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Annual Report of the Institute of Space and Astronautical Science 2019

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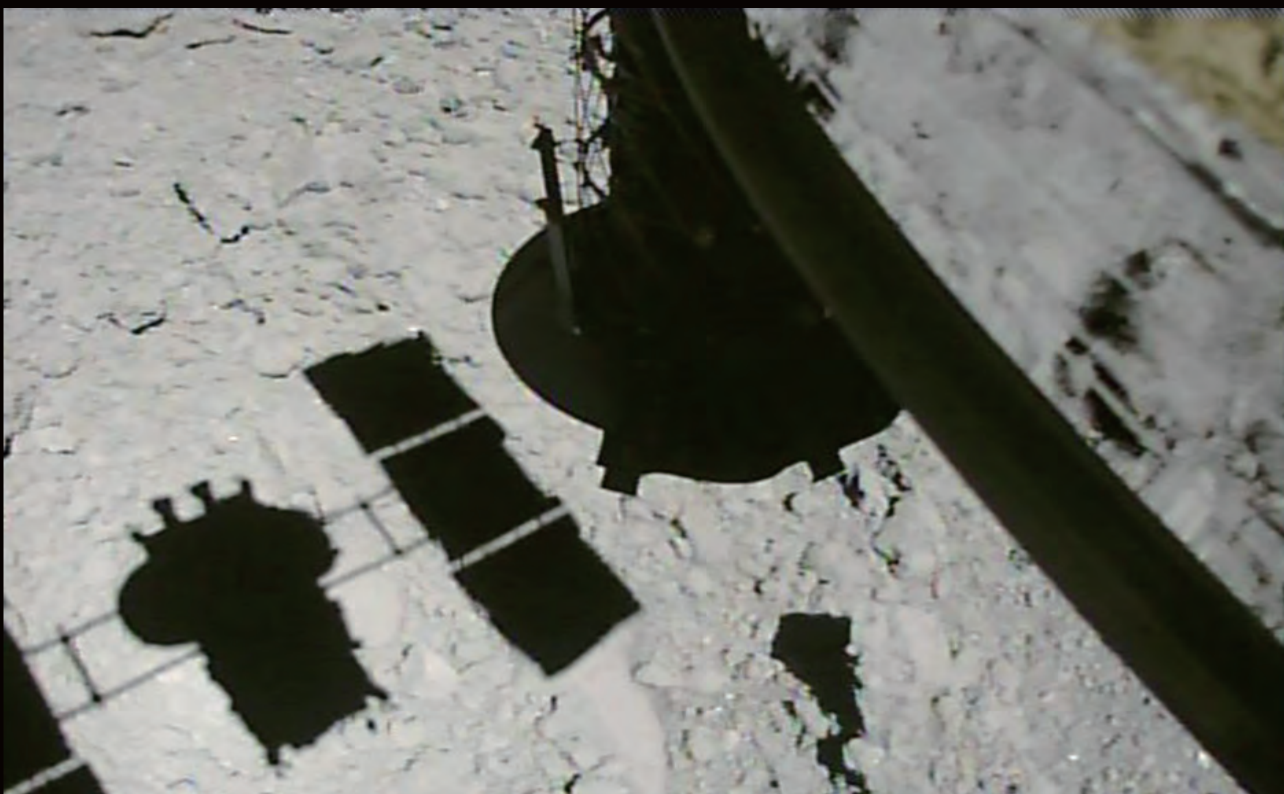
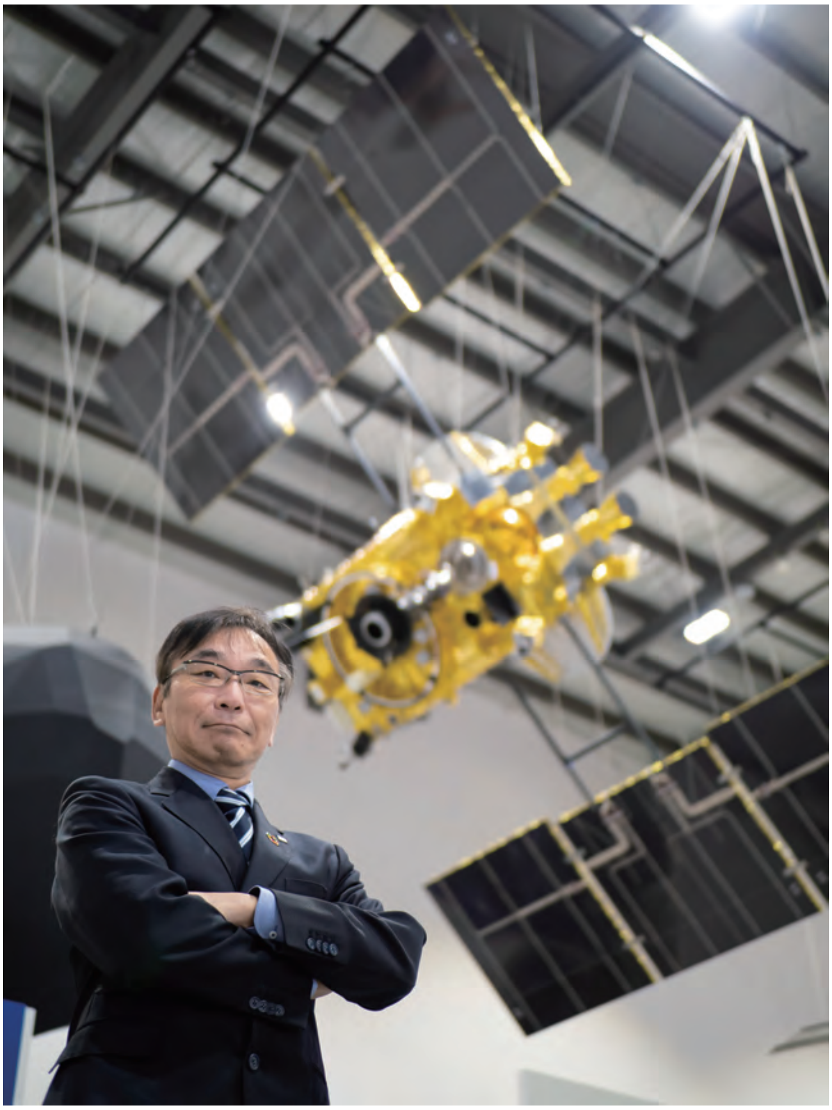


Message from the Director General

KUNINAKA Hitoshi

Director General

Institute of Space and Astronautical Science
Japan Aerospace Exploration Agency



It was 1989 when the Institute of Space and Astronautical Science (ISAS) of the Japan Aerospace Exploration Agency (JAXA) moved to Sagamihara from the University of Tokyo's Komaba Campus. On November 1, 2019, we held a commemorative ceremony to celebrate our activities here over the past 30 years and to show our gratitude to the Sagamihara city government, local organizations, and citizens. We could not have achieved our successful results without their support. Another event worthy of commemoration is the successful launch of the artificial satellite OHSUMI on February 11, 1970, which made Japan the fourth country in the world to obtain artificial satellite technology. To honor this achievement, we held a 50-year commemorative ceremony in the hall of the National Museum of Nature and Science in Ueno on February 11, 2020. Although space science activities may feel like mundane, everyday things to ISAS/JAXA personnel, we are once again reminded of the importance of the responsibility and pride of our activities, which are supported by our hometown, the nation, and the government.

Japans' landscape is ideal for launching satellites since it is bordered by the ocean on the east side, and it is advantageous to launch eastward in order to leverage the rotational motion of the Earth. Once a satellite or spacecraft is launched toward space, telemetry and telecommand communication will be operated through ground stations. There are many satellite communication stations in all parts of the world, but the Far East Northern Hemisphere area is blank. I would like to point out that Japan's position in the Western Northern Hemisphere on the Pacific Rim has the highest possible geographical advantage for space development.

Systematic and programmed approach is considered to be an important policy of ISAS in order to administer our current space projects and to plan future space missions. Under the previous scheme, each individual project or satellite was designed, developed, operated, and analyzed based on local optimization. Because we have expanded in nearly all fields of space science and accomplished several lineups of satellites in space, we are approaching the origins of life by integrating the data obtained from ISAS's and other agencies' satellites. We are applying this scheme to the space astronomy domain, and I would like to share an image of the construction of a wavelength-integrated space astronomy observation network, shown in the Figure. The network consists of the X-ray Imaging and Spectroscopy Mission, XRISM (under development); the Spectroscopic Planet Observatory Satellite HISAKI, which uses an extreme ultraviolet ray spectroscope; the Space Infrared telescope for Cosmology and Astrophysics (SPICA), which is under evaluation as one of three candidates for medium-sized Mission #5 of Cosmic Vision, the ESA space science program; the geospace exploration satellite ARASE, which observes the energy exchange process between Radio Frequency (RF) waves and particles; the cosmic microwave background (CMB) polarization observation spacecraft LiteBIRD, which is searching for space before the Hot Big Bang; and so on. Taking advantage of the characteristics of the electromagnetic waves used by each satellite, we can clearly see space in far distant places, as well as the latest activity in our solar system, or can obtain information on the ongoing activity/events not only in space, but also from ancient times. By integrating such data, I believe we can discover a new and multifaceted image of space.

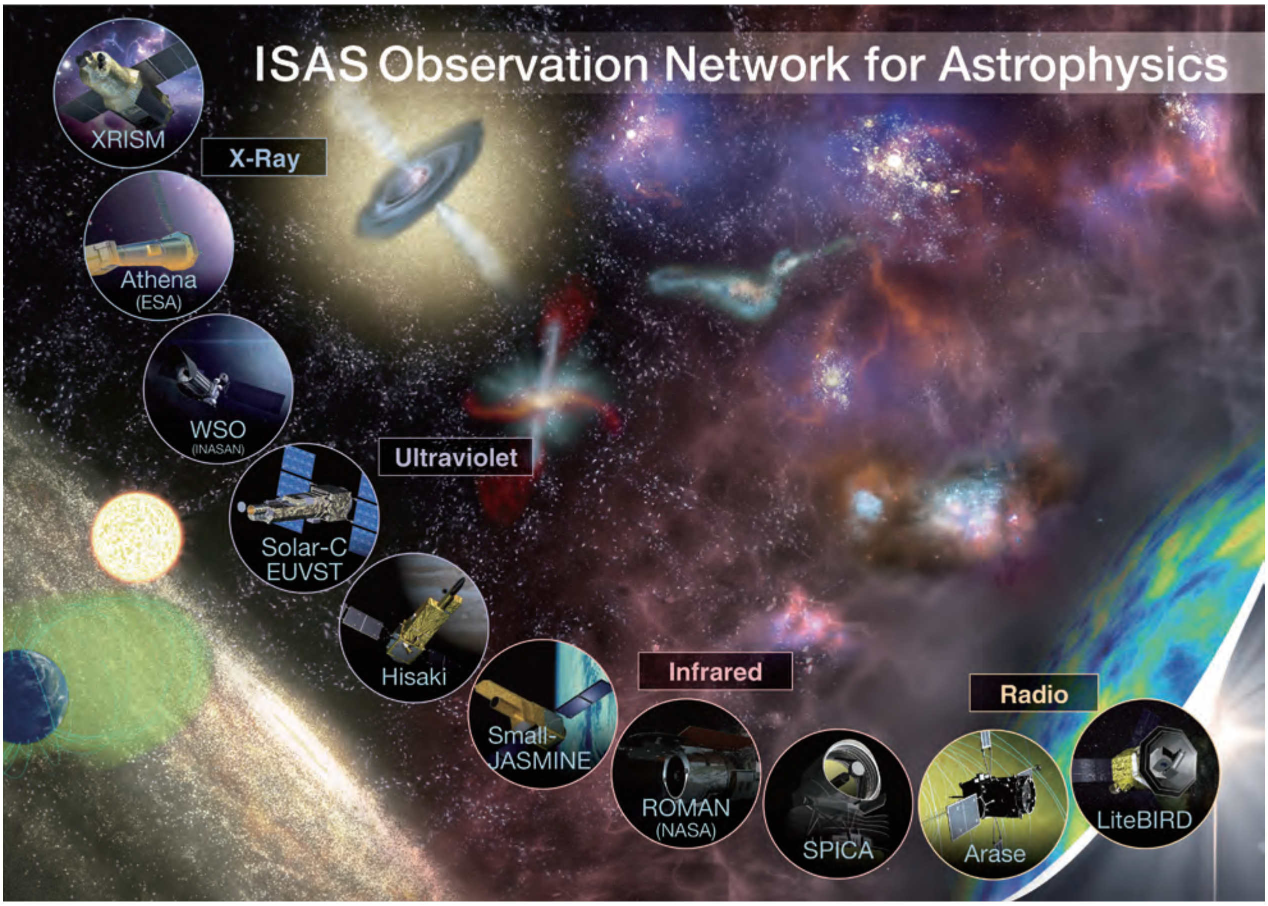
Meanwhile, the deep space exploration fleet in the planetary probe domain is enhancing its activities. BepiColombo/Mio, which was launched in 2018, is cruising toward Mercury. Hayabusa2 successfully made an artificial crater on the asteroid Ryugu in April 2019 and executed its second landing in July of the same year. Its onboard ion engines will make a powered flight toward Earth from November 2020 (as of October 2020). The Smart Lander for Investigating Moon, SLIM, has broken through the big technical difficulty called the system firing test connecting the main thrusters and auxiliary thrusters. There is also the Martian Moons eXploration (MMX) and the farther space exploration technology demonstration mission DESTINY$^+$, both of which were organized as a project/pre-project team and then proceeded into the full-scale development stage. The production of the component of Jupiter Icy Moons Explorer (JUICE) for Ganymede is also proceeding smoothly. The development of the deep space tracking station Misasa (a large parabolic antenna of 54 m in size) for deep space exploration is also advancing, and we also expect another success, that is, the reception of the X/Ka communication bands from Hayabusa2.

In parallel with this brilliant progress and noble future design, we've adapted to some undesirable outcomes during this fiscal year. The Comet Astrobiology Exploration sAmple Return (CAESAR) project, which was examined as NASA's solar system exploration New Frontiers Program No. 4, was rejected in June 2019. But ISAS has also been cooperating with the US team to supply an Earth reentry vehicle based on the achievements of HAYABUSA and Hayabusa2, and on the ongoing development for the MMX (Martian Moons eXploration). I would like to express my appreciation to the US team, for trusting ISAS's technology and R&D capabilities for the reentry capsule and leaving a very important task to ISAS. CAESAR would have been an important plan to enact part of our manifesto, "periodical sample return", but I am nonetheless deeply impressed by the high expectations that the world has of ISAS.

Furthermore, the results of the primary selection for NASA's Astrophysics Mission of Opportunity were announced in March 2020, and unfortunately none of LiteBIRD, JASMINE, and SPICA was adopted. Because these plans request contributions from the US, the results of this non-adoption invite temporary stagnation. As the funding was competitive, we understand that it was not practical for all the plans to be adopted. Because the bottom-up approach is a major principle of mission selection in Japan, ISAS cannot control each group and have them apply for a competitive funding frame. Although NASA canceled the adoption of these projects in the Astrophysics Mission of Opportunity, fortunately they did show an active posture toward cooperation/collaboration with ISAS in the future through strategic talks with ISAS. In addition to the bottom-up process, I believe that it will be possible to build effective space science if we can implement a mechanism for the process of coordination between space agencies. I also believe that this suggests the need to reduce foreign dependence, and that Japan should be able to promote our own space missions more autonomously, in terms of the planning, development, and operations. I had previously instructed the strict observance of cost caps of 30 billion yen/15 billion yen, but now I would like to propose new ideas, such as reconsideration or flexibility of the cost caps, strategic mission selection besides the bottom-up process, an ISAS-led down-selection, and technology development through front loading, and so on. I am pushing the implementation of these measures forward in both the Advisory Committee for Space Science and the Advisory Committee for Space Engineering.

Finally, I would like to express my gratitude and appreciation for your continued support and encouragement for ISAS's activities. Thank you.

KUNINAKA Hitoshi
Director General of ISAS/JAXA
October 2020



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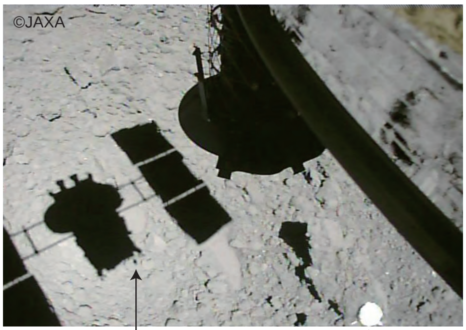
ON THE COVER

Hayabusa2: The moment of the target marker separation

This is an image of the moment the target marker (a mark for landing operations) was separated from an altitude of about 8m above the asteroid Ryugu for the second touchdown of Hayabusa2. It was taken on May 30, 2019, at 11:18 (on board, JST) by a small monitor camera (CAM-H) installed by a donation. The black silhouette in the center is the tip of the sampler horn, and the object that resembles a white ball in the lower right is the target marker. The shadow of the spacecraft is on the surface of the asteroid and, if you look closely, you can see the shadow of the target marker just below the shadow of the main body. We were able to land the target marker within the planned touchdown area. The touchdown was executed on July 11, 2019. The landing accuracy reached 60cm, and this touchdown achieved the world's first landing at two points on the same celestial body.



Shadow of the target marker. Target marker.

BACK COVER

The Picture in-flight from the Around View Camera on S-310-F45

The camera that recorded around the rocket, S-310-F45, in flight was installed for the extensive use of consumer products in space. It is possible to check the status of the mission in progress from the ground by pictures, and it is an important device that we would like to utilize more in future experiments.

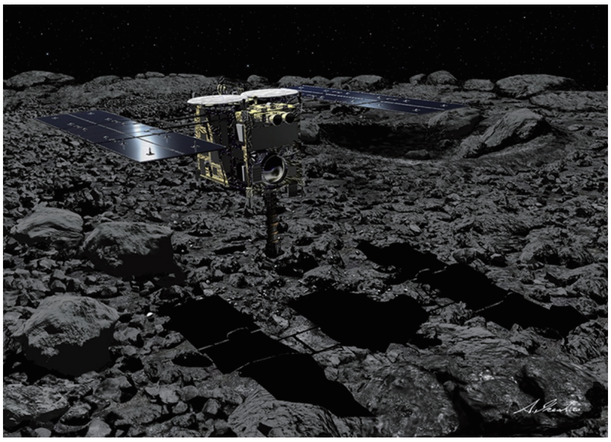
I

Scientific Highlights in FY2019

Asteroid Explorer Hayabusa2

The asteroid explorer Hayabusa2 was launched on December 3, 2014, aiming to collect the world's first samples form a C-type asteroid and bring them back to earth in order to explore the origin of water and organic matter. Continuing from 2018, in 2019 we achieved many results and completed all missions planned for the asteroid. Hayabusa2 left asteroid Ryugu in November 2019, and is now aiming to return to the earth at the end of 2020.

Leaving Ryugu heading for Earth. The moment of joy for command around 10:20 am on November 13, 2019 in the operation room of JAXA Sagamihara Campus.
©ISAS/JAXA



An image of the 2nd touchdown.
©Akihiro Ikeshita

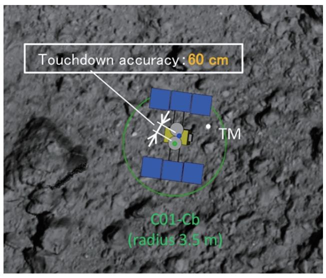
Successful Creation of an Artificial Crater and the Second Touchdown

Hayabusa2 succeeded in creating an artificial crater using the small carry-on impactor (SCI) in April 2019. In July, the second touchdown (the first touchdown was in February 2019) was performed near the artificial crater, and a sample containing subsurface materials was successfully collected. In September, we separated two target markers, and, in October, separated MINERVA-II2 and succeeded in making these small objects satellites around Ryugu and observed their orbital motions.

Seven world firsts!

In terms of engineering, we have achieved seven "world firsts" by combining the two achievements in FY2018. We were able to obtain results that far exceeded our initial expectations.

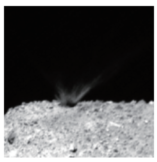
1) Mobile exploration of a small celestial body by small exploration robots (FY2018)
2) Dropping and deploying multiple exploration robots on a small body (FY2018)
3) Realization of celestial landing with accuracy of 60 cm (July 2019)
4) Creation of an artificial crater and detailed observation of its creation process (April 2019)
5) Landing on two places on the same celestial body (1st time: February 2019, 2nd time: July 2019)
6) Access to underground materials on a celestial body farther than the moon (July 2019)
7) Realization of the smallest and multiple satellites orbiting a small body (October 2019)



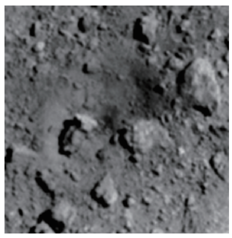
3) Realization of celestial landing with the accuracy of 60cm.

4) Creation of an artificial crater and detailed observation of its creation process

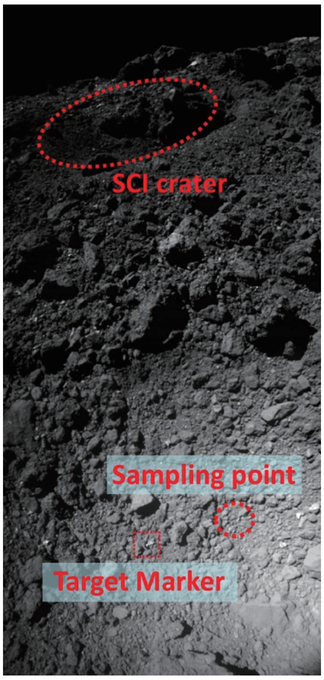
SCI taken by ONC-W1 immediately after separation



Ejecta curtain from the surface of Ryugu.



Artificial crater generated by SCI.



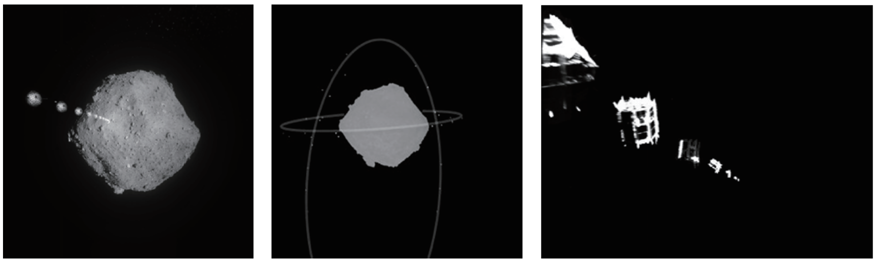
5) Landing in two places on the same celestial body.

2nd touchdown point and artificial crater.

6) Access to underground materials on a celestial body farther than the moon.

Deposits around artificial crater.

7) Realization of the smallest and multiple satellites orbiting around a small body.



Research Results and Awards for Hayabusa2

1. T. Okada *et al. Nature,* 16 Mar 2020: Vol. 579, pp.518-522 DOI:10.1038/s41586-020-2102-6
2. M. Arakawa *et al. Science,* 19 Mar 2020: Vol.386 (6486), pp.67-71 DOI:10.1126/science.aaz1701
3. S. Kikuchi: Construction of orbit and attitude dynamics theory in strong perturbation environment near small bodies, *The 12th Space Science Encouragement Award*
4. T. Saiki, H. Sawada, S. Matsuzaki: Realization of underground excavation technology for a distant celestial body by an artificial impactor, *The 52nd Ichimura Science Award*

＊For details on 1-4, see pp.4-7.
＊For other awards, see [VI. Awards] (pp.121-123).

News about Hayabusa2

"Prologue Hayabusa2 Challenge" and "Vol.3 Hayabusa2 Approaching the Roots of Earth Life" were broadcast on the special program "NHK Special Space Spectacle" series by the Japan Broadcasting Corporation (NHK). The former was awarded the Minister of Education, Culture, Sports, Science and Technology Award (education and liberal arts category) at the 61st Science and Technology Festival. The paper on artificial craters (Arakawa et al.) published in Science magazine is attracting attention not only in Japan but also in foreign media such as CNN and The New York Times.

Brian May, the guitarist for British rock band Queen and a Ph.D. in astrophysics, has been very interested in Hayabusa2, and he provided to Hayabusa2 project new stereoscopic images when Hayabusa2 left Ryugu (November 13, 2019). Below is a stereoscopic view of the image released from the project as "Goodbye, Ryugu!"

Stereoscopic image of "Goodbye, Ryugu" by Brian May.

From left: Patrick Michel, TSUDA Yuichi (Project Manager), Brian May, and YOSHIKAWA Makoto (Mission Manager).

Highly Porous Nature of Primitive Asteroids Revealed by Thermal Imaging

【Asteroid Explorer Hayabusa2】

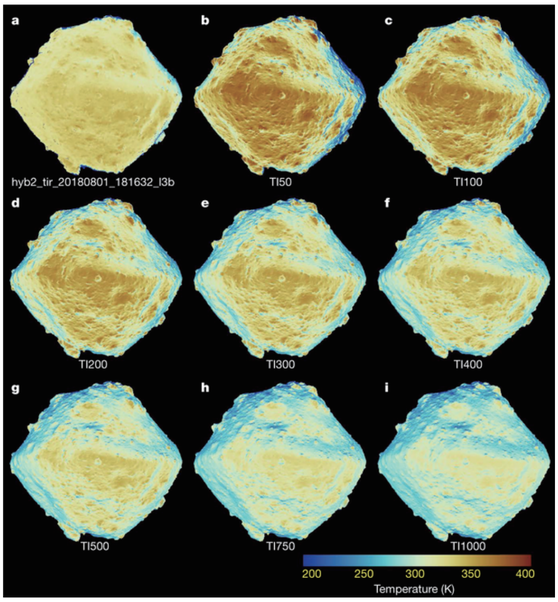
C-type (or carbonaceous) asteroids are the most common type of asteroids and mainly distributed beyond the snow line, the outer half of the asteroid main belt between Mars and Jupiter, considered to be rich in water and organics. They are relics of the early Solar System because their formation are key in understanding the evolution of the Solar System. However, the physical properties of C-type asteroids remain poorly known.

The first C-type asteroid visited and explored by spacecraft is the near-Earth asteroid 162173 Ryugu by JAXA asteroid explorer Hayabusa2. After arrival on 27 June 2018, Haybusa2 began observations from the home position, 20 km from Ryugu, to characterize the asteroid. A thermal infrared imager (TIR) has taken thermographic images of the asteroid to investigate its thermophysical properties.

The first global high-resolution thermal images of an asteroid in history were taken by TIR for one rotation on 30 June 2018. Higher resolution one-rotation global thermal images were taken by TIR from a 5 km altitude, with the spatial resolution of 4.5 m per pixel, on 1 August 2018 during the Mid-Altitude Observation Campaign. We compared the diurnal temperature profiles of Ryugu and the calculated thermal images assuming uniform thermal inertias (TI) of 50 to 1000 J K^{-1} m^{-2} $s^{-0.5}$ (tiu, hereafter), and derived the averaged TI of 300 ± 100 tiu (see Figure). This value is much smaller than the typical TI of carbonaceous meteorites (600-1000 tiu), indicating porous materials. Contrary to the predicted surface covered with dense boulders (high TI) on a granular regolith layer (low TI), it was surprising that the boulders and surroundings showed the same thermophysical properties.

The first close-up thermal images of the asteroid were taken during descent operations. The surface was covered with boulders and fragments of rock mainly larger than 10 cm in diameter but with almost no dust. Most boulders and rock fragments show low TI, similar to global observations, but there were a few “cold spots” found, boulders colder than their surroundings, showing TI of 600-1000 tiu, indicating typical carbonaceous chondrite meteorites. This result is consistent with *in situ* images taken by CAM and *in situ* thermal radiometry of a single boulder by MARA on the MASCOT lander.

The formation scenario for Ryugu has been updated. Highly porous planetesimals were formed by coagulation of fluffy cosmic dust, followed by formation of larger parent bodies of asteroids. Most parts of them remained porous and at a low degree of consolidation, except for the innermost core region. Fragmentation of parent bodies by large impacts resulted in the formation of rubble-pile asteroids that were formed from fragments of porous materials. This highly porous nature should be shared with primitive bodies and should affect the planetary formation process. The very low TI and low density can be also explained by carbon-rich materials, a question that will be answered upon sample return.



A thermal image of Ryugu taken on 1 August 2018 from a 5 km altitude in **a**, compared with calculated thermal images with uniform thermal inertia of 50 to 1000 tiu in **b-i**.

- T. Okada *et al.* “Highly porous nature of a primitive asteroid revealed by thermal imaging”. *Nature.* 2020, 579, 518-522. DOI:10.1038/s41586-020-2102-6.

In-situ Observation of Space Collision Experiment on Asteroid Ryugu with Small Carry-on Impactor SCI and Deployable Camera DCAM3

【Asteroid Explorer Hayabusa2】

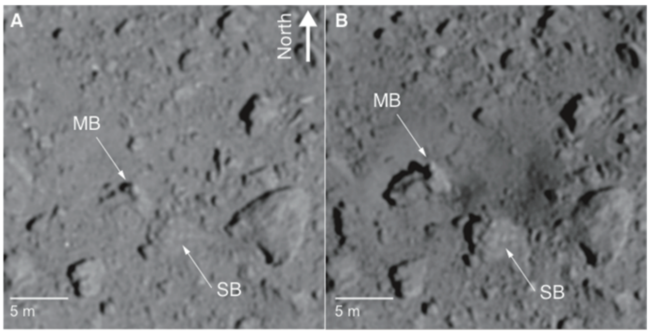
The Small Carry-on Impactor (SCI), a small-sized onboard impactor equipped on the Hayabusa2, was designed to collide a 2kg piece of copper with Ryugu at a speed of 2km/s to form an artificial crater. With this experiment, we would obtain realistic data that is not a simulation and, by exposing underground materials to the surface, we would obtain subsurface materials.

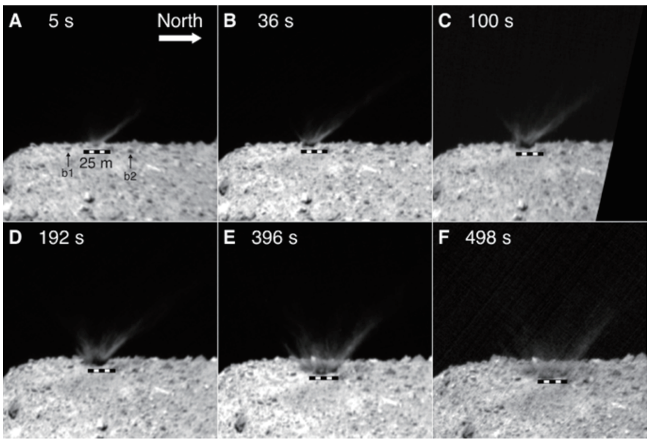
The SCI operation was conducted on April 5, 2019, and the collision ejecta ejected from the surface of Ryugu was observed by DCAM3 (Deployable Camera 3). The topography after the collision was observed by telescopic optical navigation camera (telephoto) ONC-T about 3 weeks later. We found an artificial crater of about 15m in diameter. The SCI experiment was quite successful.

Iijima rock (MB) inside the artificial crater (Omusubikororin SCI crater) moved about 3m to the northwest, but Okamoto rock (SB) did not move, so SB was buried deeper than the bottom of the artificial crater. A pit in the center (a dent with a diameter of 3m and a depth of 60cm) suggests the existence of a layer with a cohesive force of 140 to 670Pa below the surface regolith layer. From the observation of the artificial crater wall, it was estimated that the subterranean layer was mainly composed of rock mass of less than 20cm.

DCAM3 observed ejecta for more than 8 minutes from the moment of collision, showing that the ejector curtain grew to the north, while ejectors to the south were few. The heterogeneous ejecta pattern (ray) may be formed by rock mass of 0.6m or more that existed on the surface before the collision. The distribution of the surface reflectance-decreased region following the ejector ray collision revealed that the underground material had a lower reflectance than the average Ryugu surface. Since no separation of the ejecta curtain from the surface was observed, it was concluded that the structure of the artificial crater and the ejecta curtain was formed in the gravity-dominated regime.

The crater radius expected from the conventional scaling law for typical sand is 6.9 to 7.7m, which is close to the observed artificial crater radius of 7.3m, so the Ryugu surface has no sticking force like sand. This result influences the interpretation of the crater age of Ryugu, supporting the young surface age of 8.9 million years shown in previous research, and that the crater retention age of the top 1m of Ryugu is younger than about 100,000 years.





(above) ONC-T image. Ryugu surface before SCI operation (A), Artificial crater formed after operation (B). (below) DCAM 3 image. Time difference from SCI operation is 5 seconds (A), 36 seconds (B), 100 seconds (C), 192 seconds (D), 396 seconds (E), 498 seconds (F). （M. Arakawa, *et al.* Science 2020）

- M. Arakawa *et al.* “An artificial impact on the asteroid (162173) Ryugu formed a crater in the gravity-dominated regime”. *Science.* 2020, 368 (6486), 67-71. DOI: 10.1126/-science.aaz1701.

High-fidelity Simulations of Spacecraft Orbital Motion Around Small Bodies

【Asteroid Explorer Hayabusa2】

The orbital motion of spacecraft in the vicinity of small bodies, such as asteroids and comets, is strongly disturbed and exhibits complex behaviors because of weak gravitational force. It is therefore essential to precisely analyze the orbital motion of spacecraft around a target body for successful small-body missions. To perform high-fidelity trajectory analyses, mathematical models were developed to precisely describe complex orbital motions of spacecraft and complex gravitational fields of small bodies. Consequently, the basic framework to design various types of orbits around small bodies in accordance with different mission requirements was successfully established, such as stable station-keeping orbits and high-precision landing trajectories.

Examples of mission applications include the Hayabusa2 precision landing on the asteroid Ryugu. One of the unexpected characteristics of Ryugu revealed after the arrival of Hayabusa2 was its high abundance of boulders. To avoid hazardous boulders and guarantee spacecraft safety, high-precision landing with an accuracy of 3 m was required for the Hayabusa2 touchdown operation. For this reason, high-fidelity numerical simulations were performed for 100,000 cases and a landing dispersion on the asteroid surface was computed (Fig. 1). As a result, it was demonstrated that the landing operation for Hayabusa2 is feasible, even though the required accuracy was extremely high. Based on the designed trajectories, Hayabusa2 successfully landed on Ryugu in February and July of 2019. Post hoc trajectory analyses clarified that the achieved landing accuracy was 1 m for the first touchdown and 60 cm for the second touchdown (Fig. 2). This work therefore contributes to unprecedented high-precision landing of Hayabusa2 and subsequent sampling of Ryugu surface materials, which will be returned to Earth by the end of 2020. These results demonstrate the efficacy and validity of our high-fidelity trajectory simulations. Consequently, this research expands the capabilities of future small-body missions from both engineering and scientific standpoints.

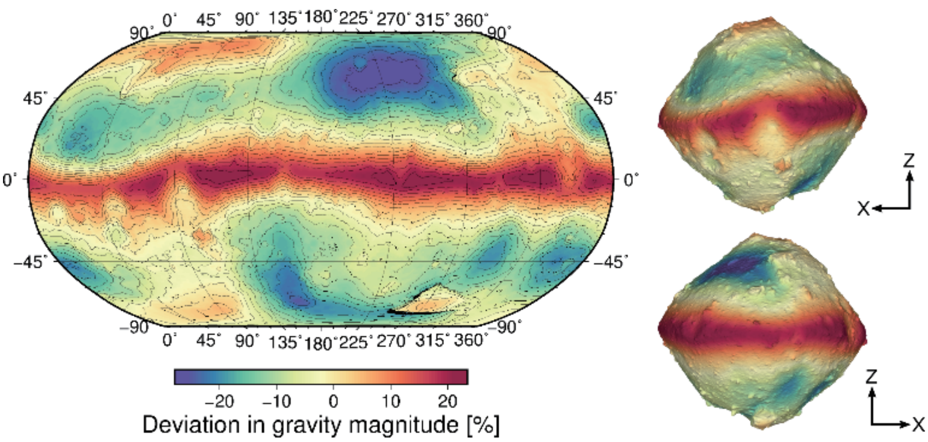


Fig.1. Gravity field of the asteroid Ryugu. The deviation in the magnitude of surface gravity relative to the point-mass model.

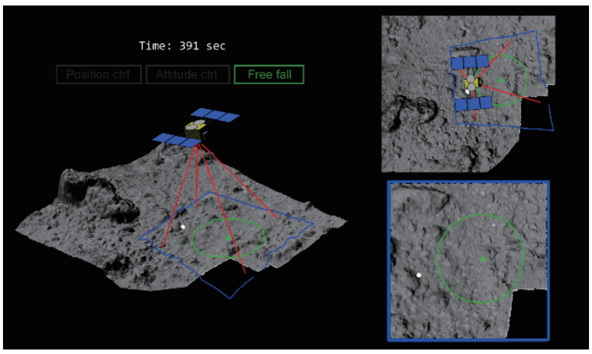


Fig. 2. Simulation for the Hayabusa2 landing operation.

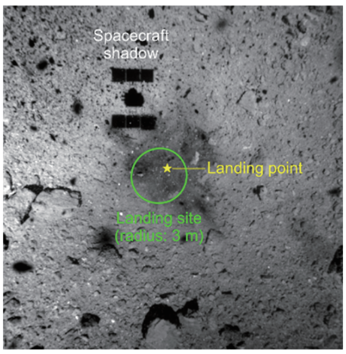


Fig. 3. Optical image of the landing site obtained immediately after the first touchdown.
(©JAXA, University of Tokyo, Kochi University, Rikkyo University, Nagoya University, Chiba Institute of Technology, Meiji University, University of Aizu, AIST)

- S. Kikuchi. "Construction of orbit and attitude dynamics theory in strong perturbation environment near small bodies". *Society for Promotion of Space Science: The 12th Space Science Encouragement Award.*
- S. Kikuchi *et al.* "Design and Reconstruction of the Hayabusa2 Precision Landing on Ryugu". *Journal of Spacecraft and Rockets, in press (available online). DOI:10.2514/1.A34683*

Hayabusa2 Kinetic Impact Experiment and Subsurface Sample Collection

【Asteroid Explorer Hayabusa2】

Hayabusa2 is a Japanese interplanetary probe launched on December 3, 2014, which arrived at asteroid Ryugu on June 27, 2018. During its stay around Ryugu, it completed several challenging operations, including deploying two rovers and a lander, conducting two sample collections, and performing a kinetic impact experiment.

Investigating the chemical and physical properties of the "internal" materials and structures is a new challenge in the Hayabusa2 mission. The surface of asteroids have been "space weathered" by millions or billions of years of exposure to solar heating, solar wind, and cosmic rays. However, subsurface materials are believed to be protected from space weathering and to hold clues as to the chemistry of an asteroid's past.

We developed a new component called the Small Carry-on Impactor (SCI) to enable sub-surface exploration and sampling of unaltered material. The SCI is a compact kinetic impact system to create an artificial crater on the asteroid surface. It is deployed from the Hayabusa2 spacecraft over the asteroid's surface and shoots a 2 kg copper projectile at the asteroid. An explosive propellant charge in the SCI accelerates the projectile up to 2000 m/s in less than 1 ms.

The SCI impact operation was conducted on April 4-5, 2019. The spacecraft started its descent on April 4, 2019, at 4:00UT, reached the minimum altitude of approximately 500 m at 1:42UT on April 5, and the SCI was released at 1:56UT (Fig. 1). About 20 minutes later, the spacecraft deployed a small camera called DCAM3 (Deployable CAMera 3. The DCAM3 was developed to observe the impact phenomenon on behalf of the Hayabusa2 spacecraft.

The impact occurred at 2:36:10UT. The impactor hit the asteroid surface, and the DCAM3 successfully observed the impact event at a distance of approximately 1 km from the impact point. In the obtained DCAM3 data a bright ejecta curtain of 40 meters or more in height was observed.

A round-shaped crater was confirmed during the law altitude observation operation on April 25, 2019. The diameter was about 10 meters, and the depth of the crater was estimated to be about 2.7 m.

The second touchdown to collect subsurface material exposed by the impact was conducted on July 10-12, 2019. The spacecraft succeeded in the touchdown and sampling from the vicinity of the resultant crater.

All the critical activities planned in the proximity operation were completed, and Hayabusa2 left Ryugu on November 13, 2019. It will return to Earth at the end of 2020.

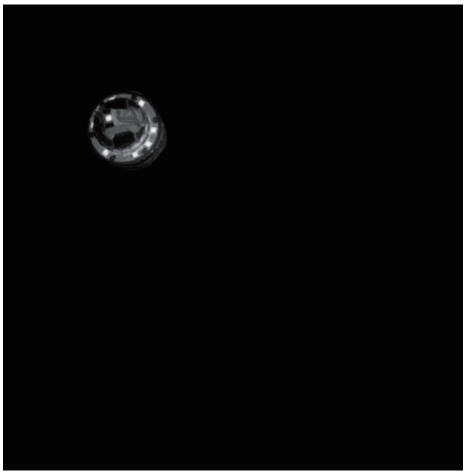


Fig. 1. The SCI captured with the onboard camera. It was released at 1:56UT on Apr. 5, 2019.

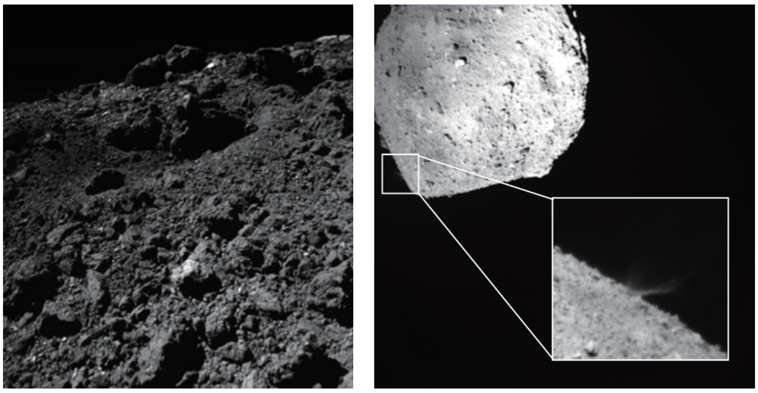


Fig. 2. Artificial crater (left). The diameter of the crater was estimated to be about 15 m. Image from DCAM3 (right). It was taken 3 sec after the impact and impact ejecta was observed.

- T. Saiki, H. Sawada, and S. Matsuzaki. "Realization of underground excavation technology for a distant celestial body by an artificial impactor". *Ichimura Foundation for New Technology: The 52nd Ichimura Prize in Science*. 2020.

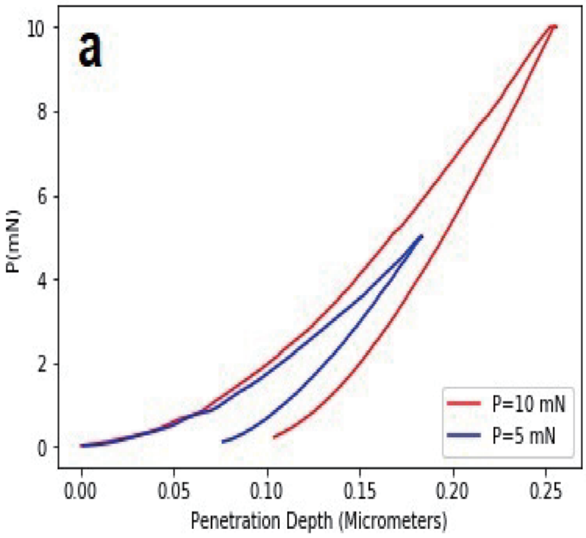
New Clues to Regolith Properties and Ancient Water on Asteroid 25143 Itokawa

【Asteroid Explorer HAYABUSA】

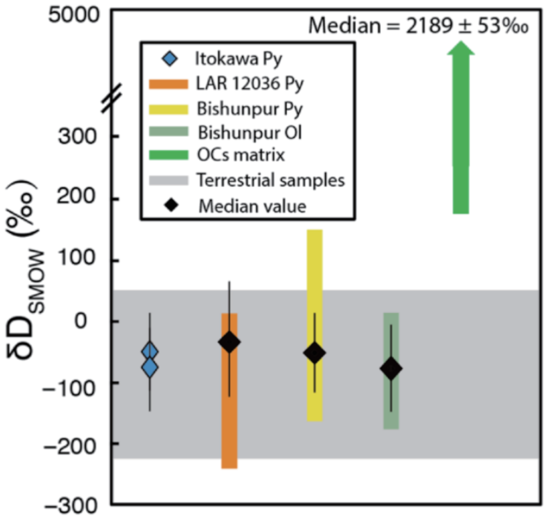
The HAYABUSA mission collected thousands of micrometer-sized particles from the regolith of asteroid 25143 Itokawa. State-of-the-art geophysical and geochemical analyses of Itokawa particles have revealed the history of Itokawa, regolith properties of asteroids, and their contributions to the volatile inventories of the terrestrial planets.

Tanbakouei *et al.* (2019) report the mechanical properties (e.g., Young's modulus) of three of the Itokawa particles using a precise technique called nanoindentation. The reduced Young's modulus values obtained for the Itokawa samples are higher than those measured for the Chelyabinsk chondrite, suggesting that asteroid regolith is more compact than typical chondrite-forming, organic-bearing mineral aggregates. This difference in the Young's modulus values may be a natural consequence of particles surviving long exposure times on the surface of an NEA (near-Earth asteroid).

Jin *et al.* (2019) performed the first measurements of the hydrogen isotopic composition and water abundances of nominally anhydrous minerals in the HAYABUSA samples. These Itokawa minerals contain 698-988 ppm of water-equivalent hydrogen, inferring that the bulk-silicate Itokawa parent body originally had 160-510 ppm of water. The hydrogen isotopic compositions of Itokawa samples are indistinguishable from those of chondritic meteorites, achondrites, and terrestrial rocks. This isotopic consistency invokes a common origin of the water in these bodies, and further implies that NEAs including Itokawa were a potential source of water during the formation of Earth and other terrestrial planets.



Young's modulas values obtained by the measurement of Itokawa grains (Tanbakouei *et al.* 2019, *A&A* 629, A119 (2019) fig. 2. (a)).

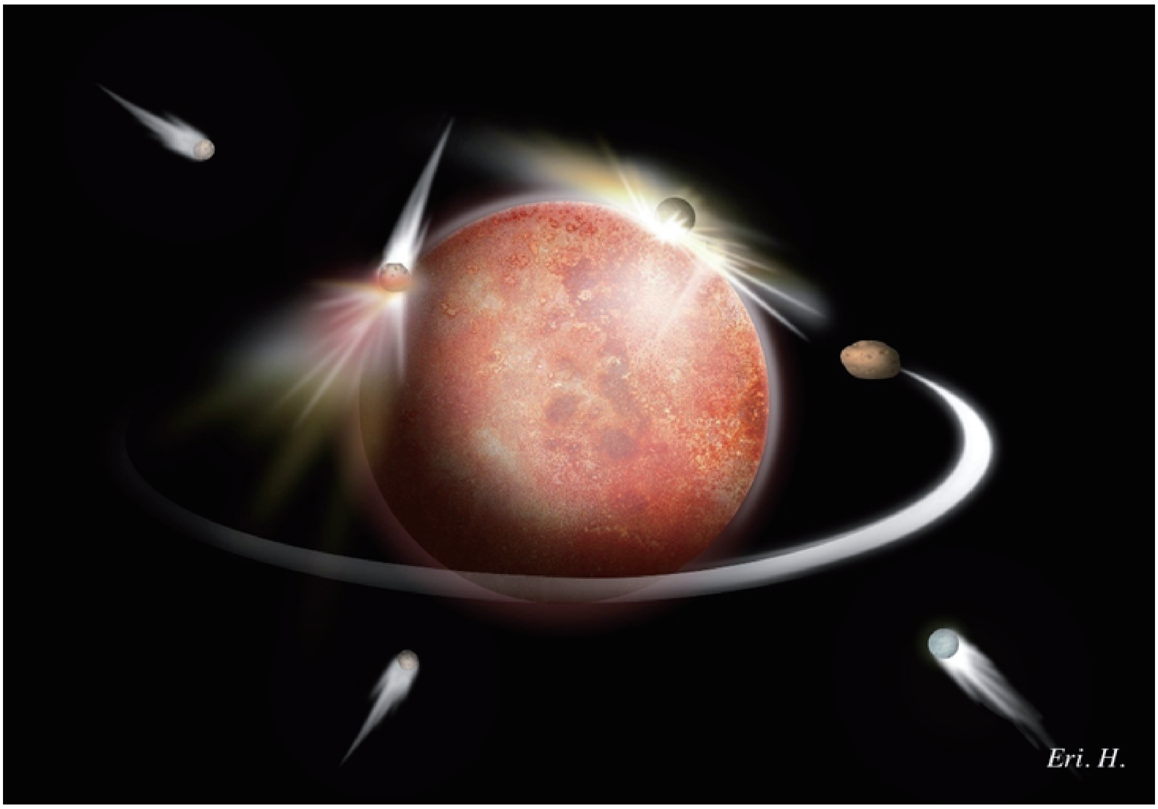


Hydrogen isotopic compositions of Itokawa particles and minerals in chondrites (Jin and Bose, *Sci. Adv.*, 5, eaav8106 (2019) fig.4).

- S. Tanbakouei *et al.* “Mechanical properties of particles from the surface of asteroid 25143 Itokawa”, *Astronomy & Astrophysics*. 2019, 629, A119. DOI: 10.1051/0004-6361/201935380.
- Z. Jin *et al.* "New clues to ancient water on Itokawa", *Science Advances*. 2019, 5 (5), eaav8106. DOI:10.1126 /sciadv.aav810.

Extensive Delivery of Impact Ejecta from Mars to Its Moon Phobos

【Martian Moons eXploration (MMX)】



A schematic figure of numerous impacts on Mars and transportation of the impact ejecta from Mars to Phobos. Impacts occur randomly on the surface of Mars and the Mars ejecta mixed in the regolith of Phobos likely covers all Martian geological eras and consists of all types of rocks, from sedimentary to igneous.

Mars has two small moons, Phobos and Demos. Phobos has been selected as a target body for the JAXA Martian Moons eXploration (MMX) mission, whose launch is scheduled in 2024. MMX is a sample return mission to Earth that plans to collect surface materials from Phobos.

After the formation of Mars, Mars has continuously experienced asteroidal impacts. These impacts have produced impact ejecta originating from the surface of Mars, and a fraction of the impact-ejecta is delivered to Phobos and Deimos. Phobos is closer to Mars and larger than Deimos and more impact-ejecta is transferred from Mars to Phobos than to Deimos.

High-resolution simulations of a variety of impacts of small bodies to Mars were performed and the resultant impact ejecta distributions were obtained for different impact conditions. Then, detailed trajectory analysis of the impact ejecta was performed to statistically evaluate the mass and conditions of the impact ejecta reaching Phobos.

These state-of-the-art numerical approaches showed that materials delivered from Mars to Phobos were much less shocked/altered than Martian meteorites and were homogeneously mixed in the regolith of Phobos. The total amount of delivery of Mars materials to Phobos surface has been updated to about 10 to 100 times larger than the previous estimation that used a simple calculation. Numerical simulations showed that Mars ejecta on Phobos surface (i.e., potential sample materials of the MMX mission) covers all its geological eras and consists of all types of rocks, from sedimentary to igneous, which would provide us a wealth of "time-resolved" geochemical information about the evolution of Martian surface environments.

In the 2020s, NASA-ESA-led Mars sample-return (MSR) missions are also planned for a specific crater Jezero Crater on Mars. MMX and MSR missions will both potentially bring Mars samples back to Earth. These independent missions will play essential and complementary roles in revealing the enigmatic history of Mars.

- R. Hyodo *et al.* "Transport of impact ejecta from Mars to its moons as a means to reveal Martian history"*Scientific Reports.* 2019, 9, 19833. DOI: 10.1038/s41598-019-56139-x.

Size Determination of DESTINY$^+$ Target Asteroid Phaethon by Stellar Occultation Observation

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

DESTINY$^+$ is a joint mission for technology demonstration and scientific observation, and is planned to be launched in FY 2024. The goal of the scientific mission is to understand the nature and origin of cosmic dust brought to the Earth, in the context of exogenous contribution of carbon and organics to the origin of terrestrial life. The objectives of the mission are (1) to measure physical properties (velocity, orbit, mass) and the chemical composition of interplanetary and interstellar dust particles around 1 au during the deep space cruising phase, and (2) to conduct geological observation of asteroid Phaethon and analyze dust particles nearby Phaethon during a high-speed flyby (33 km/sec).

Phaethon is a flyby target of the DESTINY$^+$ mission. Since it is a parent body of the Geminids meteor shower and a B-type "active" asteroid, Phaethon is of great importance in provenance of organics-bearing dust delivered to the Earth as meteor shower, and also in a near-sun, dust-ejecting primitive body that shows both cometary and asteroidal natures.

During the close encounter of Phaethon in Dec. 2017, an international observation campaign was conducted to better characterize Phaethon. As a result, the size discrepancy between a thermal IR based estimate (D=4.6 km) and a radar imaging based estimate (D=6 km) was generated and needs to be resolved for mission planning and optical design for the on-board cameras.

Stellar occultation by an asteroid is a useful way to directly determine the size and shape of the asteroid. In 2019, a total of 16 stellar occultation events by Phaethon were predicted and seven observations were conducted across countries (Table). The goal of the stellar occultation observation is to resolve the estimated size discrepancy of Phaethon above and to validate the current orbit of Phaethon. A stellar occultation in July 29 in the southwestern U.S. was an ideal condition where the target is very bright (7th magnitude), the occultation duration is relatively long (0.5 sec), and the sky was clear. The historical success in the 7/29 US observation revealed the size of 5.71 x 4.70 km (cross section upon the occultation timing). As a result, the radar model was shrunk by 3-6%, giving the best fit to the occultation chords. Also, the JPL "Horizons" orbit prediction for Phaethon was validated accurate within a few km. Observation was conducted on 8/21 in Hokkaido and 10/15-16 in Yamagata and Miyagi in Japan. A total of 30 personnel, consisting of DESTINY$^+$ project members, and professional and amateur astronomers joined the observation.

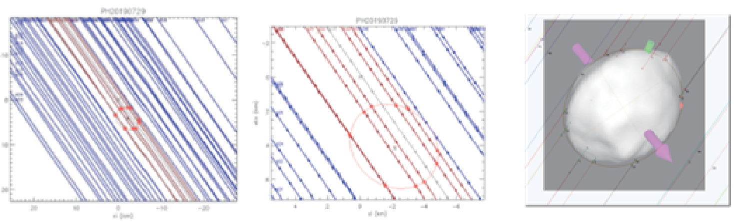


Fig. 1. (a), (b) Observation results of stellar occultation by Phaethon in the south-western U.S. on July 29, 2019. Observations were conducted at 66 sites with a spacing of 680m. Red lines and dots show positive detection and blue ones show negative detection. Fitted ellipse, 5.71 x 4.70 km is consistent with the Arecibo radar result. The prediction is good to <1km cross track (Buie, 2020). (c) The latest 3D shape model of Phaethon Updated shape model (6.4 x 6.2 x 5.2 km), generated based on multiple light curve data and radar observation conducted during the 2017 December close encounter. (Marshall et al., 2020).

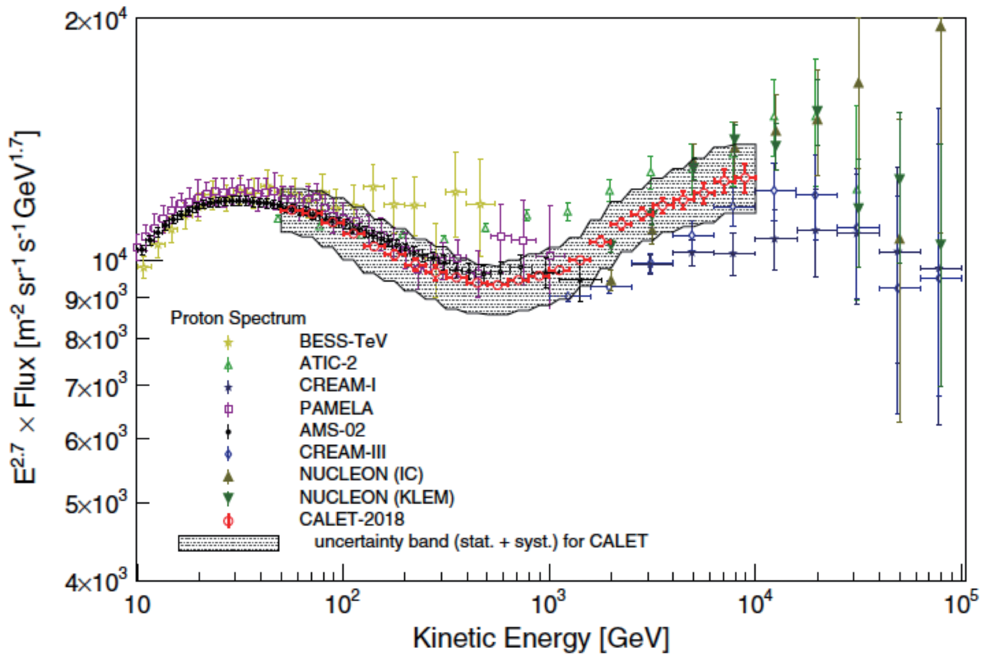
#	Date/Time (UT)	Star Name	Star mag	ΔMag	Duration (sec)	Location
1	**Jul 29, 11:12**	**HIP 24973**	**7.3**	**9.15**	**0.5**	**South western US**
2	**Aug 21, 18:35**	**TYC 3348-474-1**	**11.9**	**5.06**	**0.5**	**Northern Japan, China**
3	Sep 13, 02:01	TYC 3341-00182-1	9.3	7.7	0.4	Scandinavia
4	Sep 14, 06:43	TYC 3340-00407-1	9.7	7.26	0.4	Southern US, Mexico
5	**Sep 29, 04:21**	**UCAC4 721-029705**	**12**	**4.91**	**0.3**	**US, Canada**
6	Oct 07, 18:46	TYC 3687-02011-1	10.2	6.64	0.2	Central Asia, Russia
7	Oct 12, 04:26	TYC 3306-01824-1	10.6	6.19	0.3	Alaska
8	**Oct 12, 06:19**	**TYC 3293-01959-1**	**11.3**	**5.54**	**0.2**	**South eastern US, Mexico**
9	Oct 12, 19:59	UCAC4 712-017758	11.8	4.97	0.2	Russia, Europe, Africa
10	**Oct 15, 17:38**	**TYC 3292-570-1**	**11.5**	**5.3**	**0.2**	**Northern Japan, China**
11	**Oct 15, 19:44**	**UCAC4 707-014626**	**11.1**	**5.71**	**0.2**	**Europe, Africa**
12	Oct 18, 17:22	TYC 3287-01143-1	11	5.8	0.2	Russia, Central Asia
13	Oct 19, 01:16	HIP 8040	9.6	7.21	0.2	Africa
14	**Oct 25, 22:21**	**TYC 3268-00276-1**	**11.3**	**5.58**	**0.2**	**Russia, Europe, Africa**
15	Oct 28, 13:45	UCAC4 678-006094	11.3	5.59	0.2	Australia
16	Nov 10, 15 53.7	UCAC4 643-002256	9.6	7.7	0.3	Indonesia, Philippines
17	Nov 18 16 12.6	UCAC4 624-001265	9.7	7.8	0.3	India, China, Kamchatka

Table. Predicted stellar occultation by Phaethon in 2019. Observation of 7 events in bold was conducted. (Modified from IOTA website. Arai et al. 2020.)

Fig 2. Group photo of the observation team for Aug. 21 Phaethon occultation in Hokkaido. The observation base was located on the campus of Future University Hakodate.

Direct Measurement of Cosmic-ray Proton Spectrum on the ISS

【CALorimetric Electron Telescope (CALET) aboard the ISS Kibo】



The cosmic-ray proton energy spectrum data obtained from the CALET (between 50 GeV and 10 TeV) are shown as red points. The combined statistics and the systematic uncertainties of the CALET data are indicated by a gray band. The data obtained from other recent experiments are superimposed. Physical Review Letters, Vol. 122, 181102 (2019).

The CALorimetric Electron Telescope (CALET) is an international project aimed at revealing the acceleration and propagation mechanisms of cosmic rays, identifying nearby cosmic-ray accelerators, and detecting dark matter through observation of high-energy cosmic-ray electrons and positrons. The CALET started operating in October 2015, and since then it has been performing continuous and precise observations from the Japanese experiment module Kibo, which forms a part of the International Space Station (ISS).

In FY2019, the CALET produced its first results from the analysis of the cosmic-ray protons, using data taken over 1,000 days from October 2015 to August 2018. The determined proton spectrum covers a very wide energy range from 50 GeV to 10 TeV. This is the first time that a single instrument in space covered this wide energy range, which was investigated in most cases in separate subranges by magnetic spectrometers and calorimetric instruments.

The observed spectrum is consistent with the result reported by Alpha Magnetic Spectrometer-02 (AMS-02) but extends to nearly an order of magnitude higher energy. The spectrum shows a very smooth transition of the power-law spectral index above a few hundred GeV, confirming the existence of spectral hardening at a high confidence level by more than 3-sigma and providing evidence of a deviation from a single power law predicted by conventional models of cosmic-ray acceleration and propagation in the Galaxy.

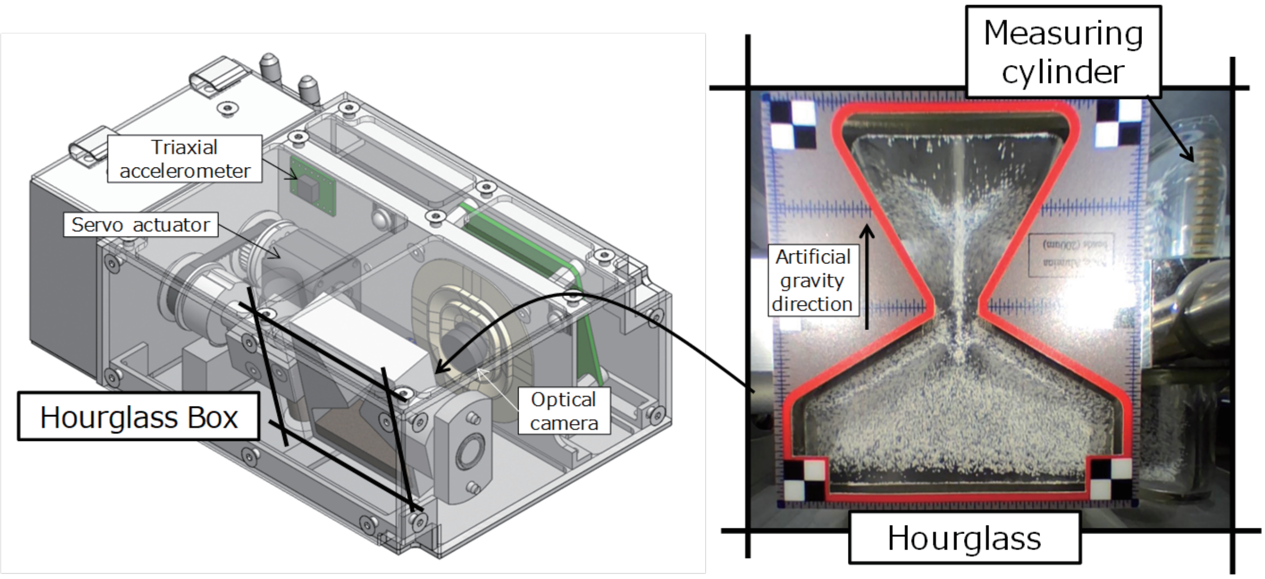
The CALET will continue collecting data on the ISS. Further precise results based on the improved statistics will set more important constraints on the mechanisms of cosmic-ray acceleration and propagation.

The article that reported these results was selected as an Editors' Suggestion of Physical Review Letters.

- O. Adriani *et al.* "Direct Measurement of the Cosmic-Ray Proton Spectrum from 50 GeV to 10 TeV with the Calorimetric Electron Telescope on the International Space Station". *Physical Review Letters.* 2019, 122, 181102. DOI:10.1103/PhysRevLett.122.181102.

Investigation into the Characteristics of Granular Media in Low Gravitational Environment

【Hourglass】



3D CAD Image of the Hourglass Box with hourglass and measuring cylinder (left) and the behavior of alumina beads in low gravity (right)

The Hourglass experiments were partially performed in the artificial gravity generator of the International Space Station (ISS) as a cooperation mission between the Institute of Space and Astronautical Science and Human Spaceflight Technology Directorate. In this experiment, the basic data to obtain the characteristics in low gravity of the granular media for future planetary spacecraft design, and to answer numerical calculations such as DEM and Terra-mechanics model, were obtained. The design, manufacturing, and testing were performed in cooperation with outside university researchers in the short period of less than 1 year from the mission start to the launch, and the expansion of the community and the human resources training were also carried out with a lot of student participation. It was considered that the obtained experimental result contributed to planetary science, spacecraft design, and that it could become strong engineering knowledge in order to construct the complementary relation with other organizations.

In the Hourglass experiments, the behaviors of regolith and ground sand in an arbitrary gravity environment are observed with an artificial gravity generator included in the Cell Biology Experiment Facility (CBEF) in the Kibo module of the ISS. An hourglass-type container and a measuring-cylinder-type container containing particles such as simulated regolith of planets and ground sand are packed into a sealed metal box (see below) mounted on the artificial gravity generator. The behavior of particles is observed with an optical camera while they are periodically reversed under arbitrary low gravity. Eight kinds of specimens are employed as the investigation samples, and dynamic behavior and sedimentation states (bulk density, angle of repose, etc.) of these granular media are evaluated. The Hourglass mission would have the contribution of understanding of the celestial growth process, provision of basic data for the construction of Terra-mechanics on celestial bodies, optimization of design for future landers, exploration rovers, automatic construction machines on the lunar surface, and manned pressurized rovers for lunar exploration, as well as the appeal of the value and ability of the “Kibo” artificial gravity environment. The initial experimental results with 4 boxes revealing the relation between the artificial gravity and the hourglass box, and the composition of the forces acting on the granular media during experiments using artificial gravity generators. The rest of the experiments are scheduled to be conducted in the next fiscal year.

- M. Otsuki *et. al.* “Investigation into the characteristics of granular materials in low gravitational environment (Introduction of Hourglass mission)”. *JpGU-AGU Joint Meeting 2020.*

Unexpectedly Frequent Escape of Molecular Ions from the Earth's Ionosphere

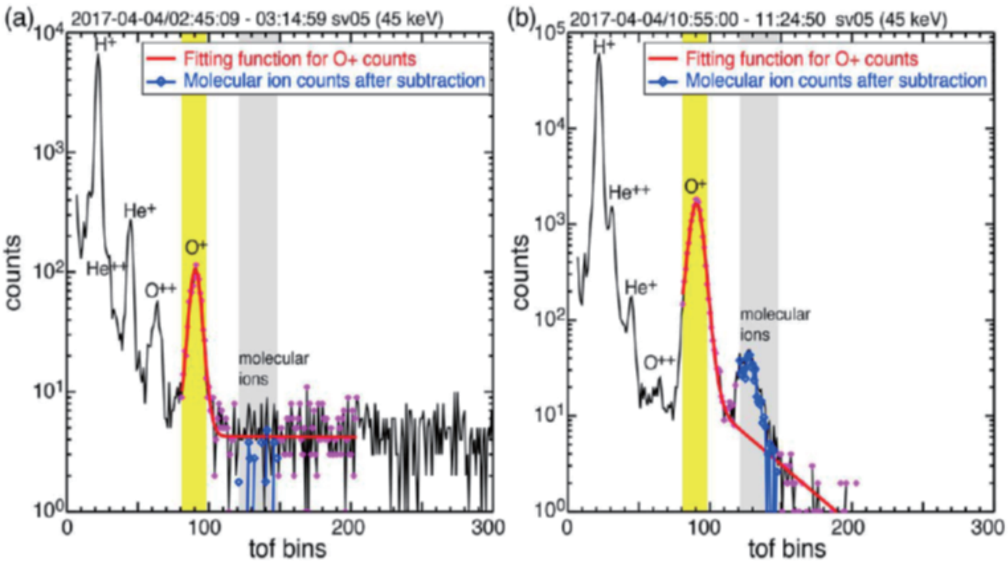
【Geospace Exploration Satellite ARASE (ERG)】

Molecular ions are usually observed only at low altitudes in the ionosphere and cannot escape into space without a fast ion outflow process. Such escape of molecular ions into the magnetosphere had been thought to occur only during strong magnetic storms. However, unexpectedly, observations by the ion mass analyzers onboard the ARASE satellite revealed that molecular ions exist in the magnetosphere even during small storms. This finding suggests that molecular ions may frequently flow out of the low-altitude ionosphere during geomagnetically active periods.

Molecular ions rapidly change to neutral atoms via dissociative recombination within a few minutes after their generation, so they are thought to exist only in the ionosphere below 300 km altitude. Fast ion outflow process is necessary to enable molecular ions to escape into space against the dissociative recombination. It had been thought that such fast ion outflows can only occur during large magnetic storms.

Statistical analysis by using the medium-energy ion mass analyzer (MEP-i) and the low-energy ion mass analyzer (LEP-i) onboard the ARASE satellite from late March 2017 to December 2017 shows that molecular ions are frequently found in the inner magnetosphere even during small magnetic storms, although no O^{2+} / NO^{+} / N^{2+} molecular ions are observed during geomagnetically quiet periods. The average energy density of molecular ions to oxygen ions tends to increase with the magnitude of the magnetic storm.

The frequent presence of molecular ions in the inner magnetosphere, even during small-scale magnetic storms, suggests that higher geomagnetic activity results in the escape of molecular ions from the low-altitude ionosphere into space. In other words, the result indicates that magnetic storms may be a driver of the efficient loss of molecular ions from the Earth's upper atmosphere. The paper was selected as one of the Editor's Highlights in 2019 of Geophysical Research Letters, which is one of the journals published by the American Geophysical Society.



Time-of-Flight (TOF) spectral distributions of 45 keV ions observed by ARASE. (a) a 30-minutes-integrated spectrum during the geomagnetically quiet time on April 4, 2017. (b) a 30-minutes-integrated spectrum at the start of a small magnetic storm on the same day. Molecular ions, which are not seen before the onset of the magnetic storm, are detected during the magnetic storm.

- K. Seki *et al.* “Statistical properties of molecular ions in the ring current observed by the Arase (ERG) satellite”. *Geophysical Research Letters. 2019, 4*6, 8643–8651. DOI: 10.1029/2019GL084163. (Selected as 2019 Geophysical Research Letters Editor’s Highlights)

"Chorus" Waves, Electromagnetic Waves in Space, Control Auroral "Beating"

【Geospace Exploration Satellite ARASE (ERG)】

Cooperative observations with the ARASE satellite and the high-speed auroral imagers deployed in the Arctic region (Northern Europe and Alaska) revealed for the first time that sub-second auroral pulsations observed from ground stations correspond excellently to sub-second modulations of chorus waves excited in geospace.

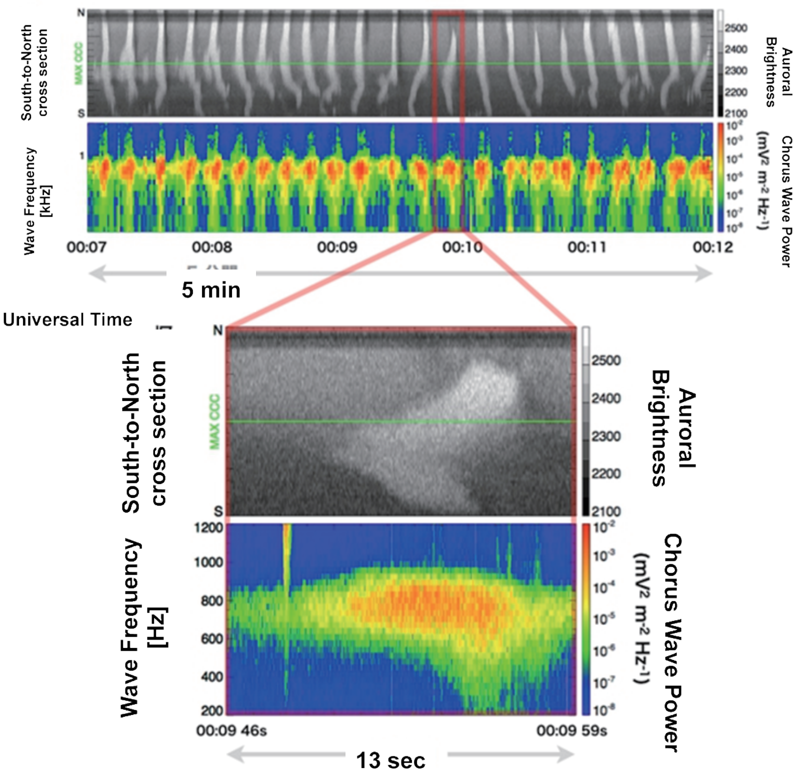
The lack of time-resolution of previous auroral imagers has prevented us from demonstrating that the "chorus" waves are the crucial controlling factor for the sub-second-long auroral "beating."

We have developed a high-speed auroral imager that can acquire a hundred auroral images per second, and simultaneous observations between the ARASE satellite and the high-speed auroral imager on the ground have been carried out to verify the correspondence between the sub-second auroral pulsation and the modulation of chorus waves in space.

During the period when the pulsating aurora appeared over Nordic Finland on March 29, 2017, the ARASE satellite observed periodic changes of the chorus waves in geospace. At the same time, the fast auroral imagers located in Scandinavia and Alaska successfully observed the auroral behavior.

The result of this international collaboration successfully demonstrates that the auroral "beating" and the modulation of the chorus wave perfectly correspond to each other on the order of sub-seconds.

This result not only provides clues to explain the various auroral morphologies but also provides insight into the formation process of the Earth's radiation belts.



An example of a pulsating aurora observed in Northern Finland on 29 March 2017. The two figures in the upper panel demonstrates that the main pulsation of the pulsating aurora (black-and-white) and the temporal variation of the chorus burst (color) are perfectly matched. The lower panel presents a zoomed-in part of the main pulsation and the chorus bursts, which clearly shows that no sub-second beating in the pulsating aurora is observed during the period without the chorus modulation.

- *K. Hosokawa, et al. "Multiple time-scale beats in aurora: precise orchestration via magnetospheric chorus waves". Nature Scientific Reports. 2020, 10, 3380. DOI:10.1038/s41598-020-59642-8.*
- *Joint press release from the University of Electro-Communications et al.* March 2019.

The First Numerical Modeling of Spontaneous Generation of Flare-prolific Sunspots

【Solar Observation Satellite HINODE (SOLAR-B)】

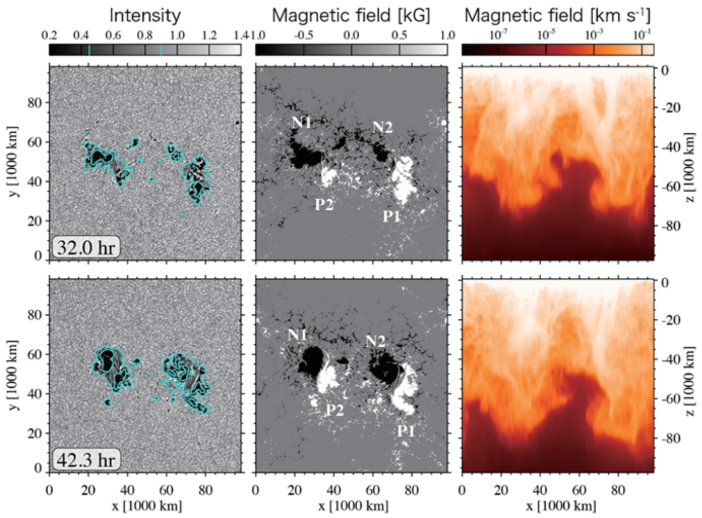


Fig. 1. Generation of delta-spots. From left to right, intensity, magnetic field strength, and field strength on the vertical cross-section. A pair of bipolar spots (P1-N1 and P2-N2) collide to produce delta-spots N1-P2 and N2-P1.

Solar flares and coronal mass ejections, the largest energy-releasing events in our solar system, can potentially cause not only geomagnetic storms and aurorae but even malfunctions in spacecraft and telecommunications. Observations revealed that major flares tend to emanate from complex-shaped sunspot regions. Among others, “delta-sunspots” are known to have caused the strongest events in history and, therefore, their generation has long been one of the fundamental targets of space weather research. In this study, with the strong support of the *K*-supercomputer and state-of-the-art simulation code, we succeed in the first-ever modeling of the spontaneous generation of delta-spots.

To investigate the process that a magnetic flux in the solar interior is elevated by realistic thermal convection, we set a computational box that stretches down to -140 Mm, which is deeper than any previous simulations of this kind, and placed a magnetic flux tube at -16.7 Mm without any artificial triggering of buoyant emergence. It was found that large-scale convective upflows elevate the flux to the solar surface at two sections and produce a pair of emerging bipolar spots (Fig. 1). The spots of opposite polarities collide against each other to eventually generate delta-spots.

Between the positive and negative polarities of the delta-spots, strongly sheared polarity inversion lines are created by rotating motions of the sunspots. Above the polarity inversion line, a helical magnetic structure (magnetic flux rope: Fig. 2) is created. All these structures are the key ingredients of the sunspot regions prone to major flare eruptions, as has been revealed by HINODE and other satellites.

This research unveils how the flare-productive sunspots are generated, which not only opens the door to understanding mysteries in solar physics but also causes significant impacts on the development of space weather forecasting and stellar flare studies. Even more detailed observations and theoretical investigations are expected in the near future with the next-generation solar-observing satellite *Solar-C* and world’s fastest supercomputer *Fugaku*.

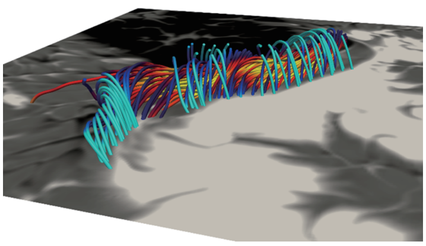


Fig. 2. Strongly twisted magnetic field lines are created in the atmosphere above the delta-spots. This structure is called a magnetic flux rope, which may be ejected into interplanetary space once a flare eruption occurs.

- S. Toriumi *et al*. “Spontaneous Generation of δ-sunspots in Convective Magnetohydrodynamic Simulation of Magnetic Flux Emergence”. *The Astrophysical Journal Letters*. 2019, 886 (1), L21. DOI: 10.3847/2041-8213/ab55e7.

The First Visualization of the Global Structure of Venusian Thermal Tides Excited by Solar Heating

【Venus Climate Orbiter AKATSUKI (PLANET-C)】

AKATSUKI's longwave-infrared camera LIR (sensitive to 8-12 micrometers) successfully visualized, for the first time ever, the global structure of Venusian thermal tides, which are excited by solar heating near the cloud-top levels (~69 km altitude in the Venus atmosphere).

Venus is shrouded by physically/optically thick cloud that is known to absorb a large portion of incoming sunlight, resulting in thermal tides being excited near the cloud-top level. There have been suggestions that thermal tides could be a major contributor to the "unsolved" super-rotation of the Venus atmosphere. However, before LIR, observations were primarily done on the sun-lit hemisphere (mostly in the ultraviolet light), hence our knowledge about thermal tides was limited to only the dayside. By imaging thermal emissions (8-12 micrometers) originating from near the cloud-top, LIR onboard AKATSUKI successfully visualized the global structure of Venusian thermal tides for the first time (Fig. 1). The near-equatorial orbit of the spacecraft also helped this.

LIR becomes more sensitive to emissions from deeper levels as it approaches nadir view. On the other hand, when in slant viewing geometry, emissions from shallower levels are captured. By utilizing such "emission angle dependencies", the team was able to obtain the 3-dimensional structure of the thermal tides (Fig. 2). The temperature variations for three altitude levels, 67.0 km, 67.6 km, and 68.9 km, were mapped and the tilted structure was found from one altitude to another. This is indicative of "vertical propagation" of thermal tides, implying that thermal tides could transfer momentum and energy vertically. This could be observational evidence that thermal tides could certainly be a contributor to maintain the super-rotation of Venusian atmosphere.

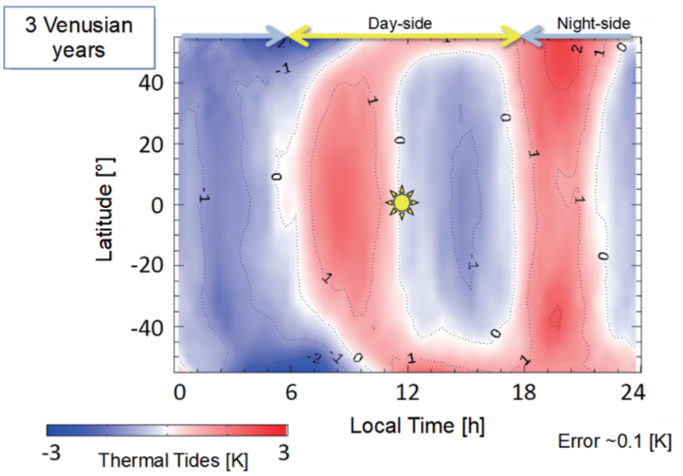


Fig. 1. The temperature variations at the cloud top (±3 K), associated with the thermal tides, are mapped from accumulated LIR observations for 3 Venusian years (3 × 115 earth days).

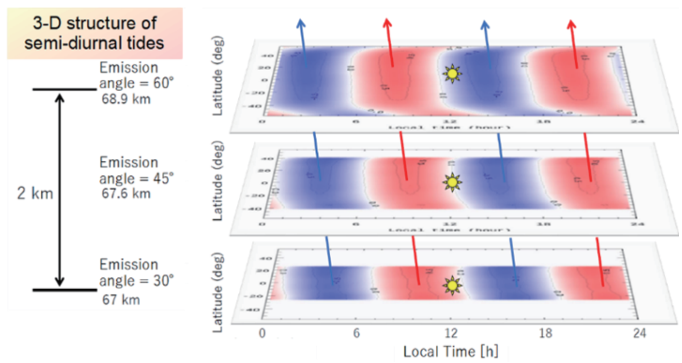


Fig. 2. Three-dimensional structure of thermal tides, for 67.0, 67.6, and 68.9 km, obtained by utilizing the "emission angle dependency" of sensing altitudes. The tilted structure is indicative of vertical propagation of the thermal tides.

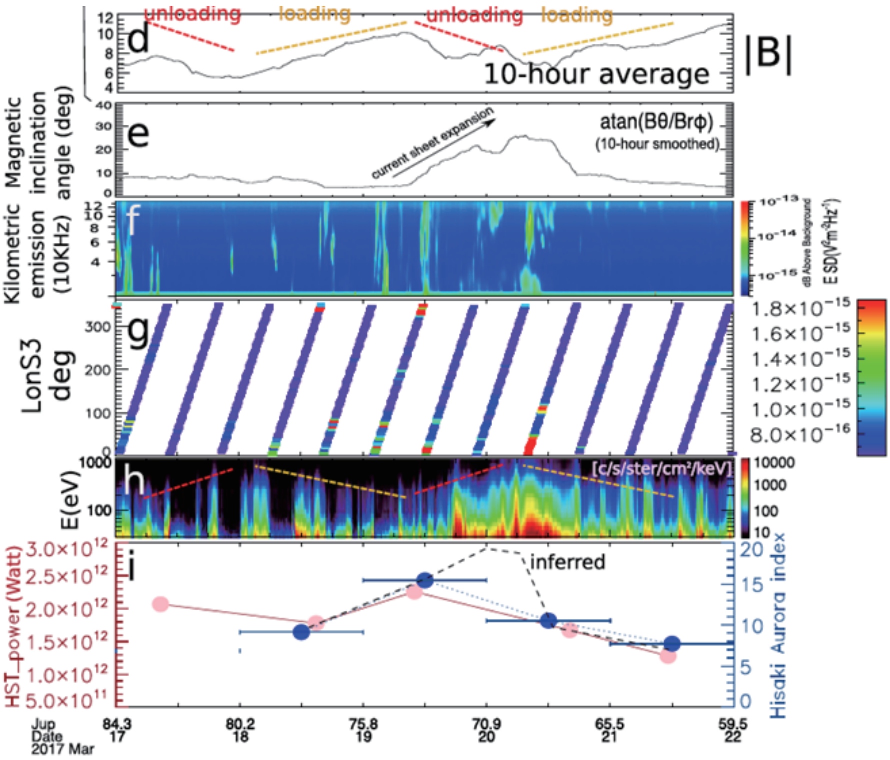
- T. Kouyama *et al.* "Global structure of thermal tides in the upper cloud layer of Venus revealed by LIR onboard Akatsuki". *Geophysical Research Letters. 2019,* 46 (16), 9457-9. DOI: 10.1029/2019GL083820.

Relationship Between Aurora Activity and Plasma Dynamics in Jupiter Magnetospherefrom Simultaneous Measurements by Juno, Hubble Space Telescope, and HISAKI

【Spectroscopic Planet Observatory for Recognition of Interaction of Atmosphere HISAKI (SPRINT-A)】

The in-situ measurements of magnetic fields, particles, and radio waves in Jovian outer magnetosphere by the Jupiter probe Juno and the observations of Jupiter aurora by the Hubble Space Telescope (HST) and the HISAKI satellite are simultaneously performed to comprehensively study Jovian magnetospheric dynamics. Accumulation and release of magnetic flux, named magnetic loading/unloading, correlate well with electron energization and auroral intensifications. It is suggested from the results that the plasma dynamics in the middle magnetosphere are coupled with the aurore variability.

The relationship between Jovian magnetospheric plasma and auroral activity is shown for the first time from the simultaneous observations on March 17 to 22, 2017, which include in-situ measurements of plasma, the magnetic field and radio waves in the outer magnetosphere about 80 RJ (Jupiter radius) to 60 RJ by the Jupiter probe Juno, auroral images by the HST, and variations of auroral extreme ultraviolet spectrum by the HISAKI satellite. The magnetic field observations show that the global magnetic flux has a periodic variation of accumulation and release. The auroral emission intensity observed by HST and HISAKI becomes strong at the time of electron energy enhancement shown by Juno. The magnetic reconnection events occur in the both magnetic loading and unloading periods. The analysis made it clear that the plasma dynamics in the middle magnetosphere is coupled with the auroral activity.



Simultaneous observation data from Juno, HST, and HISAKI. The in-situ measurements of the magnetic field, particles, and radio waves from Juno in the outer magnetosphere (d, e, g, h), and observations of Jovian aurorae from the HST and HISAKI (i). (Yao *et al.*, 2019).

- Z. H. Yao, *et al.* "On the Relation Between Jovian Aurorae and the Loading/Unloading of the Magnetic Flux: Simultaneous Measurements from Juno, Hubble Space Telescope, and Hisaki". *Geophysical Research Letters*. 2019, 46, 11632-11641. DOI: 10.1029/2019GL084201.

Development of Superelastic Deployable Nozzle for Solid Rocket Motors

A novel deployable rocket nozzle extension using a superelastic titanium alloy sheet was proposed in this study (Fig. 1). In an upper stage motor of a multistage rocket, an increase in the nozzle opening ratio is effective to increase specific impulse (Isp).

Superelastic alloys can undergo recoverable shape changes of several percent and are expected to be applied to various deployable structures in the space engineering field. However, Ti-Ni alloys, which are the most commercially widespread superelastic alloys, have poor workability and have not been applicable to large structures such as rocket motor nozzles. To face this problem, we have developed a new heat treatment technique that provides superelastic properties to certain structural titanium alloys having excellent workability. The newly developed superelastic structural sheet material will open the door for several new applications of superelasticity.

A manufacturing process for the deployable nozzle was considered by applying the superelastic titanium alloy sheet, and a full-scale nozzle extension was successfully produced through thinning, cutting, welding, and heat treatment processes (Fig. 2). Folding-deployment tests were carried out to demonstrate the shape recovery function of superelasticity, and it was confirmed that the original nozzle shape was maintained after deployment.

In addition, a combustion test was conducted for a miniature-sized deployable nozzle extension (1/4 size of the full-scale nozzle) connected to a small motor (Fig. 3). Several thermal parameters such as the heating rate per unit area of the nozzle and the heat conduction in the plate thickness direction were set as equivalent to the full-scale test. The temperature of the nozzle reached less than 1473K (Fig. 3b), while there was no damage or major shape change during the 27-second combustion period.

As the next step in development, we are planning to conduct a combustion test for the full-scale motor and deployable nozzle. This titanium alloy thin plate deployable nozzle is much lighter than the conventional composite material nozzle and significantly improves Isp with a simple superelastic mechanism, which will greatly contribute to future space exploration missions.

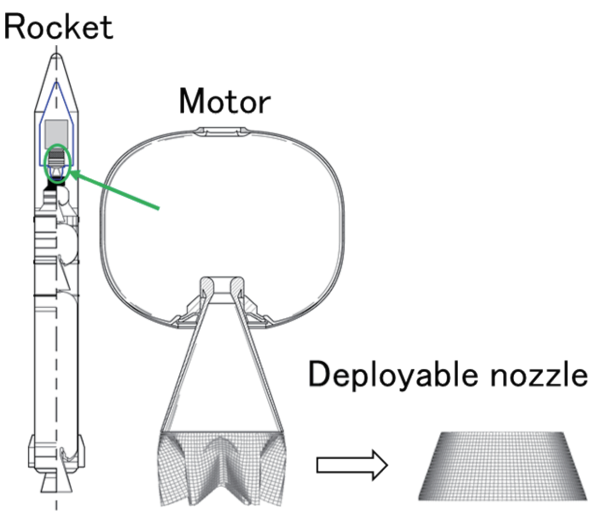


Fig. 1. Deployable nozzle extension for rocket motors.

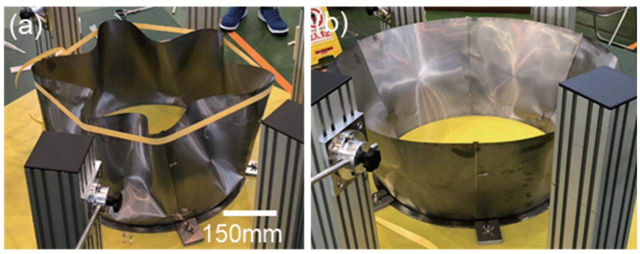


Fig. 2. Full-scale deployable nozzle (a) after folding with banding bands and (b) after deployment.

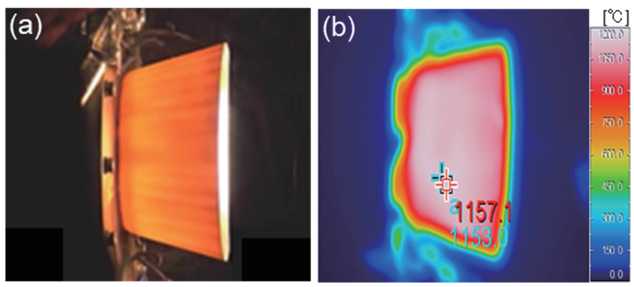


Fig. 3. Combustion test for a miniature-sized deployable nozzle: (a) optical camera image and (b) thermo-camera image.

- H. Tobe *et al.* “Deployable Rocket Nozzle Utilizing Superelastic Titanium Alloy Sheet”. *Materials Transactions. 2020,* 61, 68-71. DOI: 10.2320/matertrans.MT-MJ2019009.

Successful Reception of Radio Waves from Hayabusa2 at a New Station

【GRound station for deep space Exploration And Telecommunication (GREAT)】

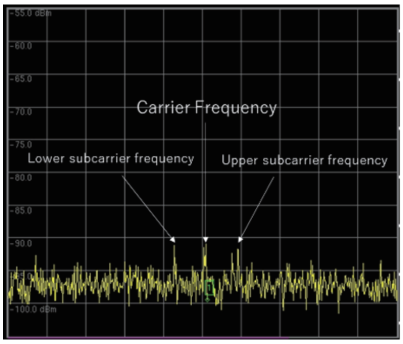
The mission of the GREAT Project Team, GRound station for deep space Exploration And Telecommunication, is to develop and build a new ground station due to operating deep space probes in Saku-city, Nagano-prefecture. The new station has a 54-m diameter parabolic antenna and will take over an existing aging ground station, which has a 64-m diameter one. As the successor to the existing station, the new station has the same performance despite its smaller diameter. This time, the new station achieved receiving radio waves at X-band from asteroid explorer Hayabusa2 in December 2019.

As mentioned above, developing and building the new station is a measure against the aging of the old one. This is why demonstrating its capability to communicate with the in-orbit probe during its development phase was required.

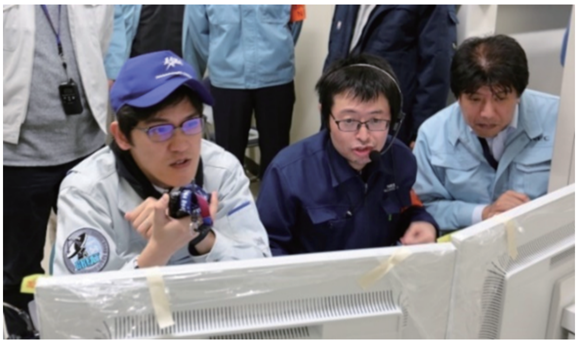
Meanwhile, since it was the first time in about 30 years to develop such a large antenna, it took a lot of time to set the project requirements in the preparation phase. As a result, there was not enough time from the project start until the communication with the probe.

However, the plan to demonstrate receiving the X-band signals from Hayabusa2 and transmitting the demodulated data to its control system at the Sagamihara campus was realized by the tremendous cooperation of major partner companies involved in the project, such as Mitsubishi Electric Corporation, NEC Corporation, and Japan Communication Equipment Co., Ltd.

The new station is going to start its routine service from April 2021 after the subsequent demonstration, such as receiving the Ka-band signals from the probe and sending test commands to it.



Radio spectrum received from Hayabusa2.



A scene during the test.

Appearance of the 54-m diameter new parabolic antenna (November 2019).

Ground Inflation Test of a 6,400 m³ Super-Pressure Balloon Covered by a Diamond-Shaped Net

A scientific balloon flies at the top of the atmosphere filling its huge envelope with floating gas. It has been used for various scientific observations and experiments, while having the weakness of being unable to fly long-duration flights because its lift decreases at night. To keep the lift constant, it is well known that the super-pressure balloon, which keeps its inner pressure higher than the ambient atmosphere, is a possible solution. However, it is difficult to realize a structure that is air-tight and pressure-resistance while also light weight. In 2010, we found that a balloon covered by a diamond-shaped net made of high-tensile fibers can increase pressure-resistance. We started the development from a small scaled model and gradually increased its size. In November 2019, a ground inflation test of a 6,400 m^3 balloon was performed and the balloon burst at the pressure of 740 Pa. This pressure resistance corresponds to the capability that the balloon can fly at an altitude of 27 km with a payload weight of 70 kg with sufficient safety. (Saito Yoshitaka *et al.,* 2020 “Development of a super-pressure balloon for long-duration flight covered by a diamond-shaped net (ground inflation test of the NPB7-1 balloon”, Procs. of the 20th Space Science Symposium, P1.51).

A zero-pressure balloon, which is usually used for scientific ballooning, has a vent duct at the bottom to prevent the balloon from bursting. Its internal pressure is the same as the ambient atmospheric pressure. However, due to this structure, the lift of the balloon decreases when the gas temperature at night becomes low and the volume of the balloon decreases. The super-pressure balloon, which has an air-tight structure with no vent duct and its internal pressure is always kept higher than the atmospheric pressure, can solve this problem. The balloon can maintain constant lift because its volume is constant. On the other hand, as the gas temperature increases during the daytime, the balloon is required to withstand the increased differential pressure. Since the difference in pressure inside and outside of the balloon is up to 10% of the atmospheric pressure, it is difficult to realize a super-pressure balloon larger than 20m in diameter. The required strength of the envelope film is proportional to the differential pressure and the local curvature of the film.

In 2010, we found that it is possible to increase the pressure resistance by covering the balloon with a diamond-shaped net, since the local curvature of the film can be kept small. We started the development from a small scale model with help of numerical simulations and gradually increased the balloon size. The standard design of the super-pressure has a structure in which the curvature of the envelope film is determined by strong ropes connecting the poles of the balloon. The separation of the ropes is an order of 1 m, while the mesh size of the net for our super-pressure balloon is 0.1 m. Since the local curvature of the envelope film is smaller, thinner and lighter film can be used. In 2016 and 2017, ground inflation tests of two 2,000m^3 balloons with diameters of 20m were performed. They burst at pressures of 1,040 Pa and 1,020 Pa, respectively. These burst pressures correspond to the capability to fly at the altitude of 22km with a payload of 40 kg.

In November 28, 2019, a ground inflation test of a 6,400m^3 balloon with a diameter of 27m was performed at Sundome Fukui. The balloon, suspended from the ceiling, was filled with air and tested for burst pressure. The balloon was inflated symmetrically (Fig.1), and burst at the pressure of 740 Pa (Fig.2). This burst pressure corresponds to the capability to fly at an altitude of 27 km with a payload of 70 kg with sufficient safety.

Fig.1. Fully inflated 6,400m^3 balloon.

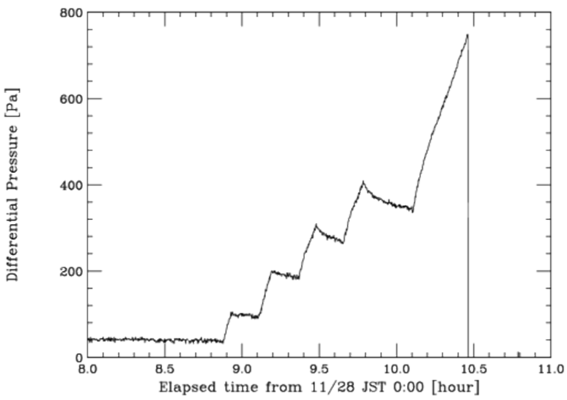


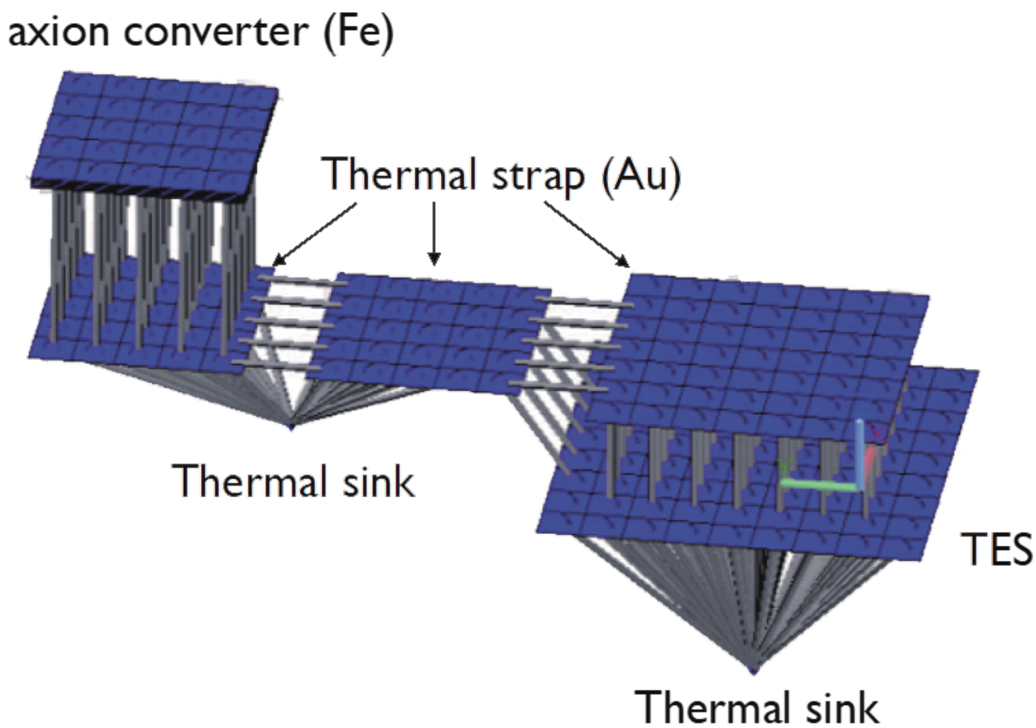
Fig.2. Time variation of the differential pressure.

- Y. Saito *et al.* “Development of a super-pressure balloon with a net for long duration flight”. *The 20th Space Science Symposium (2020).*

Development of TES Microcalorimeters with Solar-Axion Converter

The nature of dark matter in the Universe is a key question in physics. Axions are major candidates for dark matter and, if they exist, they can be emitted from the Sun via interactions between photons and strong electro-magnetic fields caused by the nuclear fusion at the center of the Sun. Searches for such "Solar axions" are conducted by several large experiments using very strong magnetic field converters, or underground large detectors of Xe, etc. No conclusive results have been obtained at present.

We focus on axions with a fixed energy of about 14 keV, which is produced by the interaction of black-body photons in X-ray bands and 57 Fe, an isotopes of iron. If these axions interact again with 57 Fe on Earth, they can be converted effectively to 14 keV photons. Detection of such photons will be proof of Solar axions, and would be a breakthrough in particle physics and have an impact on astrophysics. The trial for this search was done by a combination of thin 57 Fe film and an Si solid-state detector (SSD), and obtained an upper limit (Namba 2007). Our cutting-edge detector, TES (Transition Edge Sensor) microcalorimeter has a fine energy resolution of about 20 times better than that of SSD. In addition, the direct connection of 57 Fe as absorbers of microcalorimeters will improve the detection efficiency. We propose this detector system as a new probe for Solar axions. In this paper, we assessed the effect of magnetic fields by 57 Fe absorber, whose ferromagnetic property is a potential risk for TES calorimeters, and confirmed the thermal design of the detector. It assures our design concept, and now we will fabricate and test the detector, and observe Solar axions.



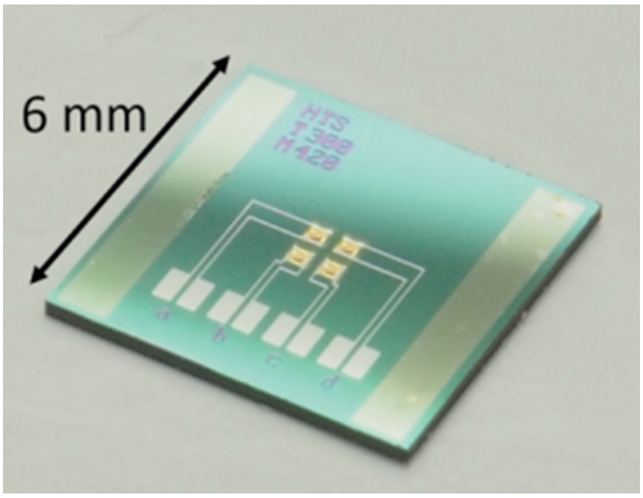
Schematic diagram of the TES microcalorimeter thermal FEM (Finite Element Method) model.

- R. Konno *et al.* "Development of TES Microcalorimeters with Solar-Axion Converter". *Journal of Low Temperature Physics. 2020, 199, 654-662.* DOI:10.1007/s10909-019-02257-9.

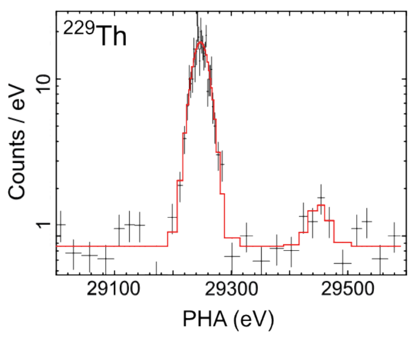
Determination of the Isomer Level of 229 Thorium for Realization of a "Nuclear Clock"

Construction of the fundamental unit (SI unit) is one of the great achievements of technology and science. The unit of time, the “second”, is now defined by Cesium clocks, which use the transition energy level of the electrons in the atoms. The accuracy of the atomic clock is thus defined by the disturbance of environmental electro-magnetic fields to the electrons bounded in atoms. If a more accurate clock is realized, it would enable us to observe the relativistic-effect of time delay in laboratories, to measure altitude and positions on the Earth using clocks, and to investigate the time variance of the fundamental physical “constant” from the birth of the Universe. The most plausible candidate for fundamental clock of the next generation is a nuclear clock that uses the transition energy of the atomic nuclei, whose interaction is not affected by electro-magnetic fields. One nuclear transition with energy low enough to be excited and locked by an UV laser is the isomer transition in 229 Thorium isotopes, which is expected to be less than 10 eV. In the past 30 years, several experiments have been performed, but conclusive results were not obtained.

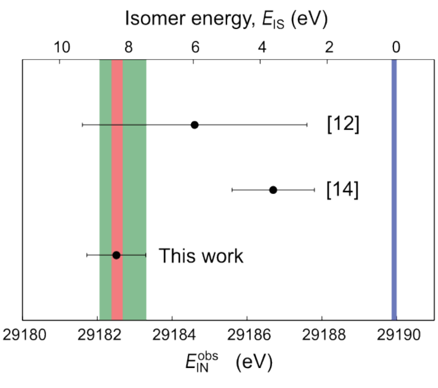
We used an TES (Transition Edge Sensor) micro-calorimeter detector system, which was designed for this experiment, as an application of an X-ray astronomy sensor for fine spectroscopy to measure ~ 29 keV energy photons from a nuclear transition. The fine energy determination of the nuclear γ photons gave us the target isomer level. Our resultant level is E=8.30±0.92 eV, which is consistent with the recent values by two independent groups. There is confidence in the consistency of these international 3 groups, and this will drive the development of laser excitation system and realization of a nuclear clock in near future.



Picture of the TES detector , fabricated in-house at ISAS.



Observed energy spectrum of the 229 Th nuclear gamma-ray.



Measured values of the 229 Th isomer levels. (Yamaguchi *et al.* 2019)

- A. Yamaguchi *et al*. “Energy of the ^{229}Th Nuclear Clock Isomer Determned by Absolute γ-ray Energy Difference”. *Physical Review Letters* (Editor’s Suggestion). 2019, *123, 222501. DOI:* /10.1103/PhysRevLett.123.222501.

Symposium on the 50th Anniversary of the Launch of Japan's First Satellite OHSUMI and the 30th Anniversary of ISAS's Relocation to Sagamihara

The 50th Anniversary of OHSUMI Launch

OHSUMI, Japan's first satellite, was launched at 13:25 on February 11, 1970, at the Kagoshima Space Center of the University of Tokyo (current JAXA Uchinoura Space Center) on the Ohsumi Peninsula, Kagoshima Prefecture.

In commemoration of this, on February 11, 2020, the National Museum of Nature and Science co-hosted the symposium for space science exploration and OHSUMI under the support of the University of Tokyo, attended by approximately 150 visitors.

In the first half of the symposium, two keynote speeches were given. AKIBA Ryojiro, former Director General and Professor Emeritus of ISAS, gave a talk on the history of the launch, interaction with the local community, and future space development. TSUDA Yuichi, Hayabusa2 Project Manager and Professor at the Department of Space Flight Engineering, gave a talk on the latest results by the asteroid explorer Hayabusa2 and the prospects for future space exploration.

In the second half of the symposium, panel discussion topics were provided from four perspectives: Space science and exploration, international space exploration programs, space exploration engineering, and space transportation engineering, and then a comprehensive discussion from various perspectives was conducted on the direction to be taken for the next 50 years.

L-4S-5 Launch (Feb 11, 1970).

The symposium held at the National Museum of Nature and Science.

The 30th Anniversary of ISAS's Relocation to Sagamihara

In April 1989, the ISAS was relocated to Sagamihara from Komaba, Meguro-ward in Tokyo, and held its 30th anniversary celebration on November 1, 2019.

About 180 people, including UENO Michiko, Deputy Minister of Education, Culture, Sports, Science and Technology, and MOTOMURA Kentaro, mayor of Sagamihara City, attended the commemorative ceremony, and we presented a letter of appreciation to Sagamihara citizens, local community associations, and related organizations for their cooperation.

In addition, for the future of the Sagamihara Campus and Sagamihara City, we have concluded an agreement on cooperation between Sagamihara City and JAXA with the aim of further strengthening cooperation.

Cherry tree planted at the time of relocation and 30 years later.

Conclusion of agreement with Sagamihara City.

II

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, the possibility of extra-terrestrial life, and at the same time to lead 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 to 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) from the 2019 fiscal year, and has completed the Critical Design Review.

MMX (Mars's Moon eXploration) is a Martian moon sample return mission. The mission executed the Phase A study as a candidate of the L-class Mission 1, and passed the System Definition Review in December 2019. It has now started the Phase B study as a JAXA project.

Two mission candidates, LiteBIRD (Cosmic Microwave Background B-mode observation) and OKEANOS (Jupiter and Trojan asteroid explorer) had been in Pre-Phase A2 (mission definition phase). In May 2019, the ISAS selected LiteBIRD as a candidate for L-class Mission 2, and it continued its Pre-phase A2 study. OKEANOS then began a concept study targeting L-class Mission 3.

SPICA (Space Infrared Telescope for Cosmology and Astrophysics) is a mission candidate led by the European Space Agency (ESA). This mission is continuing pre-phase A2 study targeting the final selection of Cosmic Vision M-5 held in June 2021.

GREAT (GRound station for deep space Exploration And Telecommunication) is a ground facility, though its development is pursued as a space science project. Its development is proceeding smoothly and expecting to be complete during the 2020 fiscal year.

c. Competitively-chosen Medium-size Focused Missions Under Development

Smart Lander for Investigating Moon (SLIM), M-class mission 1, moved to Phase C and executed Critical Design Review. Its development is proceeding smoothly.

DESTINY+, an M-class mission 2 candidate, is a flyby mission to the meteor-shower parent body, Phaethon. This mission was in Pre-phase A2. However, because it had to respond the problems of a mismatch between the rocket interface and of large cost over-run after Mission Definition Review in August 2017, it executed Delta-Mission Definition Review in January 2020. Now it is expected to move to Phase A early in the next fiscal year.

Small JASMINE, one of the candidates for M-class mission, is an infrared astrometry mission dedicated to the astrometry of stars in the Galactic bulge. It was in Pre-Phase A2 and In May 2019, the ISAS selected small JASMINE as a candidate for M-class Mission 3.

Solar-C EUVST (Extreme UV Solar Telescope mission) and HiZ-GUNDAM (High redshift Gamma-ray Burst Monitor mission) were selected for candidates of mission concept for M-class missions 3 or 4. Solar-C EUVST moved to Pre-phase A2, and preparing the down selection for M-class mission 4 early in the next fiscal year. HiZ-GUNDAM is now continuing Pre-phase A1B study.

d. Strategic Participation to Foreign-agency Flagship Missions Under Development

Japan's contribution to the ESA's Cosmic-Vision L1 mission, JUICE (JUpiter ICy moons Explorer), continued to develop the flight system.

CAESAR (Comet Astrobiology Exploration Sample Return) failed in selection for NASA's flagship mission, New Frontier 4. Accordingly, it was decided that CAESAR/SRC (sample return capsule), Japan's contribution to supply the sample return capsule, would be terninated in September 2019.

e. Missions in Operation

BepiColombo/MMO (Mercury Magnetospheric Orbiter) was launched in October 2018, and finished the early check out during the 2019 fiscal year. It now flies smoothly.

Hayabusa2 was launched in December 2014, arrived at Ryugu in June 2018, and performed its first touchdown in February 2019. In this fiscal year, it operated SCI (impactor) to make an artificial crater, and performed its second touchdown near the crater. It departed Ryugu in November 2019 and now is on the way back to earth.

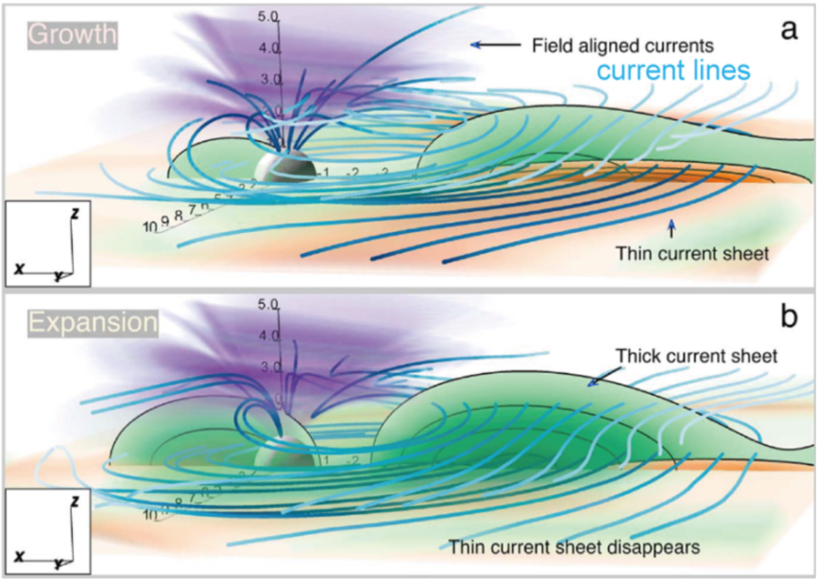
The five spacecraft in orbit, the Geo-space explorer, ARASE, the planetary spectroscopy mission, HISAKI, the Venus climate explorer, AKATSUKI, the solar observatory, HINODE, and Geo-magnetosphere explorer, GEOTAIL all conducted their observations safely and successfully.

f. Small Missions Conducted with Matching Funds with External Organizations

This fiscal year, the ISAS selected two additional projects: (1) Phenix-2 (Droplet Group Combustion Research) and (2) XL-Caliber (Balloon experiment). In addition, another six missions are on-going: (3) FERMI satellite collaboration, (4) DUST Nucleation (sounding rocket experiments), (5) GAPS (General Anti-Particle Spectrometer, balloon experiment), (6) Small Solar program CLASP2 (sounding rocket experiment) and SUNRISE-3 (balloon experiment), (7) BEAK (Breakthrough by Egg-derived Aerocapture Kilt vehicle), and (8) IXPE (Imaging X-ray Polarimeter Explorer). All the missions except IXPE will continue into the next fiscal year.

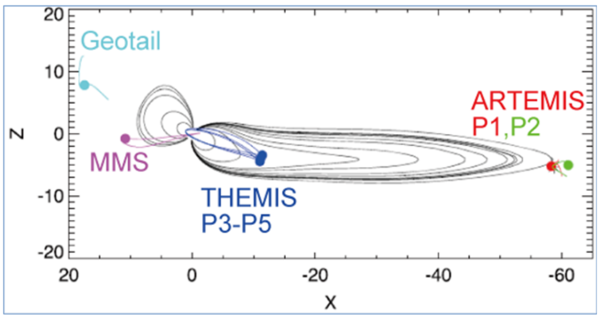
2. Space Science Programs under Operation

a. Earth Magnetosphere Observation with GEOTAIL



Empirical model of electric currents flowing in the Earth's magnetosphere during the growth and expansion phases of substorms (auroral explosion), constructed using magnetometer measurements over many decades by GEOTAIL and other missions [1].

Since the launch of the joint U.S.-Japan satellite GEOTAIL 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, other spacecraft systems and instruments are in good condition. The effect of the data recorder failure was minimal, with a data loss of about 10–15%, thanks to the support of NASA's Deep Space Network (DSN). One to two years after data acquisition, data is calibrated, archived, and made available to researchers all over the world.



The locations in the noon-midnight meridian plane of GEOTAIL, MMS, THEMIS, and ARTEMIS spacecraft on 25 December 2015, when a magnetospheric substorm developed and aurora and geomagnetic disturbances were observed on the ground [2].

The mission extension review of GEOTAIL was conducted in 2018, and operation until the end of March 2021 has been approved. NASA's senior review carried out in October-November 2017 allowed the extension of GEOTAIL operations until the end of 2020, and the next senior review is scheduled in 2020. 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. The GEOTAIL operation time in Japan has been increased for collaboration with MMS since July 2015. GEOTAIL has been providing opportunities to make simultaneous multiscale plasma measurements by carrying out coordinated observations with MMS, ARASE and THEMIS/ ARTEMIS.

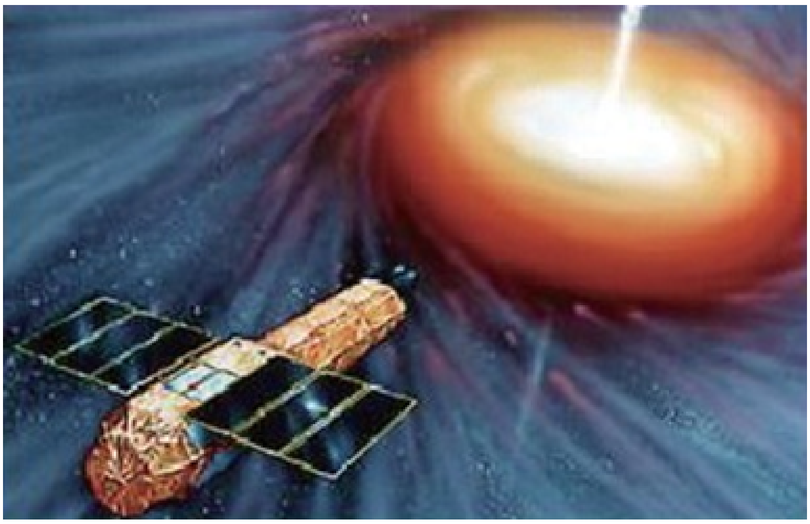
The time history of various phenomena during a substorm, including aurora, geomagnetic disturbances, and magnetic field dipolarization in the nightside magnetosphere, has been revealed by a comprehensive set of in-situ and remote sensing observations by GEOTAIL, other spacecraft, and ground-based observatory networks [2]. GEOTAIL, as a monitor of the solar wind conditions immediately upstream of the Earth's magnetosphere, helped constrain the mechanism by which the substorm observed on 25 December 2015 was initiated (left figure).

([1] Journal of Geophysical Research Space Physics, February 2019, and [2] Journal of Geophysical Research Space Physics, June 2019).

b. X-ray Astronomy with SUZAKU (ASTRO-E II)

SUZAKU (formerly called ASTRO-E II) is the fifth Japanese X-ray astronomy satellite, developed under Japan-USA international collaboration and launched on July 10, 2005, from JAXA's Uchinoura Space Center. SUZAKU is a red bird in Asian mythology, one of the four guardian animals protecting the southern skies. The SUZAKU satellite is designed to perform various kinds of observational studies of a wide variety of X-ray sources, with higher energy resolution and a higher sensitivity than ever before, over a wider energy range of soft X-rays to gamma-rays (0.4-600 keV).

Due to aging of the onboard power supply system, communication with the satellite has only been intermittent since June 2015. Recovery operations were unsuccessful, so a decision was made to end the science observations on August 26, 2015, considering the age and status of the onboard hardware associated with communications, power supply, and attitude control. Since then, the project has continued operation to shut down the onboard S-band radio transmissions. Although the operation has not succeeded yet, the project received a mission termination review by ISAS's space science committee in December 2019. The committee concluded that the mission termination was acceptable, given that plenty of science results were achieved by SUZAKU. Although the project was decided to terminate, the S-band termination operation will be continued until it is realized, which will be led by the Department of Space Astronomy and Astrophysics.



c. Small Satellite INDEX (REIMEI)

A small scientific satellite, INDEX (INnovative-technology Demonstration EXperiment, code name “REIMEI”) is a piggy back satellite with a mass of 72kg launched in 2005. It has remained in orbit for 13 years. The scientific purpose is observation of 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 highlights of INDEX in FY2019 are as follows.

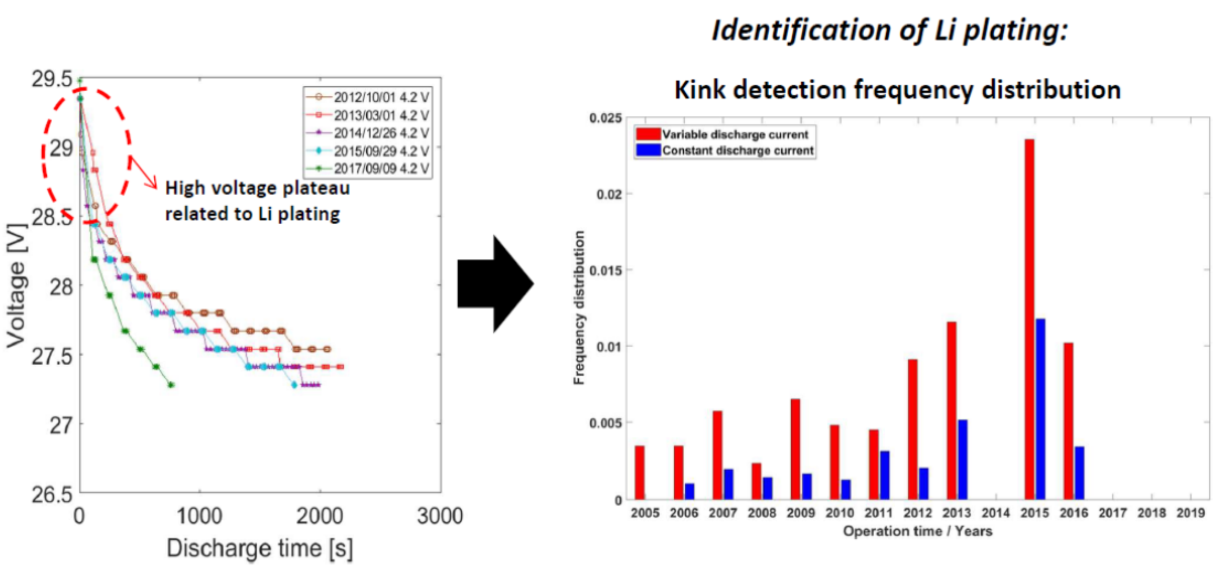
The method of constant-current and constant-voltage is widely used to charge onboard batteries. Constant current is provided at the initial constant-current phase of charging. After the battery voltage reaches a specific voltage, its voltage is maintained by the power supply circuit to recover voltage loss due to internal battery impedance. The current of this constant-voltage phase can be approximated as an exponential decay curve. We found with ground tests that the time constants of the exponential decay curve seem to be a decreasing function of battery capacity loss.

The internal impedance of the battery cells has been calculated based on the charge and discharge performance of the battery. Furthermore, the creation of the lithium metal inside the battery cells has also monitored through the understanding of the high voltage discharge phenomena. The information will be reflected for the safer passivation of the satellite in future.

Deutsches Zentrum für Luft und Raumfahrt (DLR) performs 3D electro-chemical simulations of the REIMEI battery based on its initial parameters in the development phase. They include thermochemical parameters and degradation phenomena of separator and electrolytes. We will compare the onboard charge-discharge data with the electro-chemical simulation by DLR.

Discharge curves of the REIMEI battery obtained from telemetry data

Is Li plating taking place?



Kink detection frequency distribution:

$$f_d = \frac{n}{N_{tlm,year}}$$

n: Number of times a kink is detected

$N_{tlm,year}$: Number of battery cycles obtained by telemetry per year

d. 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.

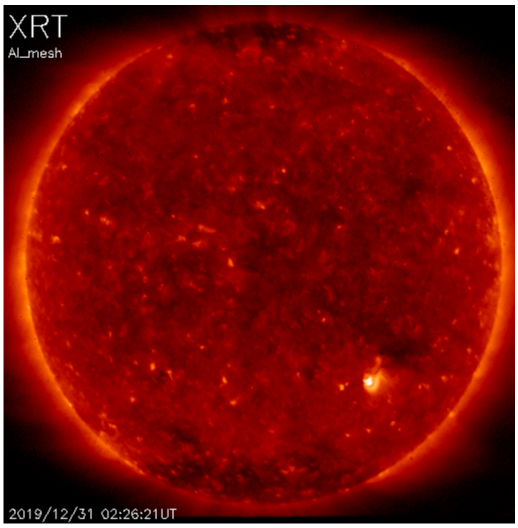
HINODE was launched in September 2006 and has been operated as an on-orbit solar observatory continuously for over 13 years. The observatory can be used by the global research community and 28 new observing proposals were delivered to the HINODE operations team in FY2019. In addition to regular closely coordinated observations with NASA's Interface Region Imaging Spectrograph (IRIS) satellite and coordinated observations with the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile, 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 initial observations in the commissioning phase of ESA's Solar Orbiter. All data acquired by HINODE is made fully available to the international research community immediately after observations.

In FY2019, 58 articles were published in refereed journals based on HINODE observations, resulting in a cumulative total of 1,306 published papers to date (as of December 2019). This publication record makes HINODE one ISAS's most-productive missions.

Review articles entitled "Achievements of Hinode in the first eleven years" (Hinode Review Team, Publications of the Astronomical Society of Japan, 71, R1) and "Flare-productive active regions" (Toriumi & Wang, Living Reviews in Solar Physics, 16, 3) were published, providing comprehensive reviews of achievements of HINODE for researchers.

So far, JAXA has confirmed the continuation of HINODE operations until March 2021. 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 2019, showing the solar-minimum Sun with appearance of a tiny bright region probably belonging to the new solar cycle 25.

e. Venus Meteorology Observations by AKATSUKI (PLANET-C)

AKATSUKI, in the Venus orbit since December 2015, continued observations of the atmospheric motion of Venus. One primary objective of AKATSUKI is to understand the mechanism of super-rotation, a high-speed westward wind encircling Venus at 100 m/s. Unfortunately, of the five on-board cameras, IR1 and IR2 became inoperable in early December 2016. Other cameras (UVI, LIR and LAC) and the ultra-stable oscillator for radio occultation measurements have continued to operate normally. The spacecraft itself is in good condition with very little signs of degradation of systems.

AKATSUKI has made many discoveries so far. A strong bow-like structure fixed to the surface topography can be seen as a temperature change at the cloud tops as far as 70 km above the ground (LIR). It was found by IR2 that there are sometimes very fast flows, called equatorial jets, at the altitude of the clouds in the middle and lower layers. The model calculation succeeds in reproducing the flow field seen in the middle and lower cloud layers seen by IR2.

We report two important findings revealed by UVI and LIR in 2019. One is the long term trend of UV albedo (Lee, Y.-J., et al., Long-term Variations of Venus's 365 nm Albedo Observed by Venus Express, AKATSUKI, MESSENGER, and the Hubble Space Telescope, AJ, 158, 126) observed by AKATSUKI and Venus Express from 2006 to 2018, and STIS of Hubble Space Telescope in 2011 (Fig. 1)

This long term variation of albedo can directly control solar heating rates, 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 (Kouyama et al., Global Structure of Thermal Tides in the Upper Cloud Layer of Venus Revealed by LIR on Board AKATSUKI, Geophys. Res. Lett., 46, 9457-9465). The global structure of the thermal tide is revealed for the first time in the world. Previously, only the sunlit hemisphere has been analyzed, and 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 (Fig. 2).

The vertical structure of the semi-diurnal tide suggests that this wave may accelerate the atmosphere and contribute to the generation of super-rotation.

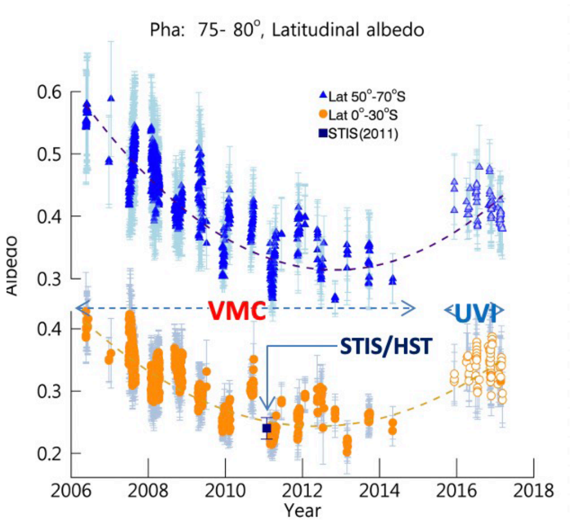


Fig. 1. 365-nm albedo has been varied by a factor of 2 in the recent decade.

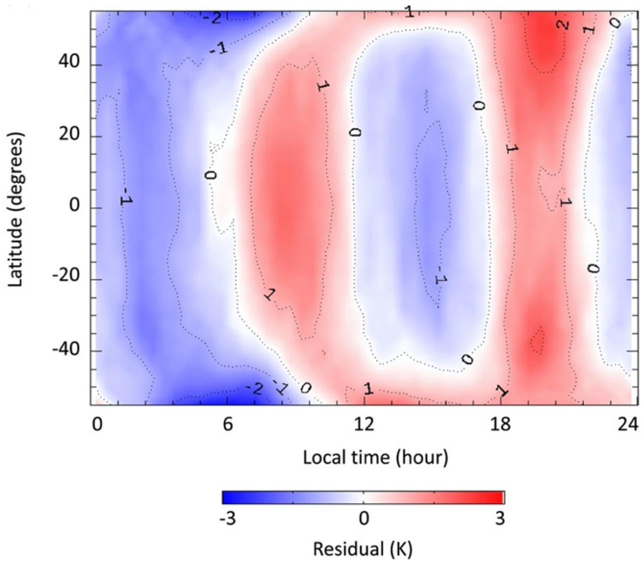


Fig. 2. Thermal tide structure obtained with a 60° emission angle condition by using the whole data period from October 2016 to January 2019. The brightness temperature in the Longwave Infrared Camera (LIR) images was averaged for every 0.5 hr local time bin and 5° latitudinal bin.

f. Solar Power Sail Demonstration with IKAROS

IKAROS, a small solar power sail demonstrator launched on May 21, 2010, achieved full success at demonstrating solar sail and solar power sail technology for the first time. Since 2012, it has alternated between hibernation and recovery, as has almost run out of fuel and cannot control its attitude. We still 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 of power generation by the thin-film solar cells will be useful for evaluating the long-term performance of solar power sail.

Achievements:

- We established a mechanical model of the solar sail, in order to analyze its orbit and attitude dynamics. In this model, the deflection and torsion of the membrane vary according to the spin rate (Fig. 1). Applying this model, we solved the sail attitude history and communication windows.
- In FY2015, we established a method to detect weak signals. In FY2016, we verified the validity of the orbit determined from the artificial range data using weak signals. In FY2017, as an extension of our activities over the last two years, we evaluated the attitude estimation using weak signals. We confirmed that the use of weak signals does not allow real-time communication; however, by integrating these signals with off-line signal processing, it could be possible to determine the solar sail orbit and attitude (Fig. 2).

Outcomes:

- Total number of papers: 109.
- The method used to obtain the telemetry range data (by postprocessing the open-loop record data and extracting the radio waves) is expected to be applicable to a wide range of spacecraft operations, including solar sails.

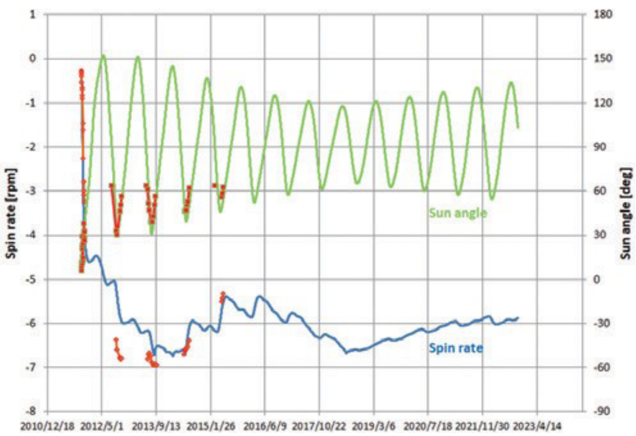


Fig. 1. Mechanical model of the solar sail.

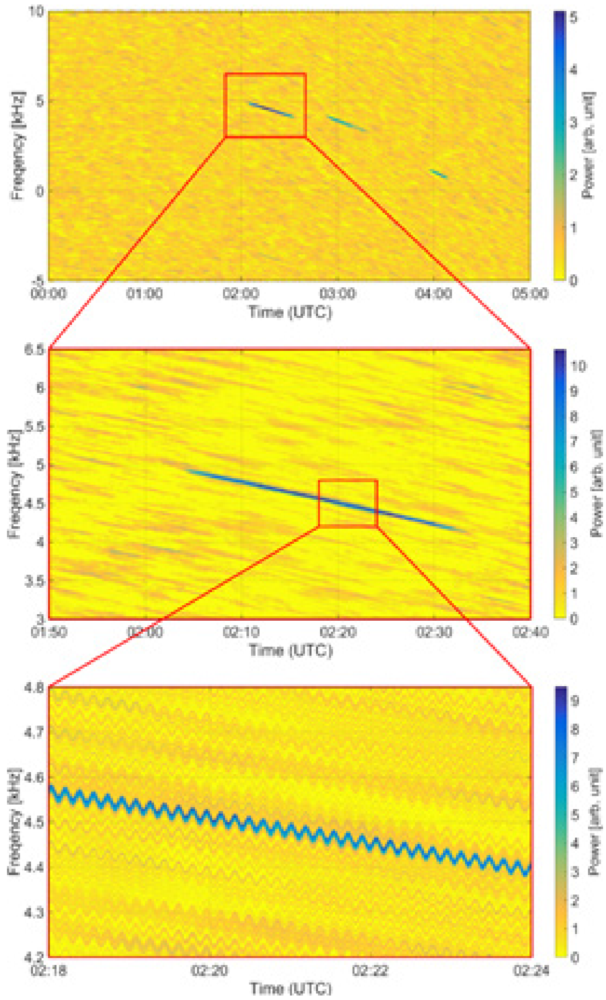


Fig. 2. Estimation of the solar sail orbit and attitude based on weak signals.

g. Extreme-ultraviolet Spectroscopic Observation by HISAKI (SPRINT-A)

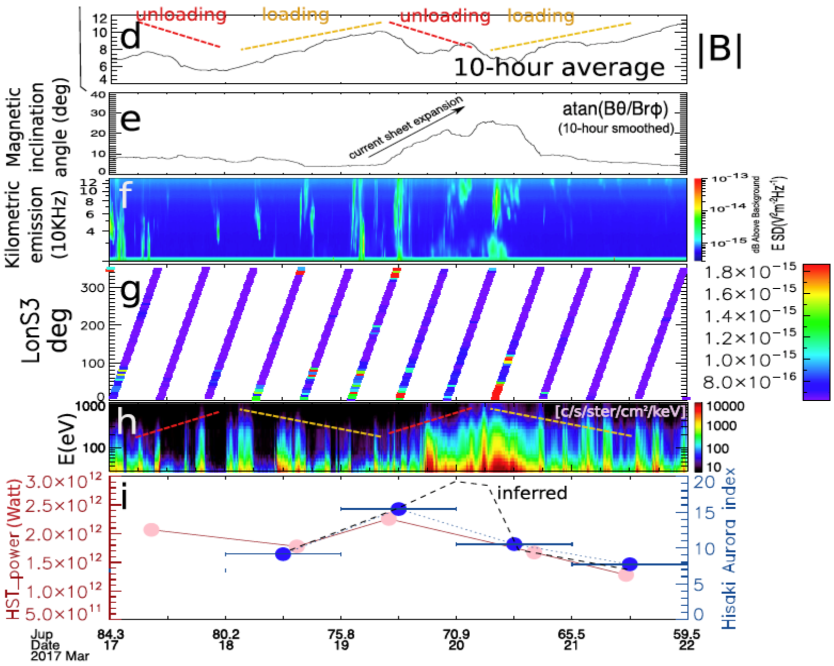
The extreme-ultraviolet (EUV) spectroscopic observatory HISAKI (formerly called SPRINT-A: Spectroscopic Planet Observatory for Recognition of Interaction of Atmosphere), which was launched on September 14, 2013, is a unique space telescope specialized for the observations of planetary atmospheres, ionospheres, 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 the Jupiter's magnetosphere and atmospheric evolution of the terrestrial planets.

HISAKI's long-term planetary observations of the Jovian magnetosphere and Venusian/Martian ionospheres were continuously performed to provide unique and important data sets of EUV spectra. A joint observation with the Hubble Space Telescope (HST) and NASA's Jupiter space probe (JUNO) implemented comprehensive studies on plasma dynamics in the Jovian middle magnetosphere for the first time. One of the results is shown below.

The observation of a galaxy cluster with a massive cool core succeeded detecting Helium I emission and was posted on the ISAS website. The study subject is beyond the scope of the HISAKI project but is a successful example of the cooperative studies between the different scientific fields.

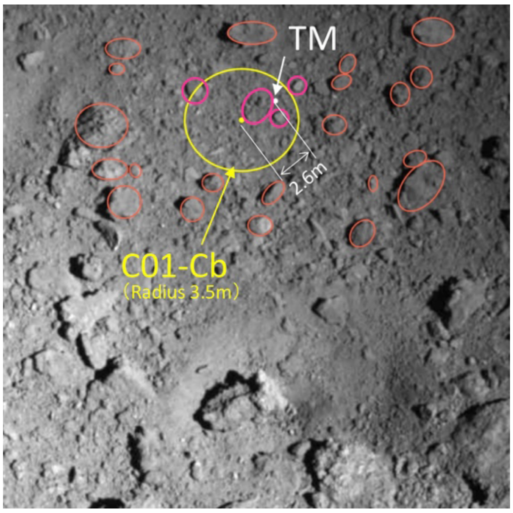
The HISAKI science team takes a principal position among scientists of Jovian magnetosphere study at the international level, including international collaboration in NASA's Participating Scientist Program (planetary scientific research program of NASA using HISAKI data). Magnetospheric physics and aeronomy scientists, who are especially members of the Society of Geomagnetism and Earth, Planetary and Space Sciences in Japan, have been working with HISAKI observation results. One of the biggest conferences on Magnetospheres of the Outer Planets (MOP) was held in Tohoku University in June, and the presentations of HISAKI's results collected considerable attention.

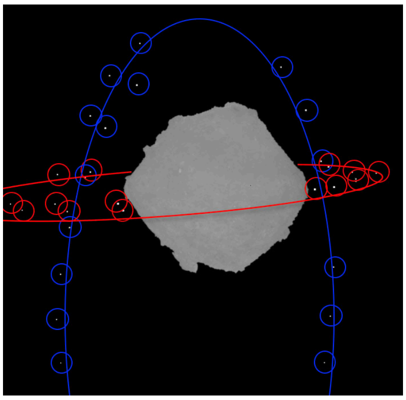
In FY2019, 7 peer-reviewed papers regarding HISAKI data were published, for a cumulative total of 47.

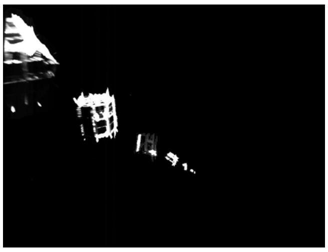


The in-situ measurements of magnetic field, particles, and radio waves from JUNO in the outer magnetosphere (d, e, g, h), and simultaneous observations of aurorae at Jupiter from the Hubble Space Telescope and HISAKI (i). The accumulation (loading) and release (unloading) of magnetic flux has good correlations between electron energization and auroral enhancement. Magnetic reconnection events identified during both loading and unloading periods indicate that reconnection and unloading are independent processes. These results show that the dynamics in the middle magnetosphere are coupled with auroral variability (Yao et al., 2019).

h. Asteroid Explorer Hayabusa2







(Fig. 1. left) Artificial crater (bottom) and second touchdown point C01-Cb. The second touchdown point is an area with a diameter of 7m, about 20m away from the center of the artificial crater. The target marker was dropped onto the touchdown area. (© JAXA, University of Tokyo, Kochi University, Rikkyo University, Nagoya University, Chiba Institute of Technology, Meiji University, University of Aizu, AIST)
(Fig. 2. middle) Trajectories of two separated target markers (© JAXA, Chiba Institute of Technology, AIST, Rikkyo University, University of Tokyo, Kochi University, Nagoya University, Meiji University, University of Aizu)
(Fig. 3. right) MINERVA-II2 going away (© JAXA, Chiba Institute of Technology, AIST, Rikkyo University, University of Tokyo, Kochi University, Nagoya University, Meiji University, University of Aizu)

The asteroid explorer Hayabusa2, which was launched on Dec. 3, 2014, is the world's second sample return mission from an asteroid. The target asteroid, (162173) Ryugu, is a C-type near-Earth asteroid. By the elucidation of the interaction of minerals, water, and organic matter in the primitive solar system, we aim to approach the origin and evolution of the earth, sea, and life. It is also important to maintain and develop the deep space round-trip exploration technology demonstrated in HAYABUSA.

Hayabusa2 finally arrived at Ryugu on June 27, 2018. Hayabusa2 stayed near the asteroid for about 1 year and 5 months, and conducted observations with remote sensing instruments, observations with a lander and rovers, artificial crater generation, sample collection by two touchdowns, and satellite experiments. Hayabusa2 left Ryugu on November 13, 2019, and will return to earth at the end of 2020. The following is a summary of our achievements in 2019.

On April 5, 2019, we operated a small carry-on impactor (SCI) and succeeded in an artificial crater generation experiment. We also succeeded in imaging the ejecta curtain ejected from the surface of Ryugu with a deployable camera (DCAM3). About three weeks after the crater generation, Hayabusa2 went down to observe it on April 25, 2019. We found a crater of about 15m in diameter. See research highlights.

On July 11, 2019, a second touchdown was performed successfully on the area near the artificial crater where ejecta from the artificial crater were piled up. We think that we were able to collect underground materials. The navigation for this touchdown was quite accurate, and the error in position of the touchdown point was just 60cm. See research highlights.

On September 17, 2019, we succeeded in injecting two target markers into Ryugu’s equatorial and polar orbits. In addition, on October 3, we succeeded in putting MINERVA-II2 into the Ryugu orbit. We also succeeded in capturing the images of these three small objects orbiting Ryugu, which will be useful for estimating the gravity field of Ryugu accurately.

Having completed all missions at Ryugu, Hayabusa2 started home from Ryugu on November 13, 2019. On the orbit returning to the earth, from December 3, 2019, to February 20, 2020, the first long-term ion engine operation was completed as planned. The second long-term ion engine operation will be done from May to September in 2020.

In FY2019, 17 peer-reviewed papers were published, and the number of peer-reviewed papers up to now has reached 127. In particular, papers on Ryugu were published in journals such as Nature and Science, as well as Icarus, Astronomy & Astrophysics, and others. In addition, many presentations were made at domestic and international conferences. In some international conferences, special sessions for Hayabusa2 were set up. We received a total of nine awards from academic societies and external organizations in FY2019.

i. 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 from 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 shed light on the generation and loss of high energy electrons in the Earth's radiation belts. This problem is a critical issue in understanding dynamic variation in 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 with the ground-based measurements. These ground measurements involve a network of radar facilities, aurora cameras, and magnetometers. 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°, ARASE's orbit allows it to cover all of the Earth's radiation belts. Its orbital period is about 570 minutes. The satellite system and all onboard mission instruments are in good condition even after over three 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 began on March 24, 2017, and it 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 during the primary mission period. Most importantly, all instruments have provided scientific data from both normal and burst observations of these storms.

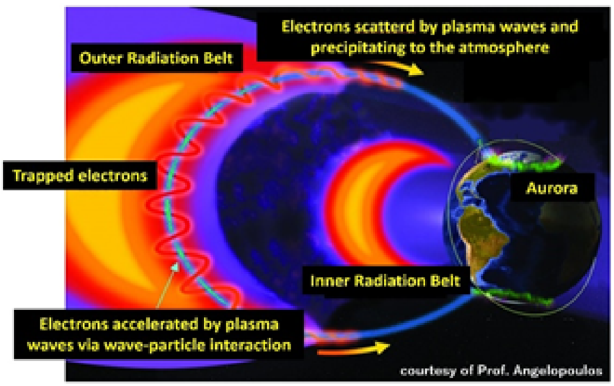
For the primary mission period, we conducted joint strategic observations with various ground-based scientific instruments to reveal the causes and consequences of wave-particle interactions and magnetosphere-ionosphere couplings. We have collaborated with various observatories of radar facilities, aurora cameras, riometers, VLF observations, standard radio networks, and magnetometers. Four campaign periods were set around the spring, autumn equinoxes, and the summer and winter solstices. More than 1,000 conjugate observations between ARASE and ground-based observatories were realized. ARASE has proven itself as a member of the international fleet of geospace satellites and has contributed to comprehensive observations of geospace plasma dynamics. More than 200 burst-mode observations of plasma waves simultaneous with the Van Allen Probes have also been completed, which simultaneous waveform data at different magnetic latitudes along the same field lines. Collaborative observations with the other satellites like THEMIS and MMS have also been carried out.

The data pipeline processing of the acquired data and data calibration is 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 by 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 the complete resource.

The processed science data products after evaluation by the ERG science team are going to be open to the public. We started to release the calibrated science data in August 2018. 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. Processing for higher-level science datasets will also be released to the research community.

Over 150 scientific papers have been published in international refereed journals since the start of the ARASE observations, including articles in Nature, Nature Communication, Scientific Reports, and a special issue of Geophysical Research Letters, "Initial results of the ERG (ARASE) project and multi-point observations in geospace." These publications show that ARASE is revealing a novel aspect of geospace, how wave-particle interactions contribute to the dynamic variation of the radiation belts. Based on this fact, the scientific review board found that ARASE has almost completed its primary mission, even though the results are only preliminary, and many scientifically important topics remain to be studied.

The first extended mission will continue until the end of March 2022. It covers the period from the declining phase of Solar Cycle 24 and the early stage of Solar Cycle 25 so that ARASE can observe dynamical variations of the radiation belts and geospace under various solar wind conditions. The extended mission will also contribute to the completion of a survey of the radiation belts over the 11-year solar cycle period that began in 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) has also been begun in 2019.



Contribution of wave-particle interactions to the radiation belts.

j. 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 these questions.

The baseline mission consists of two spacecrafts: the Mercury Planetary Orbiter (MPO) and 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). JAXA is responsible for the development and operation of the MMO, while ESA is responsible for the development and operation of the MPO, as well as the launch, cruising, and insertion of two spacecraft into their dedicated orbits. The main objectives of the MMO are to study Mercury's magnetic field and the plasma environment around Mercury, including 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.

After successful launch of BepiColombo on 20 October 2018 (UTC) from Guiana Space Center (CSG) by the Ariane-5 rocket, the initial checks of the spacecraft and instruments were performed. In FY2019, commissioning operations of high voltage part of the science instruments and launch lock release of extension instruments were completed. The parameter updates and dry run operations for the Earth flyby on April 2020 were also performed.

12 peer-reviewed papers related to the BepiColombo project were published in FY2019.

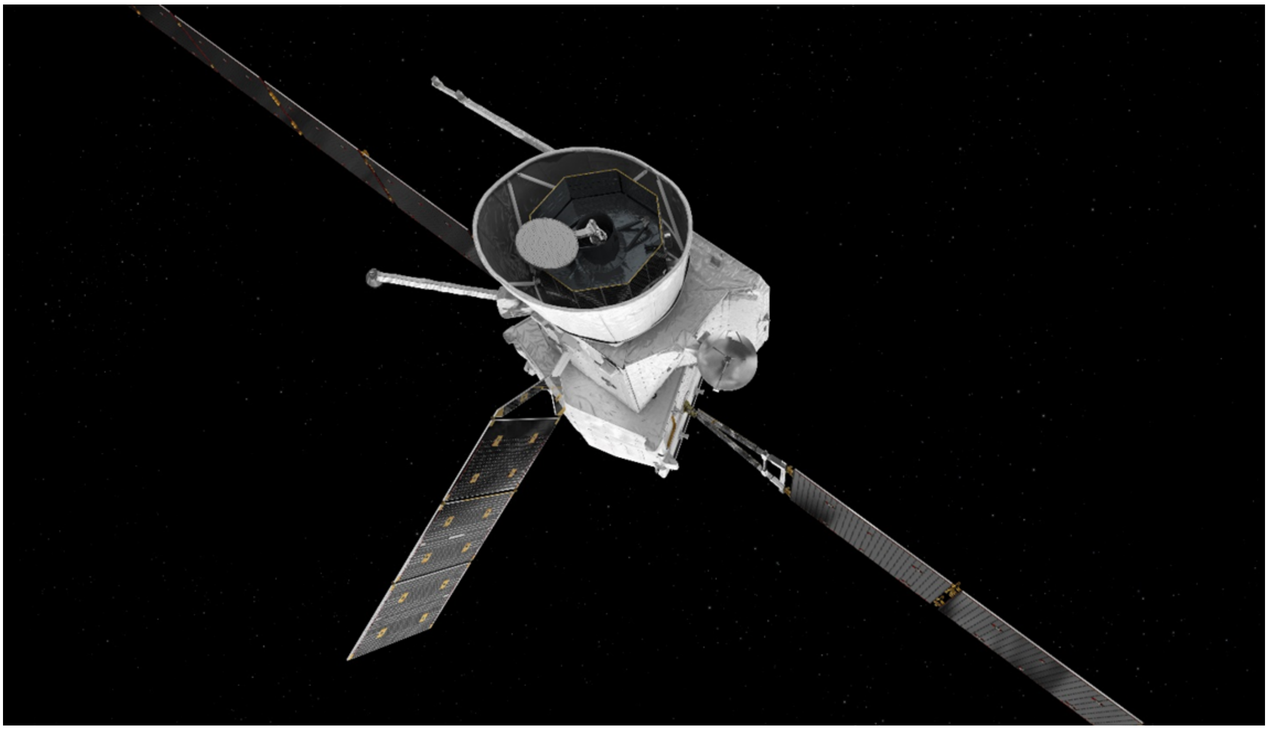
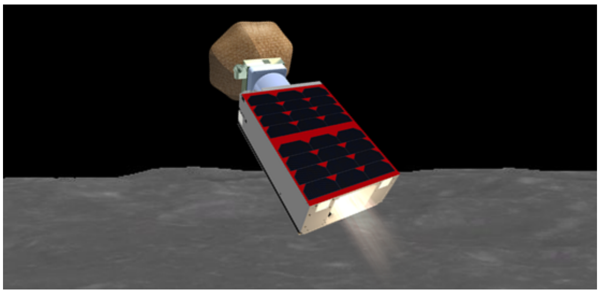


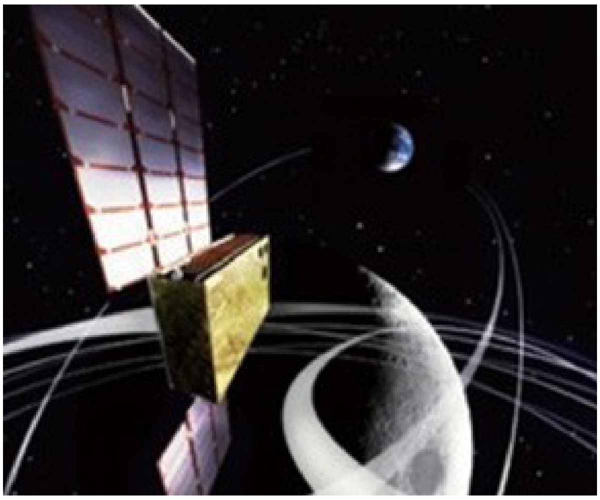
Illustration of the BepiColombo Mercury Composite Spacecraft.

3. Space Science Programs under Development

a. SLS CubeSats: OMOTENASHI and EQUULEUS



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



Artist's concept of EQUULEUS observation from L2.

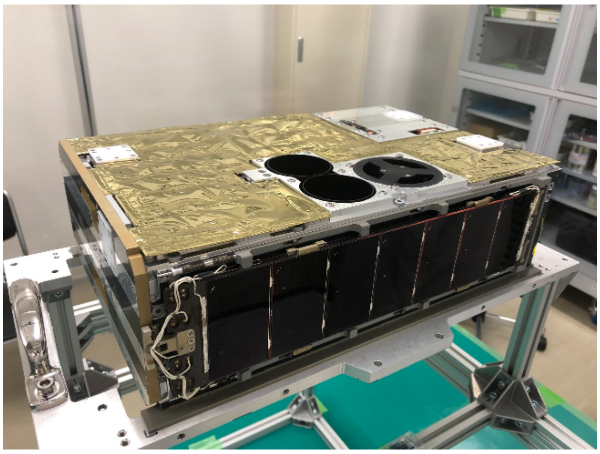
OMOTENASHI (Outstanding MOon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor) and EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) are 6U, 14-kg CubeSats that will be launched by NASA's Space Launch System (SLS) in 2021.

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 an airbag, crushable material and epoxy filler. The radiation environment will be measured by commercial portable dose meters.

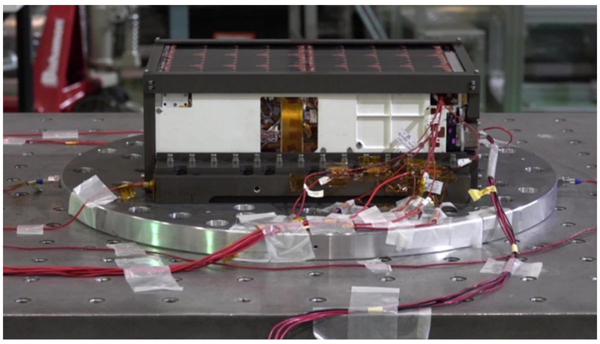
EQUULEUS has four missions. The primary, engineering mission is the demonstration of the trajectory control techniques within the Sun-Earth-Moon region by a nano-spacecraft during the flight to the Earth—Moon Lagrange point L2. A water resistojet propulsion system has been newly developed for trajectory 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 functional tests and environmental tests for both spacecraft. Currently, we are testing on-board software and considering in-orbit operations to be ready for shipment to NASA.

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.



OMOTENASHI during vibration tests.



Completed EQUULEUS flight model.

b. The Smart Lander for Investigating Moon (SLIM)

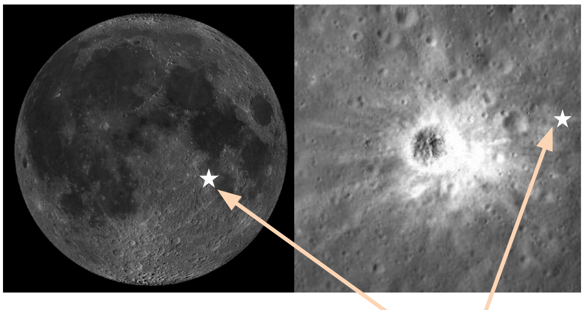
The Smart Lander for Investigating Moon (SLIM) is a project aimed at demonstrating the possibility of precise “pinpoint” landings on the lunar surface using a small and lightweight spacecraft. Pinpoint landings with accuracies of 100 m are required for future Moon explorations. Moreover, since conventional 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 it 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 continuous investigation from FY2017, suitable system configuration was discussed to adopt the situation after HITOMI (ASTRO-H) anomaly. Finally, JAXA and SLIM project team decided to launch the SLIM using a H-IIA rocket, together with an XRISM (X-Ray Imaging and Spectroscopy Mission) satellite.

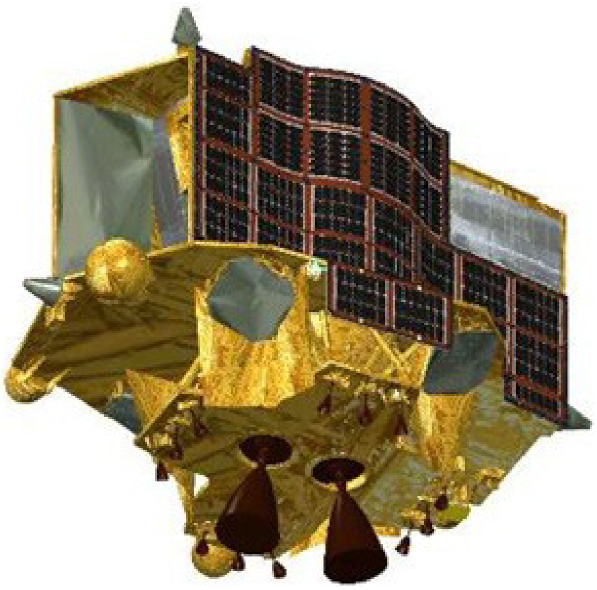
In FY2018, a preliminary design study (contemplating some modifications in response to the launcher change) was conducted, followed by a preliminary design review. This last process included component vendors, system design, and JAXA’s engineering peer reviews. Finally, at the end of FY2018, SLIM project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

In FY2019, a detailed design study and several engineering model tests were conducted. Some of these tests were systematic or extensive ones, such as propulsion system firing test, landing radar field test, electrical system test, and mechanical model test. Based on the results of these activities, detailed design review process had been started.

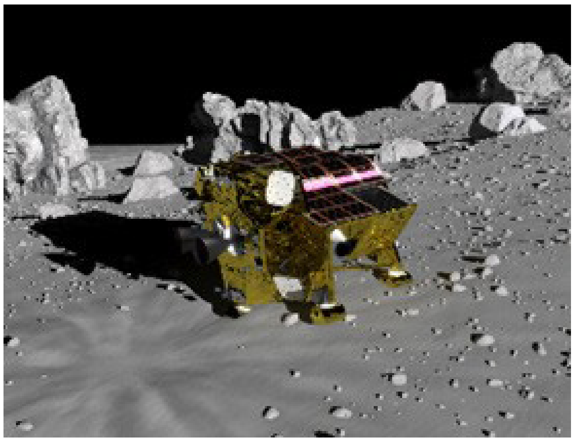
Pinpoint landing is a key technology for the next generation of lunar landers, since it will allow access to specific places on the moon that are scientifically valuable or important exploration targets. Thus, SLIM is a precursor for future national and international landing missions on the Moon, Mars,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



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



Appearance of the SLIM spacecraft.



Expected view of the SLIM on the landing site.

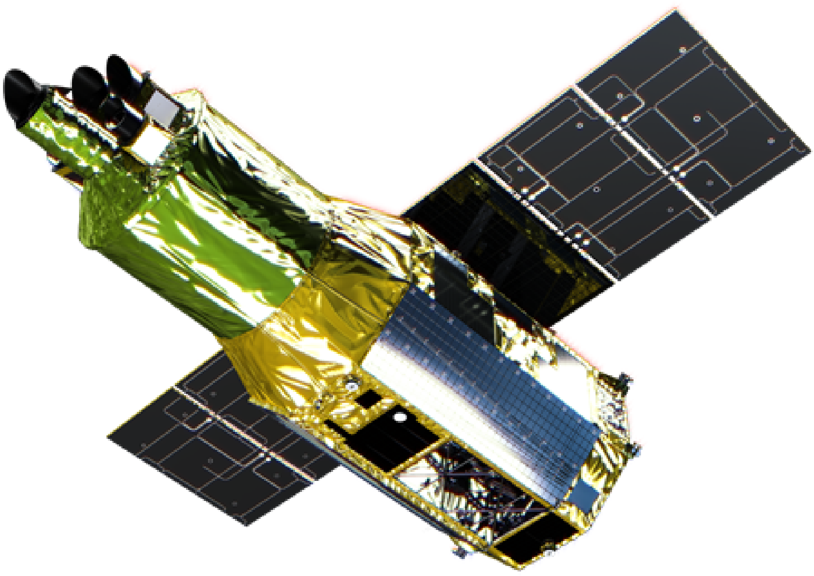
c. X-Ray Imaging and Spectroscopy Mission (XRISM)

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 scientific information 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 the Critical Design Review (CDR) was conducted for each component/subsystem/system of the spacecraft/ground systems. After completion of the integrated system CDR the integration and test will start.

The XRISM contemplates the 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, Phaethon Flyby and Dust Science (DESTINY$^+$)

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

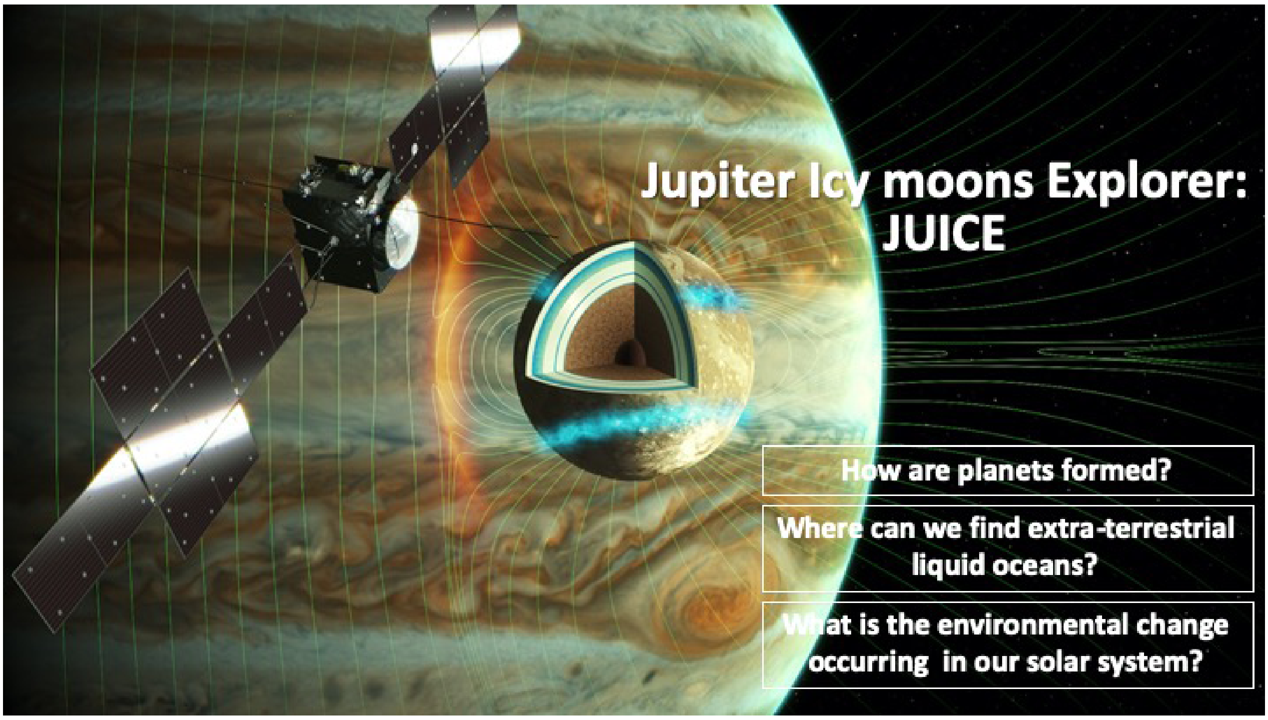
DESTINY$^+$ (Demonstration and Experiment of Space Technology for INterplanetary voYage with Phaethon fLyby and dUst Science) is a candidate of the ISAS M-class small program. The DESTINY$^+$ is a joint engineering and science mission. The mission has the following two engineering mission objectives; 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 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 the 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 launch vehicle, after which electric propulsion will be used to expand the orbit to reach the moon. At this point, it will escape Earth's gravitational sphere of influence via multiple lunar gravity assists, approach the 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 object as part of an extended mission.

DESTINY$^+$ aims to become a JAXA project in FY2020. JAXA plans to develop scientific instruments to observe an active asteroid, Phaethon during its flyby, whereas DLR has an interest in providing the DESTINY$^+$ Dust Analyzer (DDA), a field in which Germany has had the leading expertise in the world for decades. Following establishment of 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 USA as well to determine the shape and the size (see the highlight article). We have been conducting conceptual designs of the spacecraft system, light-weight solar array paddles, electric propulsion, advanced thermal control, orbit determination during orbit raising around the earth, orbit synthesis of all mission phases, mission and bus interface and the interface between the spacecraft and the “Epsilon” launch vehicle with a kick stage. Bread board models of the reversible thermal panels and the mirror pointing mechanism for the telescopic camera have been developed and tested.

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 2032, JUICE will visit Ganymede, in order to answer to 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 science 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 May 2022 by an Arian-5 rocket. After 7.5 years of interplanetary transfer and Earth-Venus-Earth-Mars-Earth gravity assists, JUICE will be inserted into an orbit around Jupiter in 2030, 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 2032, JUICE will make detailed observation of the largest icy moon in the solar system.

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

JUICE-Japan became an ISAS project after passing an ISAS project transition review in December 2017. Regarding RPWI-Japan, we completed CDR (Critical Design Review) in July 2018, and shipped the flight model for the preamplifier (RWI-pre), and the flight model for the high frequency receiver (HF) to Europe in 2019. Regarding PEP/JNA-Japan, we completed CDR in June 2019, and shipment of the flight model to Europe was completed in February 2020. For GALA-Japan, we completed CDR in March 2020 after finishing the engineering model test. Two teams of JANUS-Japan and J-MAG-Japan that were participating as science Co-Is contributed to the observation planning, etc.

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)

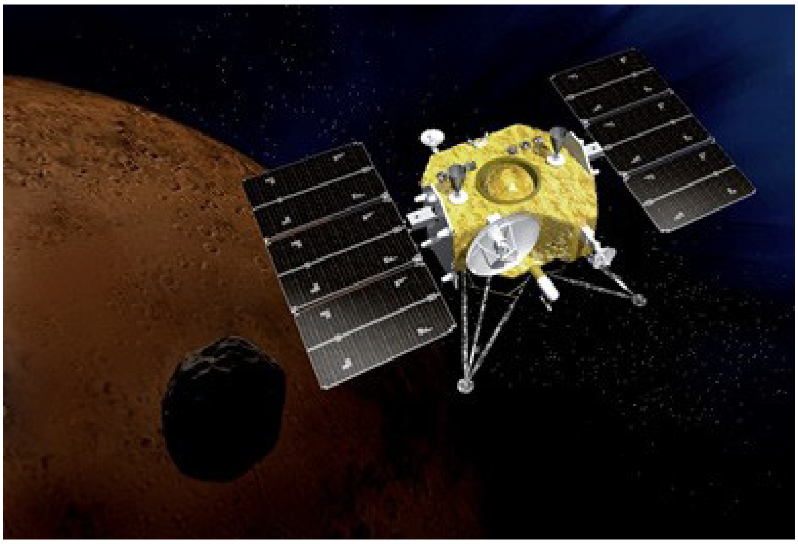


Fig.1. [Image of the MMX spacecraft] One possible MMX spacecraft configuration with a launch mass of 4,000 kg. The spacecraft consists of three main modules: return, exploration, and propulsion. The nominal mission duration will be 5 years.

The Martian Moons eXploration (MMX) mission is the world's first sample return mission from one of the Martian moons and will be launched in JFY 2024. MMX is currently in the development phase as the first strategic mid-sized satellite project.

Mars is the outermost rocky planet in the solar system, and is orbited by two moons, Phobos and Deimos. The primary missions of MMX are to survey the Martian moons and return samples from one moon. The goal of the mission is to contribute to understanding the process of "movement and supply of organic matter and water to the celestial bodies" in the early solar system. Results from MMX will clarify the existence of water and organic matter on the Martian moons, and the origin of the moons themselves, through analysis of the minerals, water, and organic matter present on the Martian moons. Fig. 1 shows an example of the spacecraft configuration.

To realize the launch in JFY 2024, front-loading activities in JFY 2019 such as development of technology for landing on a celestial body with gravity, surface exploration technology (design of propulsion module, guidance and navigation for landing, design of a sample collection device), and a feasibility study of the mission subsystem and overall spacecraft system were conducted based on the results of activities performed in JFY 2016-2018, and the development risk was successfully reduced. Fig.2 shows an example of front-loading activities. Results of the front-loading activities were implemented in the development plans.

In addition to the above, an international agreement was reached on the planetary protection policy for the Mars satellite samples to be acquired by MMX (JAXA press release on September 6, 2019).

The MMX project was discussed and approved at the 53rd meeting of the MEXT's Space Development Utilization Subcommittee on February 19, 2020, based on the results of the JAXA project approval review. The target object was confirmed as Phobos from the viewpoint of planetary science and technical feasibility.

Seven peer-reviewed papers about this mission were published in JFY2019. The total number of peer-reviewed papers to date is 32.

The MMX project was the first to propose and implement a front-loading activity aimed at "reducing uncertainty in the early phase and risk throughout the entire development process."

This allowed the MMX project to create an example of a development plan that reduced technical risk and minimized unexpected additional costs due to rework.

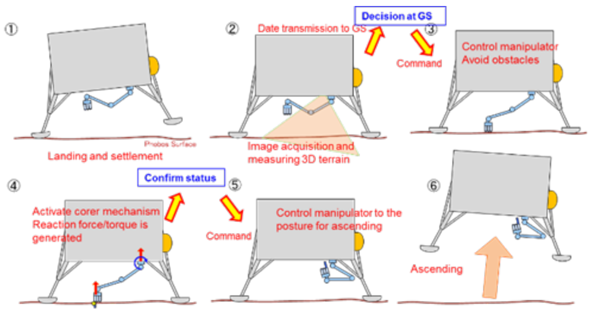
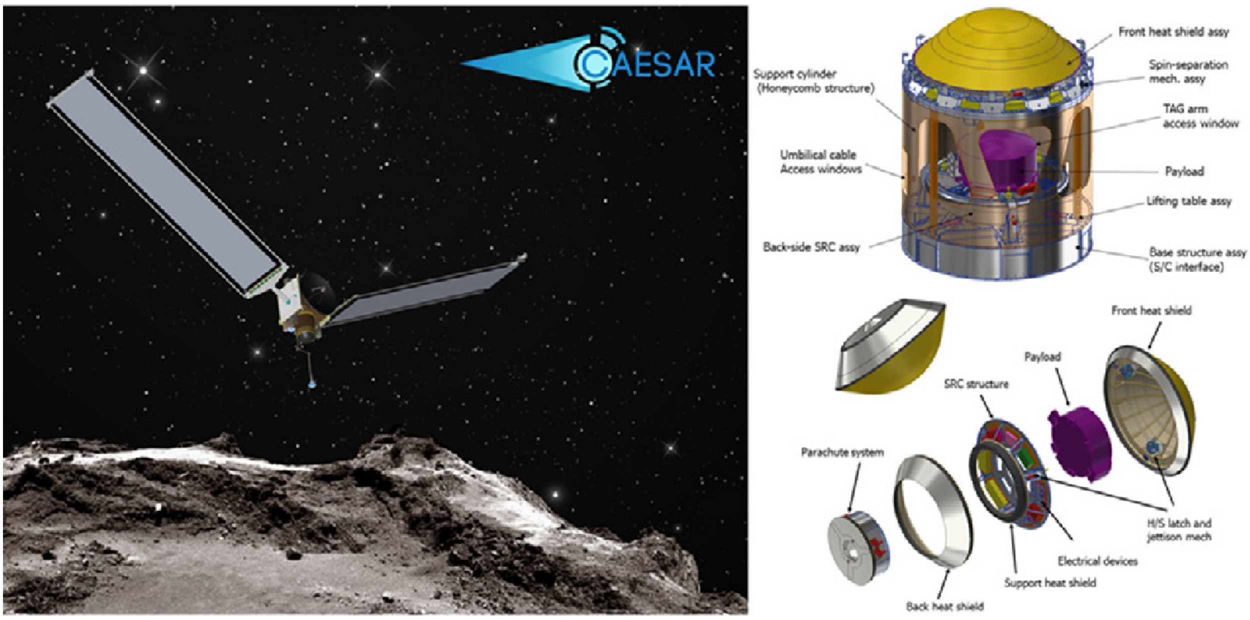


Fig.2. [One example of front loading activities] After studying an operational scenario on the surface of the Martian moon, a functional test of the robotic arm and corer mechanism was carried out to ensure satisfaction of the mission requirement: "To collect samples at a depth of two centimeters or more below the surface of the Martian moon."

g. Comet Astrobiology Exploration SAmple Return (CAESAR)



Artist's concept of CAESAR and Conceptual design of CAESAR Sample return capsule.

CAESAR (Comet Astrobiology Exploration SAmple Return) is a sample-return international mission to comet 67P/Churyumov-Gerasimenko, led by Prof. Steven Squyres of Cornell University and managed by GSFC(NASA Goddard Space Flight Center). The CAESAR mission aims to return both nonvolatile (e.g., rock, stone) and volatile samples (e.g., ice) from comet 67P. This mission was proposed for the NASA New Frontiers Program 4 (NF-4) and selected as one of two finalist missions in December 2017. JAXA and several Japanese scientists have participated in the CAESAR mission as equal partners since 2015, contributing to both engineering and sciences aspects (i.e., the development of the Sample Return Capsule (SRC) and the related scientific planning for sample return). The SRC is an indispensable subsystem for the accomplishment of the CAESAR mission, since the mission aims at a successful sample return. If the CAESAR mission will be successful, JAXA will acquire the advanced SRC technology, which could potentially lead future explorations of the international solar system. Moreover, this technology would allow the sharing of the comet's return samples among Japanese scientists and lead to remarkable scientific advances regarding the origin of life and of the solar system.

JAXA and several Japanese scientists conceived the SRC conceptual design and the necessary activity to enhance the science value and significance for the NF-4 final selection. The results and achievements of this process were shared with the CAESAR team and the final proposal was submitted in December 2018. The activity described in the final proposal include some tests and demonstrations to mitigate the development risk of the SRC critical components and to overcome the potential weakness indicated during the first selection process.

JAXA attended a "Site visit," which is an important event for final selection of NASA's NF-4 at GSFC, on May 1st, 2019, and presented the results of Japanese activity. Japanese activities and collaboration between the U.S. and Japan were highly evaluated during the selection process, and were evaluated as one of the strong points of CAESAR project. However, CAESAR was not selected in June 2019 when NASA announced the adoption of its rival project, Dragonfly (Life Exploration Project in Titan), as a final selection result for NF-4. The activities of the CAESAR project in Japan were canceled after receiving the report of its defeat, and the CAESAR project team was dissolved in January 2020.

Members from Japan who attended the Site Visit at GSFC.

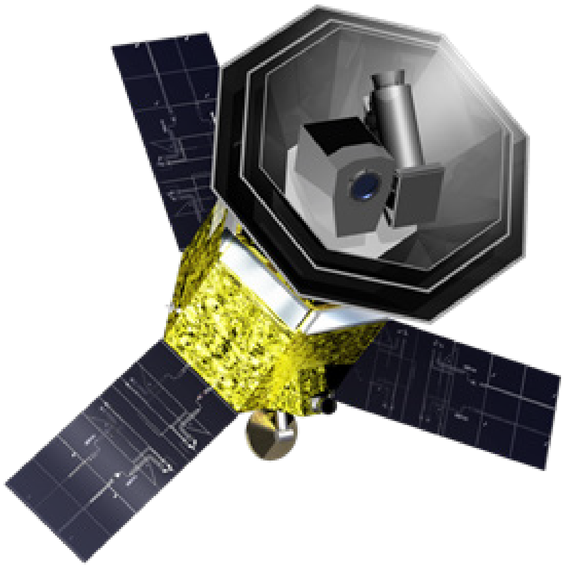
h. Lite (Light) Satellite for Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection (LiteBIRD)

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 telescopes (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 ~1 Hz (LFT) and ~3 Hz (MHFT). We use transition edge sensor (TES) bolometers as detectors, which will be read with superconducting quantum interference devices. The LFT and MHFT, including detectors and optical systems, are actively cooled down to 0.1–4 K.

LiteBIRD is based on extensive collaboration in Japan and with overseas countries. Major collaborative institutes and universities in Japan include KEK (High Energy Accelerator Research Institute), Kavli IPMU (Institute for the Physics and Mathematics of the Universe) and Okayama University. International partners include European countries, which are led by CNES, the U.S. and Canada. The U.S. is responsible for the focal plane detectors for both the LFT and MHFT and for the ADR between 4.8-1.8 K. Canada is responsible for the room-temperature readout electronics. Europe takes responsibility for the MHFT, the ADR between 0.1-1.8 K, and the pulse-tube cooler for the shield cooler.

Following the international science review and the planning review in 2016, the mission definition phase (pre-phase A2) started in September 2016 and continued for two years. We successfully passed the pre-phase A2 exit review in May 2019, and subsequently selected for the 2nd of the strategic large-class mission of JAXA. LiteBIRD was also selected as one of the important large research projects in the Master Plan 2020 of the Science Council of Japan.

After the pre-phase A2 exit review, we worked on conceptual studies of the payload module (PLM) to reduce the development risks and to define the interfaces among the subsystems and the components. Both the LFT and MHFT are cooled down to 5K using the JT cooler with the help of the radiation cooling by V-groove. Because the cooling capability of the JT cooler is limited, we need to work out very good design compatible to both the structural and thermal requirements to the PLM. The polarization modulator of the LFT is a key instrument. We are working on development to reduce the heat dissipation and to realize the full-size half wave plate. Its working temperature was raised to 20 K, which reduced the operation frequency of the holding mechanism and the associated risk. The AIVC (Assembly, Integration, Verification, Calibration) plan for LFT is studied by KEK, where AIVC will be conducted.



Artist’s impression of LiteBIRD.

i. Solar Power Sail-Craft (OKEANOS)

To maintain Japan's leadership in the exploration of the solar system, solar power sail outer planet exploration will be demonstrated.

Achievements:

i. In order to achieve significant cost reductions in the OKEANOS mission, two options were proposed for a future mission proposal: 1) reducing the number of ion engines and 2) removing the ion engines entirely. With the above options, the following proposal is planned for a future strategic medium-class mission.
   - A mast-deployed solar power sail will generate electric power while functioning as a solar sail, contributing to a three-axis attitude control. With chemical thrusters as the main propulsion, the mission will rendezvous with a primordial asteroid and perform multiple autonomous landings and in-situ sample analysis. A deployable advanced target marker (described below) will be used for a pin-point landing accuracy.

ii. To expand the versatility of solar power sails, the integration of mast-deployed solar power sail-panels to other satellites has been proposed and selected.

iii. A small-class solar power sail mission will also be proposed, as follows.
   - With solar power sails powering ion engines while simultaneously generating photon thrust, the hybrid propulsion will transport a small satellite to the outer planetary regions.

iv. For applications for large deployable membrane structures other than solar sailing, the following applications are also investigated and proposed: Thin-film aperture synthesis antennas; reflective sheets, transformable panels, and aerobraking.
   - By integrating power generation capabilities and thin-film antennas into a single deployable membrane structure, high power and high data throughput applications will be enabled for commercial space business applications. A demonstration mission was proposed and accepted for the upcoming "Innovative Satellite Technology Demonstration-3" mission with a theme titled "Demonstration of thin-film space structures with power generation and communications capabilities towards Society 5.0 applications".
   - Integrating power generation and thin-film antennas into a single deployable membrane structure will enable an autonomous active target marker (mentioned above). The thin-film antennas and reflective sheets will allow the mother ship to determine its relative attitude and position, and aid its navigation and landing.

v. Developed new models for sail storage with folding and rolling, aiding the prediction, analysis and experimental validation of the stored volume and volume expansion due to differential circumferences.

vi. For the analysis of sail deployment dynamics, the multi-particle models were enhanced to include accurate reproductions of particle-surface collisions. The new models were used to analyze the sail deployment dynamics for asymmetric deployment, and explained the cause of the asymmetry with energy minimization. The new models were also used to study the feasibility of 70~10 m solar sails.

vii. New sail shape control methods were developed, whereby controlled local deformations are applied to the sails, which are able to affect and control the overall sail shape. This method was shown to effectively control the solar radiation torque acting on the sail. Another method was developed whereby out-of-plane stimuli are applied on spinning solar sails, where the stimuli are synchronized with the sail spin rate. This method is able to create arbitrary sail shapes that are static in reference to the inertial frame. This method was also experimentally demonstrated.

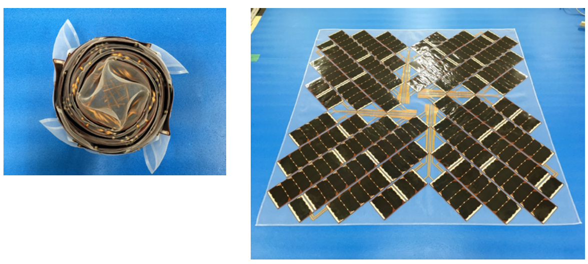
viii. A structural prototype was made for a 1 m by 1 m mast-deployed solar power sail.

Outcomes:

i. Number of peer reviewed articles published: 10 articles
   Total number of peer reviewed articles published: 137 articles

ii. The parent project to this project titled "Space Technology Demonstration Program for Space Exploration Missions" was selected as a Large-Scale Project for the Master Plan 2020 of the Science Council of Japan.

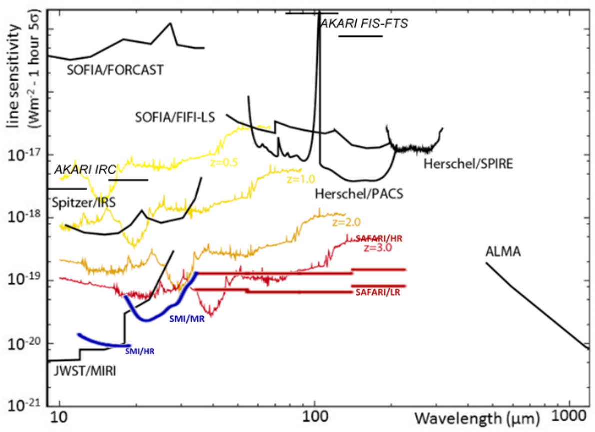
iii. Solar power sailing is one of Japan's original ideas, which is built upon the many lessons learned from past demonstration missions: The Hayabusa series and IKAROS. This technology showcases Japan's technological proficiency in the field of outer planetary exploration and long-rage space travel and navigation. By further developing this capability, future space exploration activities will be made with a "further range, higher versatility and with more advanced techniques".



1 m by 1 m prototype.

j. Next-generation Space Infrared Telescope for Cosmology and Astrophysics (SPICA)

The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) is a next-generation infrared astronomy mission expected to reveal the history behind star-formation in the universe and the formation and evolution processes of planetary systems. SPICA will achieve these goals with its 2.5 m telescope cryogenically cooled to below 8 K (-265°C). The combination of the large aperture and low temperature is expected to enable unprecedented sensitivity at mid- to far-infrared wavelengths, which is the essential spectral range for studying the formation and revolution of galaxies, stars, planets and lives.



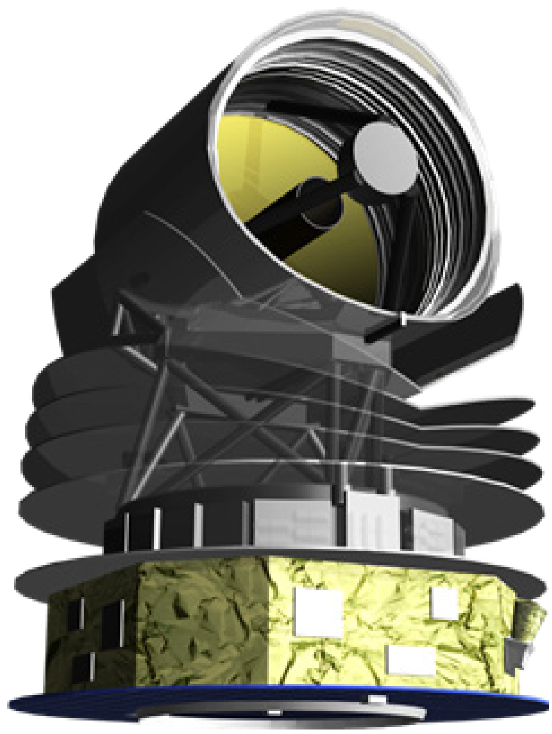
Sensitivity of SPICA instruments (SAFARI and SMI) compared with those of other missions.

SPICA is an international collaboration led by ESA. ESA is responsible for the entire satellite system, the service module and the telescope, while JAXA, as a major partner, is responsible for the integration of the payload module (PLM) with a cryogenic system and the launch operation. A series of cryocoolers, one of the key elements for the success of the SPICA mission, has been developed by JAXA, based on the technical heritage of previous JAXA-led missions, including AKARI and ASTRO-H. SPICA has three powerful focal-plane instruments: SPICA Far-Infrared Instrument (SAFARI), SPICA Mid-Infrared Instrument (SMI), and SPICA Far-Infrared Polarimeter (B-BOP). SAFARI is being developed by an international consortium led by the Netherlands Institute for Space Research (SRON), with the participation of 10 European countries, the US, Canada, Taiwan, and Japan. SMI is being developed by the SMI Consortium led by Nagoya University, Japan. B-BOP is led by CEA Saclay.

In May 2018, SPICA was selected as one of three candidate missions for the 5th M-class mission (M5) of the ESA Cosmic Vision among 25 proposed missions. Following the selection, the SPICA team has since been advancing intensive study on its conceptual design in collaboration between ESA and JAXA. The conceptual design activity will continue until mid-2021, when final selection for M5 will be announced. The intensive design work done in 2019 led us to change the spacecraft configuration from horizontal (the telescope lays on the service module; see figure) to vertical (the telescope stands on the service module).

In order to enhance the feasibility of the mission, the Japanese SPICA team has vigorously promoted development of critical technologies for PLM, cryocoolers, and SMI. The SPICA Science Promotion Committee is working actively to maximize the scientific outcome from SPICA, closely linked to ESA's Science Study Team.

SPICA is expected to play a significant role by filling the gap in wavelength to be observed by the next-generation facilities: The near-infrared by James Webb Space Telescope (JWST) and Thirty Meter Telescope(TMT), and the submillimeter by ALMA. The synergy among the next-generation facilities is indispensable for the study of astrophysics in the coming decades.



SPICA spacecraft (horizontal configuration until Dec. 2019).

4. Other Programs

a. GRound station for deep space Exploration And Telecommunication (GREAT)

The goal of this project is developing a new ground station with a 54-m antenna that will follow the aged 64-m antenna installed at the Usuda Deep Space Center (UDSC). Despite its smaller dimensions, the new antenna will be capable of obtaining more data from spacecraft in future deep-space activities. The new station, located about 1.5 km away in a straight line from the 64-m antenna, will begin operations by supporting Hayabusa2 and eventually BepiColombo.

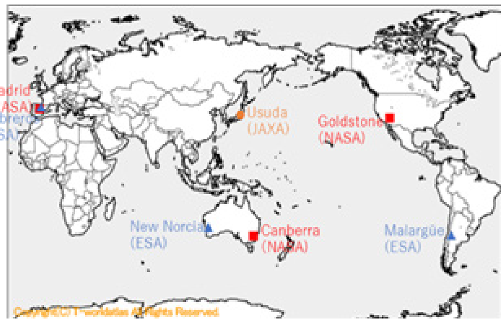
The achievements of the project in JFY2019 are as follows:

1) After all pieces of electric equipment, excluding the transmitter (refer to (4)), the station system consist of were shipped to the site, they were installed and inspected completely.
2) Mechanical adjustment and electrical testing for the antenna was completed on site.
3) After integration testing for the station system from September following 1) and 2) above, it succeeded in receiving RF signals at X-band from Hayabusa2 in December as scheduled.
4) With its assembly and adjustment work finished, the SSPA, Solid State Power Amplifier, as the transmitter of the station, which was adopted last year, was inspected at the factory before being shipped.

Low Noise Amplifier for X-band.

The new station will play an important role in international cooperation with NASA and ESA for deep-space activities. Its geographic position is advantageous because no competing stations are present in East Asia and because its location allows combined operations with NASA and ESA stations to form a very long baseline for deep space navigation. The new station is also significant for conducting future JAXA missions and maintaining ISAS and JAXA's position as international leaders in the exploration of the solar system. The station will also provide opportunities to take part in highly advanced overseas missions by participating in the international deep space network. In particular, the newly added Ka-band receiver is expected to enhance the station's usefulness in international collaboration.

Receiving RF interface unit for Ka-band (left) and Low Noise Amplifier for Ka-band (right).



Position of GREAT with respect to the global deep-space network.

Group photo of people who conducted the receiving test with Hayabusa2.

b. 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 create three cryostats. JAXA is expected to supply coolers for Cryostat #1, a concept study model, and Cryostat #3, which will be used as the ATHENA/X-IFU (X-ray integral field unit) demonstration model with microcalorimeter array. In 2017 and 2018, JAXA's Joule–Thomson (JT) 4 K and 2 K coolers were combined with a French hybrid cooler that cooled down from 2 K to 50 mK. It was the first cooling chain for space use that combined Japanese and European spacecraft cooling technology. In 2019, we published a paper that described the performance and modeling of our JT coolers. "Cooling capability of JT coolers during the cool-down phase for space science mission", K. Shinozaki et al, Cryogenics 109 (2020), 103094.

Also, we collaborated with CNES/CEA for the preparation of the critical design review of the Cryostat#3, especially for the confirmation of the fulfillment of requirements, adjustment of I/F, and assembly procedures.

To improve the robustness of this system, we investigated and specified the cause of the aging effect inside cooler compressors, and proposed updated designs and procedures to overcome the aging, which will allow us to design compressors with a 10-year lifetime. The Athena/X-IFU consortium kept their phase-B study, including the Japanese contribution to supply JT coolers. These results were input into other international missions such as SPICA and LiteBIRD

c. Small Synthetic Aperture Radar (Small SAR)

Small SAR (Synthetic Aperture Radar) demonstration satellites called StriX-α and β have been being developed by Synspective Inc. and JAXA, cooperatively. Critical instruments for the 100-kg small SAR satellite were developed in ImPACT, which is a technology development program of the Japanese Cabinet Office budget bringing innovation to society. The SAR mission instrument, which consists of a deployable SAR antenna assembly (Fig.1), an X-band solid state power pulsed amplifier unit for radar signal transmitting, an RF-front-end assembly, and a SAR signal generating and processing unit, was developed by ISAS.

Major specifications of the StriX-α are listed in the Table below. In 2019, subsystems of the first demonstration satellite were manufactured and tested. System level tests of the FM (Flight Model) in flat-sat configuration were performed. After that, all components were mounted on the satellite structure (Fig.2). System environmental tests such as a thermal vacuum test, a vibration test, etc., were finished. The first demonstration satellite will be launched in 2020.

Table

Frequency Band	X band	
Observation mode	StripMap	Sliding SpotLight
Resolution	3m	1m
Swath	30km	10km
Polarimetry	VV	
Revisit period	1 day in Asian big cities (by 6 constellation in 2022)	
Weight	100 kg class	

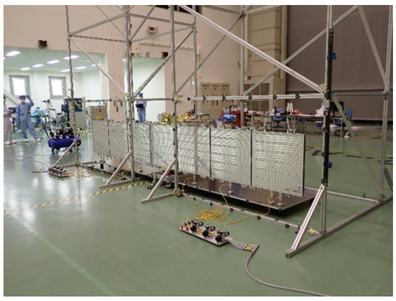


Fig.1. Deployable SAR Antenna

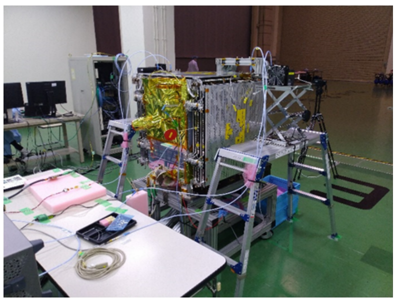


Fig.2. StriX-α (FM)

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, mainly from space. Our studies cover a variety of research fields, from cosmology to exoplanets, by making observations at wavelengths from radio waves to gamma rays. In FY2019, we studied data from the X-ray missions SUZAKU and ASTRO-H, data from MAXI and CALET onboard the ISS, data from the AKARI infrared satellite, and data from ground-based telescopes. The development of X-ray Imaging and Spectroscopy Mission (XRISM) is being proceeded with. In May 2019, LiteBIRD was selected as the 2nd of the series of strategic large class missions and Small JASMINE as the 3rd of the competitive middle- class missions. For SPICA, the proposal for ESA Cosmic Vision M5 was submitted in 2016, and conceptual development has been extensively conducted. Members of the department have contributed to these studies for future missions. The department has also worked on future technology developments, including light-weight X-ray and infrared telescopes, small-pixel infrared detectors, cryogenic X-ray spectrometers and their space cooling technology, X and gamma-ray pixel detectors, analog and digital signal processing technologies, millimeter and submillimeter ultralow-noise heterodyne receivers, next-generation Very- Long-Baseline Interferometry (VLBI) technology, and space applications of the optical lattice clock. Theoretical work and investigations using ground-based facilities (i.e., ground-based telescopes) have also been widely conducted.

2. Research Activities in FY2019

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, including SUZAKU and ASTRO-H. An analysis of the SUZAKU archive data was continued for astronomical objects from the solar system to clusters of galaxies, and the search for dark matter. We studied the metal distribution and origin of peculiar non-equilibrium plasma in supernova remnants using Chandra and XMM-Newton. New tools for a Monte-Carlo simulation were also developed to enable a comparison of theoretical models with the observational data obtained from ASTRO-H.

Development studies for more sensitive observations in the future have also been carried out. For the TES microcalorimeter, laboratory experiments including its application in transmission microscopes, the analysis of rock structures, and precise measurements of nuclear gamma-ray energy for the atomic clock have been conducted. We succeeded in the development of read-out electronics using a microwave resonant circuit, which will enable the development of larger format detectors in the future. For semiconductor sensor devices, R&D has been conducted to achieve lower background noise, a better energy resolution, a better spatial resolution, and a larger format. In the area of gamma-ray detectors, a fundamental study on a sensitive semiconductor Compton camera used to detect the trajectory of electrons 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 to other areas, such as medical imaging or negative muon beam experiments, have been carried out.

2.2. Infrared astrophysics

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 ALMA.

Using the data obtained from AKARI, various studies on galaxy formation and evolution were carried out, including studies on the evolution of the luminosity function and structure of a Compton-thick AGN. We also combined AKARI NEP survey data with data accumulated by SCUBA2 on JCMT. A variability survey of AGN on the search and study of high-redshift low-mass black holes was conducted using Subaru HSC data.

We carried out systematic studies of CO absorption toward AGN. Based on infrared spectroscopic observations by AKARI and Subaru, AKARI data suggested that the feature is attributed to the warm molecular gas in the tori around the AGN. Subaru high- resolution spectroscopic data on the CO absorption feature showed various velocity components, which gave an insight into the inner structure of the tori. We also studied other absorption features such as H_2O and their spatial distribution in ultra-luminous infrared galaxies.

Moreover, we conducted infrared studies of particle acceleration associated with AGN jets. The mid-to-far infrared emission was discovered from the west hot spot in the radio galaxy Pictor A. By comparing multiwavelength data in the radio to the optical range; it has been suggested that the infrared emission originates in recent particle acceleration sites within the hot spot. The very hard radio-to-infrared spectrum indicates that the stochastic acceleration and/or magnetic re-connection operate in the hot spot. Far-infrared emission was also detected from hot spots of the radio galaxy Cygnus A.

For studies on extrasolar planets and low-mass objects, we conducted (1) astrometric observations of M-dwarf binaries to constrain the evolutionary models of low-mass objects through a comparison with the dynamical mass, (2) the detection of icy planets beyond the snow lines using ground-based microlensing observations, (3) a comparison of a cold planet mass-ratio distribution between the planet population synthesis model based on the standard core-accretion model and the observational results from a micro-lensing survey, and (4) a study on the extinction toward the galactic bulge using Subaru/HSC to optimize the WFIRST microlensing survey fields.

Observational studies of the objects in our solar system were also conducted. Interplanetary dust was studied using AKARI mid-infrared spectra (5–13 μm) of zodiacal emissions. We confirmed the excess features within 9–12μm for all spectra, which are attributed to crystalline (forsterite and enstatite) and amorphous silicates. Variations in the feature shapes among the different sky directions may imply a difference in the mineral composition of the supply sources: Jupiter-family comets, Oort cloud comets, and asteroids.

The abundance and origin of crystalline silicates (high-temperature condensates) in comets was studied through mid-infrared observations using the Subaru telescope. Complex organic molecules were also detected in comet 21P/Giacobini- Zinner for the first time in the mid-infrared spectrum taken by Subaru. This indicates that this comet was formed in a relatively warm area in the proto-solar disk, such as a circum-planet disk around a giant planet.

In parallel with the observational studies, a 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 worked on the 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. 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 for FD-SOI CMOS.

We also conducted a study on the Japanese contributions to the WFIRST (Nancy Grace Roman Space Telescope) mission, which is a NASA flagship mission after JWST. Development of polarimetry unit optical elements and mask substrates for coronagraph Instrument, as well as the concept study for the ground system for data receiving and transportation, have proceeded with. We also held a workshop for Subaru-WFIRST synergistic observations. The concept definition phase of the small infrared astrometry satellite “small JASMINE” was conducted, and a system study of the entire satellite was applied. As a result, the project passed its pre-phase A2 exit review in May 2019.

2.3 Fundamental physics

About fundamental physics, studies on cosmic inflation based on the precise measurement of the cosmic microwave background (CMB) are being conducted. For this purpose, we are also conducting studies in relation to the development of the LiteBIRD mission under collaboration with domestic institutes such as KEK and IPMU and international partners in the U.S., Europe, and Canada. Far sidelobe pattern of 1/4 scale model of a wide-field telescope for the CMB radiation has been studied at four times higher frequencies. It was confirmed that the far sidelobe is suppressed to less than -50 dB even at a wide field of 20 degrees. We have studied the optimization of radiation cooling system for the CMB radiation observations in the Sun-Earth Lagrange 2 orbit.

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

2.4 Radio astronomy

Our radio astronomy group performed a wide variety of observational research using large radio telescopes around the world, including the Atacama Large Millimeter/sub-millimeter Array (ALMA) in Chile and the Very Long Baseline Array (VLBA) in the U.S.. Our observation targets are mainly compact objects, such as active galactic nuclei (AGN), Galactic center, and maser objects. In FY2019, we observed the Galactic center (GC) IRS13E3 using ALMA and found ionized gas rapidly rotating around it. The enclosed mass is estimated to be 20,000 solar mass, which is consistent with the typical mass of an “intermediate mass black hole”. We also found the highly excited methanol emission line around it, which indicates that the distance from the Galactic center is larger than 0.4 pc. We performed submillimeter detection of a late-type star in the GC, IRS7, using ALMA. We clarified the physical properties of ultra-compact HII regions in the GC 50 km/s molecular cloud with ALMA. In AGN research, we found phenomena in which jets of radio galaxies are collimated by the accretion disk plasma or radio lobes using VSOP, and so on. We also discovered young active galaxies forming huge radio jets by VLA. Studies on star formation and interstellar matter evolution have also been conducted through single-dish observations of molecular clouds and OH clouds using the 45m telescope at Nobeyama and the 64m antenna at Usuda. We developed a balloon-borne VLBI telescope and low-noise millimeter wave receiver for further satellite projects. We took part in the discussions of 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 the 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 50mK sensors in orbit was started in collaboration with ISAS. See section II.-3.-b for more details.

3. Research Topics

The following outline lists all the Department of Space Astronomy and Astrophysics research activities during FY2018.

3.1 Research in X-ray and gamma-ray regions
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 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 application to the SUZAKU data
3.1.1.4 Observational study for soft X-ray background radiation
3.1.1.5 Study to search for “dark-matter feature” in cosmic X-ray background radiation with SUZAKU
3.1.1.6 X-ray studies of the super nova remnants
3.1.1.7 Study of the X-ray emission region of the active galactic nuclei with the iron line
3.1.1.8 Studies in high-energy gamma-ray astronomy with FERMI LAT (USA)
3.1.1.9 Studies of X-ray sources with the all-sky monitor data from MAXI
3.1.1.10 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 substrate 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 microcalorimeter 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 spectrometer
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 galaxy formation and evolution at the peak of star-formation history in the universe using multiwavelength observations at the NEP survey region
3.2.1.2 Variability survey of AGN using with 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 Active Galactic Nuclei using AKARI data
3.2.1.6 High-resolutions Infrared spectroscopic 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 galaxy evolution for WFIRST 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 extrasolar planets by microlensing survey
3.2.1.12 Study of icy planets population beyond snow line
3.2.1.13 Subaru precursor observations for WFIRST microlensing survey
3.2.1.14 Mid-infrared spectroscopic study for the dynamical evolution of the inter-planetary dust in the Solar System
3.2.1.15 Study of comet dust mineralogy with Subaru and AKARI mid-infrared observations
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 chip
3.2.2.2 Development of monolithic multi-layer interferometric filter
3.2.2.3 Development of mid-infrared immersion grating
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 WFIRST program
3.2.2.7 System study of the small JASMINE mission
3.3 Fundamental Physics

3.3.1 Promoting 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 in radio jets of 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 receiver
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

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 from the asteroid Itokawa have been analyzed. Missions under preparation, including MMX (Martian Moons eXploration: Phobos sample return mission) and JUICE (Jupiter Icy Moons Explorer), 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 FY2019

2.1 Solar physics

HINODE, which has been in orbit for 13 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, which were published this year, include the 3D structures of the solar convection at the solar surface, the formation of hot plasma in flares captured with EUV spectroscopic overlappogram, and spectro-polarimetric diagnostics of the chromosphere for revealing chromospheric jets.

What are the prospects for solar physics for the 2020s? In addition to new instrument developments through sounding rockets and balloon experiments, the solar physics community has worked to propose new solar missions for launch during the 2020s. The Next Generation Solar Physics Mission (NGSPM) Science Objectives Team (SOT), an international advisory team supported by JAXA, NASA, and ESA to discuss the different aspects of space missions, led by T. Shimizu, Project Manager of HINODE, conducted studies and discussions aimed at (1) listing the high-priority objectives and tasks of science that need to be addressed in relation to next-generation solar physics, (2) listing the high-priority instruments required for high-priority science items, and (3) developing ideas for an international framework necessary to implement missions that will fly instruments. In the final report delivered to JAXA/NASA/ESA in July 2017, three of the highest priority instrument packages (a high-resolution coronal/transition-region spectroscopic telescope, high-resolution coronal imager, and large telescope for diagnosing the magnetic field and the dynamics of the chromosphere and photosphere, in order) were identified along with their scientific rationale and the recommendations for mission architectures used to fly the instruments. In 2018, discussions and information exchanges toward realizing the recommendations in the NGSPN-SOT report were conducted, including community-based science meetings and agency-based conversations.

As a conclusion, from a series of discussions within the solar physics community and the NGSPM-SOT report, the community has given its highest priority to the mission 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. This mission concept, called Solar-C_EUVST, was proposed to the ISAS as a candidate competitively chosen M-class mission in January 2018. 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. As a result of a selection review led by the Advisory Committee for Space Science and Engineering, Solar-C_EUVST was selected in July 2018 to proceed to the next study phase. After completing an international science review in December 2018, and a review to select a pre-project candidate in March 2019, the Solar-C_EUVST team has started study activities in the mission definition phase (PrePhase A2). Along with negotiating an international collaboration scheme for EUVST development, NASA chose “US contributions to EUVST” Mission of Opportunity proposal as one of the Phase A study missions in September 2019, accelerating mission conceptual studies. In January-February 2020, ISAS held a review for confirming the achievement in the mission definition phase before pre-project candidate downselection With the review results, Solar-C_EUVST was downselected as the 4th in the series of competitively chosen M-class missions in April 2020.

In addition, 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 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 around the mid 2020’s.

As a follow-up to the Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP) mission, a sounding rocket experiment designated 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.

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. Following the successful observation with FOXSI-3, a subsequent sounding rocket program, FOXSI-4, which plans to observe solar flares, was proposed to NASA by a joint US-Japan team.

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 at NAOJ, ISAS, and Kyoto University are preparing a focal plane instrument, called Sunrise Chromospheric Infrared spectroPolarimeter (SCIP), for the third flight of the upgraded SUNRISE (1-m telescope) observatory on a stratospheric balloon (SUNRISE-3, scheduled in 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 studies at ISAS this year include a scientific evaluation based on an analysis of numerical simulations and the development of scanning mirror mechanisms and polarization modulator mechanisms.

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. Because magnetic reconnections occur frequently on the surface of the boundary of the Earth’s magnetosphere and in the Earth’s magnetotail, these are the regions that 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 FY2019, all 16 FPI-DIS analyzers continued observation of the magnetic reconnection region in the magnetotail without 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 spacecrafts: 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 20 October 2018 (UTC) from Guiana Space Center (CSG) by the Ariane-5 rocket, the initial checks of the spacecraft and instruments were performed. In FY2019, commissioning operations for high voltage parts of the science instruments and launch lock release for extension instruments were completed. The parameter updates and dry run operations for the Earth flyby on April 2020 were also performed. In parallel, the Science Working Group worked on science operations planning. We held an international Science Working Team meeting at ESA/ESTEC in the Netherlands in October 2019 and discussed the science operations planning. The Young Scientist Working Group is at the core of such activity, and we held splinter meetings to study the latest science results, remaining issues, and observation requirements of BepiColombo. We also made progress on preparing a special issue of BepiColombo in the Space Science Review.

SS-520-3 is a sounding rocket that will be launched from Spitsbergen, Norway. The scientific purpose of the SS- 520-3 is to understand the ion up-flow phenomena in the dayside polar cusp region. Although the SS-520-3 launch was scheduled between December 6 and 19, 2017, a malfunction of the timer equipment was found during the final stage of the integration test. Because the problem could not be rectified by the deadline for transport of the SS-520-3 to the launch site, the launch was postponed. The timer equipment problem was completely fixed at the beginning of FY2018. However, it was not possible to launch SS-520-3 due to the severely poor budgetary situation at ISAS in FY2018 and FY2019. The experiment was scheduled to be implemented in January 2021, but the launch was postponed further until after FY2021 due to COVID-19.

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. The original launch schedule for LAMP was FY2020, but it has been postponed to FY2021 due to COVID-19.

The FACTORS WG was established under the Advisory Committee for Space Science in December 2018 as a community mission in Japan's space physics following the ARASE satellite to study the polar formation flight observation satellite program FACTORS. The scientific purpose of FACTORS is to realize spatiotemporal separation by observing space plasma and the Earth's upper atmosphere on multiple time and space scales by formation flight satellites and the latest observation technology, the empirical and quantitative elucidation of the basic mechanical and electromagnetic mechanisms that compose and control the Space-Earth coupled system. In FY2019, in addition to developing an electric field sensor for plasma wave observations, we also proceeded with the study of satellite systems and the configuration of multiple spacecraft launch.

2.3 Atmospheric science

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 various planets, including Jupiter, Venus, and Mars, since December 2013. HISAKI succeeded in observing Jupiter's inner magnetosphere at the same time as NASA's Jupiter orbiter, Juno, passes through the perijove, and Venus and Mars approach the Earth. The scientific results produced by the cooperative observation with Juno showed HISAKI's potential importance by providing continuous observations. A collaborative investigation using the HISAKI data has been promoting international cooperation (since 2016) within certain international frameworks, including the Participating Scientist Program by NASA. The results are presented in the Conference on Magnetospheres of the Outer Planets at Tohoku Univ. Collaborative studies have shown the important presence of Japan in the full-scale exploration of Jupiter's magnetosphere.

The noteworthy results for 2019 include the comprehensive study of the in-situ observation and remote sensing using the Hubble Space Telescope, Juno, and HISAKI. The result shows that there is a relationship between the motion of the plasma and the field in the middle magnetosphere and the emission intensity of the aurora in the polar region. Also, observation results of a massive cool core cluster are published beyond HISAKI's principal purpose. This is a very important cooperative study that exceeded the boundaries of the space scientific field.

HISAKI continues collaborative observations of Jupiter with Juno at the time of Juno's perijove passage in order to study the transport of energy and materials in Jupiter's magnetosphere, and collaborative observations of Venus with the Venus climate orbiter, AKATSUKI, 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 5 years of wondering 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 5 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- 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 equipped for radio occultation measurements to understand the vertical structure of the Venusian atmosphere. The IR1 and IR2 cameras operated for more than 1 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 is revealed for the first time in the world. Previously only the viewable hemisphere had been analyzed, and 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.

A working group was established to realize Martian atmospheric escape using a Mars orbiter (Mars Aqueous-environment Climate Orbiter, MACO) as one of the milestones of the strategic Mars exploration for the next 20 years. The MACO mission using Mars aerocapture technology for the purpose of acquiring technology for future Mars landing exploration was proposed as a space science mission concept for competitive M-class missions, but it was not adopted because its scale is out of application. The members also participated in the “Mars Science Sub-Science Team (Mars Science SST)” of Martian Moons eXploration (MMX) and advanced the examination of the Mars atmosphere observation. The scientific objectives are discussed to provide feedback to the observation plan.

World Space Observatory Ultraviolet (WSO-UV) is the 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).

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. EUV irradiation is estimated to be > 10 times higher around the habitable zone in these planets 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. Because 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 FY2019, we performed some fundamental experiments on a detector and a grating and discussed the interface information between WSO-UV and UVSPEX with the Russian team.

2.4 Planetary science

The Hayabusa2 mission has explored C-type asteroid 162173 Ryugu. After its arrival in June 2018, the asteroid was characterized by remote sensing to select landing sites. After the release of the rover Minerva-II and the European-collaboration lander Mascot, the first touchdown for sampling was conducted in February 2019. The artificial impact experiment was performed in April 2019 with the SCI (Small Carry-on Impactor) and the DCAM3 (deployable camera). After observations of the artificial crater, the second touchdown for sampling at site neighboring the crater was conducted in July 2019. Hayabusa2 departed from Ryugu in November 2019 to return samples to Earth. The main scientific results are:

1) Remote-sensing and surface thermal experiments revealed the surface boulders and rocks have very low thermal inertia, indicating highly porous materials with porosity ~50 %, corresponding to flyable and fragile rocks. This nature should be shared in common with primitive asteroids (and planetesimals in the solar nebula). This is consistent with the surface camera showing the most of rocks with cauliflower-like crumby surfaces and some with more flattened surfaces.
2) The artificial impact crater formed by SCI indicates sediment of low density and cohesionless material. The larger crater diameter than expected suggests a surface age of 10 million years by crater chronology.

Establishment of the Curation Facility for the Hayabusa2 sample to be returned in 2020 started by building a new clean room and fabricating a set of clean chambers, including a new technology to pick up samples in a vacuum environment.

The MMX (Martian Moons eXploration) project, aiming the Phobos sample return mission, transitioned into Phase B for launch in 2024. Its science and instrumentation have been developed with international collaboration on a near-infrared spectrometer and gamma-ray and neutron spectrometers. MMX is the third Japanese sample return mission, followed by HAYABUSA and Hayabusa2. The MMX spacecraft is scheduled to be launched in 2024, orbit both Phobos and Deimos (multi-flybys), and retrieve and return >10 g of Phobos samples back to Earth in 2029. The origins of Phobos and Deimos are still a matter of significant debate, namely, the capture of asteroids versus in-situ formation by a giant impact on Mars. In either case, MMX will provide clues about their origins and offer an opportunity to directly explore the satellite building blocks or juvenile crust/mantle components of Mars. MMX is also aimed at understanding the physical processes in the circumplanetary environment of Mars. The new knowledge of Phobos/Deimos and Mars will be further leveraged to constrain the initial conditions of the Mars-moon system and to gain vital insight regarding the sources and delivery process of water and organics into the inner rocky planets.

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, are expected to ramp up soon. In addition, a solar powered sail mission OKEANOS to rendezvous with and land on a Jupiter Trojan asteroid is under intensive study for scientific objectives and its instrumentation is being enabled through international collaboration. A study has been started to mount a thermal imager on ESA Hera mission, which will explore a binary asteroid and is a part of the planetary defense mission AIDA with the NASA DART mission.

Each of these exploration missions is targeting small bodies born “outside the snowline”, which refers to the distance from the sun where 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, such as when and how did this process occur? Furthermore, is it possible for habitability to be established on areas outside the snow line?

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. We successfully developed a small size and light weight communication system and a new penetration experimental system to confirm shock durability on board. We are also developing a penetrator system for Earth’s monitoring of volcanic activities for the purpose of disaster prevention.

The SLIM project team conducted a trade-off study for landing site selection from the viewpoint of science requirements and engineering constraints in FY2019, and determined the site in the neighborhood of a small crater named SHIOLI on the Moon’s nearside. An engineering model for multiband cameras onboard the SLIM spacecraft has been manufactured and tested at a ground facility. Our department contributes to the operation of environmental and optical-performance tests of camera systems, as well as coordination with spacecraft interface items.

According to the international trend for Mars exploration and potential significance for understanding the current and past surface/subsurface aqueous environments, JAXA plans a strategic Mars exploration program (JSMEP). JSMEP starts with MMX mission in 2024-2029, followed by a Mars orbiter (MO) later in the 2020s and a Mars lander/rover (ML/R) mission in the early 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.

Dragonfly is a relocatable lander with dual-quad rotors to explore Saturn’s moon Titan, selected as the 4th mission in NASA’s New Frontiers Program and its development started officially in FY2019. A drone-type spacecraft will take cyclical powered-flights and land on multiple sites on Titan to observe atmospheric gas species, surface organic compounds, and subsurface conditions. The Geophysical and Meteorological package (DraGMet) onboard Dragonfly is a suite of sensors to monitor the Titan surface/subsurface environment and it includes a single-axis seismometer. Our department contributes to the development of this seismometer to investigate the internal structure of Titan. Ultra-low temperature tests of seismometers have been conducted and the design of the installation mechanism is under study.

3. Research Topics

The following outline lists all the Department of Solar System Sciences research activities during FY2019:

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) and magnetosphere of outer planets
3.2.2 Sounding rocket: SS-520-3, RockSat-XN, and LAMP
3.2.3 Numerical simulations: PIC simulation for space plasma research and physics of proto-planetary disks
3.2.4 Instrument development: High contrast vane protected from the stray light
3.2.5 Future missions: BepiColombo (Mercury), JUICE(Jupiter), mission planning of a formation flying satellite FACTORS, satellite observation of exoplanets' atmosphere by UV, space telescope for planets by UV, and satellite observation of Martian atmospheric escape
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.
3.4 Planetary science
3.4.1 Lunar science using KAGUYA data
3.4.2 Asteroids: curation and analysis of Itokawa samples and in preparation 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, the lunar and Mars cave missions, HERACLES (lunar sample return)
3.4.4 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—and astrobiology, including the search for the precursors of life and extraterrestrial life.
- 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 about the visualization of space science data, monitoring for spacecraft malfunctions, numerical simulations, and data assimilation.
- Scientific balloons. The department is engaged in R&D of 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 FY2019

2.1 Space utilization science

In the field of materials science, phenomena that occur in extremely high temperatures are often studied using electrostatic levitation. Using the electrostatic levitator in the International Space Station, several rare-earth oxides (Tb_2O_3, Ho_2O_3, Gd_2O_3, Er2O3, and Y_2O_3) whose melting temperatures are over 2,400°C have been melted successfully and their liquid-phase thermophysical properties have been measured.

Based on the knowledge obtained from the Alloy Semiconductor experiment at the ISS, the highest thermoelectric figure of merit of 0.62 at 573 K was achieved by InGaSb crystal grown on the ground for the first time among any other III−V semiconductors. This result indicates that controlling point defects in crystal and microscale compositional segregation is an effective method for improving thermoelectric properties in multicomponent systems.

Life science activities are also underway. *Patiria pectinifera* can stick to a vertical wall, i.e., this species does not maintain posture to gravitational vector strictly. On the other hand, Astropecten species, which do not stick to vertical walls, keep posture to gravitational vector strictly. To compare righting behaviors (response to gravitational force) in these two species of star fish, supply procedures for *Astropecten* species and new experimental systems for this species were developed.

In the field of astrobiology, we have completed the four-year-long in-orbit operation of the “Tanpopo” experiment onboard the ISS Kibo exposed facility, which captured cosmic dust and exposed terrestrial organics and microbes to test the Panspermia hypothesis. Since the fall of 2019, its successor experiment “Tanpopo-2” has begun the in-orbit operation for studying chemical evolution from cosmic dust to life precursors. Initial sample analyses of post-retrieved capture panels in 2015-2019 were completed to identify an asteroidal meteoroid and to elucidate temporal variation of microparticulate environments in the low Earth orbit. As for the exposure panel analyses, temporal variation of survival rates of terrestrial extremophile microbes in space was also estimated to imply its mechanism.

In addition to the Mio dust detector and Tanpopo-2 dust collector presently in operation, we made progress in research and development of cosmic dust detectors and collectors for near-future flight opportunities such as EQUULEUS, OPENS and Gateway. Based on the space-proven technology of IKAROS, PVDF film sensor sandwiched in MLI (CLOTH) was developed while intact capture media such as the world’s lowest density silica aerogel (0.007g/cc) and carbon nano tube tapes were developed by lessons learned from Tanpopo. These instruments were calibrated with single microparticle impact experiment facilities at hypervelocity to low velocity ranges in vacuum, which have been coordinated under the international collaboration among ISAS, Hosei University and MIT. These developments directly contribute to research on sampling strategy of ocean world’s plume particles and impact sterilization techniques needed for their planetary protection countermeasures.

ISS experiments to select test organisms to investigate the survivability of life in extreme environments such as the Moon and Mars was proposed. Furthermore, the balloon and drone hybrid flight system “Barone” used for Mars life exploration was studied..

2.2 Research in 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, large-scale analysis (the number of grid points is 4.5 billion), which improves grid resolution, compared to last year’s calculation, was performed on the aircraft take-off and landing configuration. Smaller vortices can be captured by improving the grid resolution. This program is expected to run on the supercomputer “Fugaku”, which is currently under development, and we conducted speed-up tuning for “Fugaku”. As a result, the performance is expected to be 40 times faster than that of the K computer. These results were evaluated and adopted in Supercomputer “Fugaku” achievement creation acceleration program to be started next year.

The department investigated methods of visualization and studies related to visualization. (1) We developed methods to visualize 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 operations of space probes by visualizing the behavior of the probe. In order to demonstrate the methods in public, we implemented them on a portable computer with a 4K display, which has enough capability to reproduce the behavior of the probe as well as real-time visualization. (2) Based on the methods to visualize virtual asteroids, we visualized a variety of simulation data in order to investigate the physical properties of Ryugu by comparing with actual observation data. (3) We developed methods to shape 3D models using the observation data of a scientific satellite “REIMEI”. The methods are expected to be applicable to other types of observation data.

The data archive study is also handled by this department. There are two topics, namely, long-term preservation and utilization. For the long-term preservation of the planetary data archive, the global standard: Planetary Data System version 4, PDS4, is used to prepare archives for ongoing and future missions. In addition, the ancillary data archive in SPICE format is used to support science for the Hayabusa2 mission. These data were released to the public. For the implementation, the Web Service API: Planetary Data Access Protocol, PDAP, is developed to search planetary data. The engine has been unified, and it supports HAYABUSA, Akatsuki, and SELENE (KAGUYA) data. The response from the API is VOTable and is in XML format, which enables users to access the metadata using a programmatic interface. Also, the development of the efficient access method to large-scale datasets and prototype implementation is developed. For remarkable utilization, machine learning is utilized for anomaly detection using engineering conversion datasets, deep learning to classify Apollo lunar seismic events, to find central peak craters on the moon, and for super resolution from digital terrain maps with low resolution.

2.3 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, a simple model describing the differential pressure inside a balloon as a function of the atmospheric pressure, room temperature, and the expansion of the balloon was developed and applied to the results of the ground inflation tests of two 2,000 m^3 balloons performed in 2016 and 2017 to estimate gas leakage. The theoretical shape of the balloon with a diamond shaped net was derived using the variational method, and the ratio of radius to meridian length was compared with the experimental results of the 2,000 m^3 balloons, showing good agreement. A 100 m^3 balloon was developed for the LODEWAVE (Long-Duration balloon Experiment of gravity WAVE over Antarctica) project. The gas pressure inside the balloon was kept positive for 280 hours after filling the air with a pressure of 1,200 Pa. The burst pressure was measured to 3,500 Pa, which corresponds to three times the required pressure.

In space science research using balloons, detailed analyses of cosmic-ray data obtained during balloon flights over Antarctica in the Balloon-borne Experiment using a Superconducting Spectrometer were continued. The energy spectrum of antiprotons is being extended to lower energies, and hitherto undiscovered antideuterons are being searched.

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.

Furthermore, studies were promoted to continue development of the General Anti-Particle Spectrometer (GAPS), 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, detailed data analysis of the MeV gamma ray telescope SMILE-2+, which had a balloon-flight in Australia in 2018, and preparations for the next balloon observation plan, SMILE-3, were also carried out.

2.4 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 maintain and establish it as a new tool for space science and exploration, we have been conducting research activities on micro/nano-spacecraft technology since FY2019.

In this fiscal year, regarding the comet exploration mission (Comet Interceptor mission) that is being jointly studied with ESA for launch in 2028, a study WG was set up in the Space Science Committee to proceed with conceptual design. We are preparing a proposal to the ISAS to initiate the spacecraft development project.

3. Research Topics

The following outline lists all the Department of Interdisciplinary Space Science research activities during FY2019.

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
3.1.2.2 Response behavior to gravitational force
3.1.3 Astrobiology
3.1.3.1 'Tanpopo' and 'Tanpopo2' experiments onboard ISS to capture cosmic dust and expose organics and terrestrial microbes
3.1.3.2 Research and development of instrumentation for cosmic dust detection and capture
3.1.3.3 Research and development of single microparticle

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 FY2018

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 is focusing on research for spacecraft, such as interplanetary probes and advanced scientific satellites, and their navigation, guidance, and control. 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 craft 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; advanced aero-assisted propulsion system for new sounding rockets; advanced space propulsion systems, such as electric propulsion used for interplanetary transfers; and a system and its component technologies for re-entry/recovery and orbit control using the atmosphere. Furthermore, the department is evaluating and optimizing the aerodynamic characteristics of flight vehicles, in addition to fundamental research on chemical reactions, flow, heat, and electromagnetism, from 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, and 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 FY2019.

3.1 Epsilon rockets
3.1.1 Aerodynamics of Epsilon rockets
3.1.2 Guidance and control system for Epsilon rockets
3.1.3 Structural systems for Epsilon rockets
3.1.4 Static test firing of propulsion system for Epsilon rockets
3.2 Reusable space transportation system for frequent flights
3.2.1 Reusable rocket system
3.2.2 Reusable rocket engine and propulsion system
3.2.3 Aerodynamics and guidance and control system for reusable rockets
3.2.4 Fault-tolerant systems for reusable rockets
3.2.5 Development of cryogenic composite tank with electrocast line
3.3 Solid-fuel rockets
3.3.1 Solid propellant using high-energy materials
3.3.2 Solid propellant for a new gas generator used for auxiliary propulsion systems
3.3.3 Debris-less solid propellant
3.3.4 Solid propellant using thermoplastic materials
3.3.5 Solid propellant kneading system with artificial muscle actuators
3.3.6 Non-destructive reliability evaluation of solid rocket motor
3.3.7 R&D of deployable nozzles
3.4 Hybrid rockets
3.4.1 Independent control of thrust and mixture ratio in A-SOFT hybrid rocket
3.4.2 Numerical analyses of boundary layer combustion instability in axial-injection hybrid rockets
3.4.3 Safety of hybrid rockets
3.4.4 LOX vaporizing system
3.4.5 Demonstration of A-SOFT hybrid rocket engine
3.5 Technology demonstration system for space planes
3.6 Innovations for aerodynamic performance
3.7 Acoustic analysis for forecasting rocket plume noise
3.8 Problems with the aerodynamics of space transporters and other space vehicles
3.9 Thermal design, analysis, and testing of scientific satellites and new thermal control technologies for future scientific satellites
3.10 Structural systems for existing scientific satellite projects
3.10.1 Structural systems for small scientific satellites
3.10.2 Structural systems for MMO
3.10.3 Structural systems for SLIM
3.11 Structure, function, and dynamics of rockets for launching scientific satellites
3.12 Heat-resistant composite
3.12.1 Anti-environment ceramic coatings
3.12.2 Use of heat-resistant composites in various engine components
3.12.3 Damage accumulation and performance degradation mechanism
3.12.4 Weight and cost reduction of heat-resistant material used in solid rocket nozzles
3.13 Polymers and polymer matrix composites
3.13.1 Development of CFRP disks for high-speed rotation
3.13.2 High-precision composite material for large space structures
3.13.3 Carbon nanotube-reinforced composites
3.14 Strength and destruction of metallic materials
3.14.1 Creep fatigue of combustion chambers of rocket engines
3.14.2 In-situ observation of superplastic grain boundary sliding
3.14.3 Performance improvement of shape-memory alloy
3.15 Joining of ceramics and metal
3.16 In-situ observation of hypervelocity impact damage
3.17 Activities to establish international standards for materials and processes
3.18 Liquid propulsion systems
3.18.1 Combustion of bio-alcohol fuel
3.18.2 R&D of thruster that uses hydroxyl ammonium nitrate-based liquid monopropellant
3.18.3 R&D for ceramic thrusters
3.18.4 N_2O/ethanol propulsion system
3.18.5 High-energy ionic liquid propellants
3.19 Electric Propulsion
3.19.1 Ion Thruster
3.19.2 DC Arcjet
3.19.3 Pulsed Plasma Thruster
3.19.4 Magneto-plasma Sail
3.19.5 Thrust Stand for micro thrusters
3.19.6 Hall Thruster
3.20 Re-entry and planetary entry
3.21 Development of re-entry vehicle with deployable flexible structure
3.22 Mars exploration airplane
3.23 Guidance system for astronomical object landing navigation
3.24 Analysis of astrodynamics (applied spacecraft flight dynamics) and deep space exploration missions
3.25 Research for Hayabusa2
3.25.1 Analysis of the orbiting, guidance, navigation, and control of Hayabusa2
3.25.2 Astrodynamics research for Hayabusa2

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. In addition, 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; and are 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 FY2019

2.1 Technology for power supply systems

For small missions, we developed a small SUS laminate battery with high energy density. The battery will be installed in the Smart Lander for Investigating Moon (SLIM), which was selected as the third small satellite. In addition, we developed a solar cell for future exploration of the surface of Mars. Owing to their multijunction structure, solar cells must be optimized for the solar spectrum on Mars. We improved the conversion efficiency by approximately 9% compared with solar cells for the AM0 solar spectrum. We are also conducting a project on battery designs for low temperatures and electrochemical reduction electrolysis.

We confirmed the drastic degradation of the charge/discharge cycling performance of lithium-ion secondary cells with the lithium metal deposition inside the cell at temperatures lower than 10 °C. We will understand the relationship of the safety aspects of the lithium-ion secondary cells, which is operated at low temperatures.

Linked with the phenomena we observed through the experiments of lithium-ion secondary cells at low temperature, we will understand the lithium metal creation after the long-term operation of the spacecraft. The small satellite REIMEI already experienced over 14 years in space. REIMEI is one of the first satellites that used a lithium-ion secondary battery. We will identify the lithium metal deposition inside the battery cells after long term operation. This understanding will be reflected in the passivation of the spacecraft before the termination of the operation. Furthermore, understanding of the internal condition of the battery cells are simulated by the efforts of DLR under the collaboration contract.

We are continuing work on an energy carrier that uses renewable energy, based on previous research on fuel cells/renewable fuel cells, and we are currently attempting to apply the technology to the oxygen generator and CO_2 reduction devices for future manned operations.

2.2 Communication technology

In our research on components for communications and energy transmission in space, we are developing electronic cell chips that use space-capable RF nano-electronics and prototyped system-on-chips using Si and the compound semiconductor integrated circuit called “HySIC”. We developed a prototype for an active integrated antenna with a GaN Schottky barrier diode and a Si RF integrated circuit, which will be used as a component for an ultra-small phased array antenna. We also developed a prototype of a Wireless Communication and Power Transmission (WiCoPT) system and a GaN high-efficiency amplifier to be used in a marine radar.

For satellite and spacecraft systems, we developed an active integrated phased array antenna with a retrodirective function for the Solar Sail project, and evaluated a BBM for a docking radar to be used for sample return. We also fabricated a prototype for a compact wireless health monitoring sensor system to be used in spacecraft incorporating our high-performance small rectenna and a wireless power transmission system.

We completed the critical design of an X-band 20 kW class solid-state power amplifier (125 W output module, combining/dividing, filter) for a deep space exploration ground station at Mikasa.

An update of the legacy deep space transponder supporting AKATSUKI to HAYABUSA2 has been started in view of applying renewed technologies to DESTINY Plus. Pushing Ka-band technology initiated by HAYABSA2 strongly, the development advances in cooperation with the JAXA Space Exploration Center so that the technologies will be widely used for coming lunar and L2 point missions.

X-band radio-wave propagation data during solar occultation has been obtained and analyzed through AKATSUKI and HAYABSUA2 missions. These data, including future Ka-band data, will be useful for improving operations under conjunction and developing robustness of acquisition and tracking of heavily jittered signals.

Resilience for the ground station system and its performance was investigated to apply this knowledge to its construction and implementation. Opportunity for their development is so limited that continuity of knowledge and how-to is difficult, and problems are often left unveiled due to slowness of their emergence. Taking these situations into account, resilient design for station systems is becoming urgent to protect mission operations from misconduct in development.

2.3 Information and data processing technology

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), and their simulation technology. For the simulation of spacecraft components, we demonstrated that simulation of state transitions using automatically generated on-board software from the Spacecraft Information Base (SIB) works. In addition, we are establishing a space communications and data handling architecture as part of JAXA design standards to standardize communications and data handling methods across various spacecraft. Among the standards, all seven documents have been published. Furthermore, regarding SIB, we conducted a detailed comparison with the international standard XTCE (XML Telemetric and Command Exchange) and showed that almost all major information can be converted.

2.4 Navigation, guidance, and control technology

We conducted research on safe landing methods; for example, the interaction between landing legs and surface soil, sloshing effect of fuel tank at touchdown, etc. We also performed research on a method for measuring slops using Shape-from-Shading technology.

We performed research on the application of a magnetic levitation mechanism by magnetic flux pinning effects to spacecraft. The aim of this research is to shut out microscopic vibration disturbances and thermal transmission. In FY2018, the vibration transmission characteristics of a proposed system with superconducting bulk material was experimentally evaluated. The results corresponded reasonably well with the numerical model, which was also proposed by our group. This indicates the effectiveness of the proposed system and the validity of the analytical model. This research will lead to the deployment of new magnetic formation flight technologies.

We are developing a motion stage for controlling the attitude of sounding rockets more accurately. It will be used onboard the S-310 series sounding rocket in the near future.

The flight demonstration experiment was performed using S-310-45 ISAS sounding rocket with successful results. We are planning to upgrade our systems on the S-520 sounding rocket series to conduct a verification test, then for practical use as a standard option attitude control mechanism for ISAS sounding rockets.

2.5 Autonomous control and robot technology

To improve the autonomy of rovers that move around to explore the surface of the Moon, we developed technologies for environment recognition using Flash lidar and cameras; for path planning based on satellite images and detailed surface images obtained by rovers; for reconfigurable robot systems; for behavior planning for heterogeneous multi-robot systems; for path planning in consideration of slip and power consumption; and for path planning for exploration UAV in consideration of self-positioning.

To improve the ground-covering ability of rovers, we compared and evaluated hopping mechanisms; evaluated the performance of hopping by using the Resistive Force Theory; optimized the shape of hopping pads; and conducted experimental studies with the developed hopping system. With drop tower tests, we could observe the fluid behavior of the regolith under the micro-gravity, and we could understand the fluid behavior by numerical calculation of interaction force between powder and machine.

We participated in the deployment operation of Rover2 installed in Hayabusa2, developed by members from Japanese universities in September and October 2019. There was no surface activity of the probe but the distance data from the mother spacecraft were obtained using a newly implemented capability of the communication module developed by us.

A small deployable probe onto the Lunar surface installable to SLIM landing mission made great progress in the development and tests on mobile systems, mechanical configuration, and electrical components.

We evaluated the exploration behavior for MINERVA-II twin rovers by analyzing the obtained image of the Ryugu surface. We also participated in the deployment operation of Rover2 installed in Hayabusa2, developed by members from Japanese universities in September and October 2019. There was no surface activity of the probe but the distance data from the mother spacecraft were obtained using a newly implemented capability of the communication module developed by us.

A small deployable probe onto the Lunar surface installable to SLIM landing mission made great progress in the development and tests on mobile systems, mechanical configuration, and electrical components. Technical information is provided to the SLIM team for CDR.

2.6 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 developed a soft error analysis system in a laboratory as an alternative to conventional heavy ion irradiation experiment using a femtosecond pulsed laser that enables a two-photon absorption process in Si devices. By considering the results of experiments using this system, we proposed an experimental technique to significantly improve the depth resolution of a sensitive volume where devices suffer radiation effects.

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 EM 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 FY 2019, a 128×128 pixel 3D image sensor using Si-MPPC has been developed and EM manufacturing has been started as the core device for the HTV-X rendezvous sensor. Furthermore, we are developing a 3D image sensor using highly radiation-resistant InGaAs.

2.7 Orbit determination

The orbit determination group determines the orbit status of operational satellites and spacecraft to prevent problems during missions. In the orbit determination for Hayabusa2, we successfully used delta differential one-way ranging (DDOR) measurements while the ion engines were firing. By using the DDOR data with OP-NAV (Optical Navigation with on-board 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. We also participated in near-Earth object (NEO) activities led by the United Nations and continued activities for NEO observations in Asia and Japan.

2.8 Small satellite systems

We are conducting research to develop an X-band synthetic aperture radar (SAR) that can be installed in a 100 kg class satellite. This was adopted as an ImPACT program of the Japanese government and its final goal is to develop a model for an SAR with resolution of 1 m by FY2018. We developed engineering models for an antenna, a power amplifier for transmission, and an X-band high-speed transmitter for sending observed data, and verified that they achieved the desired performance. A new venture company was established in 2018 to commercialize technological products, and the company is in the process of launching the first and second demonstration SAR satellites in 2020 and 2021 with the support of JAXA.

A 2-3 Gbps high-speed downlink communication system is being developed by the ImPACT program. We applied 64APSK modulation in the X-band (8025–8400 MHz) and utilized dual circularly-polarized waves. The X-band high- speed transmitter was launched in the Rapis-1 satellite of JAXA in January 2019. In February, we received the downlink signal at the 10 m antenna, Usuda, JAXA. The signals were successfully received and demodulated at the 10 m antenna, Usuda, JAXA. We recorded a total data communication speed of 1.96 Gbps with 64APSK (RHCP) and 16APSK (LHCP) modulations. To the best of the author's knowledge, this communication speed is the world's highest in the X-band with earth observation satellites.

We have also been working on satellite architecture, components, and implementation technology while aiming to reduce the size, weight, power consumption, and production time for the satellite bus; for example, efficiency enhancement of power supply units in components, and trial production of one-chip computers based on vertical assembly techniques.

2.9 Navigation signal processing technology

We are studying image-based navigation and landing radar for the post-SLIM era. We are investigating the image-based navigation and sensor fusion for polar-region landings with severe solar illumination conditions, and are carrying out innovative studies to apply neuromorphic processors and sensors for executing complex navigation computation under the condition of severely low resources.

2.10 Space energy systems

For space solar power satellites, we have started a conceptual study on a major structure of the tethered SPS called a power generation and transmission panel, and to develop a high efficiency system. A trial model of a high efficiency amplifier module has been developed. Beamforming experiments with a new beam control system for long distance and high-accuracy wireless power transmission (WPT) were performed. We are evaluating the effect of antenna deformation on the new control system.

Carbon nanotube actuators (CNAs) have been developed to compensate for antenna deformation.

An electron irradiation experiment was carried out for 50 years as an evaluation of the tolerance to the space environment.

We have also begun to develop a solar array with an array antenna. A trial model was made and rf simulation was performed.

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

3. Research Topics

The following outline lists all the Department of Spacecraft Engineering research activities during FY2019.

3.1 Technology for power supply systems
3.1.1 Characteristic evaluation for a space solar cell under extreme conditions
3.1.2 Power storage device for space
3.2 Communication technology
3.2.1 Wireless sensor and high-efficiency circuit t echnology
3.2.2 Deep space RF communication technology for installation on satellites
3.2.3 Near-Earth communication technology for installation on satellites
3.2.4 Wireless communication technology for inside spacecraft
3.3 Information and data processing technology
3.3.1 Satellite data processing architecture
3.3.2 Application of modeling technology to satellite development
3.3.3 Software technology components for an autonomous remote system
3.4 Navigation, guidance, and control technology
3.4.1 Posture determination and control for spacecraft
3.4.2 Navigation, guidance, and control of lunar and planetary probes
3.4.3 Navigation sensor for planetary probes
3.5 Autonomous control and robot technology
3.5.1 Lunar and planetary probe robotics
3.5.2 Rover for exploration of small celestial bodies
3.6 Device technology
3.6.1 Research and development of analog integrated circuits
3.6.2 Environment-resistant electronics
3.6.3 Micromachines for space
3.7 Orbit determination
3.7.1 DDOR technology
3.7.2 Orbit determination using an open-loop receiver
3.8 Small satellite systems
3.8.1 Small scientific satellites
3.8.2 High-speed communication system for small satellites
3.8.3 Microwave synthetic aperture radar for small satellites
3.8.4 Miniaturization and electric power reduction of onboard avionics
3.9 Navigation signal processing
3.9.1 Image-based navigation for lunar and planetary lander
3.9.2 Sensor fusion for landing navigation
3.10 Space energy systems
3.10.1 Solar power satellite systems
3.10.2 Thin-film power-generating systems
3.10.3 Interaction between high power system and space environment

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. For FY2019, three new fellows were selected. 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, 2020)

Name	Former Affiliation	Research Theme	Term
IZUMI Kiwamu	California Institute of Technology (US)	Observational gravitational wave astronomy	September 2017-
BONARDI Stéphane	Massachusetts Institute of Technology (US)	Self-reconfigurable modular robots for space exploration: design and control	October 2017-
LAU Ryan Masami	California Institute of Technology (US)	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-
ODONOGHUE James	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 ITYF fellows’ research highlights in FY2019 and their published research:

IZUMI Kiwamu

In this fiscal year of 2019, my research effort was split into two projects. One is the continuing contribution to the commissioning activities in KAGRA, a Japanese ground-based gravitational wave detector. The other is the development of the photoreceiver units with the goal of providing the flight units to LISA, a space-borne gravitational wave mission.

Following the successful cryogenic operation test with the use of a part of the interferometer in FY2018, the KAGRA project moved on to the commissioning tests of the power-recycled Fabry-Perot Michelson interferometer which is close to the final configuration except that it does not use signal-recycling. I have contributed to the tests by integrating the indispensable system called Arm Length Stabilization (ALS), into the full interferometer. Consequently, our team achieved the resonance of the interferometer with the aid of ALS. The implementation and noise analysis associated with the ALS system was published in Class. Quantum Grav.

In parallel to it, the development of the photoreceivers for LISA was initiated. Since a photoreceiver unit consists of an InGaAs PIN photodiode and a transimpedance amplifier, we have split the developments into the two. Collaborating with Hamamatsu Photonics KK, we produced a batch of test InGaAs photodiode samples. While their junction capacitance, a key characteristic in this development, was found to be successfully reduced by a few pF, they did not meet the required value of 10 pF or lower. We are considering the implementation of other industrial methods to further reduce the junction capacitance. A first prototype of the transimpedance amplifier was built on a printed circuit board. The amplifier features the use of the modern implementation, namely regulated cascode, to achieve the high bandwidth as well as low noise readout simultaneously. A preliminary measurement suggested that the bandwidth was 25 MHz, meeting the requirement. The other characterization tests are currently underway.

- T. Akutsu *et al., Classical and Quantum Gravity*, Vol.36: 165008 (2019).
  https://doi.org/10.1088/1361-6382/ab28a9
- K. Yamamoto *et al., Classical and Quantum Gravity*, vol.36: 205009 (2019).
  https://doi.org/10.1088/1361-6382/ab4489
- T. Akutsu *et al., Classical and Quantum Gravity*, vol.37: 035004 (2020).
  https://doi.org/10.1088/1361-6382/ab5c95

BONARDI Stéphane

My research focus on developing novel robotic solutions for space exploration and colonization. I have been pursuing two main disruptive projects since I arrived at JAXA/ISAS:

1) Creating a network of modular robotic outposts distributed throughout the solar system to change the way we envision space missions.
2) Developing the novel concept of robotic exoskeletons to create highly adaptable swarms for planetary exploration.

On the topic of modular outposts, I have been collaborating with colleagues from the University of Liverpool and from ISAS on a sub-project aiming at creating 3D printed deployable origami based solar sails. This project constitutes the first step towards creating compact propulsion solutions to deploy a large number of modular components in the solar systems using the concept of interplanetary superhighways. The mission concept and the precise definition of this project will be further explored during an upcoming co-supervised master thesis project (Spring 2021).

Robotic exoskeletons can be defined as specialized suits that a robot can equip in order to increase 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) to perform exploration 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 the development of the first prototypes of the base unit together with the first foldable origami-based exoskeleton for locomotion. The production of the exoskeletons uses multi-material 3D printing (mixing hard and soft materials) with the ultimate goal of being able to produce them on-site using in-situ material. The base unit has a similar design to the MBlocks robot from MIT but also borrows characteristics from the Minerva platform from JAXA. Additional exoskeleton designs will be explored in a master thesis project scheduled for Spring 2021. 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.

LAU Ryan Masami

The primary research focus of my work and publications are the study of infrared (IR)-luminous transients and variables. These IR sources are particularly interesting for addressing the mysteries on the evolution and death of massive stars, which includes the nature of their remnants (e.g. neutron stars and black holes). This is an emerging research topic in the field of time domain astronomy and will be of great interest for future space observatories such as the James Webb Space Telescope (JWST) as well as the Space Infrared Telescope for Cosmology and Astrophysics (SPICA).

- Ryan M. Rau *et al., The Astrophysical Journal,* Vol.878: 71 (2019).
  https://doi.org/10.3847/1538-4357/ab1b1c

- M. J. Hankins *et al., The Astrophysical Journal*, Vol.877: 22 (2019).
  https://doi.org/10.3847/1538-4357/ab174e
- V. R. Karambelkar *et al.,The Astrophysical Journal*, Vol.877:110 (2019).
  https://doi.org/10.3847/1538-4357/ab1a41
- Jacob E. Jencson *et al., The Astrophysical Journal Letters*, Vol.880: L20 (2019).
  https://doi.org/10.3847/2041-8213/ab2c05
- M. Heida *et al., The Astrophysical Journal Letters*, Vol.883: L34 (2019).
  https://doi.org/10.3847/2041-8213/ab4139
- Jacob E. Jencson *et al.,The Astrophysical Journal*, Vol.886: 40 (2019).
  https://doi.org/10.3847/1538-4357/ab4a01
- Samaporn Tinyanont *et al., The Astrophysical Journal*, Vol.887: 75 (15 pp) (2019).
  https://doi.org/10.3847/1538-4357/ab521b
- Breanna A. Binder *et al., Galaxies*, Vol.8 (1), 17 (2020).
  https://doi.org/10.3390/galaxies8010017
- Kishalay De *et al., Publications of the Astronomical Society of the Pacific*, Vol.132: 025001 (2020).
  https://doi.org/10.1088/1538-3873/ab6069

TORIUMI, Shin

In April 2019, I started my career as an ITYF in ISAS and throughout FY2019 I engaged in theoretical and observational investigations of sunspot regions that produce major solar flares. One of my achievements is the innovative numerical modeling of flare-productive sunspots by radiative magnetohydrodynamic simulations (Toriumi & Hotta 2019: see p.15 of this Annual Report for the detailed account with figures). This model for the first time allows us to understand how the background turbulence resident in Sun's convection zone, which we cannot probe by direct optical observations, drives magnetic flux and generates violent sunspots on the solar surface. As observations show, most of the strongest solar flares in history emanate from the sunspot regions of this type. Together with the newest technology to measure and reproduce magnetic fields in the solar corona (Toriumi et al. 2019), sophisticated combinations of modeling and observation may deepen our understanding of flare occurrence and thus contribute to the further establishment of flare forecasting.

The series of researches on sunspots and solar flares motivated myself to publish the review article, in which we summarized the current understanding of the formation and evolution of flare-productive sunspots that has been brought about through decades of investigations (Toriumi & Wang 2019). It took more than a couple of years to write up this 130-page article but I have learned a lot.

I also engaged in Pre-Phase A2 study of JAXA's next-generation solar-observing satellite Solar-C (EUVST). In FY2019, I led the planning of data usage and science operation as well as the releasing of the official Solar-C webpage. Moreover, I collaborated with researchers inside and outside of ISAS to discuss solar-stellar connections, for instance, possible X-ray observations of stellar flares with the XRISM spacecraft.

- S. Toriumi *et al., Living Reviews in Solar Physics*, Vol.16 (3), 1 (2019)
  https://doi.org/10.1007/s41116-019-0019-7
- H. Hayakawa *et al., Space Weather,* Vol.17 (11), pp.1553-1569 (2019)
  https://doi.org/10.1029/2019SW002269
- S. Toriumi *et al., The Astrophysical Journal Letters*, Vol.886 (1), L21 (2019),
  https://doi.org/10.3847/2041-8213/ab55e7
- S. Toriumi *et al., The Astrophysical Journal,* Vol.890 (2), 103 (2020)
  https://doi.org/10.3847/1538-4357/ab6b1f
- K. Namekata *et al., The Astrophysical Journal*, Vol.891 (2), 103 (2020)
  https://doi.org/10.3847/1538-4357/ab7384

ODONOGHUE James

I started research at ISAS during May 2019 with a main focus on producing the highest ever spatial-resolution maps of Jupiter's upper atmosphere. Our observations were from the 10-meter diameter Keck telescope in Hawaii (the largest infrared telescope on Earth) and took place between years 2016 and 2017. These global maps depict the temperatures and intensity of infrared emission from Jupiter's upper atmosphere at resolutions of around 1000 kilometers per pixel, with uncertainties of under 5%. The most recent published maps of Jupiter's upper atmosphere are from 1997 and used 3.8-meter infrared telescope observations from 1993: these observations had resolutions of >10,000 kilometer per pixel, with >10% uncertainty. Few conclusions could be drawn from these earlier maps, so our ability to understand energy balance at Jupiter and at giant planets in general has been severely limited. This is especially important because, for over 40 years, there has been an "energy crisis" at Jupiter, Saturn and Uranus, in which the upper-atmospheres of each planet are observed to be many 100s of Kelvin hotter than models based on solar heating alone can predict. This discrepancy takes place in the non-auroral regions of each planet: the aurorae of each planet generate enormous heat through electric current systems near the poles that is well explained. It has long been thought that these high (non-auroral) temperatures are the result of auroral heat somehow dispersing down from the polar regions, but for decades global circulation models have shown that Coriolis forces confine auroral heat to the poles. Since previous observations have not been detailed or reliable enough to reveal heat transport, my main research task at ISAS/JAXA during FY2019 has been to produce global maps of Jupiter's temperature to see whether or not heat transport is occurring. Here I report that these tasks have been completed: maps have been produced for multiple days in multiple years and they all appear to confirm heat is transported. The missing heat source required to explain the energy crisis, according to these results, is apparently the redistribution of auroral heat (at least in the case of Jupiter, but by extension to other giant planets). I am currently writing two first-author papers to explain these results with the aim to publish both in FY2020. In other news from FY2019, I was successful in getting telescope time on Keck and the NASA Infrared Telescope Facility (IRTF) in order to observe an exoplanet ionosphere and Saturn's ionosphere, respectively. Our exoplanetary goals were to detect the ionosphere of an exoplanet and derive its upper-atmospheric temperature for the first time in order to better characterize exoplanetary upper-atmospheres. The upper-atmospheres of exoplanets are the most extended (and highest) layer we can see from Earth and understanding them is a key component in the search of exoplanetary life. Our Saturn goals were to observe the electrically charged water product H3O+ in the Saturn ionosphere for the first time: if we find it, we can better estimate the amount of water leaving Saturn's rings and entering the planet, helping to constrain the lifetime of the rings (currently we estimate 300 million years). I approached Dr. Sergey Yurchenko (at University College London) to ask if we his team could produce a high-resolution spectral line list for H3O+ as one was not available (see Yurchenko et al., (2020) on which I am a co-author). In this paper, Dr. Yurchenko derived H3O+ spectrum and referred to our observations within the manuscript itself. Unfortunately, both of these 2020 observing runs were cancelled due to the global pandemic, but I intend to resubmit these previously successful telescope proposals again during FY2021.

- T. Stallard *et al., Philosophical Transactions of the Royal Society A*, Vol.377(2154), 20180405 (2019)
  http://dx.doi.org/10.1098/rsta.2018.0405

HYODO Ryuki

JAXA's Martian Moons eXploration (MMX) mission is planned and ongoing. It aims to collect surface materials from the biggest Martian moon, Phobos, and bring the sample back to Earth. The launch is scheduled in 2024 and return is planned in 2029. The 2020s is "a golden age of Mars exploration". NASA-led Mars2020, UAE-led HOPE, and China-led Tianwen-1 have already been successfully launched in the 2020s. Mars2020 and Tianwen-1 will land on Mars and investigate the local geology together with the characterization of Martian habitable environment. Mars2020 is also a sample-return mission. Under such circumstances, MMX needs to clarify and answer the following question: What is the significance of sample from Phobos compared to that from Mars? To answer this question and to evaluate the scientific values of the MMX sample, we studied the processes of material transfer from Mars to Phobos during its history. Mars experience numerous crater-forming impacts through its history. We found that a fraction of impact debris (i.e., Martian materials) is ejected from its surface into space and a fraction of the ejecta deposits onto the surface of Phobos. We showed that the expected amount of the delivered Martian materials to Phobos is ~10 to 100 times larger than previously estimated. This significant update indicates that MMX mission could potentially bring not only Phobos materials but also Martian materials from Phobos, which implies that "without going to Mars, MMX might achieve the first sample return from Mars to Earth". Martian grains returned by MMX are likely to contain a variety of pristine minerals, organics and –hopefully—a remnant of Martian life. By analyzing as many Martian grains as possible, we will have a clue for understanding the time-resolved history of the Mars surface environment. (See p.9 of this Annual Report for the detailed information.)

- R. Hyodo *et al., Scientific Reports*, Vol.9, 19833 (2019)
  https://doi.org/10.1038/s41598-019-56139-x

6. R&D at the Fundamental Technology for Space Science Group

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, and Supersonic and Subsonic Wind Tunnel Laboratory. 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.112. The Inter-University Research and Facility Management Group collaborates with researchers to maximize their scientific achievements.

b. Test and Operation Technology Group

The Test and Operation Technology Group is responsible for the development of testing technologies and the operations of the testing facilities for mechanical environmental testing, structural testing, thermal vacuum testing, anechoic chamber testing, attitude control testing, magnetic shield testing, side-jet reaction control subsystem testing, and other technical facilities, such as clean rooms and mechanical assembly test facilities. The group members also participated in the projects, the pre-projects, and the working groups (WG) of the ISAS.

1. Achievements

- Support for pre-launch testing and launching of S-310-45.
- Support for combustion testing of N_2O/ethanol propulsion systems.
- Support for RV-X testing.
- Support for Scientific Balloons.
- Upgrade of the testing technologies and the operations of the test facilities.
- Support for improvement of the scientific satellite development environment.

2. Effects and Impacts

The group contributed to:

- The successful launch of the S-310-45.
- The solid development of the projects with the upgraded testing technologies and the highly efficient operations of the test facilities.
- The modification of the flight environmental test building to improve the development environment of scientific satellites.
- The establishment of the recovery system of the Hayabusa2 capsule.

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 brought 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 the technological improvement and accumulations of JAXA.

1. Achievements

- We have completed the Installation of and begun using a machining center, NC composite turning centers, a wire electric discharge machine, and a contact-type three-dimensional measuring machine.
- Introduction of a brand-new large NC turning center for larger workpieces and an NC milling machine equipped with a high-speed spindle.
- Improvement of the efficiency of new and old machine shops, which feature a new layout, and improved job safety with well-routed working traffic lines.
- Specialist staff who work in the nano-electronics cleanroom are completely trained in maintenance management and safety.

2. Effects and Impacts

- Maintaining the quick pace of setting up our production equipment and have begun test manufacturing components already placed on order.
- Expanding the size of allowed workpieces with the introduction of our large NC turning center.
- Improving the environment that our expert staff to provide the highest quality manufacturing services.
- We will continue training our users on safety and maintaining 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 FY2019 was conducted from May 27, 2019. Originally three scientific observations and four engineering demonstrations were planned, however, due to the lack of helium gas supply in Japan, only 2 experiments ; Stratospheric Microorganism Capture Experiment and Ultra-thin Perovskite Solar Cell Demonstration were conducted.
- Since the supply of helium gas in Japan seems uncertain in future, the use of hydrogen gas for scientific ballooning is being considered. To achieve issues to be solved to use hydrogen for large balloons, small rubber balloons filled with hydrogen gas were launched.
- Preparations and coordination for a 2021 balloon campaign in Australia were started.

2. Effects and Impacts

- Though only two experiments out of seven originally planned could be carried out due to lack of helium gas, those two satisfied their success criteria and academic results were published.
- In parallel with our best efforts to secure a sufficient amount of helium gas for scientific ballooning in cooperation with Japanese gas supply companies, risk analyses in using hydrogen gas for ballooning were considered, identifying several issues to be solved in nominal and off-nominal cases. Especially, to estimate the hydrogen gas density remaining in the balloon envelope on its recovery, we will measure helium gas density in the envelope in 2020.
- Since we established a good relationship with Australian partners through the 2018 balloon campaign in Australia, we planned to have the next campaign in Australia in 2021 and began technical support to three candidates selected by the Scientific Balloon Committee.
- Also, the coordination of the balloon campaign in Australia was continued with the contacts in Australia. We plan to conduct a flight verification for a newly developed balloon and a drop test for the capsule from high altitude, which has never been carried out before in Australia, and we confirmed that such experiments are feasible.

e. Sounding Rocket Research and Operation Group

ISAS is operating three types of sounding rocket, the S-310, S-520 and SS-520, with space science and engineering experiments generally being conducted every year. The Sounding Rocket Research and Operation Group will contribute to design and analysis for the manufacturing and launching of the sounding rockets in the coming fiscal year and beyond. The group provides experimental opportunities with the sounding rockets for researchers, such as engineering verification tests and scientific observations.

1. Achievements

- The preliminary design, including mechanical and electrical interfaces, of the S-310-45 rocket experiment was verified in order to prepare the onboard instruments. This experiment focused on examining a precise control strategy and the directional accuracy of multi-link structures. S-310-45 rocket was launched successfully from Uchinoura Space Center on 9th January in 2020.
- The baseline concept, including mechanical and electrical requirements of the S-520-31 rocket experiment was discussed to provide better conditions. In the experiment, a newly developed space propulsion engine will be examined in a microgravity environment. Component-level environmental tests and electrical calibration of the onboard equipment of the SS-520-3 rocket experiment were performed prior to integrated function tests. The rocket has a two-stage solid propellant design and is intended to observe the high-altitude plasma dynamics of the north polar region in Norway. This experiment has currently been postponed due to electrical problems with the avionics.
- In addition to the annual evaluation, we focused on scientific achievements and conducted experimental evaluation of the sounding rockets launched over the past 10 years.

2. Effects and Impacts

- The group has published peer-reviewed papers in Science Advances, Chemistry of Materials, and the Journal of Crystal Growth, and published a cumulative total of 126 papers since 2003.
- A subcommittee established under the Advisory Committee for Space Science and the Advisory Committee for Space Engineering evaluated our sounding rocket activities. The subcommittee concluded that the group's publications and other scientific results in relation to sounding rocket and balloon experiments were in line with the allocated resources.

f. Noshiro Rocket Testing Center

The Noshiro Rocket Testing Center (NTC) is one of the ISAS's research facilities. Since 1962, different kinds of ground firing tests for solid-propellant rocket motors have been carried out in order to verify their performance prior to launch. The center has also conducted basic research on cryogenic engines and Air Turbo Ramjet engines.

In order to conduct the above verification studies, several kinds of experimental facilities have been developed. One of these is a large-scale, sea-level static firing test stand for one of the biggest, solid propellant rocket motors, the first-stage motor (M-14) for the M-V satellite launch vehicle. The maximum thrust to be tested on the stand is 450 tf. For the purpose of testing the upper stage motors, a large-volume vacuum firing test chamber was built to achieve a low-pressure environment during solid motor firing. The second- and third-stage motors for the M-V (M-24, M-25, M-34, and M-35) together with various sizes of kick motors, such as the KM-P, KM-M, KM-V1, KM-V2, etc., were repeatedly tested in the vacuum environment. The volume of the chamber is approximately 475 m^3 with a maximum thrust capability of 150 tf.

NTC also has cryogenic test facilities primarily for the development of liquid propellant engines and Air Turbo Ramjet engines. Recently, the center developed very highly pressurized liquid hydrogen test facilities, which supplied more than 90 MPa of pressure. Using these facilities, the center examined the characteristics of high-pressure liquid hydrogen in order to perform a risk assessment of hydrogen treatment for fuel cell vehicles and their supply stands.

1. Achievements

- Advanced rocket engines

In order to meet the progressive requirements of future and near-future transportation systems, the center has actively tested advanced rocket engine systems with new propellants to better understand performance levels. A N_2O/ethanol liquid engine with a ceramic-based nozzle composite was developed for storable and non-toxic propulsion of small satellites. A hybrid rocket motor has also been examined to reduce safety requirements at the launch site. In the Flutter Wind Tunnel (FWT) experiment, inexpensive rocket motors manufactured using general purpose materials have been tested to grasp its basic performance. In 2019, a solid propellant motor FWT-4 with propellant mass of 1,000 kg was successfully examined.

- Lift-off and landing tests of reusable vehicles

The design and development of the reusable rocket vehicle RV-X is in progress based on the technical outcomes obtained from ISAS RV-X-related studies. Currently, two flight campaigns are planned for a flight demonstration study. In the first flight test campaign, we aim to demonstrate the pump-fed capability of a deep throttling engine, attitude control characteristics using main engine gimbaling during lift-off and landing with powered flight, quick turnaround, etc. In 2019, static firing tests with a stage configuration were examined to verify the total performance of engine with LH_2/LOX tanks.

- Safety technology for liquid hydrogen utilization

Based on the New Energy and Industrial Technology Development Organization's (NEDO) supporting research program, the actual behavior and risk assessment of very highly pressurized hydrogen were studied to improve safety regulations for fuel cell vehicles and hydrogen infrastructures, such as supply stands. Cryo-compressed hydrogen leakage diffusion was also investigated.

- The experimental apparatus was able to supply hydrogen at 90 MPa and various temperatures. Measurement criteria included hydrogen concentration distribution, blast pressure, flame length, and radiant heat. In addition, high-speed camera observation was carried out to investigate the near-field cryogenic hydrogen jet at supercritical pressure. Based on the above considerations, an extinguisher mechanism was simulated, and risk assessment of hydrogen treatment was performed.
- Liquid hydrogen loading system
  As a research program of the Cross-ministerial Strategic Innovation Promotion Program (SIP by JST), swivel joints and emergency release systems for liquid hydrogen were developed and demonstrated. In 2019, explosive phenomena were carefully observed in gases leaking from emergency release mechanisms, and further investigation of sealing materials for the swivel joints was successively conducted.
- Liquid hydrogen cooled HTC superconductors
  High Tc (HTC) superconductors, including MgB_2, have been tested with the support of the Advanced Low Carbon Technology Research and Development Program (ALCA by JST), which showed excellent properties under temperature of liquid hydrogen. The liquid hydrogen showed high latent heat and low viscosity coefficient. The center also investigated the thermal properties of a prototype generator using HTC materials.

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 tf, and is the largest facility in Japan. The vacuum firing test chamber has a volume of more than 450 m^3, and is also the biggest facility of such kinds in Japan. Moreover, the 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 bearing fruitful results. In 2019, at least one of the NTC facilities has been in operation for more than 200 days of the year without one human accident 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

- Sea-level combustion experiments on a solid propellant rocket motor with a laser ignition system were carried out in vacuum by the high-altitude testing facility to test the heat resistance capability of the Ti alloy expanding nozzle system (High- Altitude Testing Stand: HATS).
- A hybrid rocket combustion experiment (A-SOFT) was conducted with the liquid oxygen supply facility. A propellant burning speed measurement technique using a resistance sensor was demonstrated. Measurement of heat transfer of liquid oxygen was studied to support the design of regenerative cooling type nozzles.
- An electric and chemical hybrid thruster was demonstrated in vacuum and air at HATS, a new concept of thrust system aimed for use in deep space explorations.
- To support basic research activities, reliable inspections of the experimental facilities were conducted to maintain their conditions.

2 Effects and Impacts

- A-SOFT hybrid rocket combustion experiments were successfully carried out by the liquid oxygen supply facility. A new propellant consuming speed measurement system was successfully demonstrated. Basic data of heat transfer of liquid oxygen was successfully taken for the design of a regenerative cooling nozzle by liquid oxygen.
- An electric and chemical hybrid propulsion system for deep space exploration was successfully demonstrated and basic data to achieve design methodology for the thruster system was acquired.
- Sea-level static combustion experiments on a sub-sized solid propellant rocket motor (propellant weight, ≈ 20kg) with a laser ignition system were carried out in vacuum to demonstrate the rigidity of laser ignition system. Expanding the nozzle with shape memory Ti alloy was successfully demonstrated in vacuum to generate higher propulsion efficiency for the solid propellant rocket motor in the final stage motor of a satellite launcher.

h. Science Satellite Operation and Data Archive Unit

The Science Satellite Operation and Data Archive Unit (C-SODA) is in charge of development and operation of the ground infrastructure for science spacecraft operation and data archives. C-SODA also makes space science data available to the public to enhance the scientific outcome of JAXA programs.

1. Science Satellite Operation

1.1 Achievements

- C-SODA provided ground systems for ISAS scientific space missions and supported their mission operations.
- We renewed the spacecraft control room so that Hayabusa2 could perform rehearsals to prepare for approach and touch-down operations on the asteroid, Ryugu.
- A new IP-VPN network was introduced between Sagamihara, Tsukuba, Uchinoura and Usuda.
- Preparation of remote operation for ground stations at Uchinoura and Usuda was completed. Full remote operations for these stations started in FY2018.

1.2 Effects and Impacts

- All spacecraft in orbit or transit—ARASE, Hayabusa2, HISAKI, AKATSUKI, HINODE and GEOTAIL—have been operating safely.
- The new control room supported dozens of Hayabusa2 operations for the mission on Ryugu.
- The new IP-VPN network resulted in a redundant network and reduced network costs.
- Remote operation of grand stations also reduced operation costs.

2. Accumulation and Provision of Space Science Data

2.1 Achievements

- C-SODA developed, maintained and operated the space science Data ARchive and Transmission System (DARTS) to maximize scientific outcomes from archival data for JAXA science spacecraft
- We released new datasets, including LIDAR from Hayabusa2, HITOMI, MAXI onboard ISS, AKATSUKI, and PDS3 from KAGUYA, etc.
- 10 kinds of raw telemetry data from old spacecraft were made open to public, which have been closed for more than 30 years. (TAIYO, KYOKKOU, JIKIKEN, HZORA, HAKUCHO, TEMMA, HINOTORI, SAKIGAKE, SUISEI, HITEN, etc.)

2.2 Effects and Impacts

- Approximately 160 TB of data were downloaded by world-wide users through DARTS, totaling approximately 50 million accesses.
- DARTS maintains a large number of datasets from space science missions open to the public in a systematic manner and common data format, which helps to maximize the scientific outcome from the data, expands its scope of use and contributes to third-party verification of observation results.

i. Lunar and Planetary Exploration Data Analysis Group

Our group is conducting high-level processing and analyses dealing with a large amount of observation data obtained by lunar and planetary exploration. It aims to maximize the results of lunar and planetary exploration by providing data analyses that support the mission planning and planetary exploration strategies, and by providing high-level processing products that contribute to research into planetary origins and evolutions.

1. Achievements

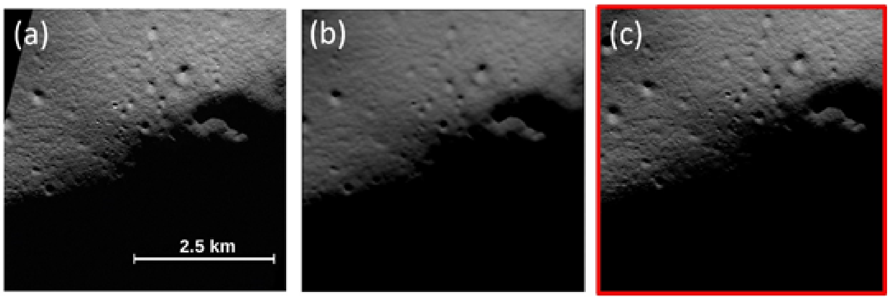
- At the request of the JAXA lunar exploration teams (e.g., lunar polar mission, the pressurized rover, HERACLES), we analyze existing remote sensing data and support mission scenario formulation. In the example of lunar polar exploration, we have reduced the artifacts and increased the resolution by correcting the displacement of the altitude data near the south-pole with high accuracy (see the figure below). As a result, it has become possible to analyze the areas of both the sunlit and the communication with earth station with higher accuracy.
- In collaboration with the National Institute of Advanced Industrial Science and Technology and the University of Aizu, we developed exploration data analysis technology using artificial intelligence. We continued to develop and improve automatic identification algorithms for boulders, enabling more accurate detection. It continues to be used for landing exploration area studies. We also developed an algorithm that automatically distinguishes low-albedo areas from shadow areas, enabling the creation of higher-resolution geological maps and the automatic generation of shadow masks. In joint research with the Tokyo Institute of Technology, we searched for a place where a long-term continuous sunshine could be expected by combining 2-3 spots in the lunar south-pole region. We have discovered a combination that achieves 8.6 months of sunshine at 2 spots and 11.7 months at 3 spots from a huge number of combinations of about $10^{7\text{-}11}$ using an original optimization algorithm.
- The satellite orbital error, which caused the position shift

of the SELENE image observation data, was corrected. This made it possible to create high-definition color maps and geological maps, especially in the lunar polar regions. In addition, based on the image data of the Hayabusa2 Optical Navigation Camera (ONC), a pseudo color map product for Ryugu was created. It will be released along with the ONC source images as a product that contributes to scientific research.

- In order to facilitate the analysis of the moon that combines a wide variety of exploration data, the integrated analysis data distribution system (KADIAS) that runs in a browser has been released and operated with continuous improvements. On the other hand, we have started to develop a system that can graphically search image data of asteroids such as ONC on the Web.

2. Effects and Impacts

- The analysis results presented to the lunar mission study teams have been used for lunar landing exploration studies as important information in determining exploration strategies. Our activities in landing-site study were widely recognized by various engineering communities, which led to new joint research with other universities. In joint research with the Tokyo Institute of Technology, we applied the original technology of the laboratory to the analysis of planetary exploration big data and produced concrete results.
- By improving the accuracy of topographical data and orbital data, it has become possible to analyze products and landing points at a high level worldwide. It has become possible to produce strategically valuable data in international space exploration.
- As a result of KADIAS operation, comprehensive analysis using a variety of lunar exploration data can be performed without image processing expertise or a high-performance computer. The range of users has expanded to young researchers and private companies.



Our terrain model with improved accuracy. (a) Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) image (50 cm/pixel), (b) conventional LRO Lunar Orbiter Laser Altimeter (LOLA) topographic model hillshade map (Glaser et al., 2014), (c) our terrain model hillshade map.

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

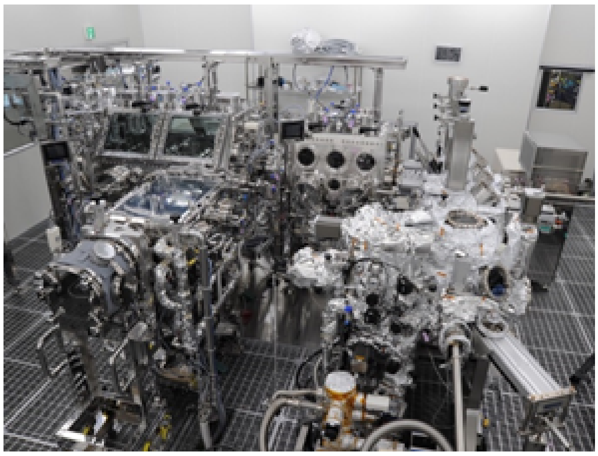
- The group performed the curatorial work of collecting, describing, and storing the samples brought back by HAYABUSA from asteroid Itokawa.
- The group published a periodical special paper online with an initial description of the Itokawa samples (i.e., sample catalog information). A total of 1170 samples are included in the most-recent catalog (JAXA-SP-19-005E).
- The group made an international Announcements of Opportunity (AO) for the Itokawa samples and samples were allocated to researchers selected by an international AO committee. By the end of FY2019, 66 proposals were accepted, and 242 samples have been distributed.
- According to an MOU between NASA and JAXA, 35 samples and 1 Teflon spatula with many fine particles have been delivered to NASA so far.
- The International Symposium for Solar System Materials was held to announce the results from the international AO research on Itokawa samples. This symposium will be held annually and was attended by approximately 100 planetary science researchers from all over the world.
- In preparation for the receipt of extraterrestrial samples from future sample return missions like Hayabusa2, we have completed the construction of a new clean room and new clean chambers, and started the rehearsal operation for Hayabusa2 return sample acceptance.
- Technical support for future sample return missions was provided through the development of sampling equipment and the examination of sample-receiving equipment.
- As for technical support for an on-site analyzer to be used in future planetary exploration missions, we began the development of a compact, high-performance mass spectrometer.
- 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

The Itokawa sample analysis results thus far are summarized as follows:

- In the research of the International AO#4, we succeeded in measuring mechanical properties of Itokawa particles brought back by the HAYABUSA mission for the first time (Astronomy & Astrophysics, Volume 629, A119, 2019). The obtained Young's modulus of Itokawa particles is about 100 GPa, which is within the range of the values of ordinary chondrites (meteorites) measured so far. It is expected that the obtained results will be very useful in future studies of the mechanical behavior of regolith on the surface of asteroids in future asteroid exploration, and in advance simulation of the landing event between the spacecraft and asteroid.
- In the research of the International AO#4, we succeeded in measuring the hydrogen isotope and water content of Itokawa particles brought back by the HAYABUSA mission for the first time (Science Advances, Volume 5, Issue 5. 2019). The obtained hydrogen isotope ratio was similar to that of inner solar system material including the earth, and the water content was similar to that of pyroxene in the earth's mantle. The measurement results can be considered as the values when the Itokawa parent body was formed, and it was found that the waters of the asteroid and the earth are likely to have the same origin.



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

k. Deep Space Tracking Technology Group

1. Tracking support for deep space missions

As tracking support for deep space missions, we continue to work mainly on Hayabusa2. We also support NASA's EM-1.

- Regarding the tracking of Hayabusa2 by NASA/DSN, from the asteroid proximity phase to the earth return phase we coordinated the use of DSN stations with the person in charge on the DSN side and contributed to the operation of Hayabusa2. Regarding the operation of Hayabusa2 in 2020, we adjusted the basic policy regarding how to use the DSN station during particularly important events.
- Regarding the tracking of Hayabusa2 by ESA/ESTRACK, we made technical adjustments with the ESA staff in charge of ESTRACK's Malargue station (in Argentina) and Cebreros station (in Spain).
- Regarding NASA's EM-1, we made technical adjustments to the tracking support at the JAXA station.

Regarding the operation of Hayabusa2, there were some critical operations in the asteroid proximity phase, but by properly arranging the tracking with NASA/DSN and ESA/ESTRACK, we contributed to the operation of Hayabusa2 without major problems. Also, by cooperating with EM-1, we were able to advance cooperation with NASA much further.

2. Work for deep space tracking stations

We worked for deep space stations in Japan. In particular, GREAT, a new deep space station, has been upgraded to the point where it actually receives radio waves from spacecraft. We also cooperated with the study of antenna arrays and the successor to the Uchinoura station for future technology.

- We carried out various tasks related to the 64m antenna at the Usuda Deep Space Center and supported the operation of spacecraft such as Hayabusa2.
- We successfully started up and maintained the 54m antenna (GREAT) in the ground station for the Misasa deep space exploration station, and succeeded in receiving Ka-band signals from Hayabusa2 and acquiring DDOR data.
- We carried out experiments of arraying antennas with 64m and 54m antennas. Signal synthesis and demodulation were successfully done off-line.
- In connection with Uchinoura's successor station, we participated in the study work on domestic and overseas stations (jointly with ESA).

We contributed to the operation of Hayabusa2 with a 64m antenna. The new 54m antenna was ready for actual operation.

3. Support for JAXA's Deep Space Projects

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

- We carried out orbit determinations for AKATSUKI, Hayabusa2, and GEOTAIL in operation.
- As for BepiColombo mission, we collaborated with ESA and created antenna prediction files. In addition, DDOR testing was performed on ESA MPO.
- We proceeded with studies related to orbit determination for future missions such as SLIM, MMX, and DESTINY⁺.
- We conducted communications-related tasks such as a compatibility test for transponders equipped with OMOTENASHI and EQUULEUS, and conducted a study related to orbit determination.

As for the spacecraft and satellites in operation, we were able to support their daily operations without serious problems. For future missions, we contributed to studies and experiments.

4. Other issues

In addition, the following projects related to deep space probe tracking were performed.

- We created a system that converts tracking data into TDM in text format.
- We discussed a generic cross support agreement with NASA.

These projects may increase the versatility of the data and make it easier to obtain tracking support for small missions.

III

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

As of March 31, 2020, JAXA has six Directorates, Institute of Space and Astronautical Science (ISAS), Space Exploration Innovation Hub Center, JAXA Space Exploration Center (JSEC), and other administrative departments.

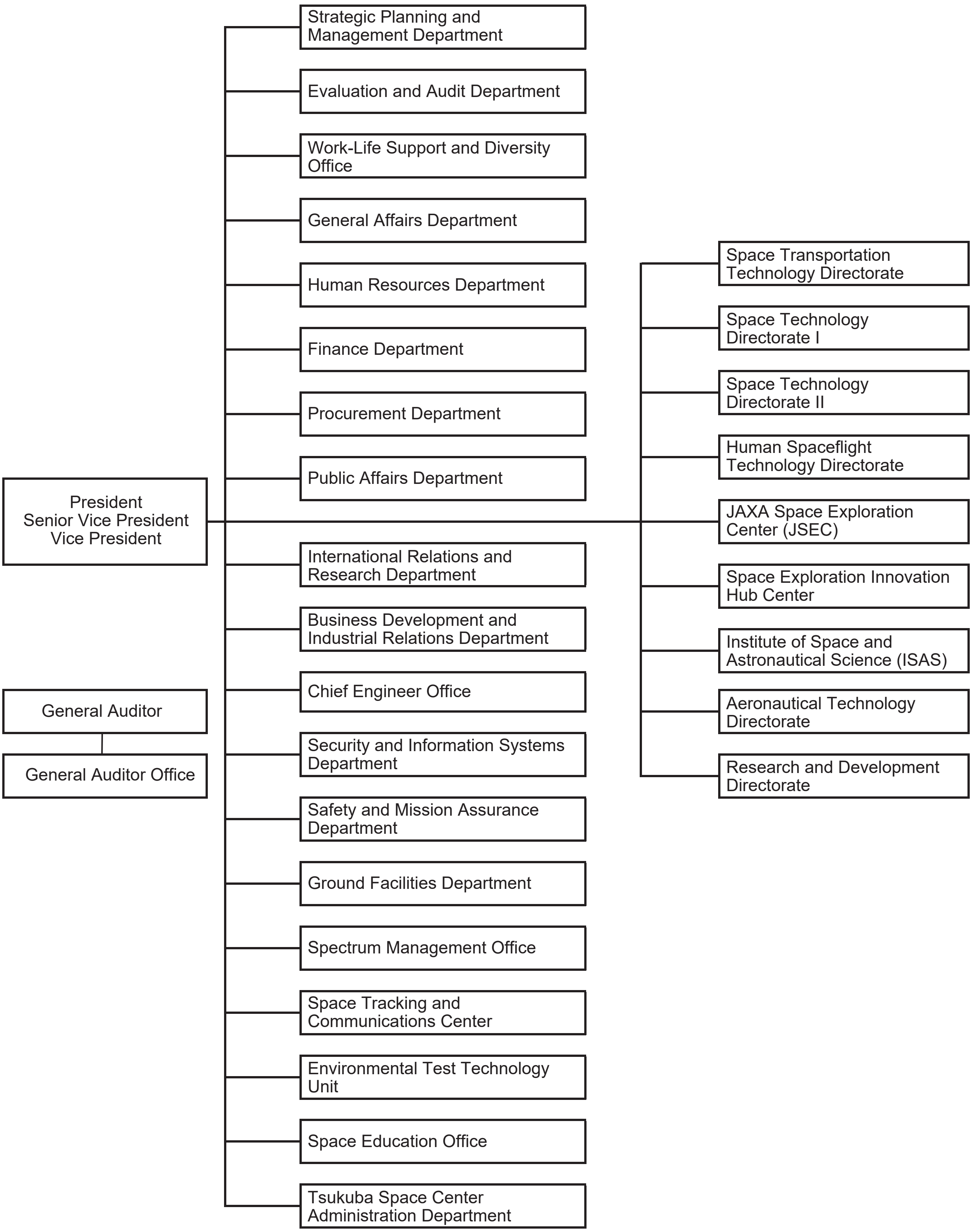
As of March 31, 2020, ISAS has five research departments:

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

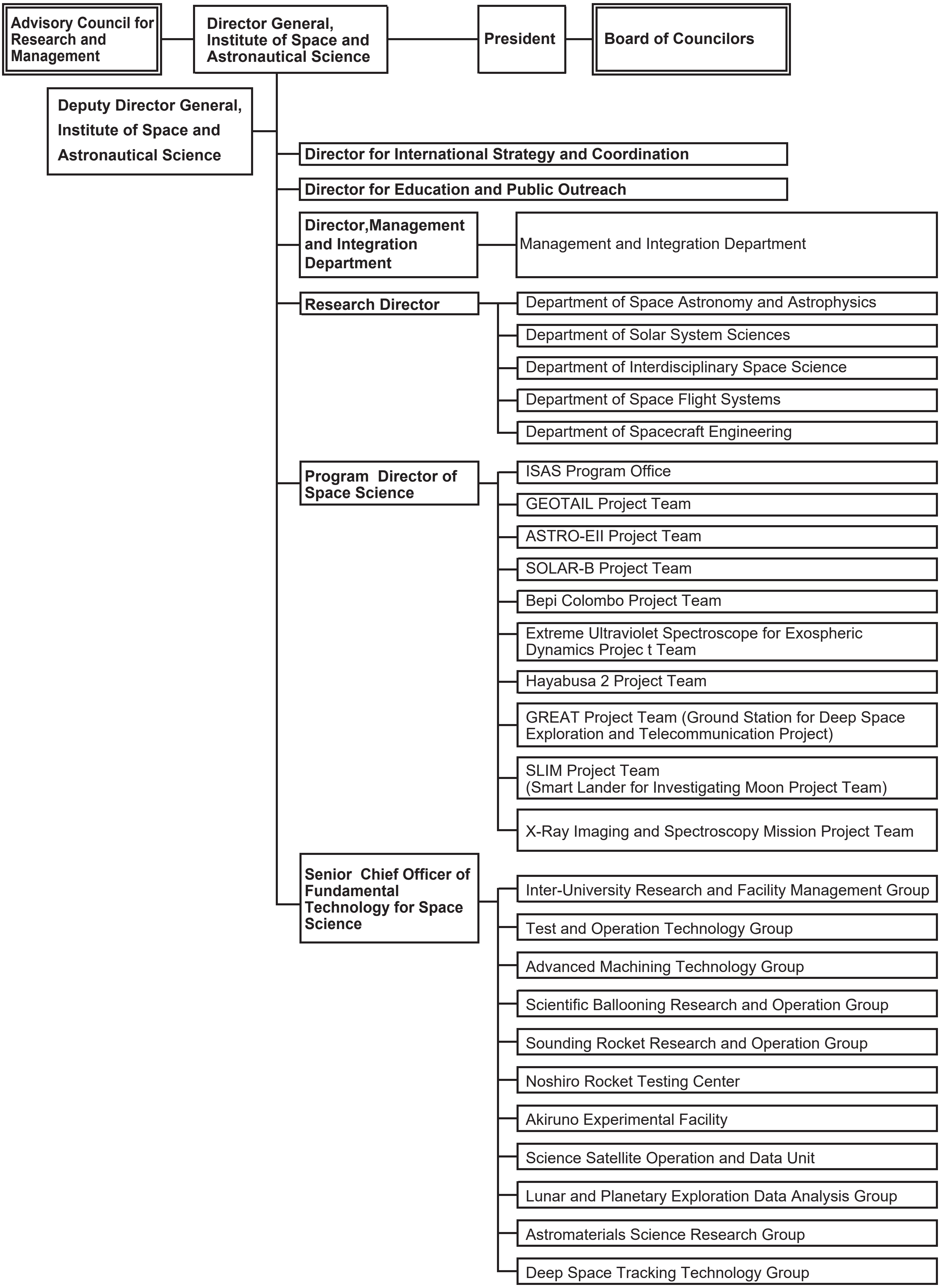
Other organizations within ISAS are the Management and Integration Department, the ISAS Program Office, the Center for Science Satellite Operation and Data Unit, 9 project teams, 8 groups, the Noshiro Rocket Testing Center, and the Akiruno Experimental Facility. In addition, the following officers and 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 efficiently operate the inter-university research system.

a. JAXA Organization Chart (as of March 31, 2020)



b. ISAS Organization Chart (as of March 31, 2020)



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. The members of each council are listed below. In addition, various in-house and research committees composed of researchers from all over Japan have been established to review various matters such as collaborative research plans.

a. Board of Councilors (as of March 31, 2020)

OKADA Kiyotaka	REC (Ryukoku Extension Center) Fellow, Ryukoku University
KAJITA Takaaki	Director, Institute for Cosmic Research, University of Tokyo
KAWAI Maki	Director General, Institute for Molecular Science, National Institutes of Natural Sciences
KUSANO Kanya	Director, Institute for Space-Earth Environmental Research, Nagoya University
GONOKAMI Makoto	President, The University of Tokyo
(Vice-Chairman)	
KOBATAKE Hidefumi	Principal, Kaetsu Ariake Junior and Senior High School, Kaetsu Gakuen Educational Association
KOMORI Akio	President, National Institutes of Natural Sciences
TAKAYANAGI Yuichi	Director, Tamarokuto Science Center
TAKEDA Hiroshi	President, Kobe University
TAJIKA Eiichi	Professor, Graduate School of Science, The University of Tokyo
CHUBACHI Ryoji	President, National Institute of Advanced Industrial Science and Technology
TSUNETA Saku	Director General, National Astronomical Observatory of Japan
HASHIMOTO Kazuhito	President, National Institute for Material Science
HASEGAWA Mariko	President, The Graduate University for Advanced Studies (SOKENDAI)
FUJII Teruo	Executive Director and Vice President, The University of Tokyo (Professor, Institute of Industrial Science, The University of Tokyo)
(Chairman)	
FUJII Ryoichi	President, Research Organization of Information and Systems
MATSUMOTO Hiroshi	President, RIKEN
YASUOKA Yoshifumi	Professor Emeritus, The University of Tokyo
YAMAMOTO Satoshi	Professor, Graduate School of Science, The University of Tokyo
YOSHIDA Kazuya	Professor, Graduate School of Engineering, Tohoku University

The term is from April 1, 2019 to March 31, 2021.

b. Advisory Council for Research and Management (as of March 31, 2020)

AOKI Takahira	Professor, Graduate School of Engineering, The University of Tokyo
IGUCHI Satoru	Vice-Director General, National Astronomical Observatory of Japan
OSHIMA Mari	Professor, Graduate School of III (Interfaculty Initiative in Information Studies), The University of Tokyo
KUSANO Kanya	Director, Institute for Space-Earth Environmental Research, Nagoya University
SASOH Akihiro	Professor, Graduate School of Engineering, Nagoya University
SUGITA Seiji	Professor, Graduate School of Science, The University of Tokyo
(Vice-Chairman)	
NAGATA Harunori	Professor, Faculty of Engineering, Hokkaido University
HIROSE Akira	Professor, Graduate School of Engineering, The University of Tokyo
FUJITA Osamu	Professor, Faculty of Engineering, Hokkaido University
YAMAMOTO Satoshi	Professor, Graduate School of Science, The University of Tokyo
WATANABE Junichi	Vice-Director General, National Astronomical Observatory of Japan

ISAS

INATOMI Yuko	Director, Department of Interdisciplinary Space Science
KUBOTA Takashi	Research Director
SAITO Yoshifumi	Director, Department of Solar System Sciences
SATO Eiichi	Director, Department of Space Flight Systems
HAYAKAWA, Hajime	Professor, Department of Solar System Sciences
HIROSE Kazuyuk (Chairman)	Director, Department of Spacecraft Engineering
FUJIMOTO Masaki	Deputy Director General
MITSUDA Kazuhisa	Professor, Department of Space Astronomy and Astrophysics
MORITA Yasuhiro	Professor, Department of Space Flight Systems
YAMADA Toru	Director, Department of Space Astronomy and Astrophysics

The term is from April 1, 2019 to March 31, 2021.

c. 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 ninth fiscal period for the committee started for FY2019.

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 necessary research and development activities. In FY2019, the committee held a WG chief meeting, confirmed progress on mission proposals with a year-end evaluation, gave feedback about those WG activities, and supported activities around the development of new missions.

The Advisory Committee for Space Science, in collaboration with the Advisory Committee for Space Engineering, asked each community to update the goals, strategies, and process tables of the research area, and compiled the information. In response to a 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 the ISAS. An evaluation committee was established for evaluation of the plans for Competitive Middle-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 are considered by open application, and research funds are allocated after review. Progress reports are shared within the ISAS community.

Working group activities and status are summarized below.

Ongoing Working Groups (WGs)

- Competitive Middle-class Projects
  - > Frontiers of Formation, Acceleration, Coupling, and Transport Mechanisms Observed by Outer Space Research System (FACTORS)
  - > Physics of Energetic and Non-thermal plasmas in the X (= magnetic reconnection) region (PhoENiX)
  - > Broadband X-ray High-sensitivity Imaging Spectrometer (FORCE) WG
  - > Superconducting Submillimeter-Wave Limb Emission Sounder (SMILES-2) WG
  - > High-z Gamma-ray Bursts for Unraveling the Dark Ages Mission (HiZ-GUNDAM) WG
  - >Orbiter and EDL demonstration mission for space weather, climate, and aquatic environment
- Small Projects
  - >GEOspace X-ray imager (GEO-X) WG
  - >Circumpolar Stratospheric Telescope (FUJIN) WG
  - >Klypve-EUSO working group onboard International Space Station WG
- Ultraviolet spectrum observation in extrasolar planets

WG.
- Strategic International Projects
  >Laser Interferometer Space Antenna (LISA)
  >Ultraviolet spectrum observation in extrasolar planets WG
  >ATHENA WG
  >Comet Intercepter WG
  >Hera WG
- Equipment Development Working Groups
  >Life Detection Microscope (LDM) WG

Working Groups whose status changed in FY2019
- ATHENA WG was approved for Pre-PhaseA1b.

Notable results are listed below.
- SOLAR-C WG (Solar-C_EUVST) was selected as a candidate for the fourth Competitive Middle-class project.
- Broadband X-ray High-sensitivity Imaging Spectrometer (FORCE) WG conducted system reviews including satellite system components, and configuration designs for spacecrafts. In addition, as a key technology development, the group has advanced the designs of the core part of the built-in ADC for SOIPIX, and of the peripheral circuit for ADC. The group submitted the proposal for the Competitive Middle-class project.
- Physics of Energetic and Non-thermal plasmas in the X (= magnetic reconnection) region (PhoENiX) WG proceeded with a study of the mission concept for Competitive Middle-class to meet its criteria. A prototype of the Wolter mirror for the higher accuracy and retention mechanism of hard X-ray mirror achieved the world's highest accuracy in electro casting technology. The group submitted the proposal for the Competitive Middle-class project.
- Superconducting Submillimeter-Wave Limb Emission Sounder (SMILES-2) WG and Mars Aqueous-environment and Climate Orbiter (MACO) WG applied for a mission proposal for the Competitive Middle-class project.

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, travel in, and perform experiments in space.

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
- Transformer Spacecraft
- Detonation Engine Kick Motor Sounding Rocket Demonstration of Putting into Orbit
- Research and Development of Micro Planetary Probes using Deployable Flexible Aeroshell
- Research on formation flying technology WG
- OPENS WG
- Study of advanced aero-assisted reusable space transportation system

Operations
- Engineering research using the REIMEI satellite

Studies on Basic Hardware Technologies
- Study on the inertial platform for payloads of ISAS/JAXA sounding rockets
- Development of an electrodeless magnetic nozzle helicon plasma thruster
- Feasibility study and demonstration of a 100kW-class laser propelled launch System
- Development of innovative heat management technology for long-term cryogenic propellant storage
- Construction of the architecture of spacecraft onboard network and software
- Study on highly-precise structures and materials for advanced scientific observations
- Guidance and Navigation Technologies for Rendezvous and Landing to Far-distant Celestial Bodies
- Research on rover for exploration of small bodies, moons, and planets
- Studies on frequently reusable space transportation system ・
- Research for Landing/Contact/Impact System on Astronomical Body Surface
- R&D on Mars airplane
- Research and development on innovation of sample return capsule for future deep space exploration
- Demonstration research on advanced solid propellant rocket system
- Research on an innovative parafoil-type vehicle for Mars exploration
- Research on innovative satellite bus technology
- BBM and Its Functional Tests for High Efficiency Cryo-Coolers abroad Spacecraft
- Studies on an innovative thermal control system
- Ultralightweight thin film solar array structure deployed by booms
- Demonstration of a super-pressure balloon for long duration flight
- Development of a next-generation hard lander
- Development of high-performance shape memory alloy actuators through additive manufacturing
- Developing Study on Motion Control Technologies for Future Scientific Satellite and Spacecraft Missions
- Feasibility study of 60% hydrogen peroxide as a propellant
- Examination of sublimable propellants for electric propulsion

- Experimental Demonstration of 2-3Gbps ultra high speed down link with RAPIS-1 Satellite
- Feasibility Study of Small Probe System for Lunar Lavatube Exploration
- Optical Tracking of the Reentry Capsule

The Achievements that have been publicly released include 84 papers, 160 presentations at international academic conferences, 326 presentations at domestic academic conferences, 22 Awards, 46 invited speeches, 6 patents, 3 published books, and 22 other media reports (including press releases).
Notable Achievements are listed below.

- Transformer Spacecraft WG: In order to realize a spacecraft that can optimize orbital control and passive cooling by controlling solar radiation pressure with posture transition, while simultaneously realizing morphological changes and attitude control using non-holonomicity, the group listed conditions for panel configuration. Based on those conditions, the group examined space infrared interferometers as scientific missions that take advantage of the characteristics of transformer spacecraft and presented a plan for spacecraft components.
- Studies on an Innovative Thermal Control System RG designed and constructed the engineering models for a thermal control system for orbital demonstration with the aim of demonstrating onboard the RAPid Innovative payload demonstration Satellite 2 (RAPIS-2).
- Innovative Satellite Bus Technology RG conducted several trial tests with the goal of achieving a compact and lightweight satellite bus that can be constructed quickly, and examined a wide range of issues raised for a proposal to space science missions. They include Micro-electro-mechanical systems (MEMS) packaging technology, a compact and high-efficiency power supply unit, distributed implementation of membrane functional elements, thrusters, and batteries for low-temperatures.
- Studies on Frequently Reusable Space Transportation System RG conducted research on elemental technologies necessary for the construction of future reusable transportation systems, such as propulsion technology, ultra-lightweight technology, failure-tolerance, and health management technology. Results, such as simulations of aircraft motion using a real-time computer and realization of precision positioning in high dynamics environments have been applied to the reusable rocket demonstrator.
- The RG for Demonstration Research on Advanced Solid Propellant Rocket Systems: The quality assurance method of the solid motor propellant, which is an inspection method using phased array probes, was demonstrated by the booster of the H3 rocket and QM motor of the SRB (Solid Rocket Booster) -3 that is to be in the first stage of the new Epsilon (so-called “Synergy-Epsilon”) rockets.
- Study on Highly-precise Structures and Materials for Advanced Scientific Observations RG conducted research on high-precision 1-D structures, 2-D structures, and high-precision materials and structural elements as part of the high-performance technology of satellites and explorers that support next-generation scientific observations. Significant results were achieved, such as large-scale one-dimensional structures that achieve pointing control at one parsec.
- Study on the Inertial Platform for Payloads of ISAS/JAXA Sounding Rockets RG: A prototype for Upper Motion Stage (UMS) was installed in the S-310-45, which was launched in January 2020, demonstrating tolerability to the launch environment with a multi-link mechanism and its operation in outer space.

2.2 Technical Committees

The Sounding Rocket Technical Committee, Committee for Space Biology and Microgravity Science, and Committee on Scientific Ballooning deliberated about application screening and research plans. Committee for International Space Exploration gave advice and recommendations to the deep-space gateway mission and the Human-Enhanced Robotic Architecture and Capability for Lunar Exploration and Science (HERACLES) mission. Space Transportation System Committee developed a research plan for a space transport system.

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 using 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 FY2019

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, 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 FY2019, we supported the LiteBIRD, OKEANOS (Solar Power Sail), SPICA, small-JASMINE, Solar-C(EUVST), HiZ-GUNDAM, CAESAR-SRC, OMOTENASHI, and XRISM projects.

Small JASMINE and Lite BIRD were selected as the competitive middle class #3 and the strategic large mission #2 respectively.

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 that 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

Reflecting the project management reform of JAXA following the Astro-H incident, the Program Office developed implementation procedures for space science projects, especially for initial phases.

The reformed project management protocol has newly 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. Support for the selection of Competitive M-class Missions

The Program Office plays two roles in mission selection. The office supports candidates, helping them to arrange their ideas in the form of proposal materials that are compatible with the CML yardstick. Second, the office serves as secretariat of the review panel.

5. 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 FY2019, the office worked with project teams to prepare review materials for the following projects (project status or activity follows the project name):

- SLIM: CDR (Kickoff meeting)
- CAESAR-SRC: Pre-project termination review
- Small JASMINE: Completion review of pre-phase A2

5. Safety and Mission Assurance Officer

In July 2017, the 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 in the strengthening of the independent evaluation system. The S&MA operations are to be done independently of ISAS, however the ISAS Safety Review Committee remains as an S&MA operation. The S&MA Office was involved as a jury member of the ISAS Safety Review Committee, while other S&MA members were involved in operation of the committee.

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

In FY2019, we ensured ground safety and flight safety of sounding rocket experiment and Hybrid rocket engine test, while holding 7 safety review meetings at ISAS.

In addition, 18 safety review meetings were conducted in FY2019 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	FY2017	FY2018	FY2019
Operating Expense Grants	14,082,128	11,472,233	14,017,719
Facility maintenance subsidy	2,602,531	2,048,725	2,252,268
Total	16,684,659	13,520,958	16,269,987

External Funds			
Grant-in-aid for scientific research (KAKENHI)	309,071	308,265	348,969
Grant-in-aid for scientific research (Accepted share of expenses)	104,553	51,731	65,007
Funded research	744,286	868,792	326,421
Cooperative research with private sector	26,651	67,977	75,768
Earmarked donations	6,000	7,819	19,125

7. Staff (as of March 31, 2020)

Director General, Institute of Space and Astronautical Science
KUNINAKA Hitoshi

Deputy Director General of Institute of Space and Astronautical Science
FUJIMOTO Masaki

Director, Management and Integration Department
MIYOSHI Hiroshi

Manager, Management and Integration Department
AOYAGI Takashi
OHSHIO Kazuo
TSUJI Hiroji

Advisor to the Director, Management and Integration Department
KATO Hideki
KOYAMA Kazuhiro
YASUDA Shin
YASUMA Toshio

Director for International Strategy and Coordination
TOUKAKU Yoshio

Director for Education and Public Outreach
IKUTA Chisato

Research Director
KUBOTA Takashi

Director, Department of Space Astronomy and Astrophysics
YAMADA Toru

Director, Department of Solar System Sciences
SAITO Yoshifumi

Director, Department of Interdisciplinary Space Science
INATOMI Yuko

Director, Department of Space Flight Systems
SATO Eiichi

Director, Department of Spacecraft Engineering
HIROSE Kazuyuki

Program Director of Space Science
SATO Eiichi

Director, ISAS Program Office
MOKUNO Masaaki

Project Manager, GEOTAIL Project Team
SAITO Yoshifumi

Project Manager, ASTRO-EII Project Team
ISHIDA Manabu

Project Manager, SOLAR-B Project Team
SHIMIZU Toshifumi

Project Manager, Bepi Colombo Project Team
HAYAKAWA Hajime

Project Manager, Extreme Ultraviolet Spectroscope for Exospheric Dynamics Project Team
YAMAZAKI Atsushi

Project Manager, Hayabusa2 Project Team
TSUDA Yuichi

Project Manager, GREAT (Ground Station for Deep SpaceExploration and Telecommunication) Project Team
NUMATA Kenji

Project Manager, SLIM (Smart Lander for Investigating Moon) Project Team
SAKAI Shinichiro

Project Manager, XRISM (X-Ray Imaging and Spectroscopy Mission) Project Team
MAEJIMA Hironori

Senior Chief Officer of Fundamental Technology for Space Science
MORITA Yasuhiro

Manager, Inter-University Research and Facility Management Group
YOSHIDA Tetsuya

Manager, Test and Operation Technology Group
MORITA Yasuhiro

Manager, Advanced Machining Technology Group
OKADA Norio

Director, Scientific Ballooning Research and Operation Group
YOSHIDA Tetsuya

Director, Sounding Rocket Research and Operation Group
HABU Hiroto

Manager, Noshiro Rocket Testing Center
ISHII Nobuaki

Manager, Akiruno Experimental Facility
GOTO Ken

Director, Science Satellite Operation and Data Archive Unit
TAKESHIMA Toshiaki

Manager, Lunar and Planetary Exploration Data Analysis Group
OOTAKE Hisashi

Manager, Astromaterials Science Research Group
USUI Tomohiro

Manager, Deep Space Tracking Technology Group
YOSHIKAWA Makoto

Department of Space Astronomy and Astrophysics [Director : YAMADA Toru]

Professor	Associate Professor	Assistant Professor
MITSUDA Kazuhisa	KOKUBUN Motohide	MAEDA Yoshitomo
DOTANI Tadayasu	KII Tsuneo	WATANABE Shin
ISHIDA Manabu	KATAZA Hirokazu	WADA Takehiko
NAKAGAWA Takao	YAMAMURA Issei	DOI Akihiro
MATSUHARA Hideo	KITAMURA Yoshimi	TAMURA Takayuki
TSUBOI Masato	MURATA Yasuhiro	ISOBE Naoki
EBISAWA Ken	YAMAGUCHI Hiroya	
YAMADA Toru	TSUJIMOTO Masahiro	
SEKIMOTO Yutaro		
YAMASAKI Noriko	ISHISAKI Yoshitaka [S]	
	HAYASHIDA Kiyoshi [S]	
	TERADA Yukikatsu [S]	
KANEDA Hidehiro [S]	FUJIMOTO Ryuichi [S]	
TASHIRO Makoto [S]	MORI Koji [S]	
SHIBAI Hiroshi [V]		
HASUMI Masashi [V]		
GOUDA Naoteru [V]		
MURAKAMI Izumi [V]		
SUMI Takahiro [V]		

Department of Solar System Sciences [Director: SAITO Yoshifumi]

Professor	Associate Professor	Assistant Professor
FUJIMOTO Masaki	ABE Takumi	HASEGAWA Hiroshi
SATO Takehiko	TANAKA Satoshi	YAMAZAKI Atsushi
HAYAKAWA Hajime	OKADA Tatsuaki	HARUYAMA Junichi
NAKAMURA Masato	ABE Masanao	SHIRAISHI Hiroaki
SAITO Yoshifumi	SAKAO Taro	HAYAKAWA Masahiko
USUI Tomohiro	SHIMIZU Toshifumi	MITANI Takefumi
	OZAKI Masanobu	MURAKAMI Go
KURAMOTO Kei [S]	SHINOHARA Iku	
TACHIBANA Shogo [S]	ENYA Keigo	SUGAWARA Haruna [S]
WATANABE Seiichiro [V]	TASKER Elizabeth	MATSUDA Shoya [S]
MIYAMOTO Hideaki [V]	IWATA Takahiro	
WATANABE Junichi [V]	ASAMURA Kazushi	
MIYOSHI Yoshizumi [V]		
TERADA Naoki [V]	YABUTA Hikaru [V]	
	HORINOUCHI Takeshi [V]	
	YOKOYAMA Takaaki [V]	

Department of Interdisciplinary Space Science [Director : INATOMI Yuko]

Professor	Associate Professor	Assistant Professor
ISHIKAWA Takehiko	KUROTANI Akemi	MIURA Akira
YOSHIDA Tetsuya	HASHIMOTO Hirofumi	YAMAMOTO Yukio
INATOMI Yuko	TAKAKI Ryoji	YANO Hajime
FUNASE Ryu	SAITO Yoshitaka	MIZUMURA Yoshitaka
	IKUTA Chisato	
SHIGETA Yasuteru [V]	FUKE Hideyuki	NAKAJIMA Shintaro [S]
ISHIKAWA Hiroshi [V]		
KATO Chihiro [V]	YAMAMOTO Masahiro [V]	

[V] Visiting, [F] Full-time, [S] Specially-appointed

Department of Space Flight Systems [Director: SATO Eiichi]

Professor	Associate Professor	Assistant Professor
ISHII Nobuaki	YAMADA Tetsuya	MORI Osamu
MORITA Yasuhiro	NISHIYAMA Kazutaka	TAKEMAE Toshiaki
SHIMADA Toru	TOKUDOME Shinichiro	MARU Yusuke
HORI Keiichi	OYAMA Akira	SAIKI Takanao
SATO Eiichi	NONAKA Satoshi	KITAGAWA Koki
MINESUGI Kenji	GOTO Ken	OKUIZUMI Nobukatsu
OGAWA Hiroyuki	HABU Hiroto	TSUKIZAKI Ryudo
SAWAI Shujiro	TAKEUCHI Shinsuke	TOBE Hirobumi
KAWAKATSU Yasuhiro	YAMADA Kazuhiko	SATO Yasutaka
FUJITA Kazuhisa		
FUNAKI Ikkoh	KOBAYASHI Hiroaki [S]	
TSUDA Yuichi	TAKAO Yoshinori [V]	
	BANDO Mai [V]	
KAWAGUCHI Junichiro [S]	ANYOJI Masayuki [V]	
NAGANO Hosei [V]		
FUNAZAKI Kenichi [V]		
SHICHIJO Naohiro [V]		
ISHIMURA Kosei [V]		

Department of Spacecraft Engineering [Director : HIROSE Kazuyuki]

Professor	Associate Professor	Assistant Professor
HASHIMOTO Tatsuaki	SONE Yoshitsugu	MITA Makoto
KUBOTA Takashi	MIZUNO Takahide	FUKUSHIMA Yosuke
YAMAMOTO Zenichi	FUKUDA Seisuke	TOYOTA Hiroyuki
HIROSE Kazuyuki	YOSHIKAWA Makoto	BANDO Nobutaka
SAKAI Shinichiro	TANAKA Koji	TOMIKI Atsushi
TAKASHIMA Takeshi	TODA Tomoaki	MAKI Kenichiro
	YOSHIMITSU Tetsuo	
KAWASAKI Shigeo [S]	MATSUZAKI Keiichi	OZAKI Naoya [S]
OTSUBO Toshimichi [V]	TAKEUCHI Hiroshi	
HARA Susumu [V]	OTSUKI Masatsugu	
NAGURA Toru [V]	KOBAYASHI Daisuke	
	FUJIMOTO Hiroshi [V]	

International Top Young Fellowship (ITYF)

Department	Name
Department of Space Astronomy and Astrophysics	LAU Ryan Masami
Department of Space Astronomy and Astrophysics	IZUMI Kiwamu
Department of Solar System Sciences	TORIUMI Shin
Department of Solar System Sciences	ODONOGHUE James
Department of Solar System Sciences	HYODO Ryuki
Department of Spacecraft Engineering	BONARDI Stephane

[V] Visiting, [S] Specially-appointed

8. Professors Emeriti (as of March 31, 2020)

Institute of Space and Astronautical Science (ISAS)

MORI Daikichiro
HIRAO Kunio
KURATANI Kenji
NOMURA Tamiya
ODA Minoru
OGUCHI Hakuro
USHIROKAWA Akio
TAKAYANAGI Kazuo
ITOH Tomizo
OBAYASHI Tatsuzo
OSHIMA Koichi
HAYASHI Tomonao
HORIUCHI Ryo
NISHIMURA Jun
MIURA Koryo
TANAKA Yasuo
NISHIMURA Toshimitsu
IWAMA Akira
AKIBA Ryojiro
SHIMIZU Mikio
KARASHIMA Keiichi
OKUDA Haruyuki
KURIKI Kyoichi
MAKINO Fumiyoshi
OGAWARA Yoshiaki
KAWASHIMA Nobuki
NAGATOMO Makoto
NISHIDA Atsuhiro
TSURUDA Koichiro
HINADA Motoki
ITIKAWA Yukikazu
YAJIMA Nobuyuki
HIROSAWA Haruto
KOBAYASHI Yasunori
MATSUO Hiroki

Japan Aerospace Exploration Agency (JAXA)

NINOMIYA Keiken
KOHNO Masahiro
NAGASE Fumiaki
MATSUMOTO Toshio
MIZUTANI Hitoshi
UESUGI Kuninori
TANATSUGU Nobuhiro
NATORI Michihiro C.
MATOGAWA Yasunori
NAKATANI Ichiro
TAKANO Tadashi
HIRABAYASHI Hisashi
MUKAI Toshifumi
MAEZAWA Kiyoshi
KURIBAYASHI Kazuhiko
NAKAJIMA Takashi
YAMASHITA Masamichi
TAJIMA Michio
FUJIMURA Akio
INOUE Hajime
KATO Manabu
SASAKI Susumu
ONODA Junjiro
YODA Shinichi
FUJII Kozo
KOMATSU Keiji
MURAKAMI Hiroshi
ABE Takashi
HATTA Hiroshi
IKEDA Hirokazu
ISHIOKA Noriaki
INATANI Yoshifumi
SAITO Hirobumi
SAKU Tsuneta
YAMADA Takahiro

9. 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

IV
International Collaboration and Joint Research

1. International Collaboration

Space is a common frontier for all humanity and many of the world's countries have worked together on a variety of space science missions over the years. Japan also sees 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 joint-university activities, the 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 is extremely important.

International collaboration will benefit space science missions in many ways. First of all, it can provide a means to realize more significant aerospace exploration efforts while reducing costs. Rather than limiting the scope to Japan-supported missions, we believe it is far more beneficial to expand our horizons and 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, international collaboration will offer 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 fields of space science.

Thirdly, international collaboration encourages members of the Japanese space science community to work with a diverse range of supremely talented people, which stimulates 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 this, the 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.

The ISAS pursued numerous international initiatives of various kinds throughout FY2019. As International collaboration initiatives for ongoing missions, the Implementing Arrangement (IA) regarding the asteroid explorer "Hayabusa2" was signed with the French National Space Center (CNES) in June. This IA has stipulated that CNES will provide an infrared hyperspectral microscope (MicrOmega) to be installed in the facility of the Extraterrestrial Sample Curation Center maintained by JAXA to improve the performance of the asteroid sample analysis that "Hayabusa2" returns to the Earth. The IA was signed by the JAXA President and CNES President in the presence of the Ministers in charge. Exchanged in front of the President of France and the Prime Minister of Japan, the IA was shown as a symbol of Japan-France space cooperation. The Hayabusa2 re-entry capsule is to land in Australia, and discussions were held with the Australian government for landing. The collection rehearsal was carried out locally in December. In addition, measures are considered for possible Australian travel restrictions as countermeasures against the novel coronavirus.

The first meeting of the Joint Executive Steering Group (JESG) on the X-Ray Imaging and Spectroscopy Mission (XRISM) was held with National Aeronautics and Space Administration (NASA) at Sagamihara Campus in May. The progress and issues of the project were reviewed. In June, JAXA President and European Space Agency (ESA) Director General signed an MOU to cooperate on XRISM at the ESA Operations Center (ESOC). ESA will contribute to the development of a part of the soft X-ray spectroscopic imaging device, which is one of the most important observation devices of XRISM through utilizing the cooperative relationships cultivated in ASTRO-H. It is also agreed that ESA will support the participation of European scientists in the XRISM project through science.

Multifaceted international cooperation is being promoted with NASA, ESA, CNES, and German Aerospace Center (DLR) regarding the Martian Moons Exploration project (MMX). Coordination with NASA has been promoted for realizing the cooperation stipulated in the LOA. The IA was signed with DLR at the Paris Airshow in France in June. DLR will contribute to MMX by conducting studies of the rover, which is to be equipped on MMX jointly with the National Centre for Space Studies and by providing JAXA with opportunities for experiments using the Drop Tower in Germany. DLR will also support German scientists for their participation in the MMX mission. The renewed IA was signed with CNES also in June. As with the Hayabusa2 sample analysis cooperation, it was signed in front of the Japanese and French ministers in attendance and exchanged in front of the bilateral summits. This IA stipulates that CNES will contribute to the mission by providing the near infrared spectrometer (MacrOmega), as well as the knowledge and expertise of the Flight Dynamics, by conducting studies with the rover, which is to be equipped on MMX jointly with DLR.

Coordination for cooperation is undergoing with NASA on Smart Lander for Investigating Moon (SLIM) to obtain DSN tracking support and accommodation of the laser retro-reflector.

Regarding the mission in the study phase, the ISAS has selected Lite (Light) satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD) as a candidate for the 2nd strategic large class mission. International coordination was promoted for cooperation from the U.S. and Europe (CNES, ESA, etc.)

The next-generation infrared astronomical satellite "SPICA", which is a strategic medium-sized future plan, was studied in collaboration with European partners.

In studies of Demonstration and Experiment of Space Technology for INterplanetary voYage Phaethon fLyby dUSt science DESTINY+, which is the 2nd competitively chosen M-class mission, cooperation was promoted at the project level as well as the interagency level for cooperation in provision of the dust analyzer based on the IA with DLR. Also, international arrangement for overseas cooperation, such as with the U.S., has been initiated for the Japan Astrometry Satellite Mission for INfrared Exploration (small-JASMINE) that was selected as the 3rd competitively chosen Medium-class mission. Support activities are carried out to obtain necessary international cooperation for next candidate missions.

In August, the LOA detailing cooperation with NASA regarding Cubesats (EQUULEUS and OMOTENASHI) on board SLS was signed. This LOA stipulates cooperation in the launch preparations for Cubesats (EQUULEUS and OMOTENASHI), the second payloads of the first SLS mission (Artemis-I). Additionally, cooperation coordination is underway regarding the MOU for launch and operation, as well as the mutual tracking support by the NASA Deep Space Network (DSN) and the JAXA tracking stations.

As for strategic international projects, cooperation is underway through provision of instruments for DLR and the Swedish National Space Agency (SNSA) in the ESA-led Jupiter Icy Moons Exploration (JUICE) mission, and provision and testing of hardware for the launch are progressing.

Mission studies have been promoted for the next NASA flagship mission in the field of space physics, the Wide-Field Infrared Survey Telescope (WFIRST). In March, the agreement (LOA) detailing cooperation with NASA, such as observation equipment provision, ground telescope observation, ground station reception, etc., was signed.

In the Asteroid Impact & Deflection Assessment (AIDA) mission jointly conducted by the U.S. and Europe, ISAS/JAXA was requested to participate in ESA's asteroid explorer HERA mission. Studies to provide a thermal imager based on the success of Hayabusa2 were promoted. Followed by a joint statement signed between the Directors in charge in September and the approval by ESA Council meeting at the ministerial level at the end of November, implementation of cooperation is underway.

Consideration on cooperation was advanced regarding World Space Observatory Ultraviolet (WSO-UV) as the Institute of Astronomy of the Russian Academy of Sciences (INASAN), the Space Research Institute of the Russian Academy of Sciences (IKIRAS) and the ISAS concluded a Letter of Intention (LoI) in April. Coordination of inter-agency cooperation with ROSCOSMOS is promoted for JAXA to provide spectrometers for exoplanet observation equipment.

Scientific ballooning campaigns and sounding rocket launches have also been involved in international collaboration. The ISAS small project, the experiment of cosmic dust particles experiment (DUST Nucleation), was successfully launched from Esrange Space Center in June with the cooperation of DLR. After concluding the IA with NASA in August, the launch experiment at White Sands was carried out in October with the cooperation of NASA.

In July, the ISAS officially joined the NASA-run Virtual Research Institute for Solar System Exploration (SSERVI) as an international partner and has been working on collaboration and outreach for international collaboration in space science and exploration.

In order to promote the above-mentioned international collaborations, inter-agency dialogue and bilateral meetings between directors in charge of space science have been actively held through mutual visits, as well as at venues such as the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) in Vienna, the Paris Air Show in June, and the COSPAR symposium in Israel in November.

The ISAS has promoted further international collaboration by staying up-to-date with the latest developments in U.S. and European space science and by presenting Japanese space-science plans.

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 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.
X-ray Astronomy Satellite SUZAKU (ASTRO-EII)	Jul 10, 2005	SUZAKU makes high-sensitivity observations of various X-ray objects in broader energy bands and with better resolution than previous satellites, with the aim of elucidating the evolution of cosmic structure (largest-scale galaxy cluster collisions, gas behavior during amalgamation, exploration of areas near black holes, etc.)	NASA (USA), MIT (Massachusetts Institute of Technology, USA)	Japan-US cooperative development of the X-ray Telescope (XRT), X-ray Spectrometer (XRS), etc.
			ESA (European Space Agency)	Participation of ESA researchers as scientific advisors for SUZAKU.
			ISRO (Indian Space Research Organization)	ISRO “ASTROSAT” satellite and cooperative observations. (Under discussion)
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 Solar Optical Telescope (SOT), 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 (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 Venus atmosphere by communication between AKATSUKI and ISRO's DSN and JAXA's DSN.
Asteroid Explorer Hayabusa2	Dec 3, 2014	A sample return mission to the C-class asteroid "Ryugu" that will provide new knowledge about the original distribution of materials in the solar system and its evolutionary process.	NASA (USA)	Deep Space Network (DSN) tracking of Hayabusa2, control support, asteroid ground observation support, OSIRISRex sample provision, etc.
			DLR (German Aerospace Center, Germany)	Hayabusa2 tracking support, microgravity experiment support.
			ASA (Australian Space Agency), Department of Industry and Science, Australian Defense Organisation (Australia)	Permission for sample reclamation capsule landing in Australia and landing operations support.

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)
Canadian small satellite project CASSIOPE (CAScade, Smallsat and IOnospheric Polar Explorer)	Sep 29, 2013	CASSIOPE is Canada's first small satellite project. Its main goal is elucidation of atmospheric outflow mechanisms from the polar region and observations of the effects of the Sun on Earth's magnetosphere and atmosphere.	Univ. of Calgary (Canada)	JAXA providing one of eight E-POP observation devices (neutral particle analyzers).
Korean Science & Technology Satellite STSAT-3	Nov 21, 2013	STSAT-3 is used for atmospheric observations and environmental monitoring, as well as galaxy observations.	KASI (Korea Astronomy and Space Science Institute, South Korea)	JAXA providing technical assistance for telescope system development of the Multipurpose Infra-Red Imaging System (MIRIS).
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 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 (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 (Centre National D'études Spatiales, 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 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
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)	Under discussion
			CNES (France)	Under discussion
			ESA (EU)	Under discussion
			DLR (Germany)	Under discussion

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

Project	Launch	Mission Overview	Cooperating partner	Partner responsibilities
Next-Generation Infrared Astronomy Mission SPICA (pre-project)	TBD	High-sensitivity infrared observations to elucidate essential processes of the universe's history, "from the Big Bang to the birth of life".	ESA (EU)	Under discussion
			SAFARI consortium (EU, Canada)	Under discussion
Solar Physics Satellite SOLAR-C (working group)	TBD	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
			ESA (EU)	Under discussion
Outsized Kite-craft for Exploration and Astronautics in the Outer Solar System (OKEANOS) (pre-project)	TBD	Solar power sail-craft aims at demonstration of exploration of the outer planetary region and will rendezvous with a Jupiter Trojan asteroid and deploy a lander that will land on the surface to collect samples from both surface and subsurface to perform in-situ analysis. Multiple kinds of deep space observation in the cruising environment and Trojan asteroid observation will be performed.	DLR (Germany)	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) (pre-project)	TBD	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.	NASA (USA)	Under discussion
			ESA (EU)	Under discussion

Cooperative projects with overseas satellite missions

Jupiter Icy Moon Explorer JUICE (pre-project)	2022 (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), SNSB, etc.	DLR: provide part of GALA (Ganymede Laser Altimeter) SNSA: provide 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
Wide Field Infrared Survey Telescope WFIRST (study team)	2025 (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 (study team)	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 (study team)	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 exoplanet observation equipment

d. International cooperation in scientific missions for space environment utilization

Project	Launch	Mission Overview	Cooperating partner	Partner responsibilities
CLASP2	Apr 2019	Aims to observe the ultraviolet light emitted by ionized magnesium atoms and 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 sounding rocket launch, onboard scientific computer and charge-coupled device (CCD) camera.
			Institut d'Astrophysique Spatiale (France)	Provision of diffraction grating.
			Instituto de Astrofísica de Canarias (Spain)	Hanle effect and Zeeman effect Model calculations
The experiment of cosmic dust particles experiment DUST Nucleation	Jun 2019	Launched by Swedish Space Corporation (SSC) sounding rocket Maser 14. The experiment to elucidate the initial formation of Earth type planet forming particle.	DLR (Germany)	Provision of DUST payload module Data analysis
	Oct 2019	Launched by NASA sounding rocket Black Brant IX from White Sands to elucidate nucleation process of silicate salt cosmic dust	NASA (USA)	Provision of DUST payload module Data analysis

e. International cooperation in atmospheric 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 atmospheric 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, the ERG science center was established at the Solar-Terrestrial Environment Laboratory (STEL) in 2013, Institute for Space-Earth Environmental Research (ISEE) in collaboration with Nagoya University. The center enabled efficient data management after the launch of the ARASE satellite, such as manipulating and providing standard data files and suggesting observation plans. As the inter-university collaboration with Nagoya University has demonstrated unique capabilities, ISAS concluded agreements with Nagoya University in supporting its international inter-university collaboration and after the agreements have expired at the end of FY2017.

This preceding activity model has enhanced further selections made during FY2017: (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.

ISAS reached separate agreements with the following organizations: Iwate University for advanced machining technology, the University of Aizu for data archiving, Saitama University for X-rays, Tokyo University for the Tokyo Atacama Observatory (TAO) Project and Space Infrared Telescope for Cosmology and Astrophysics (SPICA), the Tokyo Institute of Technology Earth-Life Science Institute for the curation of extraterrestrial life, Rikkyo University for personnel development and Okayama University for the curation of extraterrestrial materials.

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	49,510
Scientific Research (A)	8	101,400
Scientific Research (B)	16	76,340
Scientific Research (C)	27	42,408
Challenging Research (Exploratory)	4	12,202
Challenging Research (Pioneering)	1	1,040
Early-Career Scientists	5	8,053
Young Scientists (A)	1	780
Young Scientists (B)	5	4,793
Research Activity start-up	6	7,930
JSPS Fellow	8	9,235
Fostering Joint International Research	1	7,517
Fostering Joint International Research (B)	4	27,751
Total	88	348,959

Accepted Share of expenses

Research Categories	Number of Selected Projects	Total (in 1,000 JPY)
Scientific Research on Innovative Areas (Research in a proposed research area)	6	14,235
Scientific Research (S)	6	19,175
Scientific Research (A)	8	6,305
Scientific Research (B)	12	6,955
Scientific Research (C)	1	150
Challenging Research (Exploratory)	2	1,287
Specially Promoted Research	2	16,900
Total	37	65,007

b. Funded Research

Number of Researches	Total (in 1,000 JPY)
8	326,421

c. Cooperative Research with Private Sector

Number of Researches	Total (in 1,000 JPY)
44	99,118

d. Earmarked Donations

Number of Researches	Total (in 1,000 JPY)
16	19,125

4. Domestic Joint Research

a. Open Facilities for Domestic Joint Research

Facility	Number of joint research
Space Chamber test equipment	15
Ultra-high-speed collision test equipment	24
Space radiation equipment	11
Wind tunnel laboratory	29
Planetary atmospheric entry environment simulator	12
JAXA Supercomputer	28

b. Research for promoting international missions

	Number of joint research
	5

c. Joint Research Assigned to Specific Themes through Application by ISAS Educational Faculty

	Number of joint research
	45

V
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, 2020)

School or Program	Professors	Associate professors	Assistant Professor	Total
The Graduate University for Advanced Studies	21	35	16	72
The Graduate School at the University of Tokyo				
School of Science	8	5	6	19
School of Engineering	8	5	10	23
Special Inter-Institutional Research Fellows	7 (7)*	6 (6)*	1 (1)	14 (14)*
Cooperative Graduate School	12 (11)*	11 (11)*	2 (2)	25 (25)*

* Teaching staff at the Graduate University for Advanced Studies and the Graduate School at the University of Tokyo.

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 FY2019

Admission month	Admission capacity	Applicants	Accepted applicants
October	5*	2	2
April		11	7

*Of which 3 were admitted to secondary doctoral courses.

b. Interdisciplinary Studies 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/research guidance program

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.

As of March 31, 2020, ISAS was cooperating with 15 schools in 11 universities and accepts, teaches, and trains master’s and doctoral degree students.

e. Commissioned Guidance Student System

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

2. Public Outreach

Targeted investments in outreach have increased the visibility of JAXA among research institutions and agencies. Diversification of communication channels continued throughout the year. A series of critical operations conducted by the Hayabusa2 asteroid explorer attracted global attention. The results of each operation and the photos delivered to Earth made global headlines.

a. Press Activities

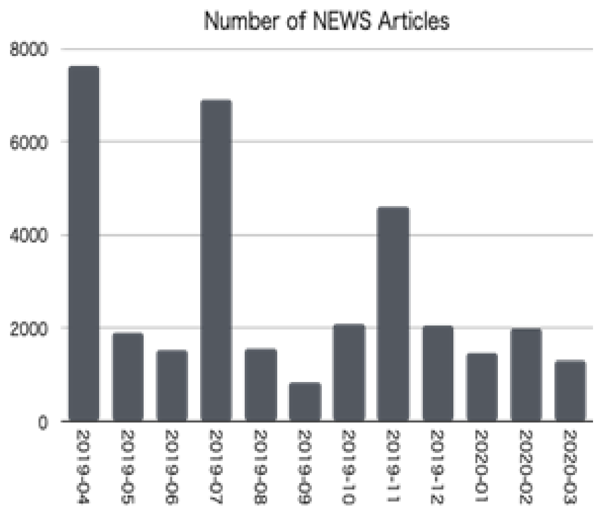
In FY2019, 23 articles were published on the ISAS’s official website. 9 of these were related to Hayabusa2, and the others covered a mix of research using ISAS experimental and analysis facilities on the ground and research using data obtained by satellites and exploration operated by ISAS.

ISAS/JAXA held a press conference whenever the Hayabusa2 project conducted critical operations such as the operation of the SCI (Small Carry-on Impactor) separation and the pine-point touchdown (or the second touchdown). ISAS/JAXA also broadcast live coverage during critical operations of Hayabusa2.

In addition to the activities of media related to the Hayabusa2 mission, in collaboration with other institutes and universities we sent press release announcements and posted web articles to communicate our research results, successes in experiments, and so on.

As a result of these activities, more than 33,800 articles were published by online news outlets in FY2019. This exceeded the number last year when the highest number was recorded. Japanese media, unsurprisingly, published the most coverage of ISAS activities. At the same time, Hayabusa2’s achievements made headlines in countries such as the United States and China.

b. Exhibition and Events

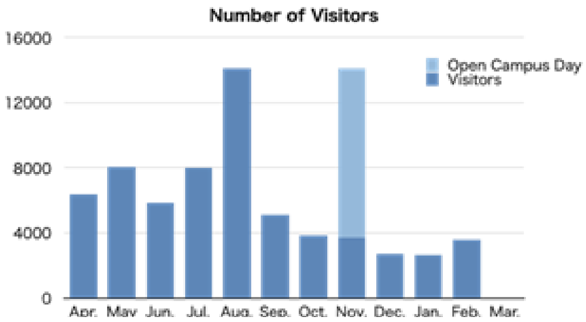


The ISAS’s Visitor Center, named the Space Science and Exploration Communication Hall, highlights the most important ISAS missions and scientific and engineering achievements. The Visitor Center is many guests’ first impression of that ISAS. It provides visitors with an exciting experience of space science in general, along with information about ISAS-specific results, missions, experiments, and technological breakthroughs.

The number of visitors peaked in August, since these months include the summer and spring holidays for Japanese schools. The number of visitors was zero in March. This is because we closed the Visitor Center amid COVID-19 outbreak measures from the end of February.

In FY2019, the Visitor Center was also used for press conferences. More than 100 representatives of the press gathered for each press conference, and an interpreters’ booth was set up in the Visitor Center for these press conferences. Bilingual streams of the conferences were broadcast via the Internet, enabling people abroad as well as domestic audiences to tune in.

An annual special “open house” day was held at the Sagamihara Campus on November 8, and more than 13,800 people visited.



Event booth locations were optimized, and smooth flow lines were planned, which alleviated the congestion that had happened in previous events. The ISAS provided educational experiences that inspired and captivated visitors of all ages in a more user-friendly manner.

“Space School” events continue to captivate each new generation of learners nationwide. In the nine Space Schools hosted at ISAS in FY2019, scientists and engineers gave presentations and answered participants’ questions during the half-day-long event. About 800 people joined in FY2019’s “Space School at Sagamihara” and “Lectures on Space Science and a Movie,” an event that commemorated the founding of the ISAS.

VI
Awards

The Sixth ISAS Award Recipients

Name	Affiliation	Reason for Award/ Title	Date
NARASAKI Katsuhiro	Sumitomo Heavy Industries, Ltd.	(Special Award for Outstanding Long-term Contribution) "Theoretical approach and practice of mechanical cryocoolers for space use".	Jan 8, 2020
HAGINO Shinji	I-Net Corp.	(Special Award for Outstanding Long-term Contribution) Contribution to space science missions through the advancement of satellites and probes and system integration.	Jan 8, 2020
KIMURA Shinichi	Tokyo University of Science	Contribution to deep-space science missions using ultra-small camera technology.	Jan 8, 2020

Award Recipients

Recipient	Affiliation	Award	Date
JAXA		The Cool Japan Association: COOL JAPAN AWARD 2019, Outbound Category. "Hayabusa" and "Hayabusa2".	May 27, 2019
Hayabusa2 Project Team		AIRBUS, Airbus Space Day 2019: The camera of the MASCOT onboard Hayabusa2.	Jun 4, 2019
IWASAKI Akihiro HABU Hiroto *et al.*	Dept. of Space Flight Systems	The Japan Society of Mechanical Engineers: Robotics and Mechatronics Division, ROBOMECH Award, Certificate of Merit for ROBOMECH Outstanding Industrial Application. "Peristaltic Continuous Mixing Conveyor for Composite Propellant Slurry Mixing - Manufacturing test and burning test of solid rocket with practical composition propellant".	Jun 2019
KOBAYASHI Daisuke	Dept. of Spacecraft Engineering	IEEE Nuclear & Plasma Sciences Society: IEEE Nuclear Space and Radiation Effects Conference Award, Short Course "Basics of Single Event Effect Mechanisms and Predictions".	Jul 8, 2019
Hayabusa2 Project Team		Federation of the Science Fiction Fan Groups of Japan: The 50th Sei Un Award, Non Section."MINERVA-II1 landed on the surface of asteroid Ryugu (the world's first man-made object to explore movement on an asteroid surface)".	Jul 27, 2019
YOSHIMITSU Tetsuo KUBOTA Takashi	Dept. of Spacecraft Engineering	The Robotics Society of Japan: The 24th Technical Innovations Award 2019. "Development of MINERVA-II Asteroid Surface Exploration Rovers".	Sep 5, 2019
YAMADA Kazuhiko	Dept. of Space Flight Systems	The ESA International Conference on Flight Vehicles, Aerothermodynamics and Re-entry Missions & Engineering (FAR) 2019, AWARD of Best Conference Paper. "Flight demonstration of Deployable Aeroshell Technology using Nano-Satellite Opportunity"	Oct 2019

OYAMA Akira	Dept. of Space Flight Systems	The Japan Society of Mechanical Engineers (JSME): Fluids Engineering Division, Frontier Award FY2019.	Nov 2019
YOSHIKAWA Makoto	Dept. of Spacecraft Engineering	City of Tochigi: Citizen honor award.	Nov 12, 2019
TSUDA Yuichi OKADA Tatsuaki OTAKE Hisashi OGAWA Naoko *et al.*	Dept. of Space Flight Systems	The Institute of Electronics, Information and Communication Engineers (IEICE): Dependable Computing (DC) Kenkyu Kai, The 6th best presentation award. "Reliability evaluation of the optical navigation electronics of HAYABUSA2 -Onboard demonstration of a high reliability system with limited resources".	Nov 2019
SAKAI Shinichiro	Dept. of Spacecraft Engineering	The Japan Society for Aeronautical and Space Sciences: The 63rd Space Sciences and Technology Conference, Young Researcher Award- Best Presentation Award.	Jan 24, 2020
TSUDA Yuichi	Dept. of Space Flight Systems	Japan Society for the promotion of science: The 16th JSPS Prize. "Pioneering Work and Its Verification on Precision Landing to an Asteroid and Interplanetary Flight Technology".	Feb 18, 2020
YAMAKAWA Hiroshi KUNINAKA Hitoshi TSUDA Yuichi SAIKI Takanao TERUI Fuyuto	Dept. of Space Flight Systems	Japan Techno-Economics Society (JATES) The 8th Technology Management and Innovation Awards, President Award.	Feb 21, 2020
KIKUCHI Shota	Dept. of Space Flight Systems	Society for Promotion of Space Science: The 12th Space Science Encouragement Award. “Construction of orbit and attitude dynamics theory in strong perturbation environment near small bodies”.	Mar 6, 2020
KUBOTA Takashi YOSHIMITSU Tetsuo	Dept. of Spacecraft Engineering	The Japan Society of Mechanical Engineers (JSME): Space Engineering Division, Space Frontier Award FY2019.	Mar 19, 2020
Frequently Reusable Space Transportation System Research Group		The Japan Society of Mechanical Engineers (JSME): Space Engineering Division, Space Frontier Award FY2019.	Mar 19, 2020
IWASAKI Akihiro HABU Hiroto *et al.*	Dept. of Space Flight Systems	The Chemical Society of Japan (CSJ): The 99th CSJ Annual Meeting, CSJ Presentation Award 2019 for Industries.	Mar 2020

Award Recipients

Student	Affiliation	Academic Advisor	Award	Date
ITOUYAMA Noboru	Graduate School at the University of Tokyo	HABU Hiroto	Japan Explosives Society (JES): 2019 JES Encouragement Award.	May 2019
TAKAKU Ryota	Graduate School at the University of Tokyo	MITSUDA Kazuhisa	The 49th Summer School FY2019 (Astronomy &Astrophysics) for Young Researchers: Observation Equipment Division, Best Oral Award.	Aug 2019
OHATA Kota	Graduate School at the University of Tokyo	SATO Eiichi	The Japan Institute of Light Metals: The 137th JILM Annual Meeting , 2019. "Effect of multi-stage heat treatment on superelasticity in base and welded parts of Ti-4.5Al-3V-2Fe-2Mo alloy sheet".	Nov 2, 2019
TAKAGI Yuya	Graduate School at Yokohama National University	NONAKA Satoshi	The Japan Society for Aeronautical and Space Sciences: The 63rd Space Sciences and Technology Conference, Excellent Presentation Award for Students.	Nov 7, 2019

Professor Emeritus	Award	Date
KURIKI Kyoichi	The Order of the Sacred Treasure, Gold Rays with Neck Ribbon	May 21, 2019

VII
ISAS Library and JAXA Repository

1. ISAS Library

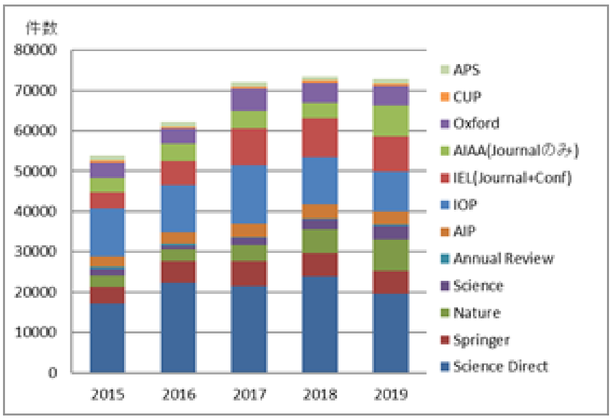
The ISAS Library actively collects materials, including books, magazines, and reports, on space science and related fields, and makes them available to ISAS's many researchers. It has also served as a library of SOKENDAI parent institute since April 2003. The library makes joint purchases of e-journals 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 to external users cooperating with other libraries in JAXA. JAXA Library Portal website (https://www-std01.ufinity.jp/jaxalib/) has launched in March 1st, 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 more convenient online search and browse functions.

ISAS Library holdings at the end of March 2020.

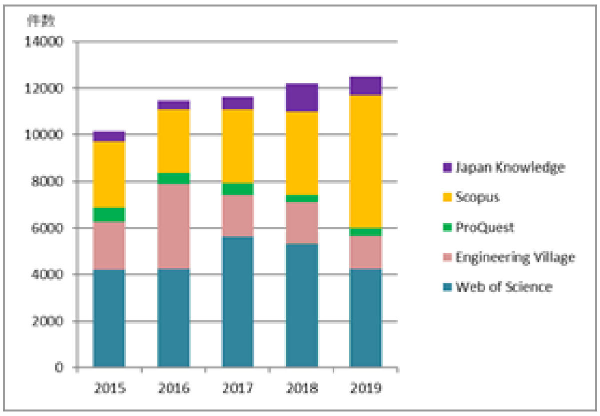
Category	Quantity
Total books	95,194
Foreign books	76,460
Japanese books	18,734
Total journals	1,200
Foreign journals	959
Japanese journals	241
Journals added in FY2019	167
Foreign journals	11
e-Journals	92
Domestic English journals	6
Japanese journals	58
e-Journals	about 4,100
IEL Online	188
IOP Journal	83
Elsevier Science Direct	128
Springer Journal	about 1,600
Wiley-Blackwell	about 1,400
JSTOR	about 680
e-Books	
AGU Geophysical Monograph Series and other	598
AIAA Education Series	69
Cambridge Books Online	160
Net Library	585
Oxford Scholarship Online (Physics)	216
Springer eBOOK	about 118,000
ProQuest Ebook Central	44
Chronological Scientific Tables Premium	

Databases

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



Number of e-journal downloads



Number of database searches

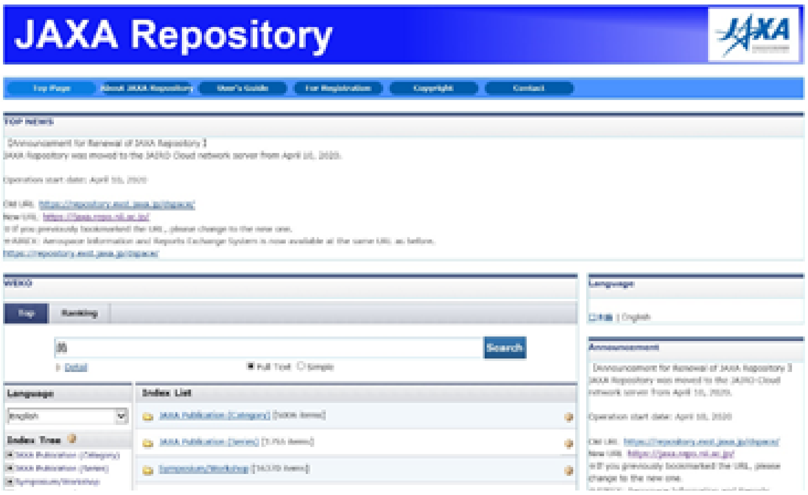
2. JAXA Repository

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 store 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, the JAXA Repository started assigning Digital Object Identifiers (DOIs) in FY2016 to registered papers from peer-reviewed academic journals by JAXA staff. In fiscal 2019, 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). Increasing DOI contents and preserving the accessibility of these materials will allow semi-permanent, open access to JAXA academic contents.



VIII

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, 3 in Science (April 2019- March 2020)
b. Number of heavily cited papers * Including papers with ISAS staff as co-author(s)	57 (Jan 2009 - Dec 2019)
c. Reviewed papers published in journals	348 (Jan 2019 - Dec 2019)
2. JAXA Publications (in ISAS)	9 (Research and Development Report: 5, Research and Development Memorandum: 2, Special Publication: 2)
3. Journals, publications, etc.	
a. Published in books	11
b. Published in reviewed journals	343
4. Presentations at domestic and international meetings, etc.	Keynote speeches: 11 Invited lectures: 89 Domestic meetings: 744 International meetings: 502
5. Awards	26 (see pp. 121-123)
6. Patents	Published patent applications: 30 Patents granted: 19

http://global.jaxa.jp/

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

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