohshiro *et al*. Discovery of a Highly Neutronized Ejecta Clump in the Type Ia Supernova Remnant 3C 397(2021), *Astrophysical Journal Letters*, 913 L34, doi:10.3847/2041-8213/abff5b

Success of BepiColombo/MIO's 2nd Venus swing-by and 1st Mercury swing-by

【BepiColombo / Mercury Magnetospheric Orbiter MIO】

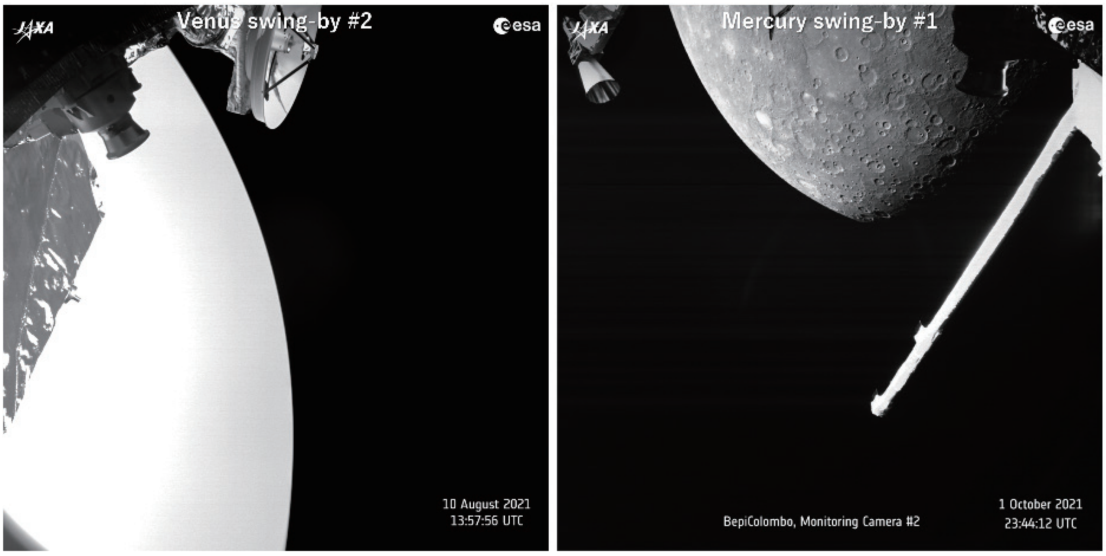


Figure 1. Venus (left) and Mercury (right) taken by the onboard monitor camera during swing-by (©ESA/BepiColombo/MTM).

The Mercury Magnetospheric Orbiter "MIO" and the Mercury Planetary Orbiter (MPO) of the JAXA-ESA joint Mercury exploration mission BepiColombo conducted their second Venus swing-by on August 10, 2021. The MPO successfully approached Venus at an altitude of 552 km and inserted itself into its target orbit. MIO carried out scientific observations of the Venusian ionosphere and the surrounding space environment by operating almost all onboard observation instruments. In particular, past plasma observations near the nadir point of the Sun were unprecedented, so this was an important opportunity to observe Venus. The observations went well, and plasma particles and magnetic fields around Venus were successfully observed. The observation data are now being analyzed by the instrument teams, and the results are being prepared for publication.

On October 2, 2021, about two months after the Venus swing-by, the first Mercury swing-by was conducted. The closest altitude of the spacecraft was 199 km at 8:34:42 a.m. (Japan Standard Time) on the same day, and it was confirmed that the orbit was on target. This is the fourth of nine planned swing-by maneuvers between launch and Mercury orbit insertion. The MPO and MIO have been conducting magnetic field observations, and careful analysis is being continued by the instrument team to rewrite the conventional understanding of Mercury's intrinsic magnetic field. During the Mercury swing-by, almost all of the instruments onboard "MIO" were operated to conduct scientific observations of Mercury's magnetosphere and surrounding space environment. In particular, it was the first time ever to perform simultaneous observation of low-energy electrons and ions on Mercury, providing valuable observational data. The observations were carried out smoothly, and the temperature and spatial distribution of Mercury's magnetospheric plasma were successfully clarified.

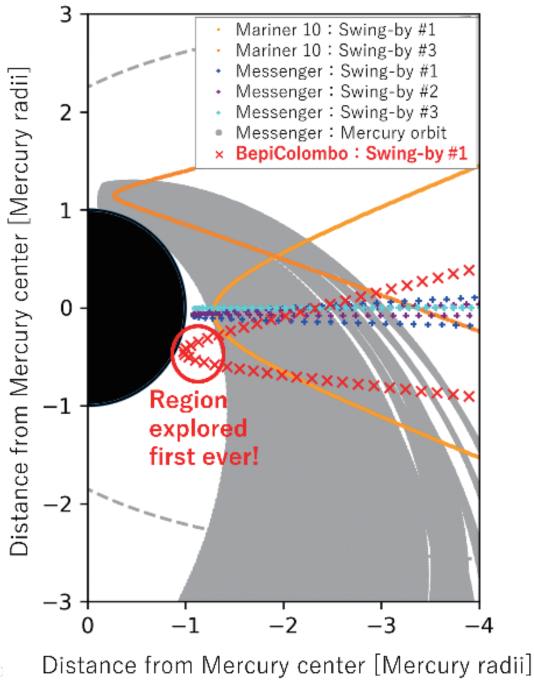


Figure 2. Comparison of orbits with all previous Mercury spacecraft.

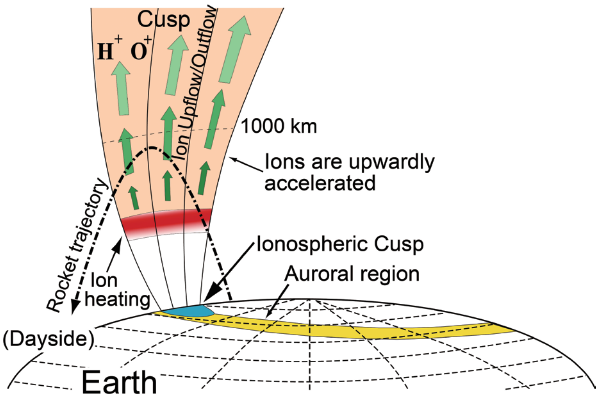
Sounding Rocket Experiment to Investigate the Ion Upflow in the Ionospheric Cusp Region

【SS-520-3 sounding rocket experiment】

Ion outflow along the geomagnetic lines of force from the polar ionosphere have been reported since the 1970's based on sounding rocket and satellite observations. The ionospheric cusp is known as a particular region where the largest flux of the ion flux is observed in the ionosphere. On November 4, 2021, in Svalbard, Norway, JAXA and related organizations conducted an SS-520-3 sounding rocket experiment with the purpose of elucidating the plasma acceleration/heating mechanism responsible for the ion outflow/upflow in the ionospheric cusp region. A combination of high time resolution in-situ rocket measurements and ground-based optical and radar observations makes it possible to approach such an important science topic. In particular, a characteristic feature of this campaign was the attempt to make an in-situ measurement of wave-particle interaction, which is believed to play a primary role in ion energization. A total of 9 science instruments were installed on the rocket: digital fluxgate magnetometer (DFG), low frequency analyzer system (LFAS), thermal ion spectrum analyzer (TSA), low energy particle experiment (LEP), ion mass spectrometer (IMS), fast Langmuir probe (FLP), needle Langmuir probe (NLP), plasma and wave monitor (PWM), and sun aspect sensor (SAS). The LFAS and TSA/IMS instruments functioned as a wave particle interaction analyzer.

In this campaign, the rocket equipped with the above instruments was launched at 11:09:25 CET from the SvalRak launch facility at Ny-Ålesund after confirming that the rocket would traverse a region of the ion upflow.

The onboard instruments performed their measurements as planned, and successfully provided data on electrons, ions, electric and magnetic fields, and plasma wave. It was fortunate that the geomagnetic condition was relatively active in early November, so that the rocket was launched on the second day of the launch window while the science conditions were satisfied. The flight trajectory of the SS-520-3 rocket was almost the same as planned, and it reached a maximum altitude of 756 km at 490 seconds from launch. At 950 seconds, the rocket splashed down within the predicted impact area in the south-southwest direction. A series of time sequences were also performed as planned. Nose-cone open and separation of the first and second stages were performed at 63 and 64 seconds, respectively, from the launch. Probes and antennae of the instruments were sequentially deployed after 92 seconds, and high voltage power supply for the electron/ion analyzers and ion mass spectrometer was on after 180 seconds. Immediately after that, all the instruments started measurements. Science data from this campaign is being analyzed by the respective instrument teams.



Schematic illustration of SS-520-3 experiment.

Due to the support and cooperation of many people inside and outside JAXA, the SS-520-3 sounding rocket experiment was successfully conducted despite the Covid-19 pandemic throughout the world.

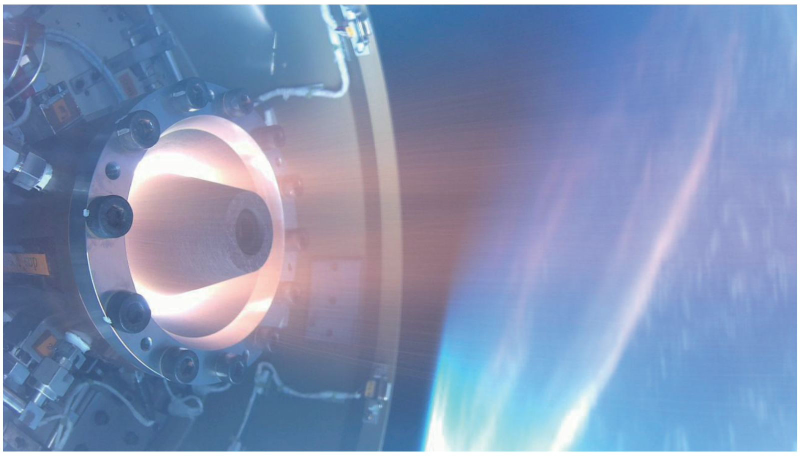
SS-520-3 rocket body inside launcher building at Ny-Ålesund.

Trajectory of SS-520-3 rocket.

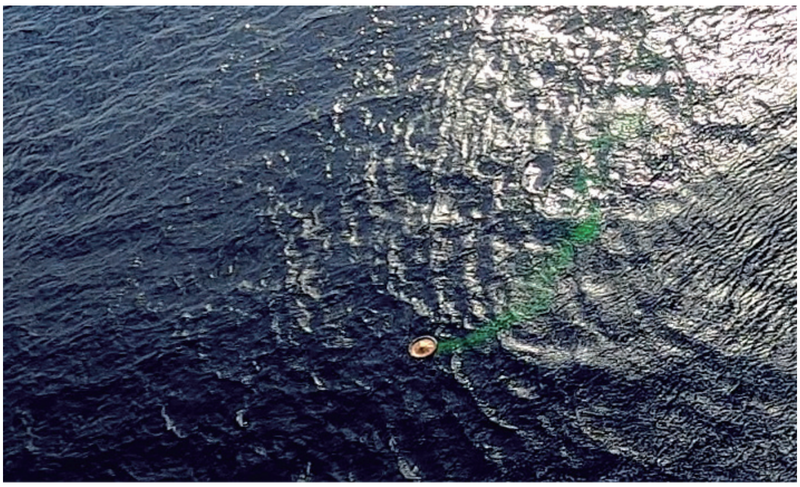
First achievement of detonation-engine combustion in space

【S-520-31, space demonstration experiment of detonation engine system for deep space exploration】

The detonation-engine is a kind of light-weight and highly-efficient rocket engine that uses detonation, which is a type of combustion involving the super-sonic expansion of combustion gas and a shock front generated by the gas. A detonation engine system (DES) that combines a rotating detonation engine (RDE) and a pulse detonation engine (PDE) was launched as part of the payload of sounding rocket S-520 and combustion tests were performed in space. In the tests, the RDE completed 6 seconds of combustion and achieved about 500 N maximum thrust and 290 s specific impulse as estimated in advance, and the PDE completed 3 sets of combustion (5 impulses were included in a single set at the intermittent rate of 2 impulses per second) to perform a roll-rate reduction of the sounding rocket. In addition to these tests, a Reentry and Recovery module with deployable Aeroshell Technology for Sounding rocket (RATS), which is a low ballistic coefficient re-entry capsule with inflatable aeroshell, was used to acquire much more data including hi-resolution images. The RATS was separated from the rocket after the combustion tests, and descended slowly to the sea surface in about 30 minutes. After it splashed down, the RATS was picked up and carried by helicopter, and important images and measured data were copied from the flash memory onboard the RATS.



RDE combustion with the blue earth in the background (credit: Nagoya University/JAXA).



The RATS on the sea surface spreading green marker (credit: Aero Asahi Corp./JAXA).

- V. Buyakofu *et. al*. Development of an S-Shaped Pulse Detonation Engine for a Sounding Rocket, *Journal of Spacecraft and Rocket* (published online 3rd January,2022. doi:10.2514/1.A35200)
- K. Goto *et. al*. Space Flight Demonstration of Rotating Detonation Engine Using Sounding Rocket S-520-31, *Journal of Spacecraft and Rocket*. doi:10.2514/1.A35401
- Yasunori Nagata *et. al*. Landing Point Analysis and Forecast Wind Data Validation for Low-Ballistic-Coefficient Flight Vehicle with a Deployable Aeroshell, *Transactions of JSASS*, 65, 6 (2022)

Human resource development measures utilizing opportunities for observation rocket experiments

【Space Science Field Experience Program】

As part of the cooperative program for graduate school education, a space science field experience program utilizing observation rocket experiment opportunities was tried out for ISAS's inbound students. This program is designed to expand the participants' perspectives and knowledge beyond their own specialty or academic field by providing them with real-life experience in space science to deepen their basic understanding of the knowledge, techniques, and ideas required to carry out space science missions, as well as cross-disciplinary experience through interaction with young JAXA engineers, and experience in organizational activities and project implementation in society. The purpose of the program is to expand the participants' perspectives and knowledge beyond their own specialty or academic field. In FY2021, three students participated in this program from June to September 2021.

Under the ISAS Human Resource Development Basic Policy established in February 2020, the Institute of Space and Astronautical Science (ISAS) has been studying the launch of a training program for students as a next-generation human resource development policy, and launched a space science field experience program in FY2021. The program was structured to take advantage of the opportunity of an observation rocket experiment to provide a short-term experience of the entire life cycle of a small but systematic and project-based activity, and was implemented from June to September 2021 for three students selected through an open call for applications from ISAS host students. The program was implemented from June to September 2021.

This program consisted of two training menus: classroom training and on-site training.

The classroom training was conducted prior to the start of the project, and provided an opportunity to gain a broad overview of observation rocket flight operations through lectures on business planning and planning management, user handbook, operations, electrical and communication systems, tracking systems, and flight plan overviews.

The on-site training is not a passive form of observation of a simple launch, but rather emphasizes independence, with the participants assigned to actual work groups (rocket group, recording group, PS (power supply) group]) and engaged in actual on-site work together with the engineers and on-site staff. Through active communication on site, the participants had the opportunity to learn a wide range of matters that can only be acquired on site, including not only basic knowledge of rocket assembly and launch, but also the attitude toward flight operations and how to interact with manufacturers and other cooperating companies. In addition, from the viewpoint of learning the importance of regional cooperation, a courtesy visit to the head of the local government and an exchange meeting with local junior high and high schools with which the Space Education Center has a cooperative relationship were also held.

Although FY2021 was positioned as a trial period, we were able to accumulate know-how in accepting trainees on site. Based on the results of this program, ISAS plans to expand the program (duration, scope, etc.) and continue it in the next fiscal year and beyond, in order to establish human resource development measures that utilize the unique on-site environment of ISAS.

Commemorative photo of HABU Hiroto, head of the Sounding Rocket Research and Operation Group Experiment Group, and the participating students (at Uchinoura Space Center)

Sharing the adventure: ISAS outreach

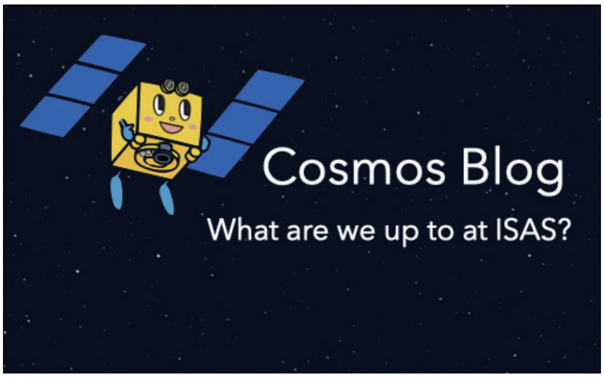
"Missions must be such things that make people happy." These words by the Hayabusa2 Mission Manager, Yoshikawa Makoto, encapsulate the importance of science communication in all our activities at ISAS.

Space research is a quest to understand our place in the Universe, from the origins of life on a planet through to the evolution of the cosmic web that stretches back to the Big Bang. It is a journey that relates to every person on this planet, and everyone should be able to share in this exploration.

ISAS has therefore been working at expanding our science communication, to offer a much wider variety of news in both Japanese and English. As people have different backgrounds and interests, a goal has been to create diverse content that more people can enjoy.

One of these initiatives has been the "Cosmos Blog", created by Associate Professor Elizabeth Tasker. Originally designed to provide news in English on missions that might only have a Japanese website, Cosmos has recently expanded to provide longer articles in both English and Japanese with the help of ISOBE Masumi in the Management and Integration Department. Unlike a press release that focusses on a specific result, Cosmos articles aim to provide background and context on new research and missions, cover interviews with ISAS researchers and our colleagues, and take a look at recent space news from around the globe.

Covering global space news is a way of highlighting the international collaborations that power space exploration. On our twitter feeds, we have begun a series of events where we publish comments from ISAS researchers on an achievement that has recently hit the news. The comment may discuss an existing collaboration with ISAS, feature a related future plan, or just show enthusiasm for the topic or an insight into its importance. Twitter is a fast and efficient way to share news, and we've been working on timely deliveries of news in both Japanese and English with images or animations to catch the eye. A tweet last year that included an animation by Dr James O'Donoghue at ISAS ramped up almost 11,000 likes!



The Cosmos blog aims to discuss our activities in space for a general audience (a 15 year old should be able to follow our discussions easily). The blog is published in both Japanese and English.

Associate Professor Elizabeth Tasker (Department of Solar System Science) has been part of the public relations team since 2021, and aims to boost English outreach activated to share our discoveries and plans with the international community.

For readers who would like a deeper dive into cutting edge results, ISAS begun "ISAS GATE" in June 2021. ISAS GATE articles describe the findings in new journal publications, written by the researchers themselves. While not completely bilingual, many posts are available in both Japanese and English.

The gallery on the ISAS website offers a peak behind the scenes of ISAS, posting regular photographs such as snapshots of our laboratories, visitors from overseas agencies and domestic institutes, and visual diaries of our rocket launches and mission results.

We have also begun a new podcast launched by NIKAIDO Toshihisa which features interviews with members of ISAS and other JAXA areas in English. Our researchers discuss their passion for space science, their careers and hopes for the future in relatable and friendly dialogue. From 2022, we will also work closely with the JAXA Space Education Center to expand our content to reach the next generation of space scientists.

At ISAS, we are involved in incredible challenges with incredible teams from around the world that make amazing stories. Let's share this adventure with everyone.

OMOTENASHI and EQUULEUS were successfully handed over to NASA

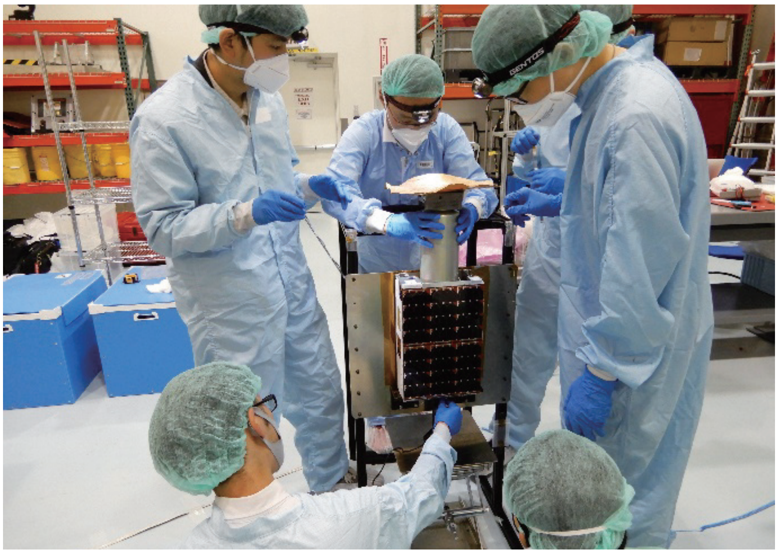
【SLS Launched CubeSats Project Team】

OMOTENASHI and EQUULEUS, which are CubeSats onboard SLS Artemis 1, were handed over to NASA in July 2021, after passing a very strict safety review. Both the CubeSats boarded the Orion spaceship, so the safety regulations for manned systems were applied to them. Hazardous items on OMOTENASHI included the solid rocket motor, actuators for separation, and Lithium-ion batteries, etc. To meet the safety regulations, the OMOTENASHI CubeSat is powered off on SLS with three switches. The safety designs of the hazardous items were also examined and analyzed, and a results report was submitted to NASA's safety review board who accepted it. Hazardous items on EQUULEUS include deployable and movable solar arrays, a water propulsion system, and Lithium-ion batteries, etc. To meet the safety regulations, the EQUULEUS CubeSat is powered off on SLS with two switches. The safety designs of the hazardous items were also examined and analyzed, and a results report was submitted to NASA's safety review board who accepted it.

We conducted the final functional tests of both CubeSats, assembled a spacecraft assembly for the solid rocket motor of OMOTENASHI because it had to be transported in a separate package, inserted both CubeSats into spacecraft dispensers, and successfully handed over the CubeSats to NASA. The project team needed to go to the NASA Kennedy Space Center (KSC) during the COVID-19 pandemic, so to reduce the risk of infection while also ensuring that the work at KSC was performed appropriately, the number of travelers was reduced with consideration given to having sufficient backup members. Due to optimally selecting the number of travelers, all work conducted at KSC was performed successfully without any infections reported.

Functional test of OMOTENASHI at KSC
(OMOTENASHI is under the arrow)

Functional test of EQUULEUS at KSC
(EQUULEUS is under the arrow)



Final assembly of OMOTENASHI spacecraft

When and how did Japanese jade rabbit begin to pound rice cake?[1]

In Asian countries including Japan, the color pattern of the lunar surface has traditionally been recognized as the shape of "rabbit". In Japan, it is believed that the jade rabbit (lunar rabbit) pounds "rice cake" on the Moon. The Japanese jade rabbit is based on Chinese tradition. However, what the Chinese jade rabbit pounds is not rice cake but the elixir of immorality. The date when the Japanese jade rabbit started to pound rice cake is not known, and the cultural background at that time is also not certain.

Based on pictures in Japanese books and arts, Shoji (2021) constrained the period when the Japanese jade rabbit started to pound rice cake. In addition, the social background in which the culture of pounding rice cake by the jade rabbit was generated is also discussed.

Referencing lunar images made between the Asuka period and the Muromachi period, the Japanese jade rabbit uses a vase-shaped pot and stands (or sits) on the ground (Figure 1). In these images, the rabbit does not use a mortar. However, in the Edo period, we can see the jade rabbit using mortar and mallet (Figure 2), which is the same composition in Chinese books published in the Ming dynasty (Figure 3). Thus, we can presume that intellectuals in Japan referenced pictures of the jade rabbit shown in Chinese books.

From the beginning of 18th century, the mortar of the jade rabbit changed from straight (Figure 2 a) to a curved shape (Figure 2 b). In Japanese tradition, a mortar with a curved shape has an older history. Mortars with straight sides were used from the mid-Edo period. Therefore, we can see that the Japanese jade rabbit gradually uses a traditional type of mortar from the 18th century. Due to this change of mortar, Shoji (2021) concluded that the beginning of the 18th century was the period when Japanese people began to think that the jade rabbit pounds rice cake on the Moon.

The spread of books and education are suggested as the background of the jade rabbit pounding rice cake. Because Japanese society became stable from the Genroku period, the general population began to read books. However, these books do not say what the rabbit makes. Comparing with analogies in their own lives, people who read such books may have imagined that the jade rabbit makes rice cake, thus the jade rabbit pounding rice cake became traditional culture in Japan.

Figure 1. (a): Tenjukoku-mandara (Chugu-ji Temple, 7th century CE, Public domain). (b): Kuyo-hiryaku (The Metropolitan Museum of Art,

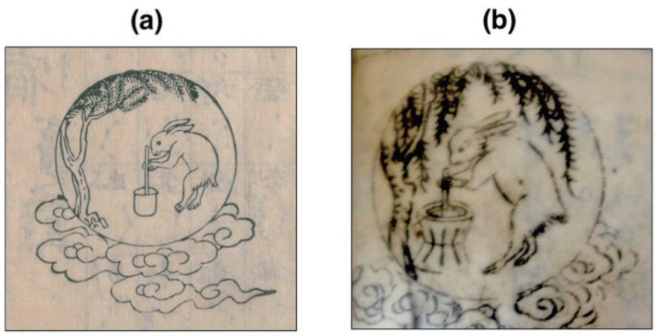


Figure 2. (a): Kinmou-zui (1666 CE, National Diet Library Digital Collection). (b): Zouho-houryaku-ohzassho (1781 CE, Author's collection).

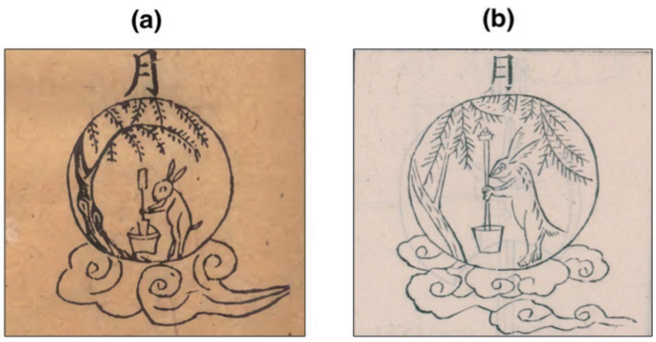


Figure 3. (a) Gokyou-taizen (1471 CE, Digital archive of National Archives of Japan). (b) Sansai-zue (1609 CE, National Diet Library Digital Collections).

1 D. Shoji. When and how did Japanese jade rabbit begin to pound rice cake? (2021) Geology and Culture ISSN 2433-6750), Vol. 4, Num. 2. 42-56.

Europlanet Prize for Public Engagement 2021 awarded to ISAS's Dr James O'Donoghue

The 2021 Europlanet Prize for Public Engagement has been awarded to Dr James O'Donoghue for his work in creating high-quality space science animations. James is a planetary scientist, specialising in the study of giant planet upper atmospheres, and online content creator working at the Japan's Aerospace Exploration Agency (JAXA). In 2018 he started creating animations around his area of expertise and publishing them online on his YouTube channel. Now, with more than 80 animated visualisations of space topics, he has reached 200 million views on YouTube, Twitter, Facebook, Instagram, Gfycat, Reddit, and received hundreds of citations in international news articles.

O'Donoghue created his first scientific animation to demonstrate an unusual scientific finding in his own work. He had discovered that the rings of Saturn were falling onto the planet in a phenomenon dubbed "ring rain". The research and animation was published in the New York Times on December 17, 2018. Just a few days later, a US Government shut-down began that was to last 35 days. Based at the NASA Goddard Space Flight Center at the time, O'Donoghue found himself with unexpected time to spare. "We were told not to work, not even check our emails!" O'Donoghue recalls. "At a loose end, I made an animation showing the eight planets rotating at their correct relative speeds and with their tilts being accurate, which I had determined did not yet exist.". A still from a similar animation is shown in Figure 1.

James's goal since then has been to paint an accurate picture of the Solar System in people's minds, highlighting its most relevant features in an intuitive way, such as the relative sizes, distances, orbits and axial tilts of the planets, or how fast a ball would fall to the surface on different Solar System objects. The animations are not only widely appreciated online: multiple educational professionals at schools, universities, planetariums, museums use his material for teaching and outreach.

Dr Federica Duras, Chair of the Europlanet Outreach Jury, said: "Among the talented and motivated science communication projects nominated this year, James O'Donoghue's brilliant animations stood out. In their simplicity they are a masterclass in outreach and communication, and the fact that they do not rely on language and translation means that they are perfectly inclusive, easily adaptable and usable all over the world. Congratulations to James, a great ambassador for the planetary science community." An awards ceremony took place during the Europlanet Science Congress (EPSC) 2021 virtual meeting on Friday 24th September, followed by 15-minute prize lecture delivered by James. The repository of animated creations can be found on James's YouTube channel: https://www.youtube.com/c/Interplanetary/videos.

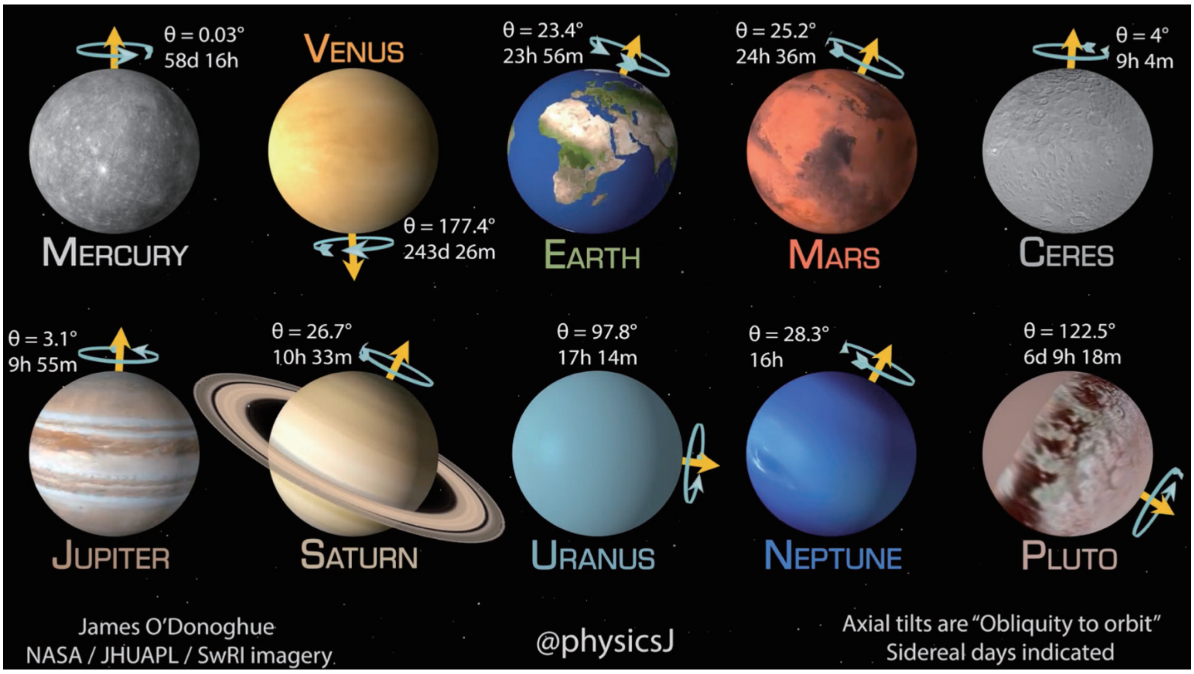
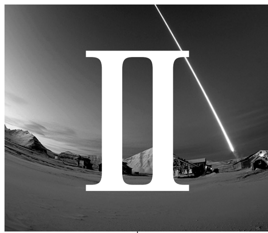


Figure 1. A still from an animation showing eight planets and two dwarf planets rotating at their correct, relative rates and axial tilts. Two dwarf planets are shown because they have maps.



Status Report

1. Space Science Roadmap

a. 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.

b. 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. The Joint Systems Engineering Team formed with NASA decided to take on-board abnormality measures. Another problem involving a He leak from the Dewar occurred in 2020, and the project has completed the recovery phase.

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.

c. 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.

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 started its MDR and detailed cost estimation is now being executed.

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.

d. 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. Japan'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.

e. Missions in Operation

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

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. The samples from the capsule are now undergoing initial analysis in the curation facility while the explorer itself has started an extended mission.

The five spacecraft in orbit, the Geo-space 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.

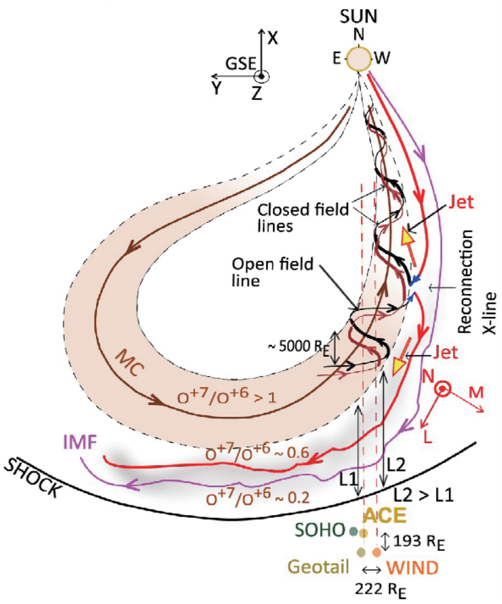
f. Small Missions Conducted through Matching Funds with External Organizations

This fiscal year, 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).

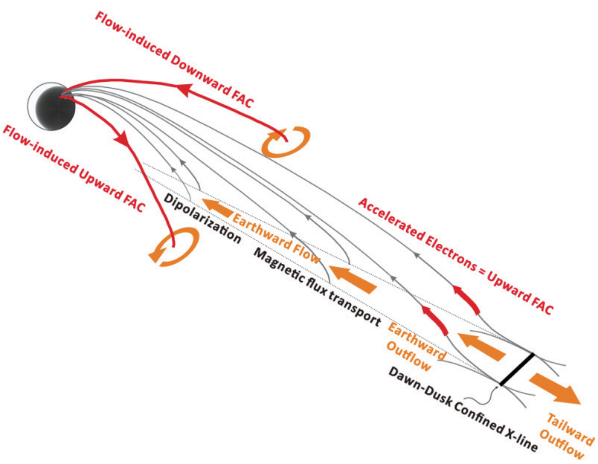
2. Space Science Programs under Operation

a. Earth Magnetosphere Observation with GEOTAIL



Schematic showing simultaneous observations by GEOTAIL, ACE, and Wind spacecraft in the solar wind of magnetic reconnection signatures at the boundary of a magnetic cloud or interplanetary coronal mass ejection [1].

Since the joint U.S.-Japan satellite GEOTAIL was launched in 1992, it has been operating continuously for more than two solar cycles. The major purpose of GEOTAIL is direct observation of plasma in the Earth's magnetotail. Except for the failure of one of the two data recorders at the end of December 2012, the spacecraft systems and instruments are in good condition. The effect of the data recorder failure was minimal, with a data loss of about 10 to 15%, thanks to the support of NASA's Deep Space Network (DSN). One to two years after data is acquired, it is calibrated, archived, and made available to researchers all over the world.



Relationship between the longitudinal locations of the magnetic reconnection site (X-line) in the magnetotail and the current system generated during the expansion phase of magnetospheric substorm. The black curves show magnetic field lines, and red arrows show electrons accelerated by magnetotail reconnection that stream downward and thus constitute the upward field-aligned current (FAC) part of the substorm current system [2].

A review to extend the GEOTAIL mission was conducted in 2018, and since the operation was approved until the end of March 2022, it was scheduled to receive another mission extension review by the end of March 2022. However, the mission extension review was postponed to the first half of FY 2022. Further, as a result of NASA's senior review carried out in August 2020, permission was granted to extend GEOTAIL operation until the end of 2023. 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. Since July 2015, the GEOTAIL operation time in Japan has been increased for collaboration with MMS. GEOTAIL has been providing opportunities to make simultaneous multiscale plasma measurements by carrying out coordinated observations with MMS, ARASE and THEMIS/ARTEMIS.

One of the main results is based on more than 50 magnetic reconnection events observed by GEOTAIL in the magnetotail [2]. The analysis combined with ground-based geomagnetic field observations revealed that the dawn-dusk extent of the magnetotail reconnection line during substorms is at most 4 Earth radii, and that the magnetotail reconnection site, when mapped along field lines, is on the upward field-aligned current of the substorm current system.

([1] Journal of Geophysical Research Space Physics, August 2021, and [2] Journal of Geophysical Research Space Physics, November 2021).

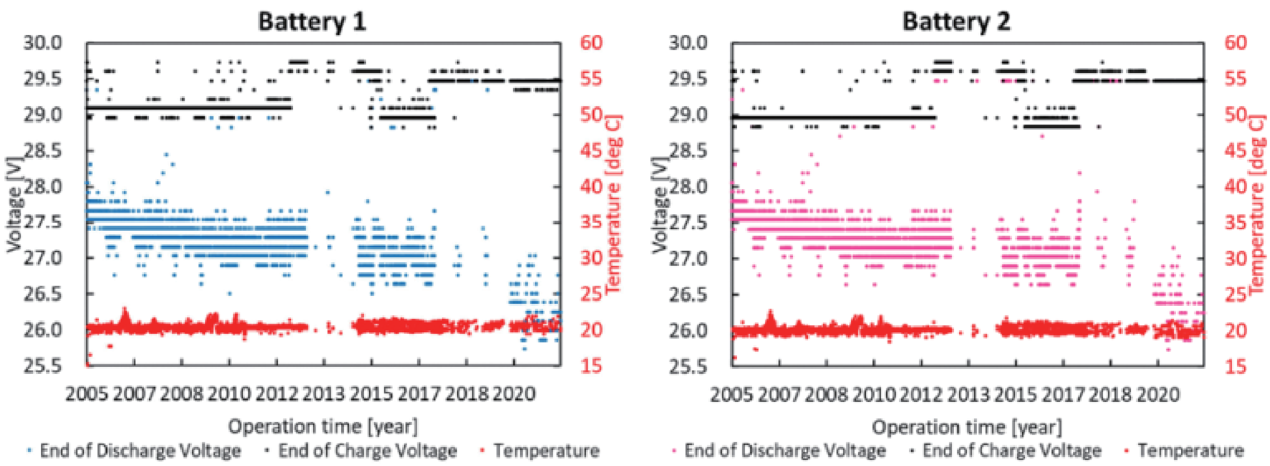
b. Small Satellite INDEX (REIMEI)

The small scientific satellite INDEX (INnovative-technology Demonstration EXperiment, code name “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. The engineering purpose is to demonstrate small satellite technologies.

The 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. 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 due to internal battery impedance. Even after over 85,000 cycles in space, the batteries still maintain a healthy condition. However, the end of discharge voltage recently dropped drastically due to the long period of operation of the satellite.

Currently, we are focusing our efforts on clarifying the internal condition of the batteries. Recently, the creation of metallic lithium inside cells has been recognized as one of the fatal phenomena of battery operation. The creation of lithium metal inside the cells of the REIMEI batteries has also been monitored through the understanding of high voltage discharge phenomena. The information will be utilized for the safer passivation of the satellite in the future.

The in-orbit information of the REIMEI batteries were transferred to universities and national laboratories. One of these activities is the collaboration with Deutsches Zentrum für Luft und Raumfahrt (DLR). DLR has a technique for simulating the internal condition of lithium-ion secondary cells. The researchers of DLR performed electro-chemical simulations of the REIMEI batteries based on their initial parameters in the development phase. Parameters include thermochemical parameters and the degradation phenomena of separators and electrolytes. We will compare the onboard charge-discharge data with the electro-chemical simulation by DLR.



Trend of the End of Discharge Voltage over 15 years of REIMEI operation.
The discharge voltage is drastically falling lower than usual.

c. Solar Observation with HINODE (SOLAR-B)

The HINODE satellite (formerly called SOLAR-B) was designed to take 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 will accurately measure the magnetic fields at the photosphere with simultaneous X-ray and extreme ultraviolet (EUV) measurements of coronal behavior.

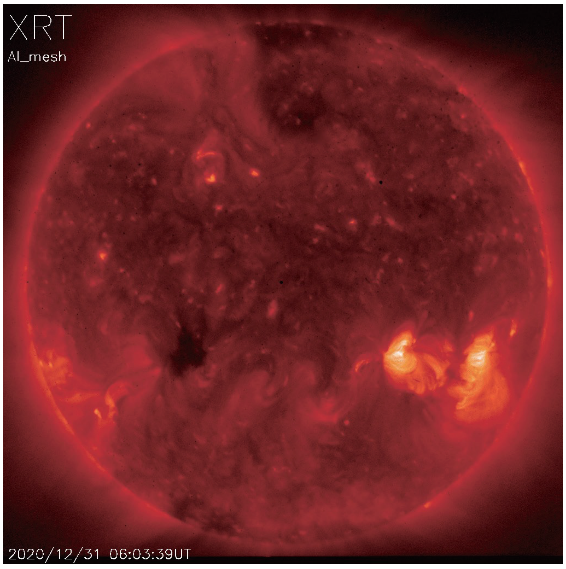
HINODE was launched in September 2006 and has been operated as an on-orbit solar observatory continuously for over 15 years. The observatory can be used by the global research community and 17 new observing proposals were delivered to the HINODE operations team in 2021. In addition to regular closely 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 3 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 2021, 72 articles were published in refereed journals based on HINODE observations, resulting in a cumulative total of 1,442 published papers to date (as of December 2021). This record shows that HINODE was one of the most productive mission in 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" in the articles published in 2018-2019 by the publisher Oxford University Press.

Based on a mission review in 2020 for the 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 at 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 X-Ray Telescope onboard HINODE taken in 31 December 2020, showing bright active regions belonging to the new solar cycle 25.

d. 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 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) reveal at the lower clouds an intriguing sharp discontinuity that propagates to the west faster than the winds while altering the clouds' properties and suffering little distortion for weeks. NASA's IRF telescope also observes a similar feature on Venus in near infrared images (Fig. 1). Results with numerical simulations combined with its absence in observations of the upper clouds evidence that this is an atmospheric wave generated below the clouds and probably pumping energy to the super rotating upper clouds.

Venusian atmospheric motion, represented by super-rotations reaching 100 m/s at the cloud tops, has conventionally been measured in the daytime hemisphere under sunlight. However, in order to separate the Hadley circulation from the thermal tidal waves that cause the difference in wind during the day and night, it is essential to observe the global atmospheric motion structure, in which LIR observations are effective. It is difficult to obtain a clear pattern with LIR images, but by overlaying and averaging multiple images, taking into account the movement of clouds due to super-rotation, we were able to reduce the noise and successfully visualize atmospheric motion by revealing temperature fluctuations as small as 0.3°C at the cloud tops. The analysis revealed the important fact that, contrary to the daytime, the cloud tops at night have a flow from the polar region to the equator at the same speed as during the daytime, and that there is almost no north-south circulation when averaged over the day and night (Fig. 2). It is suggested that thermal tide contains a large semidiurnal component including two wavelengths, which may contribute to the maintenance of super-rotation by transmitting momentum in the altitudinal direction.

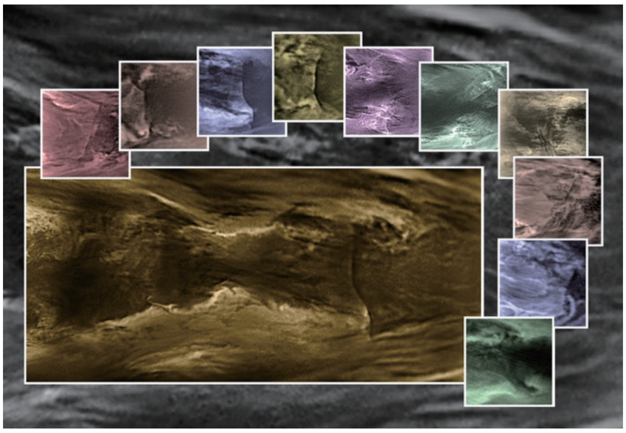


Fig. 1. The disruption and its morphological changes observed from March to October 2016 (AKATSUKI) and from November 2018 to January 2019 (IRTF).

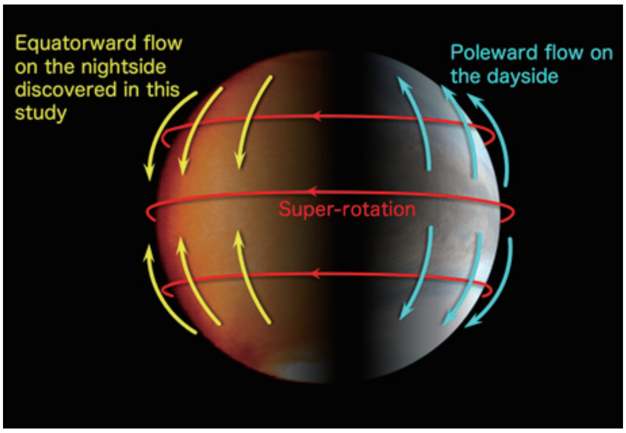


Fig. 2. LIR revealed equatorward flow on the nightside, while there is poleward flow on the dayside.

e. Solar Power Sail Demonstration with IKAROS

IIKAROS, a small solar power sail demonstrator 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 almost run out of fuel and cannot control its attitude. However, we continue the IKAROS operation to obtain data that is valuable 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 the ISAS 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

f. 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.

Observations of Venus were made at the time of the Venus swing-by of BepiColombo and Solar Orbiter in August, and with the approach of Comet Leonard to Venus in December.

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 of the actual Jupiter exploration to be promoted in the near future.

The results of collaborative observations of Jupiter's northern polar aurora with the Hubble Space Telescope (HST) and the XMM-Newton X-ray Observatory satellite conducted in 2019 have been published (see figure below).

In FY2020, two peer-reviewed papers regarding HISAKI data were published, bringing the cumulative total to 55.

Collaboration observations of Jupiter's northern polar aurora were made using HST, XMM-Newton, and HISAKI during August and September 2019. The wide wavelength range observations reveal that the timing of the sudden brightening observed by HISAKI ((f) red and (g) purple arrows) coincides with the appearance of the dawn storms and injection events captured in HST far ultraviolet auroral images, and increase of the hard X-rays emission rate by XMM-Newton.

The coincidence indicates that the hard X-ray emission and the aurora are from the same process in the middle and inner magnetosphere. However, no change in observed brightness of the soft X-rays suggests that the processes occurring outside the magnetosphere are not driven at the time. There is an independency between these processes.

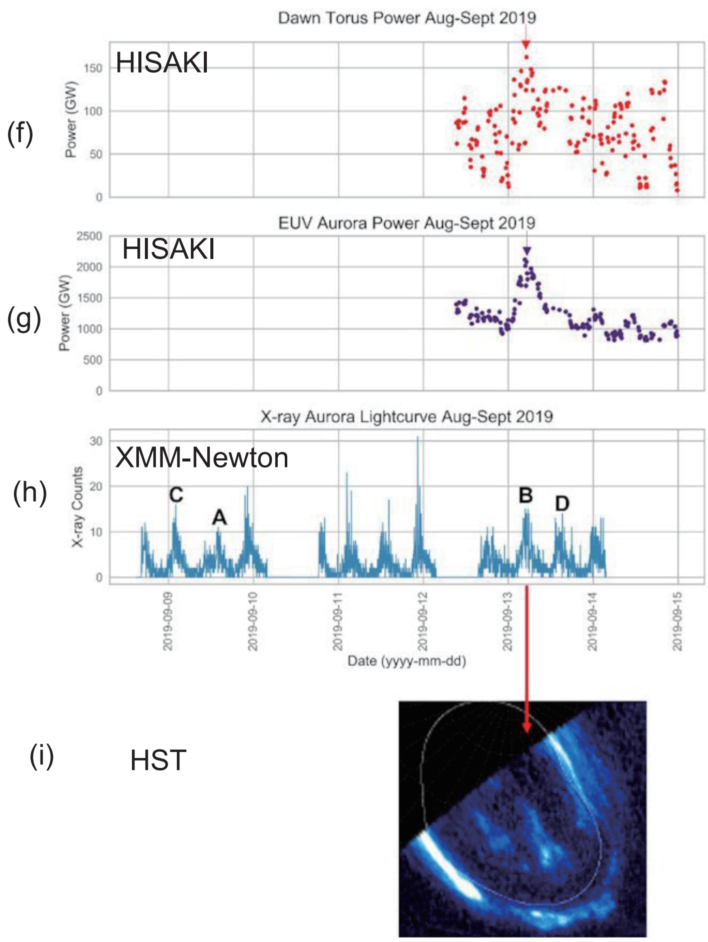


Figure. Observation results of the sudden brightening of the aurora on September 13, 2019. (f) EUV observation of the Io torus by HISAKI, (g) EUV observation of the aurora by HISAKI, (h) X-ray auroral luminosity curve from XMM-Newton observations, and (i) FUV auroral image from HST. [From Figure 4 of Wibisono *et al*. 2021, MNRAS].

g. Asteroid Exploration: Hayabusa2 and Hayabusa2 Extended Mission

Hayabusa2 is a mission to explore the C-type asteroid Ryugu and obtain samples from it. The purposes of the mission are to solve the origins of the 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 aimed 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 on the asteroid for about 1 year and 5 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 re-entry capsule returned to the Earth on December 6, 2020.

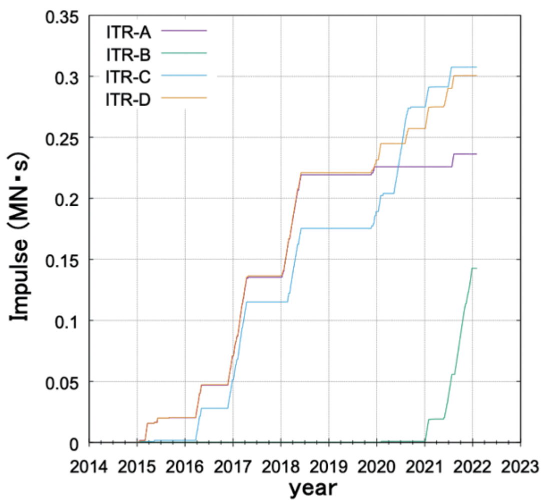
Approximately 5.4 g of samples were obtained from Ryugu, and the curation work followed by the initial analysis work were carried out. Analyses were also carried out on the science data acquired during Hayabusa2's stay at Ryugu.

Hayabusa2 left the 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. This fiscal year, zodiacal light observation was performed as a science observation.

The following results have been achieved in FY2021:

- The operation of the spacecraft has continued in 2021 after returning to Earth. To reach the final target 1998 KY26, operation of the ion engine was carried out based on the orbital plan in order to obtain the required amount of acceleration. In addition, during the period when the ion engine was not operated, the solar radiation pressure was used to reduce the consumption of chemical propellant for unloading. Furthermore, sustainable operation was performed with passes only twice a week, and labor saving of operation was also successful.
- First, the Astromaterials Science Research Group curated the obtained 5.4 g of Ryugu samples (Phase-1 curation). Then initial descriptions (color, shape, size, mass, spectroscopic data) were done and a catalog of the samples was made. Next, as the curation work for Phase-2, two groups (Okayama University and Japan Agency for Marine-Earth Science and Technology) conducted a more detailed survey of the samples.
- For the initial analysis of the samples, we organized six teams (chemical analysis, stone material analysis, sand material analysis, volatile component analysis, solid organic matter analysis, soluble organic matter analysis), and about 300 researchers from 14 countries were involved in the analysis. From May to June, samples were distributed to the initial analysis teams and initial analyses began.
- By the agreement between JAXA and NASA, 10% (about 0.5 g) of the acquired Ryugu sample was provided to NASA in November.
- Zodiacal light was observed during cruising operation and data was acquired. In particular, we were able to acquire zodiacal light data at the position where the sun distance was minimum.
- The NIRS3 and TIR bundles were released in April and October. These bundles are first PDS4-compliant data archives from JAXA. These data are available on JAXA's DARTS and NASA PDS Small Bodies Node's websites. Preparation of the LIDAR, ONC, and SPICE bundles for publication is also progressing.

Many papers have been published, including a paper on remote sensing observation data and a paper on curation of Ryugu samples published in Nature Astronomy. The number of peer-reviewed papers in 2021 was 58 (total number was 253.), and we received 10 awards from academic societies and external organizations.



Changes in the total impulse of each of the four ion engines (A to D).

Group photo taken during the delivery of the Ryugu samples to NASA on November 30, 2021 at NASA Johnson Space Center.

h. Geospace Exploration with ARASE (ERG)

The geospace explorer ARASE (ERG: Exploration of Energization and Radiation in Geospace) 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 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. The essential task of this program is the use of 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, and 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. Its orbital period is about 570 minutes. The satellite system and all onboard mission instruments are in good condition even after over five years in space. All mission instruments achieved their expected performance as designed and have continued observations. ARASE is providing data from comprehensive observations of the radiation belts.

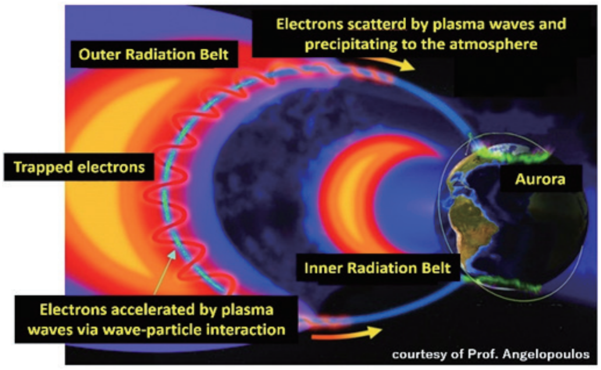
The primary mission period began on March 24, 2017, and was completed on October 16, 2018. The primary mission period corresponds to the declining phase of Solar Cycle 24. ARASE successfully observed a dozen geospace storms. Most importantly, all instruments have provided scientific data from both normal and burst observations of these storms.

We conducted joint strategic observations for the primary mission period with various 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, 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. Collaborative observations with other satellites like THEMIS and MMS have also been carried out.

The data pipeline processing of the acquired data and data calibration are operated by each instrument team and the ERG science center. 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 Institute for Space-Earth Environmental Research (ISEE) at Nagoya University 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, which is the standard data analysis software used in the solar-terrestrial space-plasma physics community. Processed higher-level science datasets will also be released to the research community.

Over 200 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.

The first extended mission will continue until the end of September 2022. It covers the period from the declining phase of Solar Cycle 24 and the early stage of Solar Cycle 25. ARASE can observe dynamical variations of the radiation belts and geospace under various solar wind conditions. The extended mission will also contribute to completing a survey of the radiation belts over the 11-year (one solar cycle) from 2012 by taking over the role of in-situ measurements from the Van Allen Probes mission, which was terminated in October 2019. The collaboration with AFRL DSX (Demonstration and Science Experiments) successfully completed, and 50 burst-mode cooperative observations had been performed for the DSX active experiments by May 2021. We are planning further mission extension after the first extended mission period to observe the inner magnetosphere in the active phase around the next solar maximum.



Contribution of wave-particle interactions to the radiation belts.

i. Mercury Exploration with BepiColombo/MMO

Although the size of Mercury is between that of the Moon and Mars, it 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 is 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 environ- ment 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 FY2021, the second Venus swing-by and the first Mercury swing-by were performed successfully. On 10 August 2021 (JST), the second Venus swing-by was performed, and scientific observations of Venus's induced magnetosphere and ionosphere were successfully obtained using the science instruments onboard MIO. On 2 October 2021 (JST), the first Mercury swing-by was performed, and scientific observations of Mercury's magnetosphere were performed. MIO successfully observed low-energy electrons and ions in Mercury's magnetosphere simultaneously for the first time ever, and also made the closest observation of the magnetic field in the southern hemisphere to date. We have also carried out several scientific observations during the interplanetary space flight, especially capturing solar energetic particle events, and we are planning scientific observations to be performed during the Mercury swing-by and interplanetary cruise in FY2022.

In preparation for arrival at Mercury in 2025, we built a MIO spacecraft simulator and observation planning/verification tool.

42 peer-reviewed papers related to the BepiColombo project were published in FY2021.

Image of Mercury taken by the monitoring camera onboard the BepiColombo spacecraft during the first Mercury swing-by on 1 October 2021 (credit: ESA/BepiColombo/MTM).

3. Space Science Programs under Development

a. SLS CubeSats: OMOTENASHI and EQUULEUS

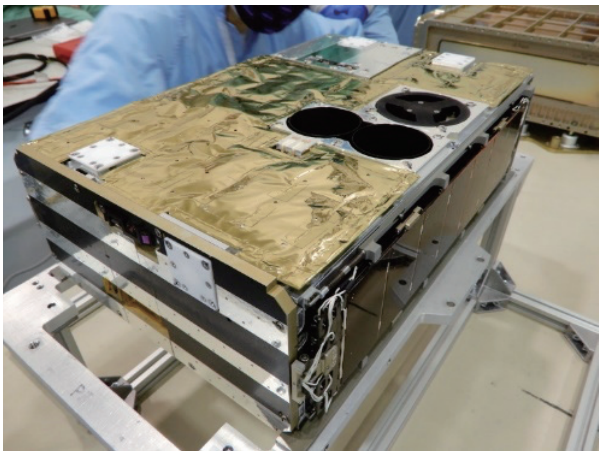
OMOTENASHI (Outstanding MOon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor) and EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) are 6U, 14-kg CubeSats that will be launched by NASA's Space Launch System (SLS) in 2022.

OMOTENASHI demonstrates technologies for the world's smallest moon lander and observes the radiation environment. To achieve a moon landing by a CubeSat, a semi-hard landing scheme has been developed. The landing speed is controlled to approximately 50 m/s using a small solid rocket motor and gas jet propulsion units. To reduce the deceleration mass, the surface probe and the rocket motor will separate from the spacecraft bus. We have also developed a shock absorption mechanism for the surface probe, consisting of crushable material and epoxy filler. The radiation environment will be measured by commercial portable dose meters.

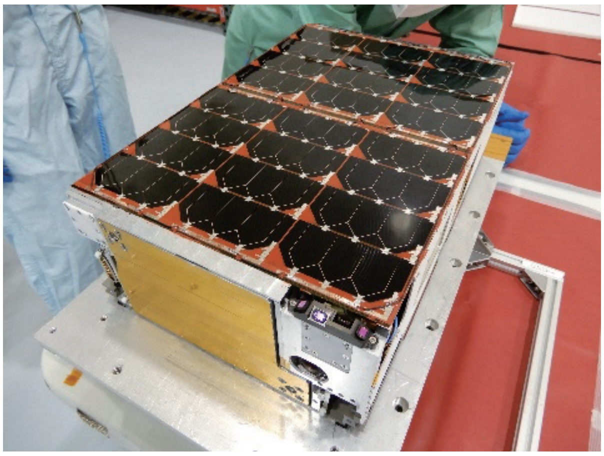
EQUULEUS has four missions. The primary, engineering mission is the demonstration of the trajectory control techniques within the Sun-Earth-Moon region by a nanospacecraft during the flight to the Earth-Moon Lagrange point L2. A water resistojet propulsion system has been newly developed for trajectory 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.

We have completed the development of both spacecraft, transported them to NASA Kennedy Space Center, conducted the final function tests, and delivered them to NASA in July, 2021. The spacecraft are on SLS rocket. Currently, we are conducting the preparation of in-orbit operations using spacecraft simulators.

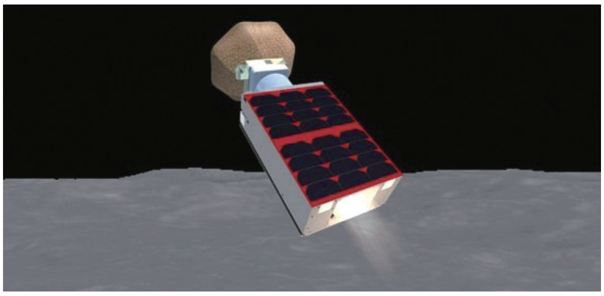
Small, light-weight and low-cost technologies developed for both spacecraft will contribute to future space science and human exploration, and will promote the participation of universities, industry, and even individuals in future space exploration.



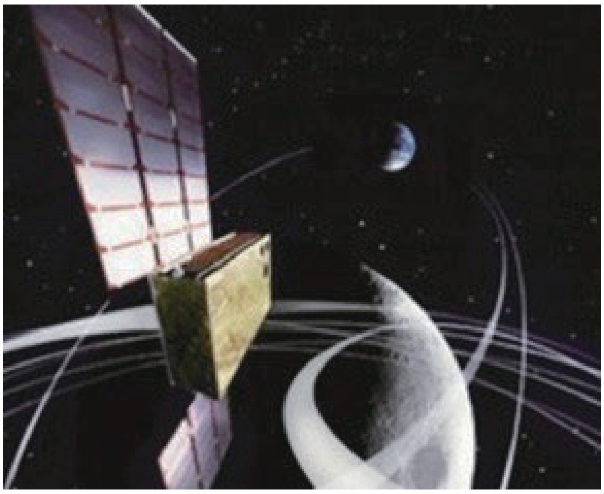
Final configuration of EQUULEUS.



Final configuration of OMOTENASHI.



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



Artist's concept of EQUULEUS observation from L2.

b. 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.

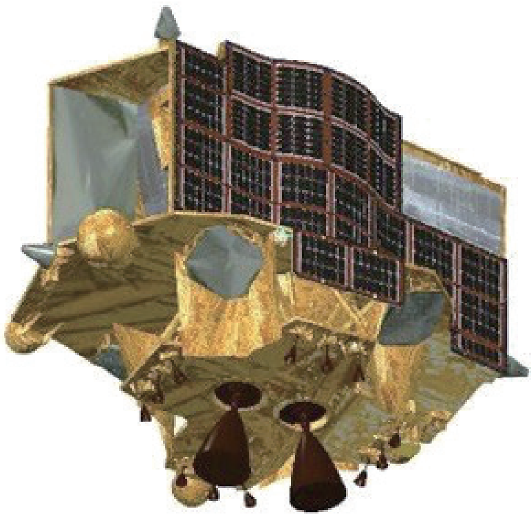
In April 2016, JAXA authorized the SLIM project and the formation of a specific project team. As a continuous investigation from FY2017, suitable system configuration was discussed to adapt to the situation after the HITOMI (ASTRO-H) anomaly. Ultimately, JAXA and the SLIM project team decided to launch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

In FY2018, a preliminary design study (contemplating some 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 start the detailed design phase (Phase-C).

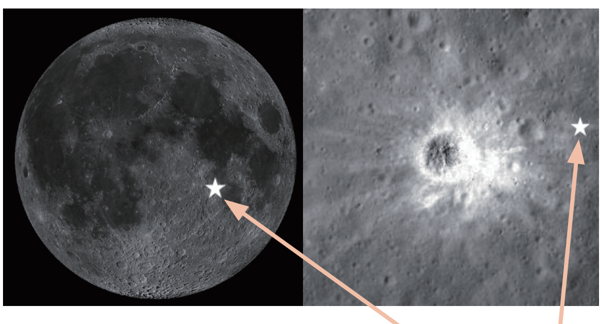
In FY2019-FY2020, a detailed design study and several engineering model tests were conducted. The results of these activities were reflected in the spacecraft system design, which was reviewed in the critical design review process. Finally, approval was given to start system assembly, integration and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

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

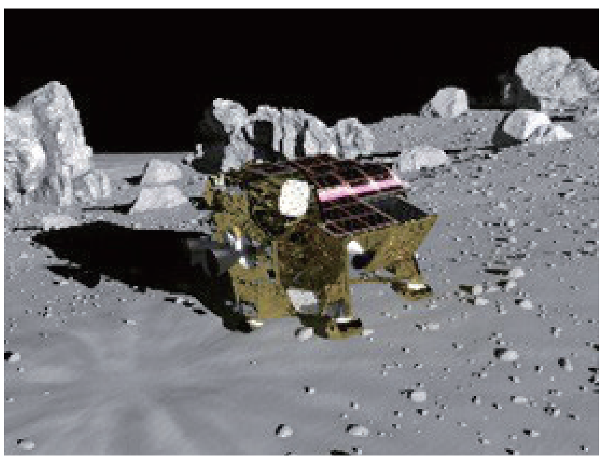
Pinpoint landing is a key technology for the next generation of lunar landers, since it will allow access to specific places on the Moon that are scientifically valuable as well as important exploration targets. Thus, SLIM is a precursor for future national and international landing missions on the Moon,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



Appearance of the SLIM spacecraft



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



Expected view of the SLIM on the landing site

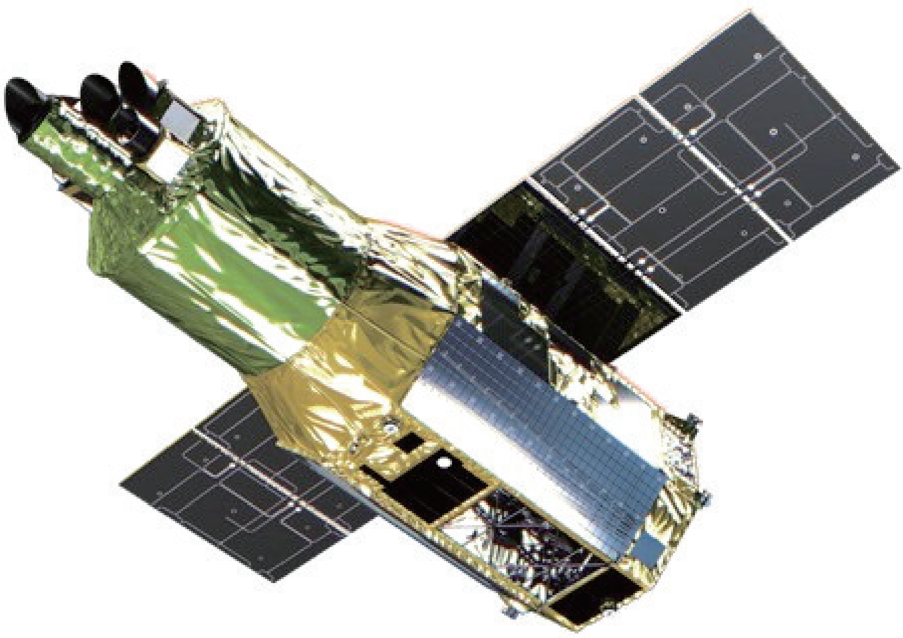
c. X-Ray Imaging and Spectroscopy Mission (XRISM)

The X-ray Imaging and Spectroscopy Mission (XRISM) has been proposed in order to reach the scientific objectives targeted at the time of launching ASTRO-H (HITOMI). The XRISM will recover the science in the shortest time possible by focusing 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 the 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; (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.

Now the XRISM development is in Phase C/D and now preparation of the spacecraft integration and test are on-going.

The XRISM is a collaboration of JAXA and NASA, with the contribution of the ESA.



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

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

In 2024, DESTINY⁺ will be launched into a highly elliptical orbit by Epsilon rocket and commence powered spaceflight for asteroid (3200) Phaethon.

DESTINY⁺ (Demonstration and Experiment of Space Technology for INterplanetary voYage with Phaethon fLyby and dUst Science) is the ISAS M-Class small program mission. DESTINY⁺ is a joint proposal by 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.

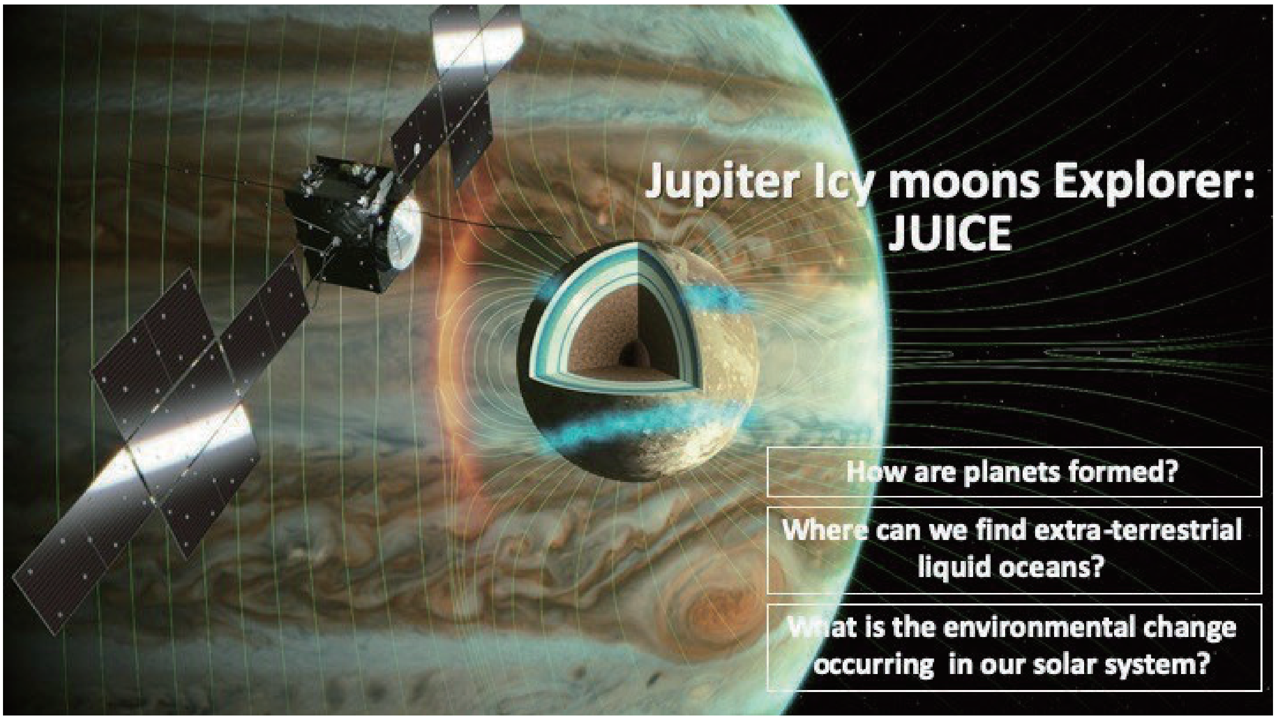
DESTINY⁺ will be put into an elliptical orbit around Earth by an Epsilon S launch vehicle, after which electric propulsion will be used to raise the orbit to reach the Moon. At this point, it will escape Earth's gravitational sphere of influence via multiple lunar gravity assists, approach asteroid Phaethon 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 is going to provide the DESTINY⁺ Dust Analyzer (DDA), which belongs to a field in which Germany has had the leading expertise in the world 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 have proceeded with the preliminary design of the spacecraft system and each subsystem, and completed preliminary design reviews (PDRs) of the ion engine system, thin-film lightweight solar array paddles, mission data processor, multi-band camera, etc. in FY2021. The PDR of other subsystems and the spacecraft system will be completed at the beginning of FY2022. Screening of CMOS image sensors for TCAP and MCAP was performed, and a thermal cycling test and a radiation test were performed afterwards. Identification of requirements and issues related to the Phaethon flyby operations and their solutions were studied. Fly-by verification analyses were conducted using a fly-by simulator, which generates images of Phaethon and the background stars according to the orbit and attitude of the spacecraft. 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).

e. 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 will be launched in April 2023 by an Arian-5 rocket. After 9 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.

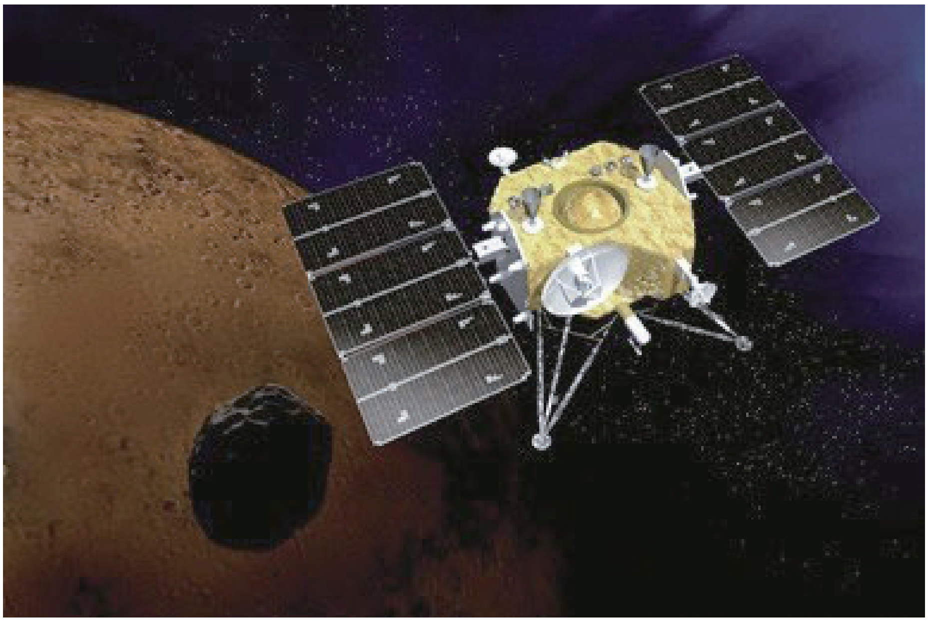
ISAS is participating in three science instruments—Radio and Plasma Wave Investigations (RPWI), Ganymede Laser Altimeter (GALA), and Particle Environment Package/Jo- vian Neutral Analyzer (PEP/JNA)—by providing hardware and two instrument groups— Jovis, Amorum ac Natorum Undique Scrutator (JANUS) and 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 RPWI-Japan, we shipped the flight model and flight spare model of the preamplifier (RWI-pre) and high frequency receiver (HF) to Europe in 2019 and 2020, respectively. For PEP/JNA-Japan, shipment of the flight model and flight spare model to Europe was completed in February 2020 and March 2021, respectively. For GALA-Japan, we completed the shipment of the flight model in August 2020 and the fabrication of the flight spare model was in progress in order to deliver the flight spare model to Europe by the summer 2022. The two teams that participated as Science Co-I, JANUS-Japan and J-MAG-Japan, 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 20 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).

f. 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.

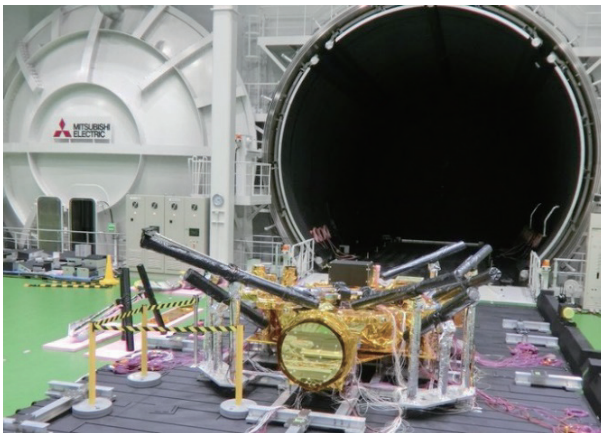
The Martian Moons eXploration (MMX) mission is the world's first sample return mission from one of the Martian moons. In order to contribute to the elucidation of the "migration of organic matter and water, and their supply to celestial bodies" in the primitive solar system, MMX will analyze hydrous 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.

Achievements:

1) The preliminary design was completed in February 2021 for the FY2024 launch. In FY2021, critical designs for the spacecraft system, mission instruments, ground system, and operational design were conducted. A series of Critical Design Reviews (CDRs) have been started in FY2021-22, and based on the results of the CDRs, the JAXA integrated CDR is scheduled to be completed in the first half of FY2022, and the project will move into the manufacturing and testing phase.
2) In parallel with the critical design, various test models were manufactured, and system-level tests (MDP interface check, thermal vacuum test using a Thermal Test Model (TTM), etc.) were conducted using these models.
3) In line with the progress of the development, agreements with international partners were established and revised. (The IA with CNES was revised in October)

Outcomes:

1) Number of peer-reviewed papers in FY2021: 17 Accumulated number of peer-reviewed papers: 56
2) The MMX project self-assessed itself as making steady progress toward realizing the first sample return from the Martian sphere.



[Exploration Module Thermal Vacuum Test]
Development tests using a Thermal Test Model (TTM) and a Mechanical Test Model (MTM) of the MMX spacecraft were conducted. During the TTM test, the space chamber pictured in the back reproduces the space environment and tests whether the MMX spacecraft will not become too hot or too cold in that environment.

g. Hera – binary asteroid exploration

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

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

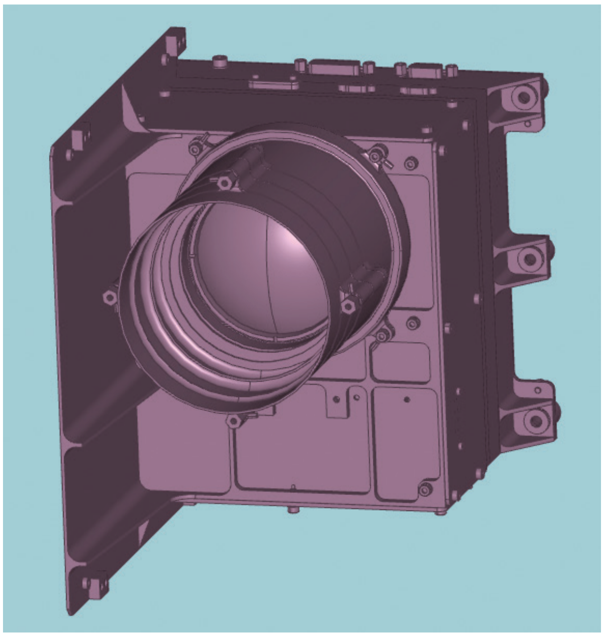
Hera is a part of the first international planetary defense Asteroid Impact and Deflection Assessment (AIDA) mission with the NASA Double Asteroid Re-direction Test (DART) mission. After the impact of the DART kinetic impactor on Dimorphos in September 2022 and the observations of its trajectory change (indeed, the change of rotation period around Didymos), Hera will be launched in October 2024 and rendezvous with the asteroid binary system in January 2027 for observations over half a year.

In FY2020, a mission design review, a system readiness review, and the pre-project approval review for joining the ESA Hera mission were conducted as a strategic international collaborative mission, and it was approved as ISAS pre-project and concept design of the TIRI instrument started.

In FY 2021, a system design review and a project approval review for the Hera-JAXA mission were conducted, and it was approved as an ISAS project and the basic design of the TIRI instrument started.

In mid-2021, a preliminary design review for the TIRI was conducted, followed by a technical review by ESA, and it was accepted for the start of manufacturing of an engineering model of the TIRI instrument, as well as the start of detailed design of the TIRI instrument.

In early-2022, a preliminary design review by ISAS was conducted for the start of the detailed design phase of Hera and the delivery of the engineering model of TIRI for assembly integration and the test phase.



CAD design of the TIRI instrument.

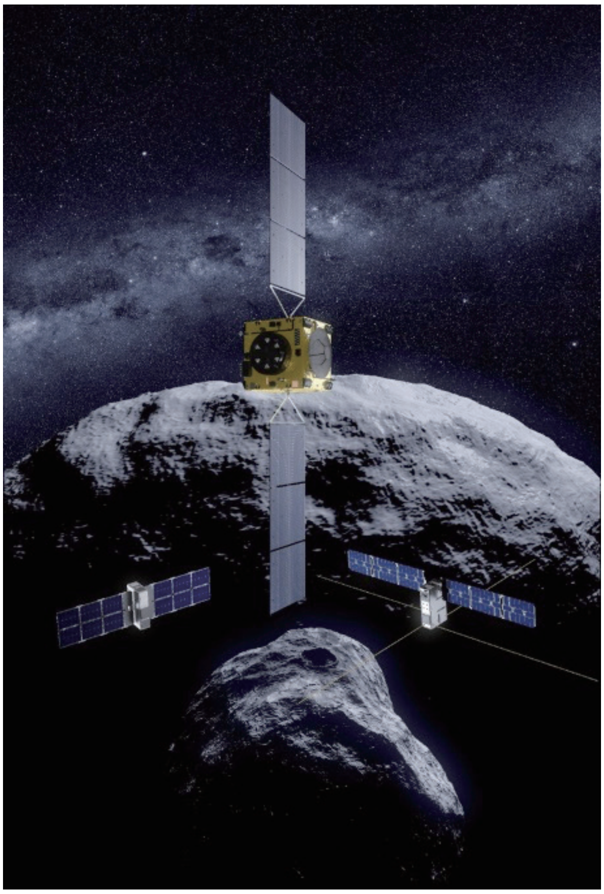
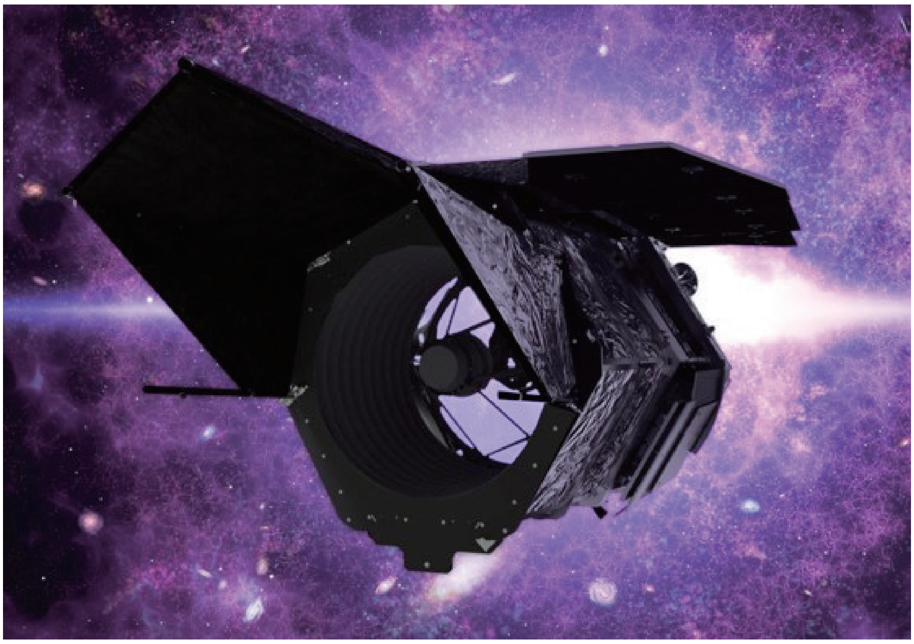


Illustration of Hera spacecraft and two CubeSats around the asteroid binary Didymos and Dimorphos.

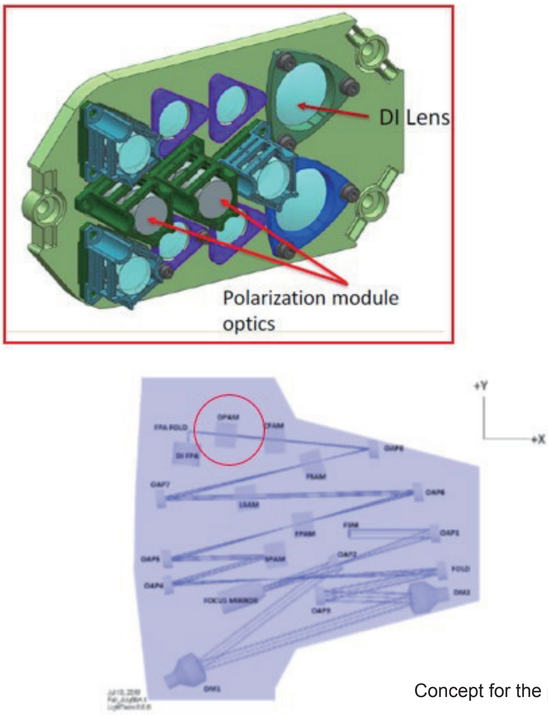
h. Roman Pre-Project (Roman)

The Nancy Grace Roman Space Telescope, which is NASA's future flag-ship mission in astrophysics, is planned to be launched in 2026. The telescope has a 2.4 m diameter primary mirror 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 conducts the Japanese contribution for Roman, including (i) providing the CGI polarization module optics and mask substrates (ii) receiving and transferring science data with the JAXA ground station, (iii) synergistic observations with the Subaru Telescope, (iv) and microlensing synergistic observations.

Following the successful Mission Definition Review in February 2021, the ISAS Roman Pre-project was formulated to advance further development. Fabrication of the flight units for the CGI polarization module optics was completed and the flight units were shipped to NASA in October 2021.



Artist concept of Roman Telescope (NASA).



Concept for the polarization module optics of CGI.

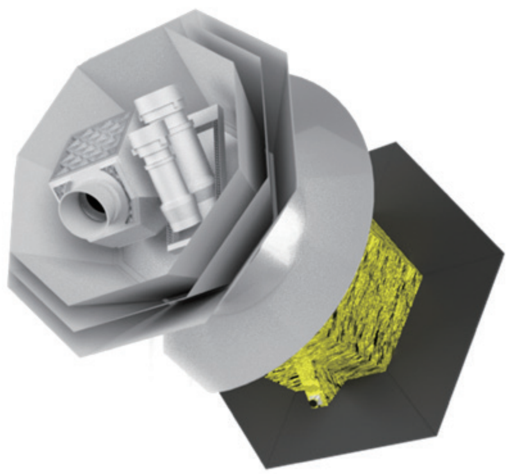
i. Lite (Light) Satellite for Studies of B-Mode Polarization and Inflation from Cosmic Background Radiation Detection (LiteBIRD)

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 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 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, UK, Germany, Netherlands, Norway, Spain, and Belgium participate in LiteBIRD, and CNES takes the lead to develop the MHFT and sub-Kelvin Adiabatic 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 in 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 ground. IPMU of Tokyo University develops the polarization modulation unit of the LFT. Okayama University leads the systematic error analysis for LiteBIRD.

Telescopes on board LiteBIRD need to have very high sensitivity and to enable the 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. Development of such telescopes is challenging, and conceptual studies and technology development of mission instruments are being undertaken vigorously in each participating country. In JAXA, it is considered that detailed tests with the full-scale bread-board models are important to mitigate various risks associated to the development of the payload module (PLM). Thus, we plan to develop a demonstration model (DM) of the LFT and a structural thermal model (STM) of the PLM. The LFT DM is mostly used to test and calibrate the optical performance of the LFT under the cryogenic condition. The STM is used to evaluate the thermal and structural performance of the PLM including the cooling chain with V-groove (nested, conical shape of radiators). Special ground equipment required to test the V-groove in the liquid nitrogen space chamber will also be verified in the course of the STM tests.

LiteBIRD successfully passed the pre-phase A2 exit review of ISAS in May 2019, and was selected as the 2nd 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

j. Solar Power Sail-Craft (OKEANOS)

Outer planetary exploration via solar power sail is demonstrated in order for Japan to lead future exploration of the solar system.

Achievements:

Following the redefinition of the science mission categories, it was decided to temporarily disband the OKEANOS pre-project candidate team and to implement 1) to 3) to lead to 4), the main concept of the OKEANOS mission. In response, the PrePhase A2 completion confirmation meeting (Part 2) was held on March 29.

1) The exploration technologies considered for OKEANOS (sample collection and in-situ analysis by lander, etc.) will be realized in the next generation small object sample return mission.
2) Demonstrate navigation technology (simultaneous orbit and attitude control, hybrid propulsion) using a micro solar power sail to dramatically improve the navigation capability of micro spacecraft.
3) By attaching various devices (thin-film solar cells, array antennas, interferometers, and reflective sheets) to the sail, it is possible to realize highly functional and innovative devices such as thin-film solar cell paddles and deployable target markers.
4) Direct exploration of the outer solar system (e.g., Trojan asteroids) by solar power sail-craft OKEANOS (revised).

Regarding 1), the Next Generation Small Body Sample Return Exploration WG was established to realize as a strategic medium-sized mission.

As a specific example of 2), we studied a micro solar power sail mission to be released from the lunar transfer orbit, to transfer to the Sun-Earth L2 halo orbit, and to stay there for a long period of time. We also propose a micro solar power sail mission that is released from a deep space orbit transfer vehicle (OTV), swing-by the Earth, Venus, etc., to a target small body.

For 3), we developed PFM of HELIOS (a mission component on RAISE-3) to demonstrate ultra-light power generation using thin-film solar cells, beamforming using array antennas, and measurement of membrane shape using interferometry. HELIOS is scheduled to be launched aboard RAISE-3 in FY2022, and preparations for HELIOS operations are underway. Furthermore, a thin-film solar cell paddle for a small spacecraft to outer solar system was manufactured, and its stowage, deployment, deployment, and attitude control (gimbal drive) were demonstrated on the ground (Figure 1). This is expected to achieve the world's highest power generation performance (over 200 W/kg).

A new program for solar power sails that takes into account 1)-4) is presented (Figure 2).

Outcomes:

Academic journals published in FY2020: 4 papers. Total number of papers: 147.

2) and 3) will produce lightweight and highly functional sails that are applicable to various spacecraft and expected to dramatically change (paradigm shift) space missions.

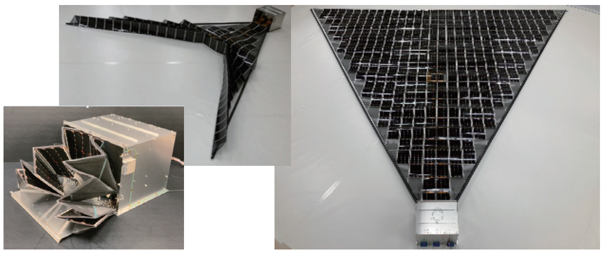


Figure 1. Thin-film solar cell paddle for small spacecraft to outer solar system

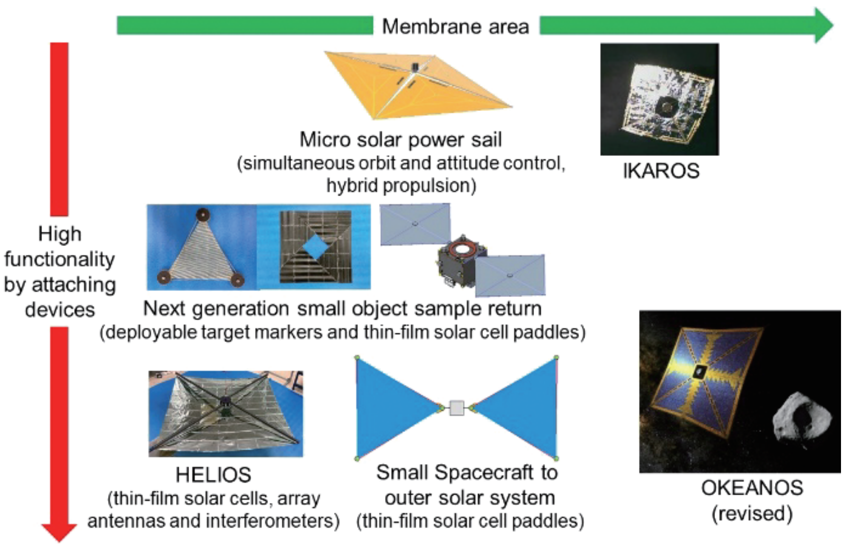


Figure 2. New program for solar power sails

k. Japan Astrometry Satellite Mission for INfrared Exploration (JASMINE)

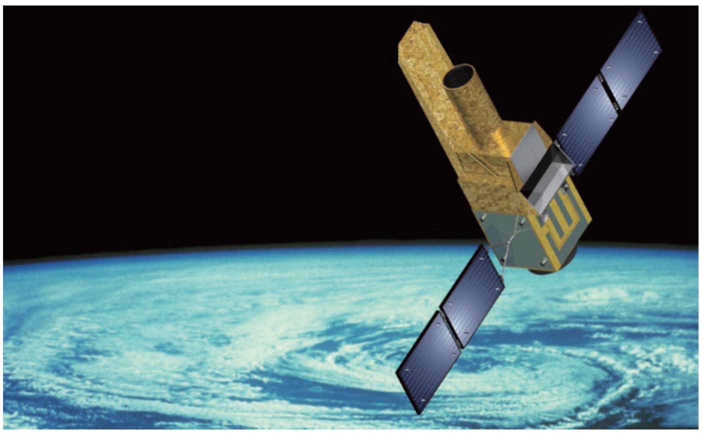
Japan Astrometry Satellite Mission for INfrared Exploration (JASMINE) is a satellite for ultra-high precision astrometry and exoplanet exploration using the transit method.

JASMINE will create and publish a catalog including astrometric parameters such as annual parallaxes and proper motions of about 100,000 stars through observing the stars hundreds of thousands of times over a three-year period. JASMINE's data processing achieves high precision astrometric measurements through self-calibrations using the relative positional relationship of observed stars to model and remove various systematic errors. The science 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 scheduled to be released around 2028) could not observe the direction of the Galactic center at visible wavelength, JASMINE can measure highly precise distance and motion information of stars in the dust- and gas-obscured central bulge with near-infrared wavelength for the first time in the world. The success of JASMINE leads to the European Space Agency's GaiaNIR mission, an infrared all-sky astrometric satellite, which is planned around 2045.

The ability of JASMINE to make repeated observations in the near-infrared will also be utilized to search for extrasolar planets. By continuously observing mid-M dwarfs, which are smaller than the Sun, for long periods and capturing slight changes in their brightness, JASMINE aims to discover terrestrial planets with orbits that might 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 3000 K. They are abundant in the vicinity of the solar system and have relatively large amplitude of light curves in transit observations. For transit observations of terrestrial planets around mid-M dwarfs, space telescopes capable of precise and continuous photometric observations are crucial. In this area of observations, JASMINE has a significant advantage over NASA's Transiting Exoplanet Survey Satellite (TESS, launched in 2018), since JASMINE has a larger aperture and uses a near-infrared wavelength range. With detailed spectroscopy using large space telescopes for atmosphere on the terrestrial planets discovered by JASMINE, a new era will be opened in the search for signatures of life on exoplanets.

The achievements of our activities in FY2021 are as follows:

1) A study was conducted to establish a methodology and feasibility for the telescope and mission structure to ensure that the optical performance, including image distortion, is stable 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 subsystems, including an infrared sensor chip, a thermal structure cooling system, and drive electronics, was conducted to meet the requirements for JASMINE. As part of the Technology Frontloading activities, we have developed an infrared sensor chip by adapting a sensor chip developed for ground-based telescopes for space applications.
3) With respect to realistic errors, a numerical simulation was constructed to show that the required accuracy for the derivation of astrometric parameters can be achieved. The simulation reflects the optical design, the mathematical model of the thermal structure, the actual data of the infrared sensor chip, and the satellite-caused errors considering the observation operation etc. Significant progress has been made in software implementation with the help of volunteers from the research community.
4) With coordination with domestic and overseas universities and research institutes, and candidate companies in charge of development, establishment of the development framework was promoted.



The JASMINE satellite on orbit (artist's illustration)

4. Other Programs

a. 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 successfully achieved production of 50 mK 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 also will 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.

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. The Athena/ X-IFU consortium is promoting their phase-B study, including the Japanese contribution, to supply JT coolers. These results were utilized in other international missions such as LiteBIRD and Athena.

b. Small Synthetic Aperture Radar (Small SAR)

Synspective Inc. and JAXA developed the small, lightweight and low cost StriX series of synthetic aperture radar (SAR) satellites, and are conducting further development of the key technologies of the SAR instruments through co-creation activities under the JAXA Space Innovation through Partnership and Co-creation (J-SPARC) program. The StriX series is a 100 kg class satellite with an X-band SAR that can accurately monitor day and night in all weather conditions. A schematic drawing and specifications of the StriX satellite are shown in Figure1 and Table 1. This co-creation activity started in 2019 and is being carried out in two phases. The first two years are the business concept co-creation phase, and the current phase is the business joint demonstration phase. In the first phase, the Strix-α and StriX-β demonstration satellites were developed. StriX-α was successfully launched by Rocket Lab's Electron rocket from a launch site in New Zealand and entered orbit as planned on December 15, 2020. Strix-β was launched on March 1, 2022. StriX-1, which is a demonstration commercial satellite was developed and launched on September 16, 2022. SAR images were acquired successfully. Figure 2 shows a SAR image from the StriX-β. In addition, further R&D activities are being carried out. One activity is the advancement of the antenna, and another activity is clarification of the discharge phenomenon in high power systems in the space environments. Figure 3 shows a thermally stable antenna using CFRP that we are developing. We are conducting discharge tests on connector joints, device joints and antennas. We are also evaluating the discharge threshold using a discharge analysis simulator. Figure 4 shows a discharge observed around SMA connector. This co-creation activity is an example of promoting the commercialization of JAXA's basic research results. Synspective Inc. aims to launch a total of six satellites into orbit by the end of 2023, and build and operate a wide-area high-frequency ground observation system using a constellation of 30 satellites by around 2026. This is expected to be a successful model of new space business creation.

Table 1. Specifications of Strix-α

	Specifications	
Orbit	Sun synchronous orbit, Altitude: around 500km	
Weight	100kg class	
Frequency Band	X Band	
Polarimetry	VV	
Observation Mode	Strip Map	Sliding Spot Light
Resolution	3m	1m
Swath	30km	10km

Figure1. Schematic drawing of StriX satellite.
(https://synspective.com)

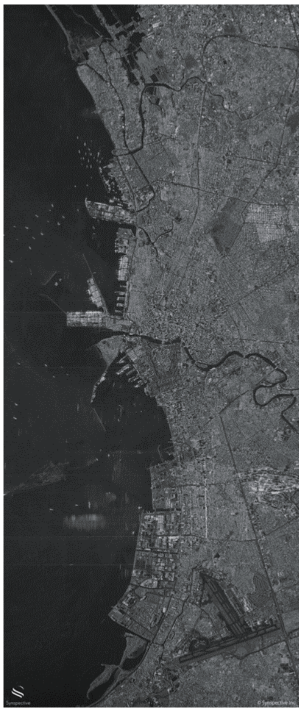


Figure 2.Acquired Image from StriX-β Observation date and time: 2022/06/05 Around 1 PM [UTC], Observation location: Manila, Philippines, Observation mode: Sliding Spotlight Mode.
(https://synspective.com)

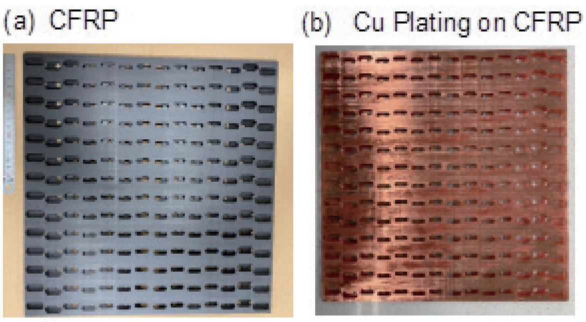


Figure 3. Thermally Stable CFRP Antenna.

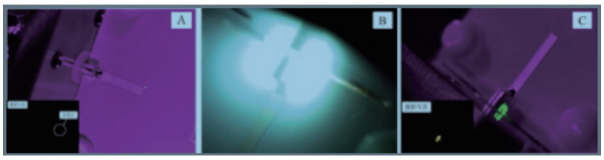


Figure 4. Discharge phenomena in SMA connectors.

5. R&D at Research Departments

a. Department of Space Astronomy and Astrophysics

1. Overview

The Department of Space Astronomy and Astrophysics is engaged in observational research in astrophysics from space, including studies for future space missions and instrumentation. Our studies cover a variety of research fields from cosmology to exoplanets, including the cosmic microwave background (CMB), clusters, active galactic nuclei (AGNs), galaxies, stars, star-forming regions, super nova remnants, compact objects, and interstellar mediums (ISMs), utilizing the data taken in various wavelengths ranging from radio to gamma rays.

In FY2021, development of the X-Ray Imaging and Spectroscopy Mission (XRISM) was advanced. The development of the CMB B-Mode polarimetry mission, LiteBIRD, which was selected as mission No. 2 in the series of JAXA Strategic Large-Class science missions, and the development of the NIR astrometry mission JASMINE, which is JAXA's Competitive Middle-Class mission No. 3, were also were advanced. Studies concerning HiZ-GUNDAM, and SILVIA, which are the candidates for Competitive Middle-Class missions, were also advanced.

Studies using the data from MAXI and CALET, which are science experiments on-board the International Space Station, were also conducted. As for Strategic International Cooperative projects, collaboration studies and development for the Nancy Grace Roman Space Telescope (NASA), Athena (ESA), and LISA (ESA) were actively conducted.

Many of the members of the department engage in these current/future mission projects. We also carry out science studies using the observational data taken by space/ sub-orbital and ground-based telescopes around the world, as well as science instrumentation and engineering for future space observations.

The department has also worked on the development of more general future technology, including space cryogenic systems, lightweight X-ray and infrared telescopes, infrared detectors, cryogenic X-ray spectrometers, X-ray and gamma-ray pixel detectors, analog and digital signal processors, millimeter and submillimeter ultra-low-noise heterodyne receivers, next-generation Very Long-Baseline Interferometry (VLBI) technology, and space applications of the optical lattice clock.

2. Research Activities in FY2021

2.1. High-energy astrophysics

In the area of observational research in high-energy astrophysics, the department conducted research using various X-ray and gamma-ray satellites. Studies were conducted for the spatial distribution of Iron-group elements in Type Ia SNR3C397 by XMM-Newton and NuSTAR, for the double ring structure in N103B SNR in LMC, for spatial distribution of the X-ray-emitting plasma of SS Cygni in quiescence and outburst, for a new X-ray reflection model to V1223 Sagittari, and for emission regions of the X-ray pulsar Hercules X-1 by Suzaku.

Through international collaboration, we have also conducted the FOXI-4 sounding rocket experiment for solar X-ray observations as well as development for the XL-calibur balloon experiment for X-ray polarimetry.

Development studies have also been carried out for more sensitive observations in the future. For the TES micro calorimeter, laboratory experiments, including with respect to its application in transmission microscopes, and development to enable large-format sensors has been conducted. For semiconductor sensor devices, R&D has been conducted to achieve lower background noise, better energy resolution, better spatial resolution, and a larger format. In the area of gamma-ray detectors, a fundamental study on a sensitive semiconductor Compton camera equipped with the ability to detect electron trajectories was conducted. For the CdTe detector used in X-ray imaging spectroscopy, which was established through the development of ASTRO-H, studies on its application in other areas, such as medical imaging or negative muon beam experiments, have been carried out.

A study concerning HiZ-GUNDAM, which is a mission concept utilizing both X-ray and infrared observations to study very high-redshift Gamma-ray bursts (GRBs) and kilo-nova, has been conducted. The scientific objectives were refined and concept development of the science instruments and the satellite system was conducted in preparation for the development in the mission definition phase.

2.2. Infrared astrophysics

The concept definition phase of the infrared astrometry mission, JASMINE, was conducted. The applicability and space qualification requirements of newly developed InGaAs near-infrared detectors were investigated. We also conducted a study on the Japanese contributions to the Roman (Nancy Grace Roman Space Telescope) mission, which is the NASA flagship mission after JWST. The development of polarimetry unit optical elements and mask substrates for a coronagraph instrument, as well as the concept study for the ground system for data reception and transportation, was advanced.

In the field of optical and infrared astrophysics, we conducted various studies using data from AKARI and other infrared satellites, as well as data from ground-based telescopes, including the Subaru Telescope and the Atacama Large Millimeter/sub-millimeter Array (ALMA).

For the AKARI North Ecliptic Pole (NEP) survey regions, where deep infrared data were obtained, a multi-wavelength photometric catalog of galaxies was constructed with the Subaru HSC imaging data. A search for proto clusters at intermediate and high redshift, and a study for galaxy merging rate were conducted. Studies for anomalous hydrogen recombination line ratios in UltraLuminous Infrared Galaxies (ULIRGs), for the inner structure of the molecular torus in the ULIRG IRAS 08572+3915 NW, for [CII] emission properties of the massive star-forming region RCW 36 in a filamentary molecular cloud, were conducted.

Studies using the ground-based telescopes and various archival data were also conducted. For AGNs, observations of near-infrared hydrogen recombination lines of radio galaxies, multi-wavelength analysis of radio galaxy jets to reveal particle acceleration, and a multi-color deep variable AGN search with Subaru HSC were advanced.

In parallel with the observational studies, basic development of future infrared technology was also carried out. The development of an immersion grating for high- dispersion spectroscopy was continued with a special emphasis on the evaluation of transmission as a function of temperature. We also succeeded in fabricating a 32 x 32-channel far-infrared sensor by combining a Ge-blocked impurity band detector with silicon support with the ROIC (Read-Out Integration Circuit) for FD-SOI (Fully Depleted Silicon-On-Insulator) CMOS.

Additionally, we worked on development of space cryogenic technology, including the evaluation of a new type of heat exchanger for Joule-Thomson coolers and thermal conductivity measurements of thermal straps.

2.3 Fundamental physics

With regard to fundamental physics, studies on cosmic inflation based on precise measurement of the CMB, on a space gravitational wave experiment, on a direct and observational dark matter search, and on a light lattice clock were conducted.

For CMB very high precision polarimetry observations, we are conducting the development of the LiteBIRD mission through collaboration with domestic institutes such as KEK and IPMU and international partners in the U.S., Europe, and Canada. A 1/4 scale model of the low frequency telescope (LFT) was developed to demonstrate and evaluate the optical design, and a method for precise polarization angle measurement was newly developed. Optimization of the cryogenic system at the Sun-Earth L2 orbit as well as optimization of a data acquisition strategy that takes into account the effect of cosmic rays was studied. Coordination for the interfaces with the international partners was also conducted.

Another activity in fundamental physics is that for gravitational wave astronomy. In parallel with the continuing contribution to KAGRA, the Japanese ground-based gravitational-wave detector, through participation in the interferometer commissioning experiments, feasibility studies on future space-based gravitational wave detectors were carried out. A group of domestic scientists consisting of members from Univ. of Tokyo, NAOJ, Univ. Electro-Communications, and our institute began to participate in the LISA consortium, where the group initiated consideration regarding the development of photoreceivers, an optoelectronic device for laser light detection onboard LISA.

2.4 Radio astronomy

Our radio astronomy group performed a wide variety of observational research using large radio telescopes around the world, including ALMA. Studies for the hot molecular core candidates in the Galactic-center 50 km/s molecular cloud was conducted

We also developed a balloon-borne VLBI telescope and low-noise millimeter wave receiver for further satellite projects. We took part in discussions on the U.S. space VLBI satellite project. Furthermore, we are participating in the construction project for the new ground-based antenna for deep space exploration, GREAT, in the context of utilizing our radio astronomy technology. In particular, we made a Ka-band cryogenic low-noise receiver in our laboratory and installed it in the antenna.

2.5. Cryogenic system for science missions

Bolometers/micro calorimeters have been proposed as extremely sensitive low-noise detectors for various fields in space astrophysics, including SPICA (infrared), LiteBIRD (microwave), and Athena (X-ray). The development of cryogenic systems, common in these projects, has been conducted in collaboration with these project teams and the JAXA Research Division. In 2016, an ESA Core Technology Program to develop cryogenic systems to achieve 50 mK sensors in orbit was started in collaboration with ISAS.

3. Research Topics

The following outline lists all the research activities during FY2021 in the Department of Space Astronomy and Astrophysics:

3.1 Research in X-ray and gamma-ray range
3.1.1 Observational research
3.1.1.1 Study of the charge-exchange soft X-ray emission from the geocorona
3.1.1.2 Study to establish the model of X-ray emission mechanism from cataclysmic variables with strong magnetic fields and its application to the SUZAKU data to estimate the white-dwarf mass.
3.1.1.3 Study of emission mechanism of X-ray binary pulsars and its application to the SUZAKU data
3.1.1.4 Observational study for soft X-ray background radiation
3.1.1.5 X-ray observations of supernova remnants
3.1.1.6 Study to search for a “dark-matter feature” in the cosmic X-ray background radiation with SUZAKU

3.1.1.7 X-ray studies of the super nova remnants
3.1.1.8 Study of the X-ray emission region of the AGNs with the iron line
3.1.1.9 Studies in high-energy gamma-ray astronomy with the FERMI LAT (USA)
3.1.1.10 Studies of X-ray sources with the all-sky monitor data from MAXI
3.1.1.11 Studies of cosmic rays, gamma-ray bursts, and space weather with the data from CALET
3.1.2 Developmental research for observational technology
3.1.2.1 Development of Si mirror substrates with high-temperature plastic deformation technique
3.1.2.2 Development of high angular resolution X-ray optics
3.1.2.3 Development of TES X-ray microcalorimeters for future space missions or ground applications
3.1.2.4 Development of X-ray CCD camera with extremely low background
3.1.2.5 Development of high-precision hard X-ray imaging spectrometers
3.1.2.6 Development of Compton camera and polarimeters for high- sensitivity gamma-ray observations
3.2 Research in the optical and infrared wavelength range
3.2.1 Observational research
3.2.1.1 Study of the galaxy formation and evolution at the peak of the star-formation history in the universe using multiwavelength observations at the NEP survey region
3.2.1.2 Variability survey of AGN using with the Subaru HSC
3.2.1.3 Study of infrared absorption-feature distribution and their relations with star-formation activity.
3.2.1.4 Study of particle acceleration at the hot spot of radio galaxies by mid- and far-infrared observations
3.2.1.5 Study of circumnuclear structure of AGNs using AKARI data in combination with numerical simulations
3.2.1.6 High-resolution Infrared spectroscopic and numerical study of molecular tori in AGNs.
3.2.1.7 Optical and near-infrared study of protoclusters at high redshift
3.2.1.8 Study of the galaxy evolution for the Roman project
3.2.1.9 Study of gas dissipation in proto-planetary disks
3.2.1.10 Infrared and radio observations of inter-stellar matter in the Galactic massive star-forming regions
3.2.1.11 Study of diffuse emission by the Infrared Satellite MIRIS
3.2.1.12 Study of star-formation regions by the Infrared Satellite MIRIS
3.2.1.13 Infrared and radio observations and radiation model study of mass ejection objects.
3.2.2 Developmental research for observational technology
3.2.2.1 Development of far-infrared imaging sensors using Ge blocked-impurity band/fully depleted silicon-on-insulator CMOS chips
3.2.2.2 Development of monolithic multi-layer interferometric filters
3.2.2.3 Development of mid-infrared immersion gratings
3.2.2.4 Development of cryocoolers for space cryogenic missions
3.2.2.5 Material characterization at cryogenic temperature for space missions
3.2.2.6 Promoting Japanese participation in the NASA Roman program
3.2.2.7 System study of the small JASMINE mission
3.3 Fundamental Physics
3.3.1 Promoting the LiteBIRD mission
3.3.2 Promoting Japanese participation in the ESA LISA mission
3.4 Research in the radio wavelength range
3.4.1 Observational research
3.4.1.1 Promotion of radio astronomy observation using JAXA's tracking antennas, including the 64-m antenna at Usuda
3.4.1.2 Observational study of acceleration and collimation mechanisms of radio jets from AGNs using VLBI
3.4.1.3 Observational study of molecular clouds and star formation mechanisms in the Galactic Center region using ALMA
3.4.2 Developments for Observation Technique
3.4.2.1 Development of a balloon-bone VLBI telescope
3.4.2.2 Development of low-noise millimeter wave receivers
3.4.2.3 Participation in the construct project of the new ground-based antenna for deep space exploration, GREAT.

b. Department of Solar System Sciences

1. Overview

The research activities by members of the Department of Solar System Sciences cover planetary science and interplanetary space physics, including planetary magnetospheres and the Sun. The underlying disciplines include space plasma physics, solar physics, magnetospheric and ionospheric physics, atmospheric science, planetary geology, astromaterial science, and theories governing the formation and evolution of planetary systems. Data from existing missions such as ARASE and GEOTAIL (magnetospheric physics), HINODE (solar physics), HISAKI (extreme ultraviolet spectroscopy for planetary science), AKATSUKI (Venus atmospheric dynamics), BepiColombo/MIO (Mercury magnetospheric physics), and Hayabusa2 (asteroid explorer) have been studied extensively, and samples brought back by HAYABUSA and Hayabusa2 have been analyzed. Missions under preparation, including MMX (Martian Moons eXploration: Phobos sample return mission), JUICE (Jupiter Icy Moons Explorer), Solar-C EUVST (EUV High-Throughput Spectroscopic Telescope), WSO-UV (World Space Observatory-Ultraviolet), Hera (planetary defense mission), and Dragonfly (astrobiology mission to Titan) are also being handled by members of the Department. In addition, we are engaged in basic research on the development of new onboard instruments for future missions and small-scale projects using sub-orbital opportunities.

2. Research Activities in FY2021

2.1 Solar physics

HINODE, which has been in orbit for 15 years, has made significant contributions to our understanding of observational solar plasma physics as well as fundamental problems, including coronal heating and flare triggering mechanisms. Some of our results that were published this year include the energy partition in coronal microflares, and the correlation between solar magnetic flux and intensities of various spectral lines.

In addition to new instrument development through sounding rockets and balloon experiments, the solar physics community has worked on a new solar mission for launch during the 2020s.

Following domestic and international community-wide discussions and information exchanges toward realizing a Japan-led next-generation solar physics mission, the department led community-wide activities to realize a mission with the concept of flying a high-resolution coronal/transition-region spectroscopic telescope (called EUVST) for diagnosing EUV/VUV spectral lines emitted by plasma within a seamless temperature range from the chromosphere to the transition region and corona and by super-hot plasma created by solar flares. The 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, by investigating the energy and mass transfer from the solar surface to the solar corona and interplanetary space. This mission is positioned at the center of the solar research roadmap in Japan and has strong support from the US and European communities. The mission was chosen as the 4th in the series of competitively chosen M-class missions in April 2020, and it is now called Solar-C (EUVST). The pre-project candidate team has had study activities in the mission definition phase (PrePhase A2). Along with negotiating an international collaboration scheme for EUVST development, NASA officially announced its participation in EUVST. Design efforts were also accelerated in US and European countries.

The solar physics community has started discussions to define a space research roadmap for the 2030s.

Magnetic reconnection is one of the most fundamentally important processes in space plasma, and the solar corona is the best place to conduct X-ray imaging observations to help us to learn more about its physical processes. Complementary metal-oxide-semiconductor (CMOS) detectors with fast readouts and low-scattering mirrors are key components that are expected to enable a new high time resolution spectroscopic imaging mission in this direction. Indeed, we have already succeeded in prototyping a Wolter-type mirror, demonstrating an extremely high level of performance. A possible Epsilon mission, PhoENiX, which aims to understand particle acceleration and the creation of high-temperature plasma under the framework of a magnetic reconnection, is currently under study with the participation of multiple disciplines. The projected launch of PhoENiX will be in the 2030's.

As a follow-up to the Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP) mission, a sounding rocket experiment designated as CLASP-2 was launched in April 2019. While the first CLASP mission succeeded in detecting polarization in the Lyman alpha line, which is a sign of the Hanle effect in the solar chromosphere, CLASP-2 is expected to detect polarization in the Mg line to obtain magnetic field information on the chromosphere. A continuous rotating polarizer, a key technology for accurate measurements of polarization, was originally developed in this Department. Following the success of CLASP and CLASP-2, another sounding rocket flight (CLASP-2.1), which will obtain 2-D maps by the pointing control of a rocket with the same equipment as CLASP-2, was launched in September 2021. Calibration on CLASP-2.1 data is actively under way for scientific output from the mission.

The development of the readout and data-recording electronics for a focal-plane X-ray CMOS pixel detector was carried out for Focusing Optics X-Ray Solar Imager 3 (FOXSI-3), which is another NASA sounding rocket experiment. FOXSI-3 was launched in September 2018 and successfully delivered imaging-spectroscopic data of the soft X-ray corona using this new instrumentation. A subsequent sounding rocket program, FOXSI-4, which plans to observe solar flares, is currently under development by a joint US-Japan team towards its launch in 2024.

The CLASP-2 sounding rocket experiment has been defined jointly with the SUNRISE-3 balloon-borne experiment as one of ISAS's small science programs, i.e., "small solar observations" programs, which will acquire new diagnostic capabilities for magnetic fields in the upper solar atmosphere.

A Japanese group consisting of scientists from NAOJ, ISAS, and Kyoto University are preparing a focal plane instrument, called the Sunrise Chromospheric Infrared spectroPolarimeter (SCIP), for the third flight of the upgraded SUNRISE (1 m telescope) observatory on a stratospheric balloon (SUNRISE-3, scheduled for 2022). SUNRISE is dedicated to the investigation of the processes governing the physics of the lower solar atmosphere, and SCIP will measure the polarization of infrared spectral lines emerging from the chromosphere and photosphere. The flight model was completed in autumn 2021 and delivered to Germany for further testing at the Balloon observatory level. The major efforts at ISAS this year include the test and verification of the flight-model instrument with scanning mirror mechanisms and polarization modulator mechanism, which were developed at the department's initiative.

2.2 Space plasma physics

The Magnetospheric Multiscale (MMS) mission is a NASA Heliophysics flagship project conducting 3D high-resolution formation flying observations of space plasma dynamics using four closely situated spacecraft. The objective of the MMS mission, launched on March 12, 2015 from the US Kennedy Space Center onboard an Atlas-V rocket, is to unveil the microphysics driving magnetic reconnection, which is considered to be one of the most important processes in space plasma physics. Since magnetic reconnections occur frequently on the surface of the boundary of Earth's magnetosphere and in Earth's magnetotail, these are the regions where the MMS spacecraft will visit to conduct unprecedented in situ observations. Members of the Department participated in developing the onboard Fast Plasma Investigation (FPI) instruments, which include four dual electron spectrometers (DES) and four dual ion spectrometers (DIS) per spacecraft. The data obtained thus far have proven to be excellent and are being made available to global research communities. Collaboration between Magnetospheric Observation Satellite GEOTAIL and MMS is ongoing. In FY2021, all 16 FPI-DIS analyzers continued observation of the magnetic reconnection region in the magnetotail without any problems.

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 baseline mission consists of two spacecraft: the Mercury Planetary Orbiter (MPO) and MIO, the Mercury Magnetospheric Orbiter (MMO). The two orbiters and the Mercury Transfer Module (MTM) will be combined in a stacked configuration, which is called the Mercury Cruise System (MCS). The MIO spacecraft is a JAXA contribution to the BepiColombo Mercury exploration program. After the successful launch of BepiColombo on October 20, 2018 (UTC) from Guiana Space Center (CSG) by the Ariane-5 rocket, the initial checks of the spacecraft and instruments were completed. In FY2021, the 2nd Venus flyby and the 1st Mercury flyby operations were successfully performed in August and October 2021, respectively. Science observations were also performed during both flybys by the instruments onboard MIO. In the second Venus flyby the closest approach altitude was ~550 km and MIO successfully observed plasma environments around Venus. In the first Mercury flyby the Mercury Plasma Particle Experiment (MPPE) instrument successfully observed low energy ions and electrons simultaneously in the Mercury's magnetosphere for the first time ever. In addition to the flybys, MIO measured solar wind electrons during the interplanetary cruise. In preparation for arrival at Mercury in 2025, we built a MIO spacecraft simulator and observation planning/verification tool.

In parallel, the Science Working Group worked on science operation planning. We held international Science Working Team meetings as virtual conferences every month. We also made progress on preparations for a special issue of BepiColombo to be published in Space Science Review.

The SS-520-3 sounding rocket was launched at 10:09:25 UT on November 4, 2021 from Ny-Ålesund, Spitsbergen, Svalbard, Norway during a magnetic storm. The scientific purpose of SS-520-3 was to understand the ion upflow phenomena in the dayside polar cusp region. Since the SS-520-3 sounding rocket succeeded in hitting its target "CUSP" and almost all the onboard instruments successfully made observations during the flight, we proceeded to analyze the obtained data.

We are also participating in two sounding rocket missions (RockSat-XN and LAMP) operated by NASA to reveal the relationship between the pulsating aurora and microburst precipitation of MeV-range electrons. RockSat-XN was successfully launched on January 13, 2019 from Andoya, Norway. The onboard instruments successfully observed precipitating high-energy electrons. LAMP was launched on March 5, 2022 from Poker Flat Research Range, Alaska, USA. The rocket successfully hit pulsating auroral patches with high-frequency optical modulations which likely have a close relationship to the microburst electron precipitations. The instruments onboard LAMP worked successfully, and analysis of observed data including US instruments and ground-based supporting observations is ongoing.

We have an opportunity to install a high-energy electron detector on a CubeSat, nicknamed BIRDS-5, developed by Kyushu Institute of Technology with the support of JSPS Grants-in-Aid for Scientific Research. Currently, we are developing Particle Instrument for NanO-satellite (PINO) in collaboration with Kyushu Institute of Technology. The objectives of the PINO mission are 1) to demonstrate a compact high-energy electron detector using Si/CdTe semiconductors and 2) to measure high-energy electron fluxes precipitating from Earth's radiation belt. BIRDS-5 is scheduled to be released from the International Space Station in the autumn of 2022. We will also endeavor to conduct simultaneous observations with the ARASE satellite in a region where the geomagnetic latitude is above 60 degrees in the northern hemisphere. The development of the PINO Flight Model finished in March 2022, and it has been installed on a 2-U CubeSat, BIRDS-5J (Taka). All the function tests have been successfully completed, and we are ready for the launch.

The FACTORS WG was established under the Advisory Committee for Space Science in December 2018 in order to study the polar formation flight satellite mission FACTORS, which is a Japanese space physics community mission following the ARASE mission. FACTORS will realize spatiotemporal separation by observing space plasma and Earth's upper atmosphere on multiple time and space scales by formation flight satellites and the latest observation technology. The scientific purpose of FACTORS is empirical and quantitative elucidation of the basic mechanical and electromagnetic mechanisms that compose and control the Space-Earth coupled system. In FY2021, we studied the satellite systems including the propulsion system and the ground system as well as the development of onboard scientific instruments.

2.3 Atmospheric science

Characteristic processes such as the ionospheric dynamo current and polarization electric field are known to exist in the lower ionosphere where the coexistence of charged particles and neutral particles is believed to play an important role. The momentum transfer between these particles affects the dynamics in this region although little observational evidence of this process has been reported. It is desirable to make a direct measurement of charged and neutral particles by using instruments on the sounding rocket. We are developing an ion drift velocity analyzer and vacuum gauge to measure the neutral atmosphere.

Sounding rocket "S-520-32" will be launched in summer of 2022 to observe a spatial distribution of plasma density during the Medium Scale Travelling Ionospheric Disturbance (MS-TID) event, in which neutral particles in the ionosphere are thought to play an important role in generating the disturbance. The vacuum gauge we are developing will be installed on "S-520-32" and make a measurement of the atmospheric pressure, and thereby the neutral number density will be estimated. The basic performance of the vacuum gauge was verified using a space science chamber in 2021.

The HISAKI satellite (Spectroscopic Planet Observatory for Recognition of Interaction of Atmosphere, SPRINT-A) was launched in September 2013 and has been observing the plasma distribution in the magnetosphere and/or ionosphere of planets in the solar system, such as Jupiter, Venus, and Mars, since December 2013. HISAKI succeeded in simultaneously observing Jupiter's inner magnetosphere when NASA's Jupiter orbiter, Juno, passed through the peri-Jove. The scientific results originating from HISAKI's continuous observation have shown HISAKI's potential importance and also the important presence of Japan in the full-scale exploration of Jupiter's magnetosphere. Venus observations are performed at the time of the Venus swing-by of BepiColombo and Solar Orbiter in August 2021 and at the Venus approach of Comet Leonard (C/2021 A1) in December 2021. The collaborative observations of Jupiter's north polar aurora with the Hubble Space Telescope and the XMM-Newton X-ray Observatory in 2019 reveal that the emission mechanisms of the soft and the hard X-ray aurorae are independently triggered. HISAKI continues collaborative observations of Jupiter with Juno at the time of Juno's peri-Jove passage in order to study the transport of energy and materials in Jupiter's magnetosphere. Collaborative observations of Venus with the Venus climate orbiter, AKATSUKI, will also be made in order to study the evolution of its atmosphere.

AKATSUKI, also known as the Venus Climate Orbiter and PLANET-C, was launched in 2010 from Tanegashima Space Center. It failed to be inserted into orbit around Venus in December 2010, but after five years of wandering around the Sun, it arrived at Venus in December 2015.

The spacecraft was designed to observe the Venusian atmosphere, especially its motion, revealing the meteorological structure of Venus, which is extremely different from that of Earth. The spacecraft was equipped with five cameras, an IR1 camera observing 1-μm infrared light, an IR2 camera observing 2-μm infrared light, an LIR camera observing 8–12-μm infrared light, a UV imager observing 283-nm and 365-nm UV light, and a LAC camera observing the lightning on Venus. These cameras take motion pictures of clouds and minor components at different altitudes to reveal the 3D structure of the Venusian atmospheric motion. Furthermore, an ultra-stable oscillator, which is identical to the one onboard Venus Express, was installed for radio occultation measurements to understand the vertical structure of the Venusian atmosphere. The IR1 and IR2 cameras operated for more than one Earth year and other cameras are still observing Venus.

We report two important findings revealed by UVI and LIR in 2019. One is the long-term trend of UV albedo observed by AKATSUKI and Venus Express from 2006 to 2018, and STIS of the HST in 2011. This long-term variation of albedo can directly control the solar heating rate, and this may affect zonal wind speed. Is there ongoing climate change on Venus? To answer this question, continuous observations by AKATSUKI are crucial. Simultaneous Venus observations with BepiColombo are planned for a couple of weeks in 2020-2021, during its cruise towards Mercury. This will provide valuable comparison data.

The second topic is the thermal tide excited by solar absorption in the upper part of the Venusian cloud layer observed by LIR onboard AKATSUKI. The global structure of the thermal tide has been revealed for the first time in the world. Previously, only the viewable hemisphere had been analyzed, while this time the thermal infrared radiation from the cloud tops has been detected in both the day and night hemisphere. This allows us to determine the detailed structure of the diurnal and semi-diurnal tide components. The vertical structure of the semi-diurnal tide suggests that this wave may accelerate the atmosphere and contribute to the generation of super-rotation.

Furthermore, it is understood from the analysis of wind velocity based on UVI and LIR data that the thermal tide in the equatorial region mainly contributes to the maintenance mechanism of super-rotation.

AKATSUKI's IR1 and IR2 (now inactive) reveal at the lower clouds an intriguing sharp discontinuity that propagates to the west faster than the winds while altering the clouds' properties and suffering little distortions for weeks. Results with numerical simulations combined with its absence in observations of the upper clouds evidence that this is an atmospheric wave generated below the clouds and probably pumping energy to the super rotating upper clouds.

AKATSUKI revealed much of the dynamics in the cloud regions of the upper atmosphere but did not reveal the bottom of the deeper atmosphere or the ground surface. AKATSUKI's research results have revealed the importance of the composition and dynamics of this part of the atmosphere. It is important for us to understand Venus more deeply if international Venus probes and Japan's successor spacecraft approach this region after AKATSUKI.

As one of the milestones for the next 20 years of strategic Mars exploration, we promoted a scientific study on Mars atmospheric dissipation research in the Mars Atmospheric Dissipation Observation Program "Strategic Mars Exploration: Mars Space Weather, Climate and Water Environment (MACO) Project by Orbiter and Exploration Technology Demonstrator" WG, which was established in 2020. We reorganized the scientific objectives and strategies to fit the international study of the next international Mars Ice Mapper (MIM) mission, in which JAXA has expressed its intention to participate, and aimed to integrate the understanding of the origin and distribution of ice and changes in the Martian environment as scientific objectives with the understanding of water resources for future human exploration of Mars in order to make the mission definition. In parallel, we participated in the Mars Science Sub-Science Team (Mars Science SST) of Martian Moons eXploration (MMX) (MMX) to study Mars atmospheric observations. We are working to refine and specify the science goals related to the Martian atmosphere, and are providing feedback on the observation plan.

World Space Observatory Ultraviolet (WSO-UV) is a Russian large space telescope with a 1.7 m primary mirror designed for observations in the ultraviolet region (115-320 nm). The scientific goals of this mission are as follows.

(1) The determination of the diffuse baryonic content in the Universe and its chemical evolution. (2) The formation and evolution of the Milky Way. (3) The physics of accretion and outflows: the astronomical engines. (4) Extrasolar planetary atmospheres and astrochemistry in the presence of strong UV radiation fields. JAXA will develop and provide one of the instruments: UV spectrograph for Exoplanets (UVSPEX). However this project is now in hold since February 2022, due to the deteriorating Ukraine-Russian situation.

Many Earth-sized planets have been discovered and some appear to lie in the habitable zone. Moreover, several Earth-sized planets were recently detected around low temperature stars near the solar system. However, it is difficult to characterize them as Earth-like or Venus-like because we have no information on their atmospheres. The habitable zone of a low-temperature star is close to the star because of the star's low luminosity. Stellar extreme ultraviolet (EUV) radiation plays an important role in the ionization, dissociation, and heating of planetary upper atmospheres. On these planets, EUV irradiation is estimated to be > 10 times higher around the habitable zone than that of Earth, which causes significant exospheric expansion. Based on the simulations of the oxygen column density on an Earth twin, Venus twin, and Mars twin in the habitable zone of a low-temperature star, only an Earth twin has significant exospheric expansion. When an Earth twin in the habitable zone of a low-temperature star transits its host star, the transit depth of the OI emission line at 130 nm becomes much deeper than that of a Venus or Mars twin. Since low temperature stars in a vacuum are dark in the UV range, including the OI emission line, a large space telescope and spectrograph with high efficiency are required to characterize these planetary atmospheres.

We are developing the UVSPEX for WSO-UV. The UVSPEX is composed of a toroidal grating and an MCP detector, which enables photon counting and is better for dark objects than a CCD detector. In FY2021, we passed the system definition review (SDR). We prepared a preliminary design of UVSPEX and started the development of UVSPEX EM.

A WG named Life-environmentology, Astronomy, and PlanetarY Ultraviolet Telescope Assembly (LAPYUTA) has been established, which aims to understand the most fundamental questions in space science, including why only Earth has habitats that nurture life, from ultraviolet observation. The purpose of this WG is to understand the life environment of planets and moons in the solar system from a universal viewpoint in order to investigate the habitable environment in the solar system, by setting the observation targets to the interaction between icy satellites (including solid surface, atmosphere and plume) of giant planets and their magnetospheric plasma, and atmospheric expansion and escape of the Earth-like planets. We also examine how the knowledge to be acquired by LAPYUTA applies to the unsolved problems in astronomy, such as galaxy formation theory and time domain astronomy, after the Hubble space telescope era. The optical design of the telescope and the detector sections is advanced, and the feasibility study of the satellite bus system is carried out.

2.4 Planetary science

The Hayabusa2 mission explored the C-type asteroid 162173 Ryugu from June 2018 to November 2019, including global and local remote sensing, in situ surface experiments using Minerva-II and MASCOT landers, an artificial impact crater experiment, and two surface samplings. Hayabusa2 returned the samples in December 2020, and the collected samples (5.4 gram in total) are now in the process of pickups and initial description at the Curation Facility at JAXA Sagamihara Campus in a non-destructive and un-contaminated manner. The Hayabusa2 mission has made many discoveries by characterizing the asteroid as a spinning top-shape structure with low average density of ~1.2 g/cm^3, low albedo of ~2%, a rugged surface covered with boulders, and uniformly distributed 2.7 μm absorption indicating water-bearing minerals, and low thermal inertia suggesting highly porous materials, and loosely-bound rubble-pile with cohesionless sediments (gravity regime).

Initial descriptions of samples show the signs of water and organics, as well as minor components of aqueously altered features such as carbonates and hydrates. Ryugu is more like a CI chondrite but with darker, more porous, and unheated features, informative for the origin and evolution of the Solar System.

The operation of Hayabusa2 is extended to conduct a flyby of asteroid 2001CC21 and rendezvous with asteroid 1998KY26 for the aspect of planetary science and planetary defense. Observations of extra Solar Systems and zodiacal lights are conducted during the long-term cruise.

The Martian Moons eXploration (MMX) project, which is the Phobos sample return mission, is preparing for launch in 2024. Its scientific observation plans and instrumentation are under development, with international collaboration on a near-infrared spectrometer and gamma-ray and neutron spectrometers. In FY2021, in particular, we executed manufacturing and testing of Engineering Models (EM) for each instrument, held Critical Design Reviews (CDR), and also proceeded with discussions on observation operation plans.

Development of the thermal imager TIRI onboard the ESA Hera mission to explore the S-type Didymos binary asteroid has been started for planetary science and planetary defense purposes, as a part of the international planetary defense mission AIDA (Asteroid Impact and Deflection Assessment) with the NASA DART mission, which is a kinetic impactor to the asteroid Dimorphos in 2022.

Japanese participation in JUICE and the Demonstration and Experiment of Space Technology for INterplanetary voYage (DESTINY$^+$) project, an M-Class planetary mission driven by a dust science theme, is expected to ramp up soon. A study on the Comet Astrobiology Exploration Sample Return (CAESAR) mission, a finalist for NASA's "New Frontiers 4" mission to bring back samples from comet 67P/Churymov-Gerasimenko, is ongoing. A new feasibility study for the Next generation Primitive Body Sample Return is started as a working group activity.

Each of these exploration missions is targeting small bodies born "outside the snowline", which refers to the distance from the Sun at which water becomes solid ice. We have formulated a roadmap that describes how these multiple missions are linked together and why such a systematic approach is required. Without a supply of water and other volatiles (including organic compounds) delivered by small bodies from outside the snow line, our planet would never have become habitable. However, there are still some fundamental questions remaining: When and how did this process occur? Furthermore, is it possible for habitability to be established on worlds outside the snow line?

The small lunar explorer "SLIM" will make a precise landing near the Shioli crater, located northwest of Mare Nectaris, and will conduct spectral observations of materials thought to originate from the deep lunar interior using a multiband camera (MBC). The flight model of the MBC has undergone environmental and optical performance tests, and a development completion review (PQR) has been completed. The flight model has been installed on the satellite bus and is currently undergoing system tests. In addition, the preparation of the observational operation plan after landing on the Moon and the development of the ground-based QL and image analysis system are in progress.

A penetrator hard landing system, which enables us to investigate the internal structure and to make in-situ observations on the surface of the Moon and planets, is under development. As a synergy of this technology, the development, manufacturing, and testing of an earth penetrator for use in volcanic eruptions and disaster areas are underway along with the development of new technologies for future exploration. In conjunction with developing a seismograph for NASA's Titan landing mission (Dragonfly), an in-situ seismic observation system in Antarctica using a penetrator is being developed to observe glacial earthquakes on Earth, which are important for understanding Titan's seismic activity.

Dragonfly is a relocatable lander with dual-quad rotors to explore Saturn's moon 'Titan' and will be launched in 2027. The Geophysical and Meteorological package ("DraGMet") onboard Dragonfly is a suite of sensors to monitor Titan's surface and subsurface environment. Our department is in charge of the development of this seismometer, which has been approved as an in-house project and full-scale activities have begun. Since the seismometer is required to operate at the cryogenic temperature of -190°C, performance evaluation and quality assurance measures are being carefully carried out. Additionally, the Science Working Group made up of Japanese researchers includes experts in planetary seismology, icy satellite study and astrobiology and is working to analyze the DraGMet data and contribute to the science results of the Dragonfly mission.

In line with the international trend for Mars exploration and potential significance for understanding the current and past surface/subsurface aqueous environments, JAXA is planning a strategic Mars exploration program (JSMEP). JSMEP will start with MMX mission in 2024-2029, followed by a Mars Ice Mapper mission (MIM) later in the early 2030s and a Mars lander/rover (ML/R) mission in the late 2030s. JSMEP's goals are 1) to address questions of water on Mars [origin and delivery (MMX), distribution and inventory (MO), and chemical evolution (ML/R)], 2) to ensure the expansion of the areas of human activities by exploring the habitable subsurface world, and 3) to acquire key technologies including EDL (entry-descent-landing) with aerodynamic control, drilling and sampling on the surface, deep space telecommunication, transportation to/from the Mars orbit, and planetary protection.

SELENE (KAGUYA) discovered huge vertical holes on the Moon, which were possibly formed on underground volcanic caves. These caves and vertical holes of the Moon are very important for lunar science and future lunar utilization. Last year, we established a Working Group (WG) to explore the holes, named the UZUME (Unprecedented Zipangu Underworld of the Moon Exploration) WG. This year, the UZUME-WG proceeded with studies for the system of the explorer and the availability of consumer products for on-board mission instruments.

We are also discussing and supporting the scientific aspect of lunar polar exploration with India (LUPEX) and mid-sized lunar landing and/or sample return missions, proceeded in the framework of international space exploration. Furthermore, the Department of Solar System Sciences has been involved in various planetary protection activities: the reviews of the Destiny^{+}, OMOTENASHI, iSpace M1, and MMX, and the revision of planetary protection standards and the drafting of the Planetary Protection Handbook for future Mars sample return explorations.

We elucidated the lunar geological structure of rock outcrops relating to the lunar crust-mantle boundary, using SELENE data, which is important in relation to future sample returns from the Moon. We also investigated the size distribution of meteorites that had collided with Ceres, the largest asteroid in the solar system, and found that the distribution was consistent with that of the Moon, while inconsistent with that inferred based on telescopic observations. These results were published in international journals.

3. Research Topics

The following outline lists all the Department of Solar System Sciences research activities during FY2021:

3.1 Solar physics
3.1.1 Solar observations: HINODE, HINODE-IRIS
3.1.2 Instrument development (photon-counting X-ray telescope, photon sensor driver, high-speed CMOS-based sensor, mechanisms), and future mission planning
3.1.3 CLASP, CLASP II
3.1.4 International balloon experiment SUNRISE-3
3.2 Space plasma physics
3.2.1 In situ and remote sensing observations: AKEBONO, GEOTAIL, REIMEI, MMS, KAGUYA, HISAKI,ARASE (ERG), BepiColombo/MIO (Earth, Venus, and solar wind during cruise) and magnetosphere of outer planets
3.2.2 Sounding rocket: SS-520-3, RockSat-XN, and LAMP
3.2.3 Development of a high-energy electron detector (PINO) for CubeSats
3.2.4 Numerical simulations: PIC simulation for space plasma research and physics of proto-planetary disks
3.2.5 Instrument development: High contrast vane protected from the stray light
3.2.6 Future missions: JUICE (Jupiter Icy Moons Explorer), Mission planning of a formation flying satellite FAC- TORS
3.3 Atmospheric science
3.3.1 Venus: AKATSUKI
3.3.2 Mars:Scientific objectives for the physics on near-Mars space and Martin atmosphere (MMX)
3.3.3 Earth's lower thermosphere and ionosphere: Observation of anomalous phenomena in the Sq current focus by sounding rocket, Observational study of the ionospheric electron density irregularity, Observational study of thermal electron energy distribution in the lower ionosphere.

3.3.4 Instrument development: Ion drift velocity analyzer, Vacuum gauge to measure neutral atmospheric density and neutral wind direction
3.3.5 Future missions: Mission planning of satellite observation of exoplanets' atmosphere by UV (WSO-UV), space telescope for planets by UV (LAPYUTA)
3.4 Planetary science
3.4.1 Lunar science using KAGUYA data
3.4.2 Asteroids: curation and analysis of Itokawa samples and initial description for Ryugu sample, Hayabusa2 to the C-type asteroid 162173 Ryugu
3.4.3 Future missions: SLIM, DESTINY$^+$, penetrator technology, landing mission to the Moon and Mars, MMX (Phobos sample return), OKEANOS mission to Jupiter Trojan asteroid, CAESAR (comet sample return), the lunar and Mars cave missions, Hera to explore the double asteroid with a thermal imager TIRI, and Next Generation Primitive body Sample Return
3.4.4 Instrument development to the C-type asteroid 162173 Ryugu
3.4.5 Instrument development

c. Department of Interdisciplinary Space Science

1. Overview

The Department of Interdisciplinary Space Science performs research and development for onboard devices and information systems deployed with flight vehicles and space platforms (e.g., balloons, rockets, satellites, and the ISS). The Department contributes to novel interdisciplinary studies in space science and peripheral fields through fundamental research in the following areas:

- Space utilization. The Department aims to use the unique characteristics of space, such as microgravity and radiation, to understand phenomena that are difficult to measure and observe on the ground. The Department conducts materials-science studies to yield materials with novel functions. We also study space biology-that is, the effects of the space environment on behavior, development, and evolution.
- Astrobiology. The Department studies the origins, early evolution, distribution, and future of life in the universe.
- Information systems. The Department studies basic computing technologies, such as data processing, computer networking, distributed processing, and high-capacity databases that will enable the high-speed processing, transmission, and storage of the large amounts of observation data generated by scientific satellites. We also perform space-engineering research on the visualization of space science data, monitoring for spacecraft malfunctions, numerical simulations, and data assimilation.
- Scientific balloons. The Department is engaged in R&D for balloons used for space science research. This includes work on balloon operating systems and experimental systems used in scientific observations and engineering demonstrations.
- Micro/nano-satellites for deep space exploration. In order to apply the technology of micro satellites that can be developed at low cost in a short period of time to space science and exploration, and to develop and establish them as a new space science and exploration tool, the Department members are conducting research and development centering on activities for proposing future missions.

2. Research Activities in FY2021

2.1 Space utilization science

In the field of materials science, the physics of high temperature melts are studied using electrostatic levitation. Using the electrostatic levitator in the International Space Station, the thermophysical properties of molten lanthanoid sesquioxides for which melting temperatures are over 2,400°C were measured. Moreover, properties of molten MgO-SiO samples were obtained. Combined with the microscopic structural data obtained by diffraction experiments, the fragility of these liquids is discussed. The ISAS Small Science Program DUST is being promoted with the aim of elucidating entire processes of material evolution from molecules, dust, and planet to organics in a history of the universe based on the fundamental physical and chemical properties of cosmic dust.

In life science activities, we continue to study the role of gravity in the biological activities of life on Earth. Starfish show a rising behavior as a response behavior to gravitational stimuli. In order to understand the localization of gravity sensors in starfish, we designed an experimental system.

2.2 Astrobiology

We continued detailed sample analyses of the meteoroid capture experiment and the microbe and organic exposure experiments from the Tanpopo-1~3 series after their space exposure onboard ISS in 2015-2021, in order to test the panspermia hypothesis and the chemical evolution from cosmic dust to terrestrial life. We also made progress in the research and development of cosmic dust detectors, collectors, and bumper shields for future flight opportunities such as EQUULEUS, Gateway, Comet Interceptor, and OPENS. For cis-lunar space exploration, the PVDF film sensor sandwiched in MLI (CLOTH) onboard the EQUULEUS spacecraft will be launched in 2022 and the low-velocity dust monitor (LVDM) composed of PZT sensors and the low-velocity dust collector with carbon nano-tubes that have already flown and returned on Tanpopo and Hayabusa2 are under development for Gateway. We also designed a bumper shield to protect the Comet Interceptor and OPENS spacecraft against impact damages much faster than 10 km/s velocities by hydrocode calculation. Calibration experiments for the above instruments were restarted after two years of interruption by the pandemic, by utilizing a group of vacuum single microparticle acceleration facilities we have developed under international collaboration with the Massachusetts Institute of Technology.

As a part of our astrobiology research, we carried out genome analysis of microorganisms supported by rock-water reactions on Earth to answer the question, “What kind of life is possibly supported by rock-water reactions in space?” In collaboration with the Space Exploration Innovation Hub, the development of fundamental technologies for efficient sterilization and decontamination of microbes is in progress for space exploration in compliance with the Planetary Protection Policy.

2.3 Research on information science and information technology

The Department performed basic research on large-scale computation applied to spacecraft development and operations. In the development of the hierarchical equally spaced Cartesian structured grid solver, we verified the analysis accuracy of the physical quantity distribution on the object surface and their integral values, which are technical issues. We also identified the cause of the oscillation of the surface physical quantity distribution. We carried out analysis of the actual aircraft geometry using the supercomputer “Fugaku” and also simultaneously improved the pretreatment tool required to realize the analysis using a hybrid grid that combines an orthogonal grid and layer grid and conducted a trial calculation.

The Department investigated methods of visualization and studies related to visualization. (1) We have reported the results of the methods for visualizing the behavior of the asteroid probe Hayabusa2 with Super Hi-Vision quality in collaboration with NHK. The purpose of the collaboration is to assist the operation of space probes by visualizing the behavior of the probes. With the results, high-definition 3D computer graphics were provided during the rendezvous with the asteroid Ryugu, Hayabusa2 re-entry capsule recovery operation, and such. (2) Based on the methods for visualizing virtual asteroids, we visualized a variety of simulation data to contribute to the analysis of the observation data of Hayabusa2. We also worked on the application of visualization methods in relevant fields. (3) We worked on the visualization of the superconducting Single-Flux-Quantum (SFQ) logic circuit, for which consideration is being given to applying it to the onboard devices of space probes in the future. We developed an interactive graphical user interface that visualizes a mechanical analogy of the SFQ circuit and corresponding parameters. We also implemented a method of numerical analysis to visualize the behavior of the circuit on the fly.

Our Department also handles the data archive study. For data archives, we defined ten tasks: Definition, Production, Documentation, Integration, Evaluation, Preservation, Publication, Identification, Utilization, and Collaboration. These tasks are supported by projects, data centers, and communities. For planetary exploration, PDS and SPICE are used as global standards, and HAYABUSA, KAGUYA, AKATSUKI, and Hayabusa2 are also archived using these standards. With the remarkable improvement in analysis environments in recent years, we have started to develop an interface that has strong affinity with recent environments. For one of them, we have studied high-speed data access research to access huge tables using counting sort, and created an archive containing Apollo seismic data as an example of huge number of records, and Hayabusa2 HK data as an example of huge number of columns.

2.4 Research on scientific balloons

A super-pressure balloon was developed to expand the possibilities for scientific observations with balloons. This balloon can achieve long-duration flights by maintaining lift and volume against differential pressure due to solar irradiation. Since 2010, intensive efforts have been underway to cover the balloon’s film with a diamond-shaped net to increase resistance to pressure during the daytime. This balloon has the advantage of being lighter than the conventional lobed-pumpkin design. This year, we developed a new launching method that avoids the risk found through a flight test in 2020 of damage to the balloon envelope if hit by the net at the time of spooler release. The method is to hold a hanging point, newly attached on the balloon around the collar attachment part, with a rope and gradually release the rope. We confirmed the procedure using a test balloon. A 200 m^3 balloon was developed for the LODEWAVE (Long-Duration balloon Experiment of gravity WAVE over Antarctica) project. Its pressure resistance was confirmed through the ground inflation test up to 2.7 times the required pressure and its gas permeability was that required for a 10-day flight. Three balloons were launched from Syowa Station in Jan. and Feb. 2022 and their flights lasted 2 to 3 days. These were the first scientific observations using super-pressure balloons developed in Japan.

In space science research using balloons, we continued detailed analyses of cosmic-ray data obtained during balloon flights over Antarctica in the Balloon-borne Experiment using a Superconducting Spectrometer. We are also investigating highly charged nuclei components, especially hitherto rarely reported beryllium isotopes.

In addition, the Department continued the operation of CALET on the ISS to observe high-energy electrons, gamma-rays, and other components of cosmic radiation such as iron and nickel nuclei.

Furthermore, studies were promoted to continue the development of the General Anti-Particle Spectrometer (GAPS), which was selected as a Small Science Program in 2017, to address the dark-matter enigma through highly sensitive observations of cosmic-ray antiparticles, including the undiscovered antideuterons.

The Department also carried out research to investigate the cosmic-ray propagation mechanisms by combining data taken in-flight and on the ground. In addition, the Crab nebula and the Galactic center region were significantly detected in MeV gamma-ray band in the flight data of the MeV gamma ray telescope SMILE-2+, which had a balloon-flight in Australia in 2018. The results are the first time in the world that an MeV gamma-ray telescope with a wide field-of-view has achieved sensitivity consistent with ground calibration. Preparations were also carried out for SMILE-3, the next observation plan using long balloon flights to open up new scientific observation fields.

2.5 Research on micro/nano-satellites for deep space exploration

Low-cost micro/nano-satellite technology has been developed and actively used mainly by universities and venture companies. In order to apply this technology to space science and exploration, and to realize further, advanced, and frequent exploration missions, we have been conducting the following research activities on micro/nano-spacecraft technology.

In this fiscal year, regarding the long-period comet exploration mission (Comet Interceptor mission) that is being jointly studied with ESA for launch in around 2029, an ISAS-internal study team was set up. The team has been conducting conceptual design and is preparing a proposal to ISAS to initiate the spacecraft development project.

As another R&D program, we are conducting research and development of technology to enable nano-satellites to reach deep space through their own propulsion system from GTO orbit or lunar transfer orbit, in order to realize deep space exploration missions more frequently.

3. Research Topics

The following outline lists all the Department of Interdisciplinary Space Science research activities during FY2021:

3.1 Space utilization science
3.1.1 Materials science
3.1.1.1 High-temperature melt and metastable phase using levitation method
3.1.1.2 Research on crystal growth
3.1.2 Life sciences
3.1.2.1 Response behavior to gravitational force
3.2 Astrobiology
3.2.1 ‘Tanpopo’ and ‘Tanpopo2’ experiments onboard ISS to capture cosmic dust and expose organics and terrestrial microbes
3.2.2 Research and development of instrumentation for cosmic dust detection and capture
3.2.3 Research and development of single microparticle acceleration experiment facilities at slow to hyper-velocity impact ranges
3.2.4 Feasibility studies on ocean world sample return missions
3.2.5 Research on planetary protection countermeasures for a life signature detection mission
3.2.6 Study on research and development to explore the survival of life in extreme environments such as Moon and Mars
3.3 Information science and information technology
3.3.1 Numerical simulation
Hierarchical equally spaced Cartesian-structured grid solver
3.3.2 Data archiving
3.3.2.1 Development of international standard protocols for sharing Moon and planetary science data
3.3.2.2 High speed access to very large science data
3.3.2.3 Application of machine learning to space science data
3.3.3 Visualization and sonification of space science data
3.3.3.1 Visualization and sonification
3.3.3.2 Research on modelling methods
3.4 Scientific balloons and space science using balloons
3.4.1 Research on balloons
3.4.1.1 Research on super-pressure balloons covered by net
3.4.2 Space science using balloons
3.4.2.1 Cosmic ray antiparticles using exotic atoms
3.4.2.2 Cosmic ray observations using superconducting spectrometer
3.4.2.3 Observation of high-energy cosmic-ray electrons and gamma rays
3.4.2.4 Observation of MeV gamma rays
3.5 Research on micro/nano-satellites for deep space exploration
3.5.1 Research on micro/nano-satellites for exoplanet exploration
3.5.2 Research on the CubeSat-type mini-probe for Comet Interceptor mission
3.5.3 Research on frequent deep space access by micro/nano-satellites

d. Department of Space Flight Systems

1. Overview

The Department of Space Flight Systems is engaged in fundamental and applied academic research on space flight systems to contribute to space science projects. The main fields of research are systems engineering (SE) related to space exploration, space transportation engineering, and discipline engineering.

2. Research Activities in FY2021

2.1 Space navigation SE

Space navigation SE research in the Department plays a role in pioneering projects and includes applied flight dynamics, control systems theory, and transport system design for spacecraft and flight vehicles. The Department focuses on research for spacecraft, such as interplanetary probes and advanced scientific satellites, as well as their navigation, guidance, and control. In addition, space flight systems, such as those for rockets, are being developed. We also perform mission planning and analysis, orbit design, and system design and testing using experimental spacecraft and computer simulations.

2.2 Space transportation engineering

Space transportation engineering research covers a variety of areas, such as propulsion systems and aerodynamics for the propulsion and navigation of space flight vehicles. The Department is involved in developing solid, liquid, and hybrid rockets for the following projects: A reusable rocket to realize future space transportation; an advanced aero-assisted propulsion system for new sounding rockets; advanced space propulsion systems, such as electric propulsion used for interplanetary transfers; and a system for re-entry/recovery and orbit control using the atmosphere as well as its component technologies. Furthermore, the Department is evaluating and optimizing the aerodynamic characteristics of flight vehicles, in addition to conducting fundamental research on chemical reactions, flow, heat, and electromagnetism, from the perspectives of mechanical engineering, fuel engineering, chemical reaction engineering, magneto fluid dynamics, heat transfer engineering, gas dynamics, and high-speed fluid dynamics.

2.3 Discipline engineering

The Department is involved in applied and fundamental research for space structures and materials for systems for various flight vehicles and other structures used on the ground, in low Earth orbit, and in geostationary orbits around planets and in deep space. We conduct investigations into structural dynamics, structure design and analysis, and mechanical environmental testing for rockets and artificial satellites. The Department also works on deployment structures, materials, and mechanisms, such as extendable booms and deployable antennas, as well as nozzles. We also conduct research on the strength and workability of structural materials for spacecraft, heat-resistant materials for propulsion systems, and materials for membranes and cables. For future space structures, the Department is helping to create and analyze new structures for precise shape control systems, ultra-lightweight structures (such as sails), and adaptive structures using high performance materials and multi-materials.

3. Research Topics

The following outline lists all the Department of Space Flight Systems research activities during FY2021:

3.1 Reusable space transportation system for frequent flights
3.1.1 Reusable rocket system
3.1.2 Reusable rocket engine and propulsion system
3.1.3 Aerodynamics and guidance and control system for reusable rockets
3.1.4 Fault-tolerant systems for reusable rockets
3.1.5 Development of cryogenic composite tank with electrocast line
3.2 Solid-fuel rockets
3.2.1 Solid propellant using high-energy materials
3.2.2 Solid propellant for a new gas generator used for auxiliary propulsion systems
3.2.3 Debris-less solid propellant
3.2.4 Solid propellant using thermoplastic materials
3.2.5 Solid propellant kneading system with artificial muscle actuators
3.2.6 Non-destructive reliability evaluation of solid rocket motor
3.2.7 R&D of deployable nozzles
3.2.8 Solid-fuel launch vehicle system
3.3 Hybrid rockets
3.3.1 Independent control of thrust and mixture ratio in A-SOFT hybrid rocket
3.3.2 Numerical analyses of boundary layer combustion instability in axial-injection hybrid rockets
3.3.3 Safety of hybrid rockets
3.3.4 LOX vaporizing system
3.3.5 Demonstration of A-SOFT hybrid rocket engine
3.4 Technology demonstration system for space planes
3.5 Innovations for aerodynamic performance
3.6 Problems with the aerodynamics of space transporters and other space vehicles
3.7 Thermal design, analysis, and testing of scientific satellites and new thermal control technologies for future scientific satellites
3.8 Structural systems for existing scientific satellite projects
3.8.1 Structural systems for SLIM
3.8.2 Structural systems for XRISM

e. Department of Spacecraft Engineering

1. Overview

The Department of Spacecraft Engineering performs research on rockets, artificial satellites, planetary probes, exploration robots and spacecraft ground systems, as well as on basic technologies in the fields of electrical and electronics engineering, measurement and control engineering, and energy engineering.

In the field of electronic materials and devices, we are conducting fundamental research and development on space semiconductor devices and materials used for a range of devices. These devices include pulse radars for detecting the altitude and speed of a lunar or planetary lander, lasers and radars, communication devices, antennas, and integrated systems installed on spacecraft. We are also investigating ways to improve the performance of lithium-ion secondary cell power supply systems for spacecraft, power storage capacitors, and the use of fuel cells in spacecraft. In the fields of navigation, guidance, and control, we are developing sensors for detecting attitude, relative position, and obstacles. Further, we are investigating high-precision attitude and alignment control technology, autonomous navigation using images, algorithms for detection and circumvention of obstacles, and guidance and control rules for landing on the Moon and planets, in addition to developing high-performance control actuators. Our research also encompasses intelligent and autonomous space probes and technology for the autonomous exploration of the Moon and planets using mobile robots (rovers). In the area of ground systems, we are studying high-precision orbit determination methods such as the combination of differential one-way ranging (DDOR) and optical navigation and large-scale information integration for spacecraft operation systems. Furthermore, we are researching the system architecture of small scientific satellites and cosmic energy systems, such as solar power satellites.

2. Research Activities in FY2021

2.1 Spacecraft systems

We are doing R&D and project support concerning functional improvement, miniaturization, and sophisticated development methods for scientific satellites and spacecraft with a background of the technical fields around electrical and electronic engineering. The standard buses for small scientific satellites that were developed and demonstrated in HISAKI and ARASE are still alive in the orbits much beyond the design life for extra scientific observation. Also, we have made several studies based on this standard bus for future small-class missions. In the SLIM project, with the aim of significantly reducing the weight of lunar and planetary spacecraft systems, we are currently developing an integrated computer and an integrated digital power control unit. The SLIM system and avionics will be heritage technology for subsequent lunar exploration missions.

We have also been working on satellite architecture, components, and implementation technology while aiming to reduce the size, weight, power consumption, and production time of the scientific satellite and spacecraft systems. In 2021, for example, within the framework of ISAS technology front loading, we executed EM-level qualification tests of the innovative MEMS IRU. The IRU using COTS technology has equivalent performance to conventional products, while the mass is halved and the power consumption is reduced by a third. In the development of such compact avionics equipment, we considered employing both approaches of applying consumer technology to conventional designs and of enhancing the reliability of nano/micro satellites so that the point where they cross over each other could be surely found.

In order to carry out missions utilizing nano/micro satellites that can be developed in a short period of time and at low cost, we should adopt an approach that maximizes the characteristics of nano/micro satellites (short development time, low cost, and small development team) while allowing some risk rather than an approach that minimizes the risk of failure. Therefore, through the development of the 30 kg class nano-satellite Comet Interceptor B1, we are studying and verifying new development methods (in particular, reviewing quality and reliability standards) that will contribute to short-term, low-cost, and efficient development.

2.2 Spacecraft control technology

We conducted research on safe landing methods; for example, the interaction between the landing legs and the surface soil, the sloshing effect of the fuel tank at touchdown, etc. Especially, we have conducted research on semi-active landing leg control under the effect of the sloshing.

We performed research on the Electro Magnetic Formation Flight (EMFF) technologies. Swarm-EMFF is a type of formation flight with many satellites controlled with electromagnetic force. Electromagnetic torque was assumed to be disturbance in previous research, however, we proposed a novel method for managing both force and torque. This method enables magnetic attitude control, in addition to magnetic relative position control. We studied the magnetic levitation mechanism using the magnetic flux pinning effect to shut out microscopic vibration disturbances and thermal transmission. We have clarified that the levitation distance can be controlled with an additional magnetic coil, and we studied its application for fine pointing control of the levitation part.

We are researching and developing a flyby tracking and guidance system using a periscope and attitude control for small body exploration (asteroids and comets). DESTINY$^+$, Comet Interceptor and Hayabusa2 extended missions will demonstrate this flyby guidance and control system in the coming years.

2.3 Robotics technology

In order to sophisticate the autonomy of rovers that explore the surface of the Moon or planets, we developed technologies for (i) path planning in consideration of uncertainty of mobility, (ii) path planning in consideration of slip and power consumption, (iii) path planning in consideration of terrain classification errors, (iv) terrain traversability prediction based on multi source transfer learning, (v) environmental map understanding by deep learning and behavior mode selection, (vi) path planning with a concurrent localization, and (vii) smart robot in sink holes and caves on the moon or Mars.

A small rover called LEV which will be deployed onto the lunar surface was installed in the SLIM landing spacecraft, after all the required pre-mounting tests were completed. The hardware of LEV was fixed and is ready for the final integration tests of the spacecraft. We performed a compatibility test of the communication module of LEV using the Deep Space Network of the United States, and a communication test with the LEV-2 probe. Through these tests, we confirmed the execution of the planned missions over the lunar surface.

2.4 Orbit determination and design

For the orbit determination of Hayabusa2, we developed the quasi-kinematic orbit determination method in which two-dimensional delta differential one-way ranging (DDOR) measurements and ranging observation were simultaneously used. This was successfully used while the ion engines were firing and contributed to the successful trajectory control of Hayabusa2 using ion engines. By using the DDOR data with OP-NAV (Optical Navigation with onboard optical telescope) data, we were able to estimate the trajectories of Hayabusa2 and its target asteroid Ryugu very precisely. This greatly contributed to the successful arrival of Hayabusa2 at Ryugu. These two results were published together as a peer-reviewed paper. The orbit determination software functions developed for the approach and proximity phases of Ryugu were transferred to ISSOP, an orbit determination system for regular operations being developed jointly with Fujitsu, to provide an environment for MMX orbit determination operations.

We also supported the "Omotenashi" and "DESTINY$^+$" projects by providing preliminary orbit determination accuracy evaluations and orbit determination operational designs.

As for activities related to NEO (Near Earth Object), we participated in UN COPUOS activities and international conferences related to planetary defense. In addition, we have continued the observational research work of NEO in cooperation with Kiso Observatory of the University of Tokyo and the Japan Spaceguard Association.

As for the orbit design, we have established a multiple revolution trajectory design method by low-thrust propulsion and a trajectory design method utilizing multiple lunar swing-bys. The research contributes to the DESTINY$^+$ mission to be launched in the coming years.

2.5 Communication technology and data processing technology

2.5.1 Communication and RF navigation and control measurement technology

The transponder that will support future missions, including DESTINY$^+$, is under development. While inheriting well-established compatibility with domestic and oversea stations from the current model, the new transponder will also cover more missions, including future lunar and L-point activities. Since the new transponder's application to DESTINY$^+$ was determined, the engineering model is being manufactured for replacing the current model by 2024 at the earliest. The new transponder is capable of being utilized for S-band and X-band transmission and reception as well as Ka-band transmission while maintaining the qualities and properties that meet the requirements of radio-science and regenerative ranging.

X-band radio-wave propagation data during solar occultation has been obtained and analyzed by using spacecraft in flight. The data has been well accumulated through AKATSUKI and Hayabusa2 missions for improving operations in conjunction and developing the robustness of the acquisition and tracking of heavily jittered signals.

Ka-band telecommunication data of Hayabusa2 obtained by overseas stations has been analyzed. A statistical approach to the data revealed numerous quantitative results regarding the deep space Ka-band operations for the first time in our country.

Our results led to a proposal for our own retransmission scheme proving to be effective for Ka- band operations for MMX and successive missions. The retransmission will be challenged in MMX.

An optical telecommunication scheme for ISAS missions has been studied for the purpose of realizing it in a hybrid system with, or in a system assisted by, radio-waves. We began by investigating a simplified scheme that avoids uplink beacon signals for onboard tracking by shedding light on the similarity to radio-waves. An onboard autonomous Earth pointing scheme using attitude and orbit data during cruise was also studied. This scheme works with an onboard small aperture optical antenna.

For the SLIM mission, we are developing the world's first small transponder based on the S-band direct-input-output software defined radio technology, and we have evaluated telecommunication performance, which is necessary for scientific missions.

A 13.5-m antenna ground station system utilizing fully COTS products has been developed for future low-cost space exploration on universities-centered, and the conceptual design has been finished and the manufacturing of the systems has been started.

For the realization of an intra-satellite bus harnessless system, technological development has been under cooperation with other divisions of JAXA. The component development of a wireless communication module (WICS) has been finished for the launch operation on the Engineering Test Satellite-9 (ETS-9). RF device research including diamond thin layer technology is under investigation. More details on this topic are provided in 2.6 Device technology.

2.5.2 Information and data processing technology

Data processing is being developed separately for ground-based systems and satellite-based systems, but how to make this development seamless will be a key development technology in the future.

In the field of information and data processing, we are developing standard components and interfaces that can be used in various spacecraft based on standard architecture (system construction principle), as well as their simulation technology. For the simulation of spacecraft components, we examined how the Generic Spacecraft Test and Operation Software (GSTOS) supports the time acceleration of simulation and provided a fundamental solution. We also examined its utilization of the simulation in function tests of spacecraft. In the simulation of spacecraft components, we demonstrated that the adoption of a standard interface between the simulation components is functional. In addition, regarding the Spacecraft Information Base (SIB), which is a notation unique to ISAS, we have started the development of a tool that converts mutually between the international standard XML Telemetric and Command Exchange (XTCE) and the SIB.

We are conducting research to apply advanced signal and image processing technology to on-board systems and ground data processing. In the onboard system, for the post-SLIM era, we investigated image-based navigation and sensor fusion in the polar region where the solar conditions are very severe. For the data processing on the ground, we considered a registration technique of multi-temporal synthetic aperture radar images over distributed targets without artificial features (e.g., forests), which is essential for interference processing, etc.

For application to future spacecraft on-board computing, we are conducting research about neuromorphic processing (e.g., spiking neural networks) that imitates the brain nerves of living organisms and neuromorphic sensors that imitate optic nerves, which are for example event-based cameras capturing changes of target brightness asynchronously. Experimental results revealed that such neuromorphic approaches can provide a lot of merits in terms of latency and low power consumption.

2.6 Sensor and device technology

In the field of electronic materials and devices, we performed fundamental research on semiconductor devices that will be installed in spacecraft, developed an environment-resistant device, and researched semiconductor materials.

We are conducting research and development of a next-generation space microprocessor (MPU) in cooperation with the Research and Development Division. Detailed evaluation of engineering models (EM products) was conducted. The design of a next-generation space MPU flight model (QM product) with 10 times higher processing performance and internal memory than the current JAXA-approved space MPU has been completed, reflecting the evaluation results. It is the world’s most advanced MPU in terms of processing performance and power consumption. The production of the QM product is scheduled to begin in June. We plan to use the design assets of this MPU in the future. The design assets of this MPU will be implemented as soft cores in the Nabridge Field Programmable Gate Array (NB-FPGA), which is capable of high-speed numerical operations and is being developed as part of the R&D Division’s “Supporting Research” project. We are also considering the realization of a soft MPU with an improved degree of freedom in the interface part, etc. by taking advantage of the features of FPGAs.

We developed LIDARX and Flash LIDAR. LIDARX, a light pulse detection integrated circuit, is a readout circuit for avalanche photodiode (APD) output of long-distance LIDAR receivers. It measures the timing and height of the pulse output from the APD. LIDARX has been adopted as the core device of MMX’s LIDAR, and the development of its FM has started. Flash LIDAR is a sensor that acquires a range image, which is used to detect obstacles during the landing process and measure the relative distance for rendezvous in orbit. In FY2021, the 3D image sensor using Si-MPPC has been adopted as the core device for the HTV-X rendezvous sensor, and FM manufacturing has started. Furthermore, we are developing a 3D image sensor using highly radiation-resistant InGaAs.

MEMS devices are highly resistant to heat and radiation due to their mechanical structure. Therefore, MEMS devices are expected to contribute not only to the miniaturization of space equipment but also to the improvement of environmental resistance. Currently, research is being conducted on sensors and electrostatically driven MEMS devices as space applications of MEMS.

In FY2021, performance evaluation and environmental tests were conducted on an Inertial Reference Unit (IRU) equipped with a MEMS gyroscope that has been developed. We also developed a cantilever-based electrostatically driven MEMS multifunctional device.

In order to improve the power efficiency and EIRP of onboard telecommunication systems, we have focused on the diamond semiconductor process, which is one of the candidates for next-generation power devices, and have been investigating technologies for space applications such as RF power amplifiers and power supplies such as DC-DC converter. Low-resource deep space exploration using small satellites and CubeSat, and satellite constellation missions are expecting to develop onboard communication systems that are reliable and low-cost, simultaneously. We are the first to design a receiver front-end that drastically reduces resources for on onboard transponders.

2.7 Energy systems

For energy generation on balloons using ultra-thin membranes that can generate electricity, Perovskite solar cells formed on flexible PET film were flown on a small rubber balloon, and performance was confirmed to be equivalent to prior ground-based evaluations. Since a small rubber balloon has a high rate of attitude change, we developed a measurement system that repeats voltage sweeps at high speed to measure current-voltage characteristics during flight, and were able to perform stable measurements.

For energy storage, targeting micro spacecraft in deep space, we started R&D on a lithium-ion secondary battery using commercially available cells. Furthermore, we started development of a battery, which is particularly important for planetary surface exploration. We fabricated a prototype cathode half-cell and evaluated its basic characteristics, which showed tolerant against operation at -40°C for 0.1C charge and 0.1C discharge.

The small satellite REIMEI has already been in space for over 16 years. REIMEI is one of the first satellites that used a lithium-ion secondary battery. To understand the internal condition of the battery cells, a simulation was performed through the efforts of DLR under a collaboration contract, which will be reflected in the passivation of the spacecraft before the termination of the operation.

We are continuing work on an energy carrier that uses renewable energy, based on previous research on fuel cells/ regenerative fuel cells, and are currently attempting to apply the technology to the oxygen generator and CO2 reduction devices for future manned operations, and future energy source generation in the outer planet.

For space solar power satellites, we are continuing with a conceptual study on the major structure of the tethered SPS called the power generation and transmission panel, and the development of a high efficiency system. We have developed preamplifiers optimized for high-efficiency GaN HEMT amplifiers and started space resistance testing. Also, a solar array equipped with antenna elements will be installed on the power transmission side of the power generation and transmission panel. Thermal and structural analysis of the solar array with antenna was performed and deformation and temperature distribution were confirmed by thermal vacuum experiments.

We carried out a conceptual study of a wireless power transmission system that adopted a digital retrodirective method, and started developing a demonstration model. We are developing carbon nanotube actuators (CNAs) to compensate for the deformation of the antenna. We are confirming the analysis model for deformation and generated force.

We also are conducting studies on the discharge mechanism and discharge suppression of high-power RF systems for spacecraft.

We started a study of the power system for the environmental development and utilization of the moon. We also conducted a survey of trends in wireless power transmission technology, which is expected to be in demand for future deep space exploration, and began research on power transmission over an aluminum honeycomb core and graphite epoxy composite sheets, which will be important for spacecraft applications.

2.8 Sounding rocket support technologies

This research is about the potential enhancement of the functionality of the sounding rocket system. Two activities have been performed in FY2021: one is to propose and develop PI Data Collector (PDC) to add TCP/IP (Ethernet/WIFI) to the data communication (including telemetry) method between payload instruments and rocket avionics, and the other is to study and develop a geometrically extendable platform for experimental and observation instruments using an inflatable structure, named Inflatable Extensible Platform for PI instruments (IEP).

In FY2021, PDC underwent a series of vibration, shock, temperature, and vacuum tests successfully, while IEP was at the stage of a proof-of-principle test using prototype-models. We will continue to enhance the attitude control capability using this device so that the sounding rocket can respond to more wide variety of observation and experiment proposals.

3. Research Topics

The following outline lists all the Department of Spacecraft Engineering research activities during FY2021:

3.1 Spacecraft systems
3.1.1 Small scientific satellites
3.1.2 High-speed communication system for small satellites
3.1.3 Microwave synthetic aperture radar for small satellites
3.1.4 Miniaturization and electric power reduction of onboard avionics
3.2 Navigation, guidance, and control technology
3.2.1 Posture determination and control for spacecraft
3.2.2 Navigation, guidance, and control of lunar and planetary probes
3.2.3 Navigation sensor for planetary probes
3.3 Robotics technology
3.3.1 Lunar and planetary probe robotics
3.3.2 Rover for exploration of small celestial bodies
3.4 Orbit determination and design
3.4.1 Orbit determination DDOR technology
3.4.2 Orbit determination using an open-loop receiver Small satellite systems
3.5 Communication technology and data processing technology
3.5.1 Communication and RF navigation and control measurement technology
3.5.1.1 Deep space and near Earth RF communication technology onboard spacecraf
3.5.1.2 Radio wave propagation measurement
3.5.1.3 Ka-band operation technology
3.5.1.4 Optical Communication
3.5.1.5 RF device techonology
3.5.2 Information and data processing technology
3.5.2.1 Satellite data processing architecture
3.5.2.2 Application of modeling technology to satellite development
3.5.2.3 Image-based navigation for lunar and planetary lander
3.5.2.4 Sensor fusion for landing navigation Space energy systems
3.6 Sensor and device technology
3.6.1 Research and development of analog integrated circuits
3.6.2 Research and development of analog integrated

circuits
3.6.3 Environment-resistant electronics Micromachines for space
3.7 Energy systems
3.7.1 Technology for power supply systems Characteristic evaluation for a space solar cell under extreme conditions
3.7.2 Power storage device for space
3.7.3 Solar power satellite systems
3.7.4 Thin-film power-generating systems
3.7.5 Interaction between high power system and space environment
3.8 Sounding Rocket Support Technologies
3.8.1 On-board 6 DOF motion stage
3.8.2 Inflatable structure
3.8.3 Separative rocket bus function service system
3.8.4 Protocol converter of communication

f. 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 31, 2022)

Name	Former Affiliation	Research Theme	Term
Stéphane BONARDI	Massachusetts Institute of Technology	Self-reconfigurable modular robots for space exploration: design and control	October 2017-
LAU Ryan Masami	California Institute of Technology	Exploring the Dusty and Dynamic Universe with SOFIA, Spitzer, JWST and Beyond	September 2018-
TORIUMI Shin	National Astronomical Observatory of Japan	From the Sun to the Stars: Establishing the Universal Picture of Spot Formation and Flare Eruptions	April 2019-
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-

The following shows research highlights in FY2021, introduced by each fellow.

Stéphane Bonardi

My research aims at developing novel robotic solutions for space exploration and colonization. I have been focusing on the novel concept of robotic exoskeletons to create highly adaptable robotic swarms for planetary exploration and space colonization.

Robotic Exoskeletons (REs) can be defined as specialized suits that a robot can equip in order to boost its performance along certain axes or to gain new functionalities. I have been working on developing such exoskeletons to equip a new type of flexible modular robot (Base Unit, BU) to perform exploration and exploitation tasks. The overall system will be controlled using an advanced AI framework optimized using a technique similar to competitive learning with auto-curricula. I have been focusing on developing BUs' prototypes together with the first foldable origami-based exoskeleton for locomotion. The base unit borrows characteristics from the CLARA platform from JAXA. I have also been working on designing REs that can accommodate multiple base units (called Multi-Unit Robotic Exoskeletons, MUREs) to create an almost scale free system. The target scenarios that I am working on are the exploration of Martian and Lunar caves (in collaboration with the UZUME team) and long-range sampling on Mars. Several MURE prototypes have been created and tested and further iterations are currently under development. This effort is made in the scope of a new venture company for which I am currently applying to the JAXA startup accreditation system.

Ryan Masami Lau

My research over FY2021 continued to focus on revisiting the impact of massive and evolved stars on their enrichment of the interstellar medium (ISM). This work utilized infrared (IR) observations from ground- and space-based observatories such as the Subaru Telescope and the Spitzer Space Telescope. The investigation of the enrichment of the ISM and the role of massive, evolved stars will be one of the key topics probed by the upcoming James Webb Space Telescope (JWST). In pursuit of this research topic, I am leading an Early Release Science (ERS) and General Observer (GO) program with JWST during Cycle 1 in 2022. In Feb 2022, I was the lead organizer of the remote meeting "IR2022: An Infrared Bright Future for Ground-based IR Observations in the Era of JWST."

Published Research in FY2021:

- Blagorodnova, N *et al*., Astronomy & Astrophysics, Vol.653, A134 (2021)
  https://doi.org/10.1051/0004-6361/202140525
- Endo, I *et al*., The Astrophysical Journal, Vol. 917 (2), 103 (2021)
  https://doi.org/10.3847/1538-4357/ac0cf1
- Jencson, JE I *et al*., The Astrophysical Journal, Vol. 920 (2), 127 (2021)
  https://doi.org/10.3847/1538-4357/ac1424
- Lau, RM *et al*., The Astrophysical Journal, Vol. 922 (1), 5 (2021)
  https://doi.org/10.3847/1538-4357/ac2237

TORIUMI Shin

In FY2021, the third year as an ITYF, I published two papers as well as one online textbook. Among these, Toriumi & Aiprapetian (2022) is a study that the extremely hot outer atmospheres of the Sun and stars are formed by a common heating mechanism (see p.14 of this Annual Report for the detailed account with a figure). The Sun hosts the corona with the temperature exceeding 1 MK and the chromosphere of about 10,000 K. However, it is unclear how these atmospheres are heated, and this has been one of the major scientific targets of various solar physics missions. Similar superheated atmospheres also exist in cool dwarf stars, and it has been a mystery whether these heating mechanisms are common. By comparing the magnetic flux and the irradiances of various spectral lines, i.e., formed at various temperatures, of the Sun and Sun-like G-type dwarf stars, we found that the scaling laws between the magnetic flux and irradiances are common to these stars. This consistency indicates that the heating mechanisms are universal, regardless of stellar age or activity level. This research was made public through a press release from American University in association with ISAS.

In addition, I continued to participate in the PrePhase A2 study of JAXA's next-generation solar-observing satellite Solar-C (EUVST). FY2021 was a pivotal year as the Mission Definition Review was initiated.

In September 2021, my extension review of the ITYF was conducted, and the extension was successfully approved for FY2022 and beyond. In March 2022, I was awarded the 14th Space Science Promotion Award in recognition of my research activities, which is a great honor for me.

Published Research in FY2021:

- Toriumi, S *et al*., Advances in Space Research, Vol. 70 (6), 1549-1561 (2022)
  https://doi.org/10.1016/j.asr.2021.05.017
- Toriumi, S *et al*., The Astrophysical Journal, Vol. 927 (2), 179 (2022)
  https://doi.org/10.3847/1538-4357/ac5179
- Kusano, K *et al*., Earth, Planets and Space, Vol. 73 (1), 159 (2021)
  https://doi.org/10.1186/s40623-021-01486-1
- Toriumi, S. "PSTEP Open Textbook" Section 3-3-1, (2021) (online, in Japanese)
  https://doi.org/10.18999/pstep.2021.3.3.1

James O'Donoghue

Science highlight: Jupiter's upper atmosphere is measured to be around 700 Kelvin at the equator and mid-latitudes, but based on the amount of sunlight received at Jupiter it should only be 160 K. This discrepancy between data and model has persisted for nearly 50 years and the situation is referred to as the "Giant Planet energy crisis". This crisis also occurs at Saturn, Uranus and Neptune. Finding the missing heat source is essential to fixing this problem, so with my team I created global maps of Jupiter's upper atmosphere temperatures at the highest resolution ever obtained. Our maps contained several thousand data points across the planet, whereas previous maps contained only tens of data points, therefore our work gave our field the first window into global energy circulation at Jupiter. In FY2021 these maps were published in the journal Nature. In these maps we discovered, or perhaps uncovered, that Jupiter's aurorae heat the entire planet as winds redistribute auroral heat globally: we found the missing heat source.

More science: we also found an unexpected heating event on top of this global energy circulation, which I briefly discussed in the Nature paper above, but I plan to write-up in FY2022 in more detail as a separate paper. In late FY2021 a Saturn paper was published on which I was a co-author. This was a high-impact result to our field: the aurora of Saturn were found to be partly generated by the upper atmosphere itself, which is the first example of its kind in the solar system. In April 2022 we performed observations of two exoplanets with the world's largest infrared-capable telescope, Keck, in order to attempt exoplanetary auroras for the first time. These were high-risk high-reward observations: we have a very faint signature of light from one exoplanet, perhaps enough to publish a short 'upper-limit' paper, but we may instead try observing again for a longer period of time with different instrumentation in 2023. Also in late FY2021 I have almost completed a Review Paper for the remote-sensing of the upper atmospheres of Jupiter, Saturn, Uranus and Neptune, which will be published in FY2022. I gave a talk at JAXA ISAS Planetary Exploration Workshop on 'Future Science at the Outer Planets' and I was a Keynote speaker at the European Planetary Science Congress (EPSC) on the topic of Giant Planet Upper Atmospheres in September 2021.

Synergistic activities and science communication: I won the "Europlanet Prize for Public Engagement" in FY2021 and gave an award talk at EPSC and also a finalist for the American Association for the Advancement of Science (AAAS) Early Career Award for Public Engagement with Science. I helped out with numerous international outreach events between ISAS/JAXA and the world, for example I acted as the bridge between NASA and JAXA for Observe The Moon Night, which is a global event, and also made numerous animations for JAXA about BepiColombo and Hayabusa2.

Published Research in FY2021:

- O'Donoghue, J *et al*., Nature, Vol. 596 (7870) ,54-57 (2021)
  https://doi.org/10.1038/s41586-021-03706-w
- Chowdhury, M.N. *et al*., Geophysical Research Letters, 49, e2021GL096492 (2021)
  https://doi.org/10.1029/2021GL096492

HYODO Ryuki

For the FY2021, I have worked on scientific topics regarding (1) planetesimal formation, (2) Ryugu and Hayabusa 2, (3) Phobos/Deimos and MMX, (4) small body's dynamical evolution, and (5) impact phenomenon in general. I was awarded The Outstanding Young Scientist Award from the Japanese Society for Planetary Sciences (JSPS).

Topics of particular interest this year include Phobos/Deimos and MMX. With collaborators, I have investigated meteorite impacts on Mars and transport processes of the impact ejecta from Mars to Phobos in detail, using high-resolution impact simulations and particle orbital calculations.

Collaborators and I found that some of the Martian materials reach Phobos without experiencing a strong impact shock or complete melting. This indicates that if there is life on Mars, or if there are traces of life such as fossils, they can be transported to Phobos without being damaged and destroyed. If living organisms are transported to Phobos, they are sterilized by cosmic rays on Phobos. Therefore, the traces of life that can be found on Phobos' surface are carcasses (SHIGAI in Japanese) that comply with the requirements of planetary protection policies.

These results clarified MMX's unique role of in the search for Martian life in the Matrian system exploration programs pursued also by other countries in the 2020-2030s. This is highlighted in the ISAS/JAXA news report (https://www.isas.jaxa.jp/en/topics/002679.html).

Published Research in FY2021:

- Arakawa, S *et al*., The Astronomical Journal, Vol. 162 (6), 226 (2021)
  https://doi.org/10.3847/1538-3881/ac1f91
- Charnoz, S *et al*., Astronomy & Astrophysics, Vol.652, A35 (2021)
  https://doi.org/10.1051/0004-6361/202038797
- Charnoz S *et al*., Icarus, Vol. 364, 114451 (2021)
  https://doi.org/10.1016/j.icarus.2021.114451
- Hyodo, R *et al*., Astronomy & Astrophysics, Vol. 660, A117 (2022)
  https://doi.org/10.1051/0004-6361/202142345
- Hyodo, R *et al*., The Astrophysical Journal, Vol.913 (2), 77 (2021)
  https://doi.org/10.3847/1538-4357/abf6d8
- Barucci, MA *et al*., Earth, Planets and Space, Vol. 73 (1), 211 (2021)
  https://doi.org/10.1186/s40623-021-01423-2
- Sugiura, K *et al*., Icarus, Vol. 365, 114505 (2021)
  https://doi.org/10.1016/j.icarus.2021.114505
- Hyodo, R *et al*., Science, Vol.373 (6556), 742 (2021)
  https://doi.org/10.1126/science.abj1512

6. R&D at Groups of Fundamental Technology for Space Science

a. Inter-University Research and Facility Management Group

To promote space science activities in Japan, JAXA maintains and operates the facilities that constitute the Inter-University Research System. Researchers at public and private universities are able to utilize these facilities, such as the Space Chamber Laboratory, Hypervelocity Impact Facility, Supersonic and Subsonic Wind Tunnel Laboratory, and Low-Speed Wind Tunnel. Opportunities to use these facilities are announced annually, and the proposals are reviewed and approved by the program advisory committees as shown in the table, “Domestic Joint Research”, on p.106. The Inter-University Research and Facility Management Group supports space science experiments and collaborates with researchers to maximize their scientific achievements.

b. Research, Test and Operation Technology Group

In order to systematically promote R&D required specially for space science missions, our group was reorganized in April 2021 by including a lot of researchers with specialized skills in each subsystem into the prior Test and Operation Technology Group that had been in charge of development and operation of various test techniques and equipment. We organize a specialized technology area and a basic technology area within the group to execute R&D and support projects and experiments.

In the specialized technology area, we are doing project support and R&D in collaboration with the Research and Development Directorate in the following technical fields.

- Orbit
- Guidance, navigation, and control
- Electric parts, devices, and electric power
- Communication and data handling
- Propulsion
- Thermal and fluid control
- Structure, mechanism, and material

Technical activities in these fields are carried out very widely, including by members who are concurrently assigned to the group. Below are some examples of the topics.

In the field of thermal protection, group members are participating in the heat shield development of the sample return capsule for the MMX mission and are proceeding R&D of future heat shield materials. Activities include application of JAXA’s polyimide resin, acquisition of mechanical properties with destructive testing, quantitative evaluation using non-destructive testing such as a CT scans, and Arc heater testing. Also we are studying the ablative thermal protection system with density gradient, and improvement of accuracy in the numerical method of the ablative thermal protection system.

In the field of electric propulsion, we supported the development of the ion engine for DESTINY$^+$, and the hall thruster, and conducted research for plasma diagnosis and wear evaluation of hollow cathodes used as neutralizers.

In the field of quality and reliability assurance of electric parts, we surveyed various models for predicting the solar energetic particle environment. In addition, we investigated the radiation resistance of oxide semiconductor memory, which is a state-of-the-art part, by heavy particle irradiation tests. We also study ways to convert commercial parts for use in small-scaled spacecraft together with the related project team.

The basic technology area is responsible for the development of testing technologies and the operation of the testing facilities for spacecraft assembly test equipment (mechanical environmental testing, structural testing, thermal vacuum testing, anechoic chamber testing, attitude control testing, magnetic shield testing, side-jet reaction control subsystem testing, and clean rooms). The members also participate in the projects, the pre-projects, and the working groups (WG) of ISAS.

1. Achievements

- Continued development of operational system reform of spacecraft assembly test equipment
- Epsilon-6 mechanical environment and structural function test support
- Test support in RV-X, S1R-B3-1TVC, S1R-B1-1TVC ground combustion test (repair of various stand equipment for design, manufacture and operation of equipment related to thrust calibration and thrust measurement, design, manufacture and operation of diffusion cylinder and diffusion cylinder closure mount)
- SDX, CRD2 thermal test support
- Support for RV-X testing
- Upgrade of the testing technologies and the operations of the test facilities
- Support for improvement of the scientific satellite development environment
- Development of ground test equipment for DESTINY$^+$ including the kick stage

2. Effects and Impacts

- Received the President’s Award for spacecraft assembly test equipment operation system reform

- Solid development of the projects with the upgraded testing technologies and highly efficient operation of the test facilities
- Modification of the flight environmental test building to improve the development environment of scientific satellites

c. Advanced Machining Technology Group

JAXA has inaugurated the Advanced Machining Technology Group to improve front-load iterations of product development for planned aerospace missions and projects. The researchers and technical staff will team up to do as much in-house manufacturing as possible, from experimental jigs to flight models, to take fullest advantage of the limited funding. In addition to a new numerical control (NC) machine shop, we have integrated an existing machine shop, an electronics shop, and a space nano-electronics group, which was a part of the Department of Spacecraft Engineering, into the Advanced Machining Technology Group. The restructuring has created synergy among these groups and has sped up the R&D process. The group participates in the development of devices incorporating nano-electronics, designs circuits, and performs top-quality machining with its NC machines. The group is making effective use of its R&D funding and will greatly contribute to accumulating and improving the technologies of JAXA.

1. Achievements

- Completed installation of and started using a machining center, NC composite turning centers, a wire electric discharge machine, and a contact-type three-dimensional measuring machine.
  Introduced a brand-new large NC turning center for larger workpieces and an NC milling machine equipped with a high-speed spindle
- Improved the efficiency of new and old machine shops, which feature a new layout, and improved job safety with well-routed working traffic lines
- Completely trained specialist staff who work in the nano-electronics cleanroom in maintenance management and safety

2. Effects and Impacts

- Maintaining the quick pace of setting up our production equipment and started test manufacturing components already placed on order
- Expanded the size of potential workpieces with the introduction of our large NC turning center
- Improved the environment for our expert staff to provide the highest quality manufacturing services
- Continuing training our users on safety to maintain our record of zero accidents

New machine shop

Nano-electronics cleanroom

d. Scientific Ballooning Research and Operation Group

The Scientific Ballooning Research and Operation Group develops stratospheric balloon systems and provides flight opportunities for scientific observations and engineering demonstrations. It also studies next-generation balloon systems for use in future space science.

1. Achievements

- The domestic balloon campaign for FY2021 was conducted from May 17, 2021. The campaign was conducted while undertaking measures for the COVID-19 pandemic. Of the five planned experiments, two heavy-balloon experiments ["Balloon Experiment to Determine the Upper Boundary of the Biosphere (BIOPAUSE)" and "Demonstration Experiment of Alignment Monitor (DREAM)"] and one light-balloon experiment ("Balloon Flight Test of Thin-film-type Perovskite Solar Cell") were conducted.
- Since the supply of helium gas in Japan is still uncertain, a sufficiently long lead time was given for delivery, and

the helium gas necessary for the FY2021 campaign was obtained.
- Preparations and coordination for the next balloon campaign in Australia were performed. The flight target was shifted from 2022 to 2023 due to the COVID-19 pandemic.

2. Effects and Impacts

- Three experiments could be carried out. They achieved new insights, and the academic results were presented. The other two experiments were postponed because no flight opportunities were obtained mostly due to inadequate high-altitude winds caused by climatic anomalies.
- In parallel with our best efforts to secure a sufficient amount of helium gas, risk analyses in using alternative hydrogen gas for ballooning were discussed. We confirmed that helium gas remains in the balloon envelope on its recovery and found that the hydrogen gas remaining in the balloon envelope on its recovery is a major risk to be addressed.
- Studies to increase balloon flight opportunities were carried out to compensate for the decrease in opportunities due to recent climatic anomalies such as the meandering of the tropopause jet stream. For example, a new launch method was applied to the “Demonstration Experiment of Alignment Monitor (DREAM)” to enable its launch under rainy conditions.
- In order to maximize the achievements available from the limited flight opportunities, a study to upgrade the telecommunication system between balloons and the ground station and make it faster and more reliable was started.
- Since we established a good relationship with Australian partners through the 2018 balloon campaign in Australia, we carried out preparations for the next campaign in Australia. Technical support was provided to three candidates selected by the Scientific Balloon Committee. Coordination for the balloon campaign in Australia was also continued with the contacts in Australia.

Scientific Balloon experiments in FY2021

Experiment ID	Balloon Type	Science Objective	Science Principal Investigator	Result
B21-05	B100A	Mars Airplane Balloon Experiment (MABE)	OYAMA Akira, ISAS/JAXA	Cancelled due to the delay in preparation and because no flight opportunity was obtained due to climatic anomalies of high-altitude winds.
B21-06	B100A	Balloon Experiment to Determine the Upper Boundary of the Biosphere (BIOPAUSE)	OHNO Sosuke, Chiba Institute of Technology	Launched on August 5. Highest altitude: 32.8 km Flight duration: 2 h 8 min
B21-07	B30B	Balloon-borne Very Long Baseline Interferometry (VLBI) Experiment	KONO Yusuke, NINS/NAOJ	Cancelled because no flight opportunity was obtained due to climatic anomalies of high-altitude winds.
B21-08	B15C	Demonstration Experiment of Alignment Monitor (DREAM)	ISHIMURA Kosei, Waseda University	Launched on July 9 Highest altitude: 29.4 km Flight duration: 2 h 24 min
BS21-07	Rubber Balloon	Balloon Flight Test of Thin-film-type Perovskite Solar Cell	TOYOTA Hiroyuki, ISAS/JAXA	Launched on July 4 Highest altitude: 30.9 km Flight duration: 1 h 21 min

e. Sounding Rocket Research and Operation Group

ISAS operates three types of sounding rockets (S-310, S-520 and SS-520) and generally conducts space science and engineering experiments every year. The Sounding Rocket Research and Operation Group will contribute to the design and analysis for the manufacture and launch of the sounding rockets in the coming fiscal year and beyond. With the sounding rockets, the Group provides experimental opportunities for researchers, such as opportunities for engineering verification tests and scientific observations.

Achievements

The payload of the detonation engine, the new space propulsion system, developed by Nagoya University for S-520-31 was launched successfully from Uchinoura Space Center on July 27, 2021. The detonation engine worked well in space and generated 500 N of thrust within five seconds. The reentry capsule called RATS was separated in space and fell into the ocean close to Tanegashima. Drifting on the ocean, the RATS was picked up by a helicopter, and the stored experimental data in RATS was delivered to researchers successfully.

SS-520-3 was launched from Andoya Space Center in November 2021. The payloads worked well in space and scientific data of the cusp region was obtained.

Future Plan

Flight Number	Experiment	Proposer
S-520-32 (Winter 2022)	Study of Medium Scale Traveling Ionospheric Disturbance (MS-TID)	ASHIHARA Yuki, National Institute of Technology

f. Noshiro Rocket Testing Center

The Noshiro Rocket Testing Center (NTC) was established in 1962 as one of the affiliated research facilities of the Institute of Space and Astronautical Science (ISAS). Large rocket motor combustion test facilities with a maximum thrust of 450 tons and vacuum combustion test facilities have been established to verify propulsive performance on the ground prior to rocket launch. In addition, a cryogenic propellant supply facility has been installed for research and development of Liquid-Oxygen (LOX) / Liquid-Hydrogen (LH2) rocket engines and LH2-fueled air-breathing engines. In recent years, a wide variety of hydrogen energy utilization technologies have been actively developed using the cryogenic propellant supply facility.

1. Achievements

Hydrogen energy technology research

NTC is conducting R&D on hydrogen, especially liquid hydrogen, which is common to both industrial energy technology and space technology, in cooperation with various external organizations. In 2021, NTC conducted a full-year LH2 supply equipment test based on a joint research agreement with related organizations at a large-scale hydrogen supply technology test facility. Many kinds of equipment were tested, including large valves for LH2, low temperature hydrogen Boil-Off Gas (BOG) compressors, LH2-cooled superconductors, and ship-to-shore hydrogen couplings.

Research on reusable space transportation systems

The ISAS space transportation research program is promoting activities aimed at establishing an inter-orbit transportation network connecting the ground and deep space. In particular, the realization of reusable rockets for high-frequency transport to low earth orbit is an urgent issue, and preparations are underway at the NTC for flight tests of the RV-X experimental reusable rocket. In 2021, a ground firing test for the RV-X flight test and a ground firing test of the Air-Turbo-Rocket (ATRIUM) engine were successfully conducted.

Rocket motor combustion tests

Space-One Corporation (S1) conducted a ground firing test of the 3-stage and 1-stage solid motors of the KAIROS small launch vehicle, which is under development for launch in FY2022. This rocket is the first commercial application of Japan’s solid rocket system technology, which has evolved and developed since the Pencil rocket. This test has contributed to the maintenance and development of Japan’s solid motor technology and its testing technology.

2. Effects and Impacts

NTC has many unique facilities for experimental verification of transportation technologies and cryogenic properties. The static firing test stand has a maximum thrust capability of more than 450 tons, making it the largest facility in Japan. The vacuum firing test chamber has a volume of more than 450 m^3, also making it the biggest facility of its kind in Japan. Moreover, NTC has the only very highly pressurized liquid hydrogen supply facility in Japan. As a result, a large number of experimental studies have been conducted at NTC and bore fruitful results. In 2020, at least one of the NTC facilities was in operation for more than 160 days in total without any human accidents being reported.

g. Akiruno Research Center

The Akiruno Research Center aims to carry out various basic and educational experiments to develop key components of rocket and/or satellite systems. Its unique experimental facilities support ISAS’s basic research activities and projects.

1. Achievements

- We carried out a verification test of the sample return capsule for the Martian Moons Exploration (MMX) project. We designed the sample return capsule for MMX using the technical heritage established from the HAYABUSA and Hayabusa2 satellites. Its shape is almost the same as the HAYABUSA capsule, however, its size is planned to be 1.5 times larger in diameter. We planned the verification test to measure the delivery speed of the rear heat shield to finalize the design of the delivery system for the rear heat shield and the deceleration parachute. In the test, we used a dummy heat shield made from aluminum of the same size and mass.

- We carried out research on reducing the size of the slag in the exhaust gas of a solid propellant rocket motor using two types of propellant setup redesigned based on the knowledge obtained from the combustion test carried out the previous year (2020). We measured the delivery speed and size of the expelled slag during combustion experiments. We tested two kinds of solid propellants set on φ250 solid rocket motors in a vacuum on the high altitude testing stand (HATS) to elucidate thrust performance and slag size.
- To support basic research activities, we conducted reliable inspections of the experimental facilities to maintain their condition. An old gasoline engine type forklift that had been used for more than 30 years was replaced with a new diesel engine type forklift with the same loading capability.

2. Effects and Impacts

- We carried out a delivery experiment for the rear heat shield of the sample return capsule for MMX in two steps. In the first experiment, we validated the electronic circuit for igniting the explosives that release the rear heat shield. The newly designed electronic circuit for ignition operated correctly, and the release system of the rear heat shield was electronically validated. After electronic validation, we carried out a delivery experiment with a dummy rear heat shield. The delivery speed after the release of the locking system was measured by a high speed camera and a laser displacement sensor. The operation of the delivery system was successful and the dummy heat shield was correctly released. However, its speed was not high enough to fulfill the designed speed and a retest has been planned for next year (2022).
- We conducted φ250 solid rocket motor combustion experiments in a vacuum at HATS to examine the validity of the redesigned concept of the solid propellant for lower space debris. We tested two types of solid propellants and validated that the redesigned propellant setup decreased the size of slags in the exhaust gas. This result successfully established the design of the low slag solid propellant rocket motor. A larger size combustion test for the future practical use is now under planning after these basic experiments.

h. Science Satellite Operation and Data Archive Unit

The Science Satellite Operation and Data Archive Unit (C-SODA) is in charge of the development and is the service provider regarding ground systems for science spacecraft operation, data processing, and data archives. C-SODA is also responsible for enabling access to space science data for worldwide space science researchers and public users and contributes to enhancing outcomes from JAXA's science programs.

1. Development of the ground systems for science spacecraft operation and providing services for using these systems

C-SODA is developing and maintaining the satellite operation systems and the data transmission system for scientific spacecraft operation. C-SODA also provides the services for using these systems to each project team. C-SODA applies the requirements of new projects to our systems and supports their uses from the development to operation phases. C-SODA also supports the scheduling of the spacecraft operation and the assignment of the spacecraft up- and downlink paths.

1.1 Achievements

- We continued to support the operations of spacecraft, such as Geotail, HISAKI, HINODE, AKATSUKI, Hayabusa2, ARASE, and BepiColombo.
- We continued to support the post-launch operations (Interplanetary Cruise Phase operations) of BepiColombo.
- We proceeded to build the operation system for spacecraft under development, such as SLS, SLIM, XRISM, and Martian Moons Exploration Mission (MMX).
- We prepared the main control rooms for SLIM and XRISM launch and initial phase operations.
- We continued to provide the Automatic Telemetry MOnitor Software (ATMOS) for HISAKI, ARASE, and Hayabusa2 teams to increase the safety and reliability of their spacecraft operations and also proceeded to prepare the ATMOS service for the spacecraft system verification tests of XRISM and SLIM.
- To improve the availability of the spacecraft operations, we introduced redundancy and virtualization technologies to the science spacecraft operation support system. We proceeded to implement our services on the system.
- We made the system compatible with the spacecraft operation system and the operation support system with the Misasa Deep Space Station (MDSS). We also supported the spacecraft operation teams using MDSS to prepare

the MDSS use.

- Regarding Command Issuing Software in GSTOS (Generic Spacecraft Test and Operation Software), there was a problem that the technology used to implement the GUI was old (Motif on X-Windows), and it was difficult to keep engineers for any function modifications, which caused the increase of its maintenance cost. To solve this problem, we divided it into the core and the GUI parts. The core part is implemented as the server software, while the GUI part is the client software. We have developed a new version based on the above concept.
- We established a method for converting from SIB2 (Spacecraft Information Base version 2), which was developed uniquely by ISAS, to XTCE, an international telecommand notation standard, and have started to develop a conversion tool.
- We have developed COSMS (C-SODA Configuration Management System) as an information-sharing system to manage incidents, issues, and changes in our business.

1.2 Effects and Impacts

- C-SODA supports each spacecraft operation team to ensure that spacecraft are operated normally, thereby underpinning the creation of scientific achievements of each mission.
- Efficient verification tests become available, using the spacecraft operation system from the spacecraft development phase.
- C-SODA prepared the main control rooms for the SLIM and XRISM projects, contributing to the maintenance of substantial operational activities to support the simultaneous launch of the two missions.
- C-SODA has enabled monitoring of spacecraft status during invisible periods by introducing ATMOS into operations, contributing to increasing the safety of spacecraft operations.
- By separating the core and GUI parts of the GSTOS command issuing software, the core part can be stably operated without significant modification. In contrast, the GUI part can be easily modified to improve usability and catch technological advances, enabling necessary changes at lower risk and lower cost.
- Since the telecommand described in the international standard is easily exchanged in an international cooperation mission, implementing the telecommand conversion tool between SIB2 and XTCE enables us to facilitate interface adjustments including document preparation.
- C-SODA provides spacecraft project teams with a number of shared software such as SIB2/GSTOS. However, sharing information with users, such as the status of bugs and requests for improvement, is difficult. The introduction of COSMS will improve the information sharing between project teams and C-SODA.

2. Archiving and release of space science data

C-SODA has developed and is providing the services of space science and engineering databases for science spacecraft to archive science spacecraft data permanently and to improve the usability of scientific data. C-SODA also proceeded to process and validate Akari data products.

2.1 Achievements

- We maintained the services of SIRIUS (Scientific Information Retrieval and Integrated Utilization System), L1TSD (Level 1 Time-Series Data processing software), and the spacecraft time calibration system.
- We maintained the service of EDISON (Engineering Database for ISAS Spacecraft Operation Needs)
- We have registered science data from the spacecraft in operation in DARTS (Data ARchives and Transmission System). The data processed through the ISAS's publicly solicited program, such as Hayabusa2 curation data, Akari POI data, IKAROS orbital information, and sounding rocket data, have been newly released from DARTS. In addition, we proceeded to prepare the data storage for spacecraft data (XRISM, SLIM, MMX) scheduled in the near future.
- We maintained the service of the DARTS system and have improved it, such as implementing vulnerability countermeasures, SSL-enablement, and application distribution via WAF. The service of the DOI (Digital Object Identifier) assignment has been regularized.
- Almost all public data products and contents of the infrared astronomy satellite Akari have been transferred from the Akari data processing and analysis team to the DARTS team.
- We proceeded to examine the specification of the future DARTS system, not only the use of the on-premise system but also the use of cloud services, which governmental agencies have increasingly used in recent years.
- L1TSD had a problem of consuming the amount of memory much larger than that required for data processing. Therefore, we optimized the processing algorithm and developed a new version of L1TSD with reduced memory usage and accelerated processing time.

2.2 Effects and Impacts

- We have further enhanced the quick look and search systems to assist users in finding their desired data. We have also contributed to maximizing scientific outcomes using science data acquired by ISAS via providing stable services of our data archives.

The released science data are systematically managed with related information using the standard formats in each research field (astronomy, solar physics, lunar and planetary science, etc.). Such activity contributes to the promotion of outcome creation, the longevity of data availability, and the improvement of third-party verifiability of observations.

i. Lunar and Planetary Exploration Data Analysis Group

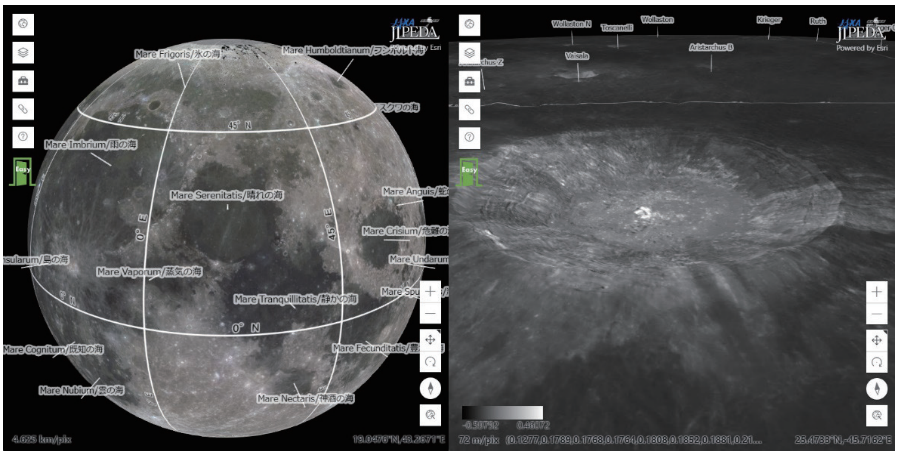
Our group specializes in the analysis of observation data obtained by lunar and planetary exploration and the development of analytical techniques. The group aims to maximize the results of lunar and planetary exploration by analyzing the data necessary for planning lunar and planetary exploration and by providing high-level processing products for scientific research to elucidate the origin and evolution of lunar and planetary bodies.

1. Achievements

- We have been analyzing existing lunar and planetary exploration data and supporting mission scenario development for JAXA's Lunar Landing Exploration Study Teams (SLIM, LUPEX, Lunar Takeoff and Landing Demonstration, Manned Pressurized Rover, etc.). In the case of LUPEX, we created data products for post-landing operations near the lunar South Pole.
- In collaboration with universities, we are developing new data analysis techniques. In collaboration with the University of Aizu, we developed an algorithm for automatic boulder identification, a geographic information system for irregularly shaped small celestial bodies, and gravity field analysis of Phobos. In collaboration with the University of Tokyo, we developed a technique for creating a high-precision topographic model (DEM) for the lunar polar region and a technique for verifying the accuracy of the model.
- We are developing a system that enables easy viewing, analysis, and acquisition of lunar and planetary exploration data on a web browser. The Hayabusa2 ONC data search system (JADE) allows users to extract and display individual observation data from various filters while displaying Ryugu in 3D. The service is already in use by the ONC team and will be made available to the public soon. The next version of the KAguya Data Integrated Analysis System (KADIAS) (Fig. 1) will be released within the next fiscal year, and will be able to display a wide variety of data in 3D, and perform simple analysis in a browser.
- We have established a special team to support the archiving of new observation data obtained from exploration projects. For SLIM-MBC, we assisted the creation of the SPICE kernel and the data in PDS4 format. For MMX, we conducted SIB2 reviews to prevent the lack of telemetry information necessary for archiving. Through these supporting activities, our team is accumulating knowledge on archiving procedures.

2. Effects and Impacts

- The landing site analysis of the lunar South Pole region, which incorporates technology from other fields such as information science, was highly evaluated and received the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology (Science and Technology Promotion Category). The analysis results are used as important information in determining exploration strategies for each exploration study.
- The development of new product creation techniques enabled analysis of landing sites using more accurate topographic data. At the same time, it became possible to generate data of strategic value for international space exploration.
- The development of JADE and next version of KADIAS has lowered the barrier to accessing lunar and planetary exploration data, allowing users from a wider variety of communities to benefit from exploration. It has also led to the development of systems that can be used in future spacecraft operations.
- By providing support for archive processing work, the project team has more time to focus on instrument development, leading to improved operational efficiency. The quality of archived data will be improved, which could promote the use of the data by overseas researchers.



Screenshots of the next version of the KAGUYA Data Integration and Analysis System (KADIAS).
Global view, locations and names of the mare (left), and bird's-eye view around Aristarchus crater (right).

j. Astromaterials Science Research Group

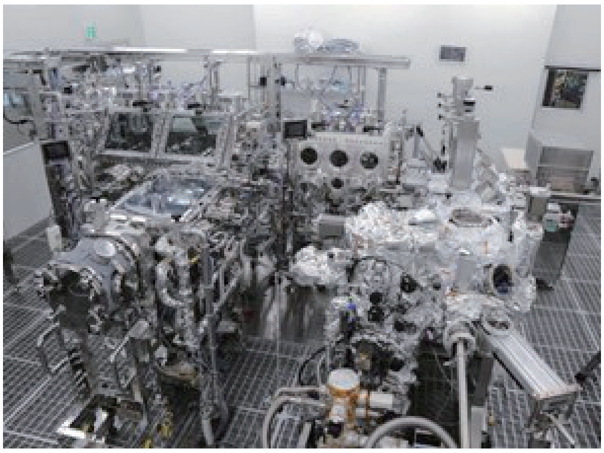
The Astromaterials Science Research Group operates the curation facility at JAXA. The Group acquires knowledge about planetary materials based on non-destructive and uncontaminated analysis of extraterrestrial materials.

1. Achievements

- The Group performed the curatorial work of collecting, describing, and storing the samples brought back by HAYABUSA from asteroid Itokawa.
- The Group performed the curatorial work of collecting, describing, and storing the samples brought back by Hayabusa2 from asteroid Ryugu.
- The Group publishes a periodical special paper online with an initial description of the Itokawa samples (i.e., sample catalog information). A total of 1296 samples are included in the most recent catalog (JAXA-SP-21-007E).
- The Group publishes a periodical special paper online with an initial description of the Ryugu samples (i.e., sample catalog information). A total of 401 samples are included in the most recent catalog (JAXA-SP-21-006E).
- The Group made an international Announcement of Opportunity (AO) for the Itokawa samples and samples were allocated to researchers selected by an international AO committee. By the end of FY2021, 68 proposals had been accepted and 252 samples were distributed.
- The Group made an international Announcement of Opportunity (AO) for the Ryugu samples and available sample number is 74 in total.
- The Group distributed 32 samples to the Initial Analysis team, 24 samples to the Phase2 curation team, and 29 samples to NASA. An international symposium (Hayabusa 2021 Symposium) was held in November as the first opportunity to present the results of detailed analyses obtained from the Ryugu samples. Although the symposium was held remotely due to the COVID-19 pandemic, it was attended by 345 people (40% of whom were overseas researchers).
- The construction of a facility to receive samples from the asteroid Bennu was started.
- Technical support for future sample return missions was provided through the development of sampling equipment, the examination of sample-receiving equipment, and maintenance and operation of the Group's associated facilities and equipment.
- Project researchers, postdoctoral fellows, and young researchers were hosted, and they performed extraterrestrial sample analysis and other studies.

2. Effects and Impacts

- Two papers on initial description results were published in Nature Astronomy. One paper integrating the observation results of the Hayabusa2 spacecraft touchdown site and the initial description of the recovered samples was accepted for publication in Science.
  i. T. Yada, *et al*. “Preliminary analysis of the Hayabusa2 samples returned from C-type asteroid Ryugu”, Nature Astronomy (2021). doi:10.1038/s41550-021-01550-6
  ii. C. Pilorget, *et al*. “First compositional characterization by the MicrOmega hyperspectral microscope of Ryugu returned samples”, Nature Astronomy (2021). doi:10.1038/s41550-021-01549-z
  iii. S. Tachibana, *et al*. “Pebbles and sand on asteroid (162173) Ryugu: In situ observation and particles returned to Earth”, Science (2022), doi: 10.1126/science.abj8624
- The initial description of the returned samples indicates that the Ryugu samples are the most primitive type of extraterrestrial material samples available to mankind, and detailed analysis of these samples is expected to produce first-class scientific results. The curation sample handling was conducted in an Earth-atmosphere-deprived environment, making them the first primitive extraterrestrial samples that have not been contaminated by Earth materials, and thus allowing the material analysis of the extraterrestrial samples to be conducted with high reliability.



New clean chambers installed in a new clean room for Hayabusa2 samples.

k. Deep Space Tracking Technology Group

1. Tracking support for the current deep space missions

As for the tracking support for the current missions (artificial satellite, spacecraft), we have continued to work on Hayabusa2, AKATSUKI, GEOTAIL, and BepiColombo.

- For Hayabusa2, tracking and orbit determination were performed for the extended mission.
- Regarding the tracking of Hayabusa2 by NASA/DSN, we coordinated the use of DSN stations with the person in charge on the DSN side. Regarding the operation of the Hayabusa2 extended mission in 2022, we adjusted the basic policy regarding how to use the DSN station.
- We carried out orbit determinations for AKATSUKI.
- We carried out orbit determinations for GEOTAIL.
- As for the BepiColombo mission, we collaborated with ESA and created antenna prediction files.

Regarding the satellites and spacecraft currently in operation, we were able to provide tracking support and contribute to each project.

2. Support for future deep space missions

We performed orbit determination and communication related work for future missions.

- We made studies of orbit determination for future missions such as SLIM, MMX, and DESTINY+.
- We conducted some tests of FM-equipped communication systems and ground systems of OMOTENASHI and EQUULEUS. We also made studies of orbit determination for these probes.
- Regarding NASA's EM-1, we established an interface for tracking support at the JAXA station and prepared for tracking support using LRO.
- We investigated the precise position-determination method for lunar landers such as LUPEX and pressurized rover.

We contributed to the future missions by supporting orbit and communication related issues.

3. Work for deep space tracking stations

Regarding the work related to domestic deep space stations, we supported the operation of Usuda Station and Misasa Station, and we studied possibilities for future deep space stations at JAXA.

- We carried out various tasks related to the 64 m antenna at Usuda Station and the 54 m antenna (GREAT) at Misasa Station and supported the operation of satellites and spacecraft.
- We examined the future development of deep space stations, including the successor station to Uchinoura, and summarized the problems in relation to user requests. This work was carried out in collaboration with the Space Tracking and Communications Center and the JAXA Space Exploration Center.
- We continued to hold discussions with ESA regarding future use of Malargüe Station by JAXA.
- Regarding the array of antennas, we discussed what we should do in future.

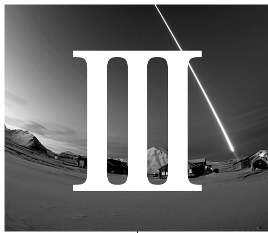
We contributed to the operation of spacecraft at Usuda Station and Misasa Station. In addition, we were able to present specific information that will be helpful for the construction of deep space stations in the future.

4. Other issues

The following works related to the tracking of the deep space missions were performed.

- A system that converts tracking data into text format TDM has started operation in an actual operation environment.
- Discussions on the generic cross-support agreement with NASA were held with the tracking network, and coordination within JAXA was completed.

These tasks made the data more versatile and made it easier to obtain tracking support for small missions.



Administration

1. History and Mission of ISAS

As a part of JAXA, Institute of Space and Astronautical Science (ISAS) cooperates with external research organizations, such as universities, to promote space science research. Space science research is defined as comprising fields of scientific research on the upper atmosphere or beyond, as well as work in related fields that facilitates this research. This integrated research approach includes physical science and engineering research conducted both in space and on the ground. Since before its integration with JAXA, ISAS has maintained and developed an inter-university research institute system. By utilizing this collaborative framework, ISAS has been developing and fostering space research and launching new space science projects, as well as conducting academic space science research as an education resource.

The roots of ISAS can be found in the Aeronautical Research Institute, which was first established at Tokyo Imperial University in 1918 and was then reorganized in 1946 as the Institute of Science and Technology at the University of Tokyo. Space Research and Development (R&D) began in 1955, with the launch of a pencil rocket by the Avionics and Supersonic Aerodynamics research group at the Institute of Industrial Science of the University of Tokyo. In 1964, ISAS was established at the University of Tokyo by integrating the Institute of Aeronautics with the sounding rocket research group in the Institute of Industrial Science. The goal of the institute was “to carry out integrated research on theory and application in the fields of space science, space engineering, and aviation.”

Aeronautical space engineering and space science research was carried out mainly under the lead of ISAS, with collaboration from researchers at various organizations, such as other national, public, and private universities. This collaboration, and the intellectual freedom that it promoted, led to major achievements, such as the successful launch of Japan’s first artificial satellite, Ohsumi, by an advanced Lambda sounding rocket in 1970. The 1970s saw the development of ever more sophisticated and powerful vehicles, the Mu rockets, designed for satellite orbital insertion.

In 1981, ISAS was separated from Tokyo University and reorganized as an inter-university research institute under the Ministry of Education. Its objectives were “to carry out research on theory and application in the fields of space science and engineering, as well as serving the educational staff of national, public, and private universities engaged in research. Furthermore, it is to provide cooperation in graduate education at the request of national, public, and private universities.” In 2003, JAXA was founded as an independent administrative agency by integrating three separate institutes—ISAS, the National Space Development Agency of Japan, and the National Aerospace Laboratory—to establish an organization that more efficiently and effectively performs and promotes space science research, space development, and aerospace technology R&D. The mission of ISAS under JAXA is inter-university research, facilitation of space science development, and graduate education.

On April 1, 2015, JAXA’s status was redefined as a national R&D agency. To accommodate the new policy framework and implement the new emphasis on R&D, JAXA has been reorganized into seven directorates or Departments. Furthermore, in July 2018, JAXA Space Exploration Center (JSEC) was established (see the JAXA organization chart). Following medium-term goals provided by the Minister of Education, Culture, Sports, Science and Technology, ISAS concentrates on promoting “highly original space science research with a respect for the autonomy of research participants” and “space science projects using flying objects such as satellites.” The former is of an exploratory nature with research conducted by individuals or groups of researchers. A representative example of the latter is scientific satellite projects, which include satellite development, data analysis, and publication of the results.

2. Organization

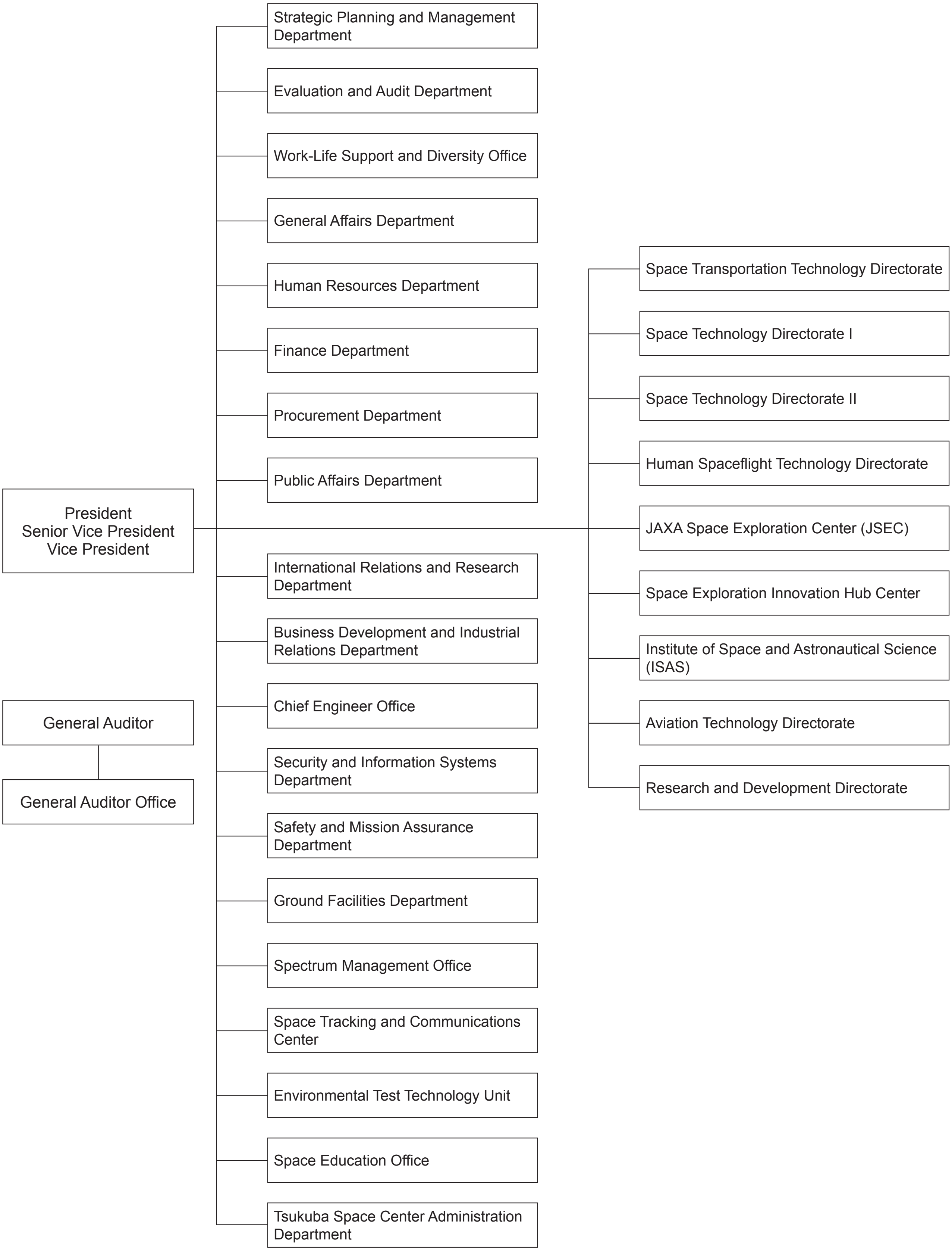
AJAXA has six Directorates, Institute of Space and Astronautical Science (ISAS), Space Exploration Innovation Hub Center, JAXA Space Exploration Center (JSEC), and other administrative departments.
ISAS has five research departments:

- Space Astronomy and Astrophysics
- Solar System Sciences
- Interdisciplinary Space Science
- Space Flight Systems
- Spacecraft Engineering

Other organizations within ISAS are the Management and Integration Department, the ISAS Program Office, the Center for Science Satellite Operation and Data Unit, 9 project teams, 8 groups, the Noshiro Rocket Testing Center, and the Akiruno Experimental Facility. In addition, the following officers and directors report to the ISAS Director General: Deputy Director General, Research Director, Program Director of Space Science, Senior Chief Officer of Fundamental Technology for Space Science, Director for International Strategy and Coordination, and Director for Education and Public Outreach (see the ISAS organization chart).

At JAXA, a Board of Councilors advises the President regarding space science and the nomination and selection of candidates for Director General of ISAS. The Advisory Council for Research and Management was established within ISAS to select and nominate candidates for the faculty members, as well as to efficiently operate the inter-university research system.

a. JAXA Organization Chart (as of FY2021)



b. ISAS Organization Chart (as of FY2021)

- **President, JAXA** YAMAKAWA Hiroshi
  - **Board of Councilors**
  - **Director General, Institute of Space and Astronautical Science** KUNINAKA Hitoshi
    - **Advisory Council for Research and Management**
    - **Associate Director General** FUKAI Hiroshi
    - **Deputy Director General, Institute of Space and Astronautical Science** FUJIMOTO Masaki
    - **Director for International Strategy and Coordination** TOKAKU Yoshio
    - **Director for Education and Public Outreach** FUJIMOTO Masaki
    - **Director of Management and Integration Department** OGAWA Shinji
      - **Management and Integration Department**
    - **Research Director** YOSHIDA Tetsuya
      - **Department of Space Astronomy and Astrophysics** YAMADA Toru
      - **Department of Solar System Sciences** SAITO Yoshifumi
      - **Department of Interdisciplinary Space Science** INATOMI Yuko
      - **Department of Space Flight Systems** SAWAI Shujiro
      - **Department of Spacecraft Engineering** MIZUNO Takahide
    - **Program Director of Space Science** SATO Eiichi
      - **ISAS Program Office** MOKUNO Masaaki
      - **GEOTAIL Project Team** SAITO Yoshifumi
      - **ASTRO-EII Project Team** ISHIDA Manabu
      - **SOLAR-B Project Team** SHIMIZU Toshifumi
      - **Bepi Colombo Project Team** OGAWA Hiroyuki
      - **Extreme Ultraviolet Spectroscope for Exospheric Dynamics Project Team** YAMAZAKI Atsushi
      - **Hayabusa2 Project Team** TSUDA Yuichi
      - **SLIM Project Team (Smart Lander for Investigating Moon Project Team)** SAKAI Shinichiro
      - **XRISM Project Team (X-Ray Imaging and Spectroscopy Mission Project Team)** MAEJIMA Hironori
      - **DESTINY+Project Team (Demonstration and Experiment of Space Technologyfor Interplanetary Voyage with Phaethon Flyby and Dust Science Pre-Project Team)** TAKASHIMA Takashi
    - **Senior Chief Officer of Fundamental Technology for Space Science** MORITA Yasuhiro
      - **Inter-University Research and Facility Management Group** NONAKA Satoshi
      - **Research, Test and Operation Technology Group** FUKUDA Seisuke
      - **Advanced Machining Technology Group** NAKATSUBO Shunichi
      - **Scientific Ballooning Research and Operation Group** FUKE Hideyuki
      - **Sounding Rocket Research and Operation Group** HABU Hiroto
      - **Noshiro Rocket Testing Center** ISHII Nobuaki
      - **Akiruno Experimental Facility** GOTO Ken
      - **Science Satellite Operation and Data Unit** SHINOHARA Iku
      - **Lunar and Planetary Exploration Data Analysis Group** SATO Hiroyuki
      - **Astromaterials Science Research Group** USUI Tomohiro
      - **Deep Space Tracking Technology Group** YOSHIKAWA Makoto

3. Operation

The Advisory Council for Research and Management and the Board of Councilors were established to oversee the interuniversity research system and obtain advice from external scholars on ISAS business plans and other important issues regarding space science research at ISAS. In addition, various in-house and research committees composed of researchers from all over Japan have been established to review, for example, collaborative research plans.

Advisory Committees

ISAS has two advisory committees: the Advisory Committee for Space Science and the Advisory Committee for Space Engineering. Its main responsibility is to oversee the conduct of academic research and related work on space science in cooperation with universities and in consultation with the ISAS Director General.

The Sounding Rocket Technical Committee, Committee for Space Biology and Microgravity Science, Committee on Scientific Ballooning, and Committee for International Space Exploration were also organized under the Advisory Committee for Space Science and the Advisory Committee for Space Engineering. The Curation Technical Committee was organized under the Advisory Committee for Space Science, while the Space Transportation System Committee was established under the Advisory Committee for Space Engineering.

1. Advisory Committee for Space Science

The Advisory Committee for Space Science formulates research plans and reviews technical issues related to space science. The tenth period for the Committee started in FY2021.

1.1 Developing Missions on the Roadmap for Space Science and Exploration

To enhance mission development, the Committee promoted working group (WG) activities and research group (RG) activities and urged the relevant parties to proceed with the necessary research and development activities. In FY2021, the committee held a WG chief meeting, confirmed the progress of mission proposals through a year-end evaluation, gave feedback about such WG activities, and supported activities around the development of new missions.

In response to consultation from the Program Director of Space Science, the Committee has established a task force to strengthen university collaboration and discuss the role and enhancement of the space science communities, including universities and ISAS.

Furthermore, based on the recommendation of the Mission Category Task Force last year, the Task Force on Mission Initiation Methodology was established in collaboration between both Committees to make proposals for future space science projects more effectively. Based on the recommendations of the Task Force, preparations were made for the establishment of the Groupe de Discussion Intensive (GDI), an interdisciplinary group for planning Strategic Large Class missions.

1.2 Strategic R&D

For new initiatives (i.e., “pre-project”), WGs conduct R&D to address technical issues that may obstruct the path to achieving mission goals. Research proposals were solicited from WGs, and a total of more than 110 million JPY was allocated after review. Technical issues to be focused on are shared with the WGs based on proposals and interviews, and funds are allocated based on the priorities. Progress reports are shared within ISAS community and confirmed by the Committee members, and feedback is provided as necessary. In addition, the definition and termination methods for the WGs were changed, based on the report from the Task Force on Mission Initiation Methodology.

Working group activities and status are summarized below.

Ongoing Working Groups (WGs):
[Competitive Middle Class]
- Frontiers of Formation, Acceleration, Coupling, and Transport Mechanisms Observed by Outer Space Research System (FACTORS) WG
- Physics of Energetic and Non-thermal plasmas in the X (=magnetic reconnection) region (PhoENiX) WG
- Broadband X-ray High-sensitivity Imaging Spectrometer (FORCE) WG
- Orbiter and EDL demonstration mission for space weather, climate, and aquatic environment (MACO: Mars Aqueous-environment and Space Climate Orbiter) WG
- Life-environmentology, Astronomy, and PlanetarY Ultraviolet Telescope Assembly (LAPYUTA) WG
- Unprecedented Zipangu Underworld of the Moon Exploration (UZUME) WG

[Small Projects]
- Circumpolar Stratospheric Telescope (FUJIN) WG
- Klypve-EUSO working group onboard International Space Station (K-EUSO) WG

[Strategic International Projects]
- Laser Interferometer Space Antenna (LISA) WG
- Ultraviolet spectrum observation in extrasolar planets WG Established in FY2021:
- STORM WG

Working groups whose status changed in FY2021:
- Superconducting Submillimeter-Wave Limb Emission

Sounder (SMILES-2) WG was terminated for achieving pre-defined goals.
- High-z Gamma-ray Bursts for Unraveling the Dark Ages Mission (HiZ-GUNDAM) WG was approved for pre-project team.
- GEOspace X-ray imager (GEO-X) WG was approved for Small Projects.

The HiZ-GUNDAM and GEO-X WGs are progressing toward their pre-defined goals as Competitive Middle Class and Small Projects. In addition, the five WGs aiming at Competitive Middle Class are preparing to submit proposals in FY2022.

1.3 Basic R&D on Onboard Equipment

The objective of basic R&D is to develop onboard equipment for space science observation and space experiments. These initiatives have an exploratory nature that requires proof-of-principle prior to acquiring external funds, such as a Grants-in-Aid for Scientific Research (KAKENHI). For continuing proposals, the review committee will ask questions electronically, and will guide the development of technology that can be applied in future missions through careful reviews, such as checking the progress and key issues with reference to the FY2020 report.

In FY2021, 18 proposals were accepted out of 25 candidates, including 17 new proposals, and a total of 30 million JPY was allocated to be used for joint research with university researchers. The adopted areas were X-ray technology (7 proposals), ultraviolet technology (3), infrared technology (6), and in-situ Earth/Planet observation technology (2).

An achievement report was submitted prior to the end of the fiscal year, evaluating the plan, achievements, and the relationship with the domestic space science community, and the evaluation results are also referred to in the proposals to be continued in FY2022.

2. Advisory Committee for Space Engineering

The Advisory Committee for Space Engineering is a research committee established to formulate research plans, plan research projects, and review other technical issues related to the engineering of hardware used to reach, transport, and perform experiments in space.

The tenth period for the committee started in FY2021.

2.1 Strategic R&D

The objective of strategic R&D is to propose future engineering missions involving scientific satellites and spacecraft and to conduct research in element technologies for innovative scientific satellites, spacecraft, and rockets.

Working Groups:
- Detonation engine kick motor sounding rocket - Demonstration of putting into orbit
- Study of advanced aero-assisted reusable space transportation system
- Transformer spacecraft
- Study on formation flying technology WG
- OPENS WG

Operations:
- Engineering research using the REIMEI satellite

Studies on Basic Hardware Technologies:
- In FY2021, a total of 27 research themes advanced their studies.

The achievements that have been publicly released include 81 papers, 129 presentations at international academic conferences, 312 presentations at domestic academic conferences,

10 awards, 12 invited speeches, three patents, and 15 other reports (including press releases).

Notable achievements are listed below.
- WG for detonation engine kick motor sounding rocket demonstration of putting into orbit: The space flight of the detonation engine system by the sounding rocket S-520-31 was successful, achieving a thrust of 518 N and the specific impulse of 290 ±18 sec. The world's first successful space operation of a double cylinder - aerospike nozzle methane oxygen propellant. A pulse detonation engine (PDE) was mounted in the rocket in flight configuration, and PDE plateau pressure generation was successfully achieved in space.
- WG for the study of advanced aero-assisted reusable space transportation system: The WG proposed a unique sounding rocket with ISAS's air breather reusable rocket technologies, while carrying out four main tasks; (1) system research, (2) engine prototype research, (3) aerodynamic element research and (4) engine combustion test, as planned. The university-led engine prototype research completed the ATRIUM engine and progressed to a comprehensive combustion test. In addition, the design and partial prototyping of a small FTB were also initiated.
- Transformer spacecraft WG: Based on the results of the previous year on orbit integration control and nonholonomic attitude control, these major features of the transformer spacecraft were developed to be more mission-feasible. For the subsystem, the design and structural property evaluation including hold/release mechanism, panel deployment evaluation and control law proposal, analysis and experimental characterization of heat transfer at the hinge, basic verification of inter-panel communication, and demonstration by BBM of the mission instruments were carried out.
- Study on formation flying technology WG: FF Technology

Demonstration Plan was developed, and a conceptual study of the ultra-precise FF technology demonstration satellite SILVIA was conducted and proposed to the 2019 Competitive Middle-Class program, which was approved for phase-up to Pre-Phase A1b. With the goal of the phase-up of SILVIA to Pre-phase A2, the group have been working on the trade-off between the satellite development scheme as an action item, formulation of a research scheme, study of the responsibility boundary between the satellite and FF, and study and evaluation of FF control mode, launch vehicle loading method, satellite resources (mass, power, etc.), and the necessary work to achieve CML3 and TRL3. The group also conducted the necessary work for cost evaluation and technical feasibility confirmation of mission equipment hardware BBM design, fabrication, testing, and evaluation.

- Study on Guidance and Navigation Technologies for Rendezvous and Landing to Far-distant Celestial Bodies: The group has achieved the following; (1) Completion of on-board relative image navigation algorithm and its BBM, (2) Confirmation of feasibility of deep space rendezvous guided navigation based on technology developed/owned by ISAS, (3) Trade-off study including prototyping of docking mechanism, (4) Development of scenario connecting inter-orbit transportation, sample return, and ultra-small deep space probe with deep space rendezvous docking.
- Technical Demonstration of a Deployable Flexible Aeroshell Atmospheric Entry System RG: The research group focuses its R&D activities on conducting two technology demonstration tests (BEAK and RATS) to improve the technology of deployable flexible aeroshells. Flight test of the sounding rocket experiment data recovery module RATS was conducted, and the module successfully entered the atmosphere and was recovered, acquiring valuable flight data on the deployed aeroshell. As for the BEAK micro-technology demonstration satellite for a small planetary lander, the FM hardware has been completed and is ready for flights in the next fiscal year and beyond.
- Development of Resin-Based Solid Lubricants for Mechanical Parts of Spacecraft RG: The research group achieved the following. (1) Development and property evaluation of contamination-free solid lubricants were carried out, based on the policies of lubricants composed of substances that do not contaminate samples from the viewpoint of physical analysis, and lubricants that are hard wearing in the first place. (2) To improve the accuracy of contact state estimation, the group achieved higher accuracy in predicting the mechanical state by processing noise during strain measurement. (3) Tribological tests in vacuum and formulation of life curves: Tribological tests in vacuum were conducted to compile a database of coating life and to formulate life curves necessary for life prediction.

2.2 Technical Committees

- The Sounding Rocket Technical Committee, Committee for Space Biology and Microgravity Science, and Committee on Scientific Ballooning deliberated on application screening and research plans.
- The Committee for International Space Exploration proceeded with discussions on science in the Artemis program.
- The Space Transportation System Committee developed a research plan for a space transport system for the space science community.

Other issues such as how to proceed with future space science more than 10 years from now, and what the framework should be, were examined by the Committee for the Future Framework of Space Science.

4. ISAS Program Office

a. Overview

ISAS projects and experiments are executed by relatively small teams with highly skilled members who are undertaking challenging missions. Shared support and strategic program activities that take a bottom-up approach are crucial for the reliable implementation of these projects.

The ISAS Program Office was thus established to provide interdepartmental support for various project teams while utilizing limited human resources. The Office also provides effective support to Working Groups (WGs) in the early phases of projects.

The following are some specific activities of the ISAS Program Office:

(1) Support for projects and experiments:
- Consultation services and interfacing with related departments.
- Collaboration in planning and preparation for management reviews.
- Other activities related to project implementation and specific technical challenges.

(2) Sharing information related to projects and experiments and providing risk-management services.
(3) Developing implementation methods suitable for space science projects.
(4) Support for the selection of competitive missions.

(5) Secretarial services for technical reviews and evaluations of space science projects.

(6) Support for the Chief Engineer Office.

b. Summary of Work in FY2021

1. Support for Space Science Projects

Project Support by the Program Office

WGs include many members who are not part of JAXA and have little experience in space science projects. Thus, providing support during the early phase of project planning is essential to minimize problems that may arise in the development phase. Therefore, the Office mainly supports the initial phases of project activities, such as clarifying scientific goals, setting mission requirements that support those goals, verifying the adequate selection of system requirements, identifying issues and risks, and developing risk-management measures.

In FY2021, we supported the LiteBIRD, small-JASMINE, Solar-C, HiZ-GUNDAM, SILVIA, and OMOTENASHI projects.

HiZ-GUNDAM passed the pre-project candidate transition review and started its mission definition phase.

ISAS made significant effort to establish the Strategic International Collaboration mission as the category next to the Strategic L-Class and Competitive M-Class missions. We supported Hera/TIRI, WSO-UV/UVSPEX, Roman-J, Comet Interceptor-J, Dragonfly-J, and Athena-J.

Project Support by SE and PM Senior Experts

The Program Office has selected experts to provide sensible support for space science projects and WGs. These experts provide advice and suggestions to improve systems engineering (SE) and project management (PM) during the technical meetings organized by each project team. The experts mainly consist of retired JAXA staff who are experienced in system development for satellites and spacecraft.

2. Issue tracking for projects and technical activities

The Program Office organized monthly progress-report meetings to monitor progress, challenges, and risks in all projects under development, and to ensure that information is shared among projects. These meetings include the Director General, Deputy Director General, Program Director, and Director of the Management and Integration Department. Various experts were also involved in these meetings and detailed discussions about technical topics were conducted from the perspective of project management.

The Office also held another monthly meeting to confirm the status of projects in on-orbit operations and to coordinate technical demonstration activities at ISAS.

3. Implementation Procedures for Space Science Projects

The Program Office developed implementation procedures for space science projects, especially for initial phases.

The reformed project management protocol has adopted the Concept Maturity Level (CML) as a yardstick for mission concept development in addition to the Technology Readiness Level (TRL). Implementation for Space Science Projects also uses both yardsticks.

4. Evaluation of Space Science Projects

The Program Office serves as the secretariat for project review and evaluation meetings at ISAS, in cooperation with the Management and Integration Department. In FY2021, the Office worked with project teams to prepare review materials for the following projects (project status or activity follows the project name):

- HiZ-GUNDAM: Pre-project Candidate Transition Review
- WSO-UV/UVSPEX: SDR/Project Transition Review
- Hera/TIRI: SDR/Project Transition Review
- Roman-J: Optical Device Pre-shipping Review

5. Safety and Mission Assurance Officer

In July 2017, the position of Safety and Mission Assurance (S&MA) Officer was established under the direction of the Senior Chief Officer of Safety and Mission Assurance in response to organizational changes made in strengthening the independent evaluation system. The S&MA Officer is mainly responsible for evaluations in the design review of projects independent of ISAS, and review support to the ISAS Safety Review Board. As for the evaluations, we responded to a total of 62 review meetings during FY2021, for projects such as XRISM, SLIM, MMX, and DESTINY+. The S&MA operations are to be performed independently of ISAS; however, the ISAS Safety Review Committee continues to be operated by S&MA. The S&MA Office was involved as a jury member of the ISAS Safety Review Committee, while other S&MA members were involved in the operation of the Committee.

The ISAS Safety Review Committee has two roles in the safety review meetings for research on large-scale experiments and the safety evaluation of small experiments.

In FY2021, we ensured the ground safety and flight safety of a sounding rocket experiment and hybrid rocket engine test, while holding 12 safety review meetings at ISAS.

In addition, 17 safety review meetings were conducted in FY2021 for small-scale combustion experiments at the Noshiro Rocket Testing Center and other test sites, which ensured and improved safety.

6. Budget

(in 1,000 JPY)

ISAS Budget	FY2019	FY2020	FY2021
Operating Expense Grants	14,017,719	14,602,929	21,554,177
Facility maintenance subsidy	2,252,268	0	0
Total	16,269,987	14,602,929	21,554,177

External Funds			
Grant-in-aid for scientific research (KAKENHI)	348,969	572,116	404,053
Grant-in-aid for scientific research (Accepted share of expenses)	65,007	59,775	124,250
Funded research	326,421	289,668	127,678
Cooperative research with private sector	75,768	318,585	337,089
Earmarked donations	19,125	8,250	14,919

7. ISAS Sagamihara Campus and Related 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 are performed for basic R&D and verification of onboard instruments for launch vehicles and satellites. 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 Facilities

Sagamihara Campus (ISAS)

Location:
3-1-1 Yoshinodai, Chuo-ku,
Sagamihara, Kanagawa
lat 35° 33′ 30″ N long 139° 23′ 43″ E
Site: 73,001m^2
Gross floor area: 58,733m^2

Noshiro Rocket Testing Center

Location:
Asanai, Noshiro, Akita
lat 40° 10′ 10″ N long 139° 59′ 31″ E
Site: 61,941m^2
Gross floor area: 3,633m^2

Akiruno Experimental Facility

Location:
1918-1 Sugao, Akiruno, Tokyo
lat 35° 45′ 14″ N long 139° 16′ 24″ E
Site: 2,008m^2
Gloss floor area: 698m^2

JAXA's Facilities related to ISAS

Uchinoura Space Center

Location:
1791-13 Minamikata, Kimotsuki-cho, Kimotsuki-gun, Kagoshima
lat 31° 15′ 05″ N long 131° 04′ 34″ E
Site: 718,662m^2
Gross floor area: 16,117m^2

Usuda Deep Space Center

Location:
1831-6 Omagari, Kamiodagiri, Saku, Nagano
lat 36° 07′ 59″ N long 138° 21′ 43″ E
Site: 97,111m^2
Gross floor area: 3,089m^2

Taiki Aerospace Research Field

Location:
Taiki Multi-Purpose Aerospace Park169 Bisei,
Taiki-cho, Hiroo-gun, Hokkaido
lat 42° 30′ 00″ N long 143° 26′ 30″ E
Site: 90,357m^2
Gross floor area: 4,554m^2

Tsukuba Space Center

Location:
2-1-1 Sengen, Tsukuba-shi, Ibaraki

International Collaboration and Joint Research

1. International Collaboration

Space is a common frontier for all of humanity, and many of the world's countries have worked together on a variety of space science missions over the years. Japan also regards international collaboration as an important means of pursuing space science missions and the nation has long been at the forefront of diverse areas of space science on a global level.

As a national pivot point for inter-university activities, ISAS must continue to play a central role in creating excellent outer space exploration missions that win support from the space science community at home and abroad. To this end, close communication and cooperation with our international colleagues are extremely important.

International collaboration benefits space science missions in many ways. Firstly, it can provide a means to realize more significant aerospace exploration efforts effectively and efficiently. Rather than limit the scope to Japan-supported missions, we believe it is far more beneficial to expand our horizons to take advantage of the superior observational equipment of other countries and to encourage others to use our facilities, in order to enhance the value of all missions.

Secondly, the international collaboration offers the space science community more opportunities, despite the tight financial conditions that limit the frequency of space science missions. Accordingly, we choose to invite international colleagues on our missions and/or send members of our community along on theirs, thereby enriching the community base, which is fundamental to realizing value in the field of space science.

Thirdly, the international collaboration encourages members of the Japanese space science community to work with a diverse range of supremely talented people, which stimulate our intelligence base and facilitates exposure to more scientific data, thus paving the way to new scientific knowledge and innovation in aerospace technologies.

Given the importance of all of this, ISAS needs to further engage in strategic discussions with space agencies, research institutes, and universities abroad in order to strengthen our ties with our prominent counterparts around the world.

Despite the continued restrictions such as travel bans imposed due to COVID-19, ISAS pursued numerous international initiatives of various kinds throughout FY2021. The main feature in international collaboration initiatives for ongoing missions is the activity of curating the sample from the asteroid Ryugu retrieved by the Hayabusa2 spacecraft. The science team consists of researchers from domestic and international institutions are working on initial analysis of the sample. Installed in the JAXA Extraterrestrial Samples Curation Center, the infrared spectroscopy microscope (MicrOmega) provided by the French National Center for Space Studies (CNES) significantly contributed to the curation activities. A part of the Ryugu samples were distributed to domestic and international research institutions from June, and in November, 10% (0.5g) of the total sample collected was handed to NASA at Johnson Space Center in Houston based on the plans laid down in the NASA/JAXA Memorandum of Understanding (MOU). In parallel, preparation was promoted to receive a sample from asteroid Bennu collected by NASA's OSIRIS-REx. In the extended mission which aims to explore another celestial body, Hayabusa2 continues to be supported by the NASA's DSN stations, and coordination for continued cooperation for participation of US researchers is underway.

Other international collaborations are under development. At the final phase of the development of the X-Ray Imaging and Spectroscopy Mission (XRISM), frequent travel to Japan by NASA and SRON personnel was required to work on assembly and testing in the field. Measures for travel restrictions due to COVID-19 were discussed and coordinated with the related government entities, and the relevant personnel were able to travel to Japan in a timely manner. The second XRISM Joint Executive Steering Group (JESG) meeting was held online with NASA in December. The repair which was completed with NASA's cooperation was reviewed and plans for the launch were updated. The result of the JESG meeting was reported during the meeting between the Director General of ISAS and Associate Administrator of NASA Science Mission Directorate, and further cooperation at the final phase toward the launch was confirmed.

Multifaceted international cooperation is being promoted with NASA, European Space Agency (ESA), CNES, and German Aerospace Center (DLR) regarding the Martian Moons Exploration (MMX) project. The Implementing Arrangement with NASA was amended for integration testing using a testing model and flight hardware. Cooperation with ESA on provision of onboard communication components for the probe, assistance in satellite tracking control, and contribution through science cooperation was facilitated. Also, an Implementing Arrangement related to the provision of the CNES's near infrared spectrometer, and expertise in Flight Dynamics was signed. Coordination for the provision of a CNES-DLR jointly developed rover was also further carried out.

For cooperation on the Smart Lander for Investigating Moon (SLIM), a Letter of Agreement (LOA) regarding provision of DSN tracking support services, accommodation of the laser retroreflector array (LRA), and coordination with the Lunar Reconnaissance Orbiter (LRO) was exchanged with NASA in December. Compatibility testing was conducted, and the LRA was delivered to JAXA. In studies of the Demonstration and Experiment of Space Technology for INterplanetary voYage Phaethon fLyby dUSt science DESTINY⁺, which is the 2nd competitively chosen Medium-Class mission, DLR and JAXA promoted cooperation such as provision of one of the main scientific instruments, DDA (the DESTINY⁺ Dust Analyzer) based on the Implementing Arrangement (IA) signed in November.

Regarding the missions in the study phase, international coordination was also promoted for the Lite (Light) satellite for studies of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD), which was selected as the 2nd strategic Large-Class mission. As the European lead, CNES signed an Implementing Arrangement with JAXA at the 72nd International Astronautical Congress (IAC) which was held in Dubai, United Arab Emirates in October. The Implementing Arrangement stipulates the cooperative activities regarding concept studies to realize development and provision of a Medium and High Frequency Telescope and a Sub-Kelvin cooler.

Additionally, international coordination was initiated for the Japan Astrometry Satellite Mission for INfrared Exploration (JASMINE), which was selected as the 3rd competitively chosen Medium-Class mission. Cooperation with the U.S. and Europe was promoted for the next-generation solar-observing satellite Solar-C EUVST (EUV High-throughput Spectroscopic Telescope), which was selected by ISAS as the 4th competitively chosen Medium-Class mission. An Implementing Arrangement regarding pre-launch cooperation was signed with NASA in September. The preparation of documents for agreeing on the cooperation activities with European agencies such as CNES and Italian Space Agency (ASI) is underway. Support activities are being carried out to obtain the necessary international cooperation for the next candidate missions.

In July, an MOU defining the activities of the launch and operation phase of CubeSats (EQUULEUS and OMOTENASHI) onboard SLS (Artemis-1) was signed with NASA. The CubeSats were delivered to NASA at Kennedy Space Center (KSC) and have already been installed onto the SLS rocket. Together with the separate agreements concluding the mutual tracking support to be provided by the NASA Deep Space Network (DSN) and the JAXA tracking stations, the preparation for launch of Artemis-1, unmanned flight test of crew vehicle Orion, and operation of JAXA's two CubeSats are underway. As for strategic international projects, cooperation is underway through the provision of instruments for DLR and the Swedish National Space Agency (SNSA) in the ESA-led Jupiter Icy Moons Exploration (JUICE) mission, and the provision and testing of hardware for the launch are in progress.

For the next NASA flagship mission, the Nancy Grace Roman Space Telescope, cooperation is underway with NASA. An Implementing Arrangement regarding study and development, including with respect to observation equipment provision, ground telescope observation, and ground station reception, was signed in April. Hera is an ESA-led international planetary defense mission to carry out observations of the Asteroid Impact & Deflection Assessment (AIDA) mission jointly conducted by the U.S. and Europe. An agreement stipulating JAXA's contribution to the mission by providing a thermal infrared camera based on the success of Hayabusa2 as well as science collaboration was concluded in February 2021 as a result of coordination. Cooperation was advanced regarding the World Space Observatory Ultraviolet (WSO-UV) with the Institute of Astronomy of the Russian Academy of Sciences (INASAN), the Space Research Institute of the Russian Academy of Sciences (IKIRAS) and ISAS. An MOU for confirming inter-agency cooperation with ROSCOSMOS for JAXA to provide spectrometers for an exoplanet observation equipment was signed in July. Coordination for a consensus document for the provision of equipment was commenced, but due to the deteriorating Ukraine-Russian situation, coordination with ROSCOSMOS has ceased.

Scientific ballooning campaigns and sounding rocket launches have also been involved in international collaboration. The ballooning campaign, which was scheduled to take place in Alice Springs, Northern Territory of Australia, was postponed to 2023 due to the COVID-19 pandemic. ISAS rearranged the schedule with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the University of New South Wales.

The sounding rocket SS-520-3, jointly planned with the Norwegian Space Agency (NOSA) and of which the launch was shelved due to the pandemic in 2021, was successfully launched from the Svalbard rocket range in Ny-Ålesund in November 2021. The launch was realized with the aid of NOSA and the Japanese Embassy in Norway for the Japanese team to obtain special entry permits from the Norwegian Government and to deliver the rocket and the experimental equipment to Norway. The data obtained is being analyzed.

In order to promote the above-mentioned international collaborations, in spite of the travel restrictions imposed due to the COVID-19 pandemic, ISAS actively held space agency level, space institution level, and staff level dialogues by utilizing the advantages of virtual meetings and secured implementation of ongoing international missions and promoted creation of new international missions. By staying up to date with the latest developments in U.S. and European space science and by presenting Japanese space science plans, ISAS continues to promote further international collaboration.

a. International cooperation in satellite missions at the operational stage

Project	Launch	Mission Overview	Cooperating partner	Partner responsibilities
Magnetosphere Observation Satellite GEOTAIL	Jul 24,1992	GEOTAIL is a cooperative mission with NASA for research on the dynamics of the structure of the magnetosphere and for participation in the International Solar-Terrestrial Physics (ISTP) project.	NASA (National Aeronautics and Space Administration, USA)	Rocket launch and approximately one-third of observation equipment.
			MPS (Max Planck Institute for Solar System Research, Germany)	Provision of the Low Energy Particle Detector (LD) for the High Energy Particle (HEP) detector.
Solar Physics Satellite HINODE (SOLAR-B)	Sep 23, 2006	As a globally available solar observatory, HINODE observes various explosions and heating phenomena that occur in the solar surface and corona. By capturing fluctuation phenomena of magnetic energy generated in the Sun's atmosphere, we can explore fundamental problems from cosmic plasma physics, such as the origin of the corona (the Sun's outer atmosphere), the relation between changes in the electromagnetic structure of the photosphere and dynamic corona phenomena.	NASA (USA)	Japan–US cooperative development of the Solar Optical Telescope (SOT), the X-ray Telescope (XRT), etc. Also, Japan–US–UK cooperative development of the Extreme-ultraviolet Imaging Spectrometer (EIS).
			STFC (Science and Technology Facilities Council, UK)	Japan–US–UK cooperative development of the Extreme-ultraviolet Imaging Spectrometer (EIS).
			ESA (European Space Agency, EU), NSC (Norwegian Space Centre, Norway)	HINODE scientific data received at a Norwegian facility.
Venus Climate Orbiter AKATSUKI (PLANET-C)	May 21, 2010	As the world's first mission to thoroughly investigate the mechanism of movement of Venus's atmosphere, AKATSUKI uses newly developed infrared sensors to uncover atmospheric phenomena hidden beneath the planet's clouds. This will allow us to elucidate the mechanism of Venusian atmospheric dynamics that cannot be explained by conventional meteorology (planetary-scale high-speed winds) to obtain a comprehensive understanding of weather phenomena on this planet.	NASA (USA)	Provision of the Deep Space Network (DSN) tracking for AKATSUKI, scientific support.
			ESA (EU)	Participation of ESA Venus Express team researchers in cooperative research.
			ISRO (India)	Conduct radio wave occultation observation of the Venus atmosphere by communication between AKATSUKI and ISRO's DSN and JAXA's DSN.

Asteroid Explorer Hayabusa2	Dec 3, 2014	A sample return mission from the C-class asteroid “Ryugu” that will prove the new knowledge about the original distribution of materials in the solar system and its evolutionary process.	NASA (USA)	The Deep Space Network (DSN) tracking of Hayabusa2, control support, asteroid ground observation support, OSIRIS-REx sample provision, etc.
			DLR (German Aerospace Center, Germany)	Hayabusa2 tracking support, microgravity experiment support.
			ASA (Australian Space Agency), Department of Industry, Science, Energy and Resources, DOD (Department of Defence) (Australia)	Permission for sample reclamation capsule landing in Australia and landing operations support.
			CNES (Centre National D’études Spatiales, France)	Provide MicrOmega to JAXA's Extraterrestrial Sample Curation Center.

Cooperative projects with overseas satellite missions

Gamma-ray Burst Observation Mission Swift	Nov 20, 2004	Swift is an international collaboration with the US, UK, and Italy for investigating the formation of gamma-ray bursts, the largest known explosive phenomena.	NASA (USA)	JAXA, Saitama Univ., Univ. of Tokyo to provide Burst Alert Telescope (BAT).
Magnetosphere exploration satellite constellation THEMIS (Time History of Events and Macroscale Interactions during Substorms)	Feb 17, 2007	THEMIS is a US-led mission, consisting of five magnetosphere exploration satellites and full-sky cameras. Combining these with magnetosphere observation equipment will elucidate the occurrence mechanism of “substorms”, the explosive development of the aurorae.	NASA (USA), UC Berkeley (USA)	JAXA researchers participating as science personnel.
Gamma-ray Space Telescope Fermi	Jun 11, 2008	Fermi is an international mission involving the US, France, Germany, Japan, Italy and Sweden. It will perform observations of black holes, neutron stars, active galactic nuclei (AGNs), supernova remnants and gamma-ray bursts, the largest known explosive phenomena.	NASA (USA)	Hiroshima Univ. providing semiconductor sensors for the gamma-ray Large Area Telescope (LAT)

Magnetospheric Multi- Scale Mission MMS	Mar 12, 2015	MMS is a NASA-led mission. It uses observations with ultra-high temporal resolution from four identically constructed satellites to elucidate magnetic reconnection and other space plasma phenomena that occur near the Earth.	NASA (USA)	JAXA providing technical support for development of the MMS Dual Ion Sensor (DIS) in the Fast Plasma Instrument (FPI).
Exploration of energization and Radiation in Geospace ERG	Dec 20,2016	This mission aims at discovering how high-energy electrons that are repeatedly created and destroyed in “space storms” resulting from solar wind disturbances are produced in the Van Allen radiation belt, and how these space storms propagate.	NASA (USA)	Cooperative observation with NASA’s “Van Allen Probes.”
			CSA (Canadian Space Agency, Canada)	Cooperative observation with CSA’s “ORBITALS” satellite.
			AS (Academia Sinica, Taiwan)	Provision of the Low- Energy Particle Experiment (LEP-e).
Mercury Exploration Mission BepiColombo	Oct 20,2018	This is the first in-depth cooperative mission between Japan and the ESA, using two satellites—the ESA’s Mercury Planetary Orbiter “MPO” and JAXA’s Mercury Magnetosphere Orbiter “MMO”—to conduct comprehensive observations of Mercury’s magnetic field, magnetosphere, interior and surface, thereby revealing mysteries of Mercury’s past and present.	ESA (EU)	MPO development, rocket launch, etc.
			CNES (France)	Partial provision of the MMO- mounted Mercury Plasma Particle Experiment (MPPE) and Plasma Wave Investigation (PWI) experiments. Also, Japan–France co-development of Probing of Hermean Exosphere by Ultraviolet Spectroscopy (PHEBUS) experiment.
			IWF (Austrian Space Research Institute, Austria)	Provision of Magnetic Field Measurement (MGF) device on MMO.
			SNSA (Swedish National Space Agency, Sweden)	Provision of Energetic Neutral Atom (ENA) and Mercury Electric Field In-Situ Tool (MEFISTO) electric field measuring instrument.
			FSA (Russian Federal Space Agency, Russia)	Provision of the Mercury Sodium Atmosphere Spectral Imager (MSASI) on MMO.
			DLR (German Aerospace Center, Germany)	Provision of the equipment for the ion mass analyzer on MMO.

b. International cooperation in satellite missions at the development stage

Project	Launch	Mission Overview	Cooperating partner	Partner responsibilities
X-ray Imaging and Spectroscopy Mission (XRISM)	FY2022 (Planned)	Following the termination of the ASTRO-H (HITOMI) mission, XRISM aims to provide breakthroughs in the study of "structure formation of the universe", "history of flows of mass and energy in universe", and "the composition and evolution of celestial object" as well as to discover "unprecedented science through high resolution X-ray spectroscopy". In order to achieve these science objectives, "flows of mass and energy and evolution of celestial object in hot gas plasma" is to be elucidated through unprecedented characteristic and performance.	NASA (USA)	SXS, SXI, Mission SE, Ground SW development, Science Operation, Science
			ESA (EU)	SXS LHP Development, STT Delivery, Science
			SRON (Netherlands)	SXS FWM/E Development, Science
Smart Lander for Investigating Moon (SLIM)	FY2022 (Planned)	Aiming to demonstrate precise, pinpoint lunar landing. The lighter lunar and planetary exploration system will contribute to the highly frequent exploration.	NASA (USA)	Laser retro-reflector (LRA) on board DSN tracking support
Demonstration and Experiment of Space Technology for INterplanetary voYage with Phaethon fLyby and dUst Science (DESTINY⁺)	FY2024 (Planned)	Through collection of interplanetary dust as well as flyby observation of the Geminids meteor shower parent body “Phaethon”, the mission will elucidate physical properties and chemical composition of dust particles and the picture of “Phaethon”. Also the mission aims for technically demonstration to implement sustainable low-cost and highly accurate future deep s pace exploration.	DLR (Germany)	DDA (DESTINY⁺ Dust Analyzer).

Martian Moons eXploration (MMX) Mission	FY2024 (Planned)	By analyzing a sample from a Mars satellite return mission and performing on-orbit observations, we will pursue an overall goal of better understanding the evolution of pre-life environments through the following scientific findings; 1) uncovering the origins of the Martian satellites, in preparation for deciphering the formation process of Mars, 2) using sample analysis to place restrictions on possibilities for Mars's formation (depending on findings related to the origin of Mars's satellites), 3) unraveling the history of Mars's environment, and 4) globally observing Mars's atmosphere and surface.	NASA (USA)	Neutron and gamma-ray spectrograph
			CNES (France)	Near-infrared spectrometer small rover
			ESA (EU)	Deep space communication equipment.
			DLR (Germany)	Small rover, testing facility

c. Satellite missions in preparation or under proposal (international cooperation being planned)

Project	Launch	Mission Overview	Cooperating partner	Partner responsibilities
Solar Physics Satellite SOLAR-C	FY2026-2027 (planned)	Understanding plasma dynamics as a single system extending from the solar surface to the corona and extending to inter-planetary space to elucidate universally appearing elementary plasma processes. To that end, three tasks are performed: 1) elucidating the mechanism of chromosphere– corona and solar wind formation, 2) elucidating the expression mechanism for solar surface explosion phenomena and acquisition of knowledge for predicting its generation, and 3) elucidating the variation mechanism of solar radiation spectra that affect global climate change.	NASA (USA)	Under discussion
			ASI Italian (Space Agency, Italy) CNES (France), DLR (Germany), ESA (EU), and others	Under discussion

Cosmic microwave background radiation polarization observation satellite “LiteBIRD” (Lite (Light) satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection)	FY2028 (planned)	This mission aims at a thorough investigation of the inflation model of cosmology. Cosmic inflation is expected to have produced primordial gravity waves and their after-effects are predicted to have been imprinted in the cosmic microwave background polarity map as “B-mode” perturbations. This mission will perform full-sky observations free of strong foreground signals so that polarized B-mode signals due to primordial gravity waves should be strongest.	ESA (EU), CNES (France), CSA (Canada) and others	Under discussion

Cooperative projects with overseas satellite missions

Jupiter Icy Moon Explorer JUICE	2023 (planned)	JUICE is an ESA-led mission. It will map the surfaces of Jupiter and its larger satellites (Ganymede, Callisto, and Europa) and perform interior observations to investigate the possibility of life.	ESA (EU), DLR (Germany), SNSA, etc.	DLR: provide a part of GALA (Ganymede Laser Altimeter) SNSA: provide a part of RPWI (Radio. & Plasma Waves Investigation), and PEP/ JNA(Particle Environment Package/Jovian energetic neutral atom analyzer).
Advanced Telescope for High ENergy Astrophysics ATHENA (working group)	2028 (planned)	ATHENA is an ESA-led mission. It will observe ultrahigh-temperature matter immediately before it falls into a black hole to elucidate fundamental contributions of black holes to galaxy formation.	ESA (EU), CNES (France), etc.	Under discussion
Nancy Roman Grace Telescope (formerly known as WFIRST) (pre-project)"	2026 (planned)	Direct imaging which is a next large step in extrasolar planet observation. Japanese provision of instruments and cooperation in observation will realize world’s only space telescope.	NASA (USA)	Provision of Coronagraph Instrument, provision of Subaru observations, provision of ground station reception.
HERA Dual asteroid probes (pre-project)	2024 (planned)	In the aim of preparing for the possible asteroid collision to Earth, planetary defense has been promoted in trilateral cooperation by Europe, US, and Japan. Enhanced by international space cooperation, it has a significant meaning in space security in the broad sense.	ESA (EU)	Provision of a thermal imager.

WSO-UV (pre-project) (Cooperation is currently suspended.)	2025 (planned)	Observation of the composition of upper atmosphere of Earth type extrasolar planet is a next large step in extra solar planet observation. Utilizing the large telescope that can be realized through international cooperation and combining the Japanese highly sensitive detector will open a new frontier in space observation.	ROSCOSMOS (Russia)	Provision of spectrometers for the exoplanet observation equipment.

d. International cooperation in sounding rocket experiments

Project	Launch	Mission Overview	Cooperating partner	Partner responsibilities
CLASP2	Apr 2019	Aims to observe the ultraviolet light emitted by ionized magnesium atoms and to detect the scattering polarization, as well as the Hanle and Zeeman effects, to quantitatively measure the vector magnetic fields in the chromosphere by launching a sounding rocket.	NASA (USA)	Provision of the sounding rocket launch, onboard scientific computer and charge-coupled device (CCD) camera.
			Institut d'Astrophysique Spatiale (France)	Provision of the diffraction grating.
			Instituto de Astrofísica de Canarias (Spain)	Hanle effect and Zeeman effect Model calculations

e. International cooperation in scientific balloon experiments

Project	Experiment Overview	Cooperating partner	Partner responsibilities
General Anti-Particle Spectrometer GAPS	Investigating problems from cosmophysics such as the elucidation of dark matter by high-sensitivity searches for antiparticles contained in trace amounts in cosmic rays.	Columbia Univ. (USA)	Cooperative development of observational equipment, etc., with JAXA.
Japan-France scientific balloon joint experiment	Construction of future wide-ranging cooperative relations, starting with the development of marine reclamation technologies.	CNES (France)	Provision of information pertaining to long-term tracking of balloon systems after splashdown.
Japan-Australia balloon joint experiment	A joint balloon experiment and space science research with long-time flight and the retrieval of experimental equipment on land, which were difficult in domestic balloon experiments	Commonwealth Scientific and Industrial Research Organisation (Australia)	Permission for experiment location and experiment support

f. Framework agreements, etc., in the space science fields with overseas universities

Partner	Description
SRON (Netherlands)	Discussions on the possibility of inter-institution cooperation with a view toward future space science research.
Stanford Univ. (USA)	Promoting coordination and cooperation between our organizations to promote cooperative research in astronomy
Yale Univ. (USA)	Promoting coordination and cooperation between our organizations for academic research in the space science fields, and considering frameworks for contributing to the development of R&D and education.
Univ. of Arizona (USA)	Carrying out cooperative research related to applied research of gamma-ray detection systems.
Univ. of Southampton (UK)	Conducting joint research on fundamental electron source (cathode) technologies for Hall thrusters and other next-generation high-power electric propulsion systems.

2. Domestic Collaboration

ISAS established and operates centers for inter-university collaboration and works to improve acceptance of academic researchers and non-Japanese researchers at the Sagamihara Campus with the aim of ensuring that the ISAS-centered space science community continuously yields results from cutting-edge research.

Regarding centers for inter-university collaboration, (1) School of Engineering, Hokkaido University for research and development of a kick-motor for Piggy-back Space Probes, (2) Planetary Exploration Research Center at the Chiba Institute of Technology for the development of fundamental technology in planetary probes and personnel development, and (3) the Kavli Institute for the Physics and Mathematics of the Universe for hard X-ray and gamma ray imaging, have been working to produce results since FY2017, and the research and development are processing in accordance with the implementation plan set forth at the time of adoption.

Although the agreement for inter-university collaboration with Hokkaido University has been concluded in FY2021, research activities will continue in various forms due to budgetary measures from the university, acquisition of external funds, and the establishment of venture companies.

In addition, as a cooperative project with universities, preparations are underway to establish a research center for further promotion of heliospheric system science (Heliospheric Science Center) with the Institute for Space-Earth Environmental Research (ISEE) of Nagoya University, with which we had cooperated as an Inter-University Research Center.

Moreover, ISAS has been conducting collaborative activities under agreements with the following organizations: Iwate University and Kanazawa University for advanced machining technology, the University of Aizu for data archiving, Saitama University for X-rays, the University of Tokyo for infrared observation, the Tokyo Institute of Technology Earth-Life Science Institute for the curation of extraterrestrial life, Rikkyo University for personnel development and Okayama University for sample curation.

3. Research by External Funds

a. KAKENHI (Grants-in-Aid for Scientific Research)

Research Categories	Number of Selected Projects	Total (in 1,000 JPY)
Scientific Research on Innovative Areas (Research in a proposed research area)	2	48,590
Transformative Research Areas (A)	3	84,320
Transformative Research Areas (B)	2	4,030
Scientific Research (S)	1	30,810
Scientific Research (A)	7	82,160
Scientific Research (B)	15	67,180
Scientific Research (C)	27	33,975
Challenging Research (Exploratory)	4	9,032
Early-Career Scientists	16	20,083
Research Activity start-up	3	3,242
JSPS Fellows	6	7,789
Fostering Joint International Research (B)	3	12,842
Total	89	404,053

Accepted Share of expenses

Research Categories	Number of Selected Projects	Total (in 1,000 JPY)
Specially Promoted Research	3	56,745
Transformative Research Areas (A)	1	520
Transformative Research Areas (B)	1	8,086
"Scientific Research on Innovative Areas (Research in a proposed research area)"	4	7,280
Challenging Research (Pioneering)	1	1,560
Challenging Research (Exploratory)	3	1,796
Scientific Research (S)	4	7,150
Scientific Research (A)	19	14,976
Scientific Research (B)	18	19,578
Scientific Research (C)	4	3,764
Fostering Joint International Research (B)	6	2,795
Total	64	124,250

b. Funded Research

Number of Researches	Total (in 1,000 JPY)
14	121,178

c. Cooperative Research with Private Sector

Number of Researches	Total (in 1,000 JPY)
63	201,574

d. Earmarked Donations

Number of Researches	Total (in 1,000 JPY)
10	14,919

4. Domestic Joint Research

a. Open facilities for domestic joint research

Facility	Number of joint research
Space Chamber test equipment	16
Ultra-high-speed collision test equipment	22
Space radiation equipment	12
Wind tunnel laboratory	23
Planetary atmospheric entry environment simulator	12
JAXA Supercomputer	29

b. Joint research assigned to specific themes through application by ISAS academic staff

Number of joint research	20

Education and Public Outreach

1. 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, 2022)

School or Program	Professors	Associate professors	Assistant professors	Total
The Graduate University for Advanced Studies (SOKENDAI)	20	40	15	75
The Graduate School at the University of Tokyo				
School of Science	8	4	7	19
School of Engineering	9	5	9	23

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 2003. ISAS established the SOKENDAI Department of Space Science in what was then the School of Mathematical and Physical Science. Academic staff from ISAS also teach at SOKENDAI, instructing students in 5-year doctoral programs and other courses.

SOKENDAI Department of Space Science Admissions in FY2021

Admission month	Admission capacity	Applicants	Accepted applicants
October	5*	0	0
April		11	7

* 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 14 schools in 12 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.

2. Public Outreach

In order to increase the visibility of ISAS's activities, its public outreach (PO) activities must be upgraded. To this end, the restructuring of the ISAS PO office was started in the summer of 2020. The first big job under the renewed framework was the outreach activities for the Hayabusa2 sample recovery operation. An effort to enhance its communication capability (via web page content and twitter messages), especially global communication in English, was started in February 2021. In FY2021, enhancement of ISAS PO activities continued under the new framework.

a. New PO Office

It has been clearly defined that the ISAS PO activities are sustained by three pillars and the restructuring of the Office has been performed according to this principle. The three pillars are correspondence with the press, science communication, and interaction with the local community via the ISAS visitor center (Space Science Communication Hall).

For more effective public outreach, the following points have been agreed upon: In corresponding with the press, collaboration with JAXA HQ PO Office is crucial and timely sharing of information should be ensured. As a research institute, science communication is an important element of ISAS itself, and the effort to enhance its communication capability needs to be continued in a systematic way with the vision shared among ISAS executive members. Local interaction with Sagamihara City, with Space Science Communication Hall positioned at the core, should be conducted by always keeping the concept of civic pride in mind, or in other words, make the local people feel good that ISAS is located in the city where they live.

b. Hayabusa2

Hayabusa2, which brought back samples from the primordial asteroid Ryugu, continues to be a focal point of the ISAS PO activities. In FY2021, releasing the results from Initial Analysis of Ryugu samples through the publication of papers in high impact journals was the main activity. One of the difficulties we realized is that people are not as excited about sample analyses progress reports as they were for Hayabusa2 mission progress reports. While it is understandable, instead of giving up too early, we are trying to find ways to interest people in sample analysis. And there are indeed a variety of bonus results coming out of the initial analysis activity. Interest in participating in Ryugu sample analysis is very high among experts due to the high value of the samples, which should be proportionally communicated to the public.

c. Enhancing the communication capability

A native English speaker joined the science communication team as a writer and the communication capability has been substantially enhanced since then. Needless to say, our global communication in English has become smoother and has expanded. A more crucial change is that we started to interview ISAS members and publish articles. In other words, the PO Office is no longer a mere passive channel between ISAS researchers and the public, but now has a new function of actively designing PO activities, such as what the website content should be and what messages should be conveyed via twitter, and so on. In FY2021, the change we sensed after performing the new style for a year is that ISAS members are now more inclined to send out messages.

d. Space Science Communication Hall

Many have argued that there is strong potential for the hall to be more attractive. However, given all the limitations, the most prominent of which is budget-related, we need to be strategic. Instead of positioning the hall like an encyclopedia that offers details only to those who have a prior interest in space science upon their visit (which is what it is now), we may take an ambient approach, that is to provide a pleasant atmosphere that only slightly touches on space science. Then, those who have not decided whether they care about space science upon entry to the hall may start to wonder what space science is about. In line with this thinking, development of a new concept for the communication hall is ongoing. In FY2021, we have started dialogue with Miraikan and Science Museum London to broaden our path to reach out.

Awards

The Eighth ISAS Award Recipients

Name	Affiliation	Reason for Award	Date
Hansjörg Dittus	Universität Bremen(at the time)	(Special Award)Contribution to the development of MASCOT lander for Hayabusa2 mission	January 6, 2022
FUNAZAKI Kenichi	Professor, Faculty of Science and Engineering, Iwate University (at the time)	Contribution to building a cooperative relationship between the ISAS Advanced Machining Technology Group and Iwate University	January 6, 2022

Award Recipients at ISAS

Recipient	Affiliation	Award	Date
Asteroid Explorer "Hayabusa 2", Japan Aerospace Exploration Agency (JAXA)		Association of Media in Digital : The 26th AMD Award, Digital Contents of the Year '20.	April 2021
Hauabusa2 Project Team		Société astronomique de France [French astronomical society] : Le Prix international d'astronautique 2020 à l'équipe de l'Agence spatiale japonaise (Jaxa), qui a mené l'incroyable mission Hayabusa-2 de collecte d'échantillons sur l'astéroïde (162173) Ryugu. [International Astronautics Prize 2020 for Hayabusa-2 mission to collect samples on the asteroid (162173) Ryugu.]"	April 2021
Asteroid Explorer "Hayabusa 2"		The Nikkan Kogyo Shimbun, Ltd : The Japan Industrial Technology Awards, Special Award.	April 8, 2021
OOTAKE Hisashi, SATO Hiroyuki, INOUE Hiroka, and others	Lunar and Planetary Exploration Data Analysis Group and others	Ministry of Education, Culture, Sports, Science and Technology (MEXT): Awards for Science and Technology (Science and Technology Promotion Category). "Contribution to international space exploration by analyzing big data of KAGUYA and other exploration projects".	April 14, 2021
TSUKIZAKI Ryudo	Department of Space Flight Systems and others	Ministry of Education, Culture, Sports, Science and Technology (MEXT): Young scientists' prize for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology in FY2021. "Research achievements on the ion engine that realized the Asteroid Explorer 'Hayabusa2' ".	April 14, 2021
OGAWA Junko, YOSHIKAWA Kento, and others	Hayabusa2 project and others	Ichimura Foundation for New Technology: The 53rd Ichimura Prize in Science for Excellent Achievement.	April 19, 2021

MORI Osamu, KUSHIKI Kenichi, NARUO Yoshihiro, SAWAI Shujiro, SHIDA Maki, MARU Yusuke, MICHIGAMI Keisuke, NAKATSUKA Junichi, and others	Department of Space Flight Systems and others	The Japan Society for Aeronautical and Space Sciences: The 30th (FY2020) Best Paper Award. "Development and Outward Operation of Hayabusa-2 Chemical Propulsion System".	April 20, 2021
YOSHIMITSU Tetsuo, KUBOTA Takashi, TOMIKI Atsushi, and others	Department of Spacecraft Engineering	The Japan Society for Aeronautical and Space Sciences: The 30th Technology Award [Project Category]. " MINERVA-II Rover-1A, 1B for Hayabusa2 ".	April 20, 2021
OKADA Tatsuaki, TSUDA Yuichi, SAIKI Takanao, MIMASU Yuya, YOSHIMITSU Tetsuo, and others	Hayabusa2 project and others	Space Ops2021 (International Committee on Technical Interchange for Space Mission Operations & Ground Data Systems) : Outstanding Manuscript for Space Ops 2021.	May 2021
HABU Hiroto and others	Department of Space Flight Systems and others	The Japan Society of Mechanical Engineers (JSME): Robotics and Mechatronics Division, Certificate of Merit for Excellent Paper. "Study on peristaltic continuous mixing conveyor for composite propellant slurry mixing".	June 7, 2021
ODAGIRI Kimihide and others	Department of Space Flight Systems	15th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Best Paper Award. “Characteristics of Thermo-Fluid Behavior in a Micro-Grooved Evaporator of Loop Heat Pipe Based on Microscale Infrared / Visible Observations and Modeling”.	July 2021
FUKE Hideyuki, KANAYA Shusaku, MIYAZAWA Yu, TOYOTA Hiroyuki, and HIROSE Kazuyuki	Department of Interdisciplinary Space Science, Department of Spacecraft Engineering and others	11th SOLARIS 2021 (International Symposium on Solar Energy and Efficient Energy Usage), Best Paper Award. “Balloon flight test of thin-film-type perovskite solar cell”.	September 2021
YOSHIMITSU Tetsuo, and KUBOTA Takashi	Department of Spacecraft Engineering	The Robotics Society of Japan (RSJ): The 35th JRSJ Paper Awards. "Engineering Challenges and Results by MINERVA-II Asteroid Surface Rovers (Journal of RSJ, Vol.38, No.8, pp. 754-761)".	September 8, 2021
KARIYA Kazuki, and FUKUDA Seisuke		Japanese Neural Network Society: Outstanding research award. "Application of Neuromorphic Computing to Spacecraft Navigation with Crater Classification Task".	September 23, 2021
O'DONOGHUE James	Department of Solar System Sciences	2021 Europlanet Prize for Public Engagement.	September 27, 2021
KUNINAKA Hitoshi		The Hattori Hokokai Foundation: The 91st Hattori Hokokai Hokokai Award.	October 8, 2021
Hauabusa2 Project Team		International Astronautical Federation (IAF) : IAF World Space Award 2021 “Hayabusa2 Team”.	October 21, 2021

Hauabusa2 Project Team, JAXA		The Japan Aeronautic Association (JAA): Aeronautics special award.	November 2021
FUNAKI Ikkoh, HABU Hiroto, TAKEUCHI Shinsuke, ARAKAWA Satoshi, MASUDA Jun’ichi, MAEHARA Kenji, YAMADA Kazuhiko, NAKAO Tatsuro, and others	Department of Space Flight Systems and others	Combustion Society of Japan : 2021 Photo exhibition of fire and flame, best photo. "The world's first space flight for the rotating detonation engine."	November 2021
NISHI Ryotaro, ONG Fei Shen, TOBE Hirobumi, and SATO Eiichi	Department of Space Flight Systems	The Japan Institute of Light Metals: The 141st JILM Annual Meeting, Poster session, Japan Light Metal Welding & Construction Association Award.	November 13, 2021
MIZUNO Takahide, IKEDA Hirokazu, and others	Department of Spacecraft Engineering	International Display Workshops, IDW '21 Best Paper Award, “Geiger-mode Three Dimensional Image Sensor for Flash LIDAR”	December 24, 2021
O'DONOGHUE James (Finalist)	Department of Solar System Sciences	American Association for the Advancement of Science (AAAS), Early Career Award for Public Engagement with Science, Finalist	February 10, 2022
TORIUMI Shin	Department of Solar System Sciences	Society for Promotion of Space Science: The 14th Space Science Incentive Award.	March 8, 2022
MIURA Masashi and others	Department of Space Flight Systems	The 14th Information Systems Education Contest (ISECON2021), Grand Prize. "Introductory Education for System Design and Project Management with Gamification ."	March 5, 2022

Student

Student	Affiliation	Academic Advisor	Award	Date
TAKASAGO Tamiaki	Graduate school at Chiba Institute of Technology	HORI Keiichi	Japan Explosives Society: 2021 "Observation of the combustion surface of GAP/AP propellant using a high-speed camera."	May 2021
YAMASHITA Yusuke	School of Engineering, The University of Tokyo.	NISHIYAMA Kazutaka	IEPC Summer 2021, Second Place Award, "Novel diagnostics of neutral density inside gridded ion thruster by using two-photon absorption LIF"	July 2021
MATSUMOTO Kosei	School of Science, The University of Tokyo	NAKAGAWA Takao	Galaxy-IGM Workshop 2021: Summer school, Best group work award.	August 2021
NISHANTH Pushparaj	Department of Space and Astronautical Science, SOKENDAI	KAWAKATSU Yasuhiro	2021 IAF Emerging Space Leaders, the IAF Emerging Space Leaders Sub-Committee	August 24, 2021

YAGI Yuta	School of Science, The University of Tokyo	YAMASAKI Noriko	The 51st Summer School FY2021 (Astronomy &Astrophysics) for Young Researchers: Best Oral Award.	August 26, 2021
MIYAGAWA Rikuta	School of Science, The University of Tokyo	YAMASAKI Noriko	The 51st Summer School FY2021 (Astronomy &Astrophysics) for Young Researchers: Best Oral Award.	August 26, 2021
WANG Chang-Chin and others	School of Science, The University of Tokyo	USUI Tomohiro	The 29th Satellite Design Contest, Design Section: Society of Geomagnetism and Earth, Planetary and Space Sciences (SGEPSS) Award. "MORSE (Moon Orbital Relay for South-polar Exploration)."	November 23, 2021
SUGIMOTO Ryosuke and others	Department of Space and Astronautical Science, SOKENDAI	YAMADA Toru	FY2021 Student Presentation Award of the Physical Society of Japan. "Development of back-linked Fabry-Perot interferometer for frequency stabilization in space gravitational wave telescope: III."	September 14, 2021
NIMURA Naruhiko	School of Engineering, The University of Tokyo.	OYAMA Akira	The Japanese Society for Evolutionary Computation: Evolutionary Computation Symposium 2021: Evolutionary Computation Competition, Second prize.	December 26, 2021
NAKAZAWA Junichiro	Department of Space and Astronautical Science, SOKENDAI	SUZUKI Shino	The 15th space unit symposium: Outstanding award. "Feasibility Research on a Flyby Sampling System for Impacting Microparticles at Extreme Hypervelocities."	February 6, 2022
ITO Daichi	Department of Space and Astronautical Science, SOKENDAI	KAWAKATSU Yasuhiro	33rd International Symposium on Space Technology and Science (ISTS): Modi Memorial Jaya-Jayant Award, "Round Trip Trajectory Design by Trajectory Parts Connecting Method."	March 4, 2022
NISHANTH Pushparaj	Department of Space and Astronautical Science, SOKENDAI	KAWAKATSU Yasuhiro	33rd International Symposium on Space Technology and Science (ISTS): SPSS (Society for Promotion of Space Science) President Award, "Bifurcated Quasi-Satellite Orbits for Martian Moons eXploration (MMX)."	March 4, 2022
NISHANTH Pushparaj	Department of Space and Astronautical Science, SOKENDAI	KAWAKATSU Yasuhiro	33rd International Symposium on Space Technology and Science (ISTS): Best Poster Award (1st Prize), "Optimal Transfer Trajectory Analysis of Relative QSOs around Phobos."	March 4, 2022

Orders, decorations, and medals

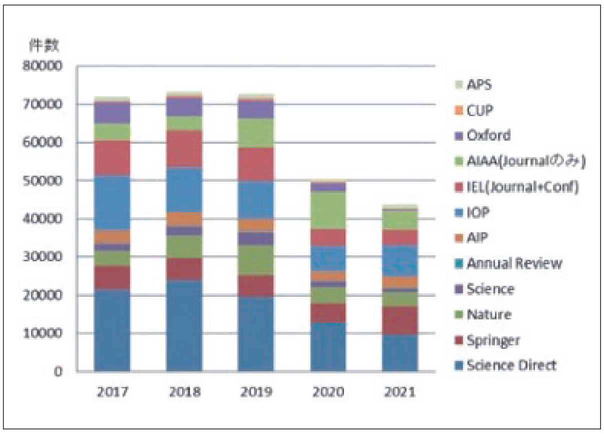
Recipient	Order	Date
KUNINAKA Hitoshi	Medal with Purple Ribbon	November 2021
NINOMIYA Keiken	The Order of the Sacred Treasure, Gold Rays with Neck Ribbon	November 2021

ISAS Library and JAXA Repository

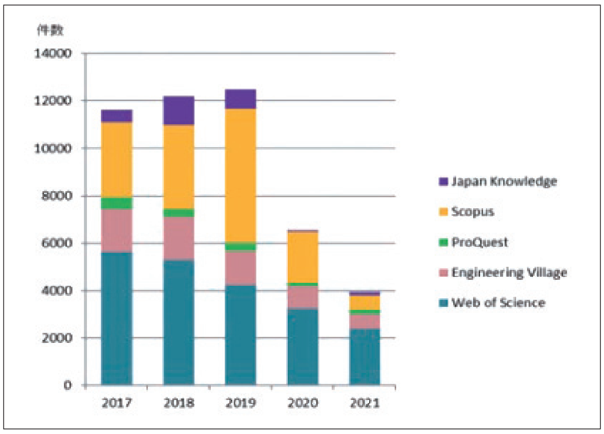
1. ISAS Library

The ISAS Library actively collects materials, including books, magazines, and reports, on space science and related fields, and makes them available to our researchers. The library also contributes widely to graduate school education, as it has also served as a library of SOKENDAI parent institute since April 2003 and the library makes joint purchases of e-journals and contributes to graduate education. After the establishment of JAXA on October 1, 2003, the ISAS Library created a website to share e-journals and diverse services with external users by cooperating with other libraries at JAXA. The JAXA Library Portal website (https://www-std01.ufinity.jp/jaxalib/) was launched on March 1, 2018 to fully integrate all JAXA Library websites with clearer navigation and improved information about the resources and services that users need. It works toward increasing available references and improving services, such as providing more convenient online search and browsing functions. In FY2021, under a state of emergency declared in August and September by the Japan's government, the library remained open, and services were continued while implementing measures to prevent infection. In addition, the air conditioning system was renewed.

Renewed air-conditioner at ISAS Library



Number of e-journal downloads



Number of database searches

ISAS Library holdings at the end of March 2022

Category	Quantity
Total books	95,935
Foreign books	76,588
Japanese books	19,347
Total journals	1,200
Foreign journals	959
Japanese journals	241
Journals added in FY2019	164
Foreign journals	10
e-Journals	91
Domestic English journals	5
Japanese journals	58

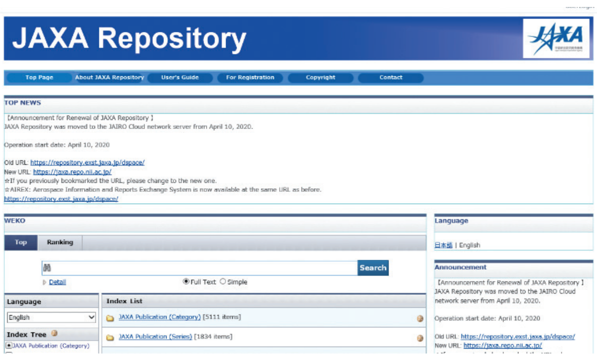
e-Journals	about 4,100
IEL Online	195
IOP Journal	98
Elsevier Science Direct	118
Springer Journal	about 1,600
Wiley-Blackwell	about 1,400
JSTOR	about 680

e-Books	
AGU Geophysical Monograph Series and other	618
AIAA Education Series	69
Cambridge Books Online	160
Net Library	585
Oxford Scholarship Online (Physics)	216
Springer eBOOK	about 134,000
ProQuest Ebook Central	222
Chronological Scientific Tables Premium	

Databases
ProQuest (CSA Technology Research Database)
Engineering Village
Scopus
Web of Science
Japan Knowledge

2. JAXA Repository

https://jaxa.repo.nii.ac.jp/



In the JAXA Repository, references, papers in journals and dissertations published mainly by JAXA staff are available for public viewing. Users can view information about references summarizing R&D results and their full text (with some exceptions).

Since the JAXA Repository was established in 2009, ISAS has added over 1,000 items each year. The Repository plays an important role as a source of useful information.

From 2013, the JAXA Repository has been sharing achievements presented at symposiums organized by ISAS.

The launch of an online ISAS symposium application system in FY2015 contributed to the efficiency of procedures ranging from symposium registration to publishing presentation proceedings. All the ISAS symposium proceedings held after 2003 have become available in the Repository, which has promoted the presence of the Repository.

Furthermore, in FY2016, JAXA started assigning Digital Object Identifiers (DOIs) for peer-reviewed materials in the JAXA Publication series. In FY2019, the system was migrated to JAIRO Cloud, a cloud-based repository service jointly operated by the National Institute of Informatics (NII) and the Japan Consortium for Open Access Repository (JPCOAR).

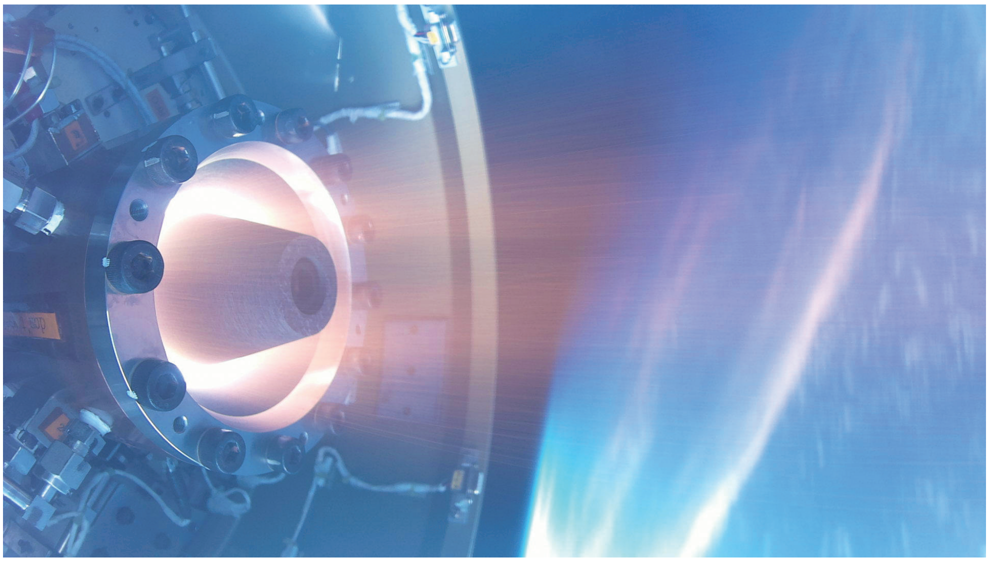
In addition, with the aim of permanently preserving the library materials published at ISAS, we have been digitizing mainly ISAS-published materials since FY2020. Among them, in FY2021, digital archiving of ISAS Nenji-Yoran, which had been published in Japanese annually, (including publications before the merger with JAXA) was conducted in the JAXA Repository.

WEKO2, the repository software of JAIRO Cloud, is currently planned to be upgraded to WEKO3 and new features will be introduced. Preserving the accessibility of these materials will allow semi-permanent, open access to JAXA academic content.

Publications, Presentations, and Patents

Publications, Presentations and Patents

Item	Achievements
1. Publications on Web of Science	
a. Papers in prestigious academic journals by ISAS staff	2 in Nature, 2 in Science (April 2021- March 2022)
b. Reviewed papers published in journals	363 (January 2021 - December 2021)
c. Number of highly cited papers in past ten years	48
* Source: Essential Science Indicators data updated in March 2022.	
* Including papers with ISAS staff as co-author	
2. JAXA Publications (in ISAS)	11 (Research and Development Report: 5, Research and Development Memorandum: 4, Special Publication: 2)
3. Publications	
a. Published in books	7
b. Published in reviewed journals	404
4. Presentations at domestic and international meetings	Keynote speeches: 5 Invited lectures: 28 Domestic meetings: 243 International meetings: 183
5. Awards	39 (see pp. 113-117)
6. Patents	Published patent applications: 17 Patents granted: 13



https://global.jaxa.jp/

Institute of Space and Astronautical Science,
Japan Aerospace Exploration Agency (JAXA)

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