ISAS’s Deep Space Fleet
Electric Propulsion Expands Horizon of Human Activities

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Abstract: Institute of Space and Astronautical Science, Japan Aerospace Exploration
Agency is now putting our space assets from Mercury to Jupiter, and then will accomplish to
make the ISAS’s Deep Space Fleet in the Solar System. After the powered flight in 3.5 years
by the microwave discharge ion engines, Hayabusa2 is exploring asteroid Ryugu in 2019.
ESA’s BepiColombo with ISAS’s Mio is going to Mercury by T6 ion engines. DESTINY+ will
flyby asteroid Phaethon using the microwave discharge ion engines. Akatsuki is circulating
around Venus. SLIM is under development to land on Moon. MMX will achieve the sample
return from Phobos of Mars. ISAS cooperates with ESA in JUICE mission toward Jupiter.
In the ISAS’s Deep Space Fleet the electric propulsion plays an important role.

1. Introduction

Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA) is now putting
our space assets from Mercury to Jupiter, and then will accomplish to make the ISAS’s Deep Space Fleet in space,
illustrated in Fig.1, in which a lot of spacecraft swarm to investigate the history of the solar system in 4.7 billion
years. Akatsuki is an active Venus probe. SLIM is under development for a lunar lander. MMX aims to the sample
return from Phobos of Mars. ESA and JAXA develop JUICE toward Jupiter. After the powered flight in 3.5 years by
the microwave discharge ion engines, Hayabusa2 is exploring asteroid Ryugu in 2019. ESA’s BepiColombo with
ISAS’s Mio is going to Mercury by T6 ion engines. DESTINY+ will flyby asteroid Phaethon using the microwave
discharge ion engines. The electric propulsion is the key technology to realize the ISAS’s Deep Space Fleet.

Figure 1. ISAS’s Deep Space Fleet.
II. Current Projects in Deep Space

A. Hayabusa2 Asteroid Explorer

Hayabusa2 is a spacecraft with a mass of about 600 kg and was launched on December 3, 2014 by the H-IIA Launch Vehicle No. 26, which was partially upgraded to support interplanetary flight. The mission was to explore the asteroid Ryugu and to collect samples from the surface and bring them back to Earth. Hayabusa2 follows the basic design of Hayabusa, and installs the same ion engine system. However, a lot of improvements have been made in some respects and this section outlines the changes specifically related to the ion source and neutralizer. The detail description is seen in Ref. 1.

Regarding the initial plasma ignition failure of one ion source and the shortage of life of three neutralizers, which became problems in Hayabusa, the following measures were taken after estimating the root cause. Ion source microwave supply cables were replaced with more reliable and proven products. In addition, the length of the cylindrical waveguide portion of the discharge chamber and the length of the antenna inserted into the waveguide were carefully adjusted to provide an enough margin for the plasma ignitability of the ion source.

In order to extend the life of the neutralizer, the inner wall of the discharge chamber is protected from plasma, and the magnetic field is effectively enhanced to reduce the potential difference between the neutralizer and the ion beam necessary for electron emission. This is an improvement from the ground durability test in the Hayabusa project. The durability test of the engineering model neutralizer was started in 2012 under a harsh environment simulating space, in which temperature cycles are applied once a week. Ten thousand hours of neutralizer operation is required to make a round trip between Earth and Ryugu, but 20,000 hours of ground operation twice that amount was successfully achieved by the launch of Hayabusa2. Durability tests continued after launch, and 59,000 hours have passed as of the end of August 2019. When the inside of the discharge chamber was observed using a fiberscope after 40,000 hours had passed, no damage was observed, and no increase in the voltage, which is a performance index for electron emission, occurred. After the accumulated 40,000 hours, aiming at application to the two future deep space missions described later, in order to cope with the neutralization of the 200-mA ion beam current for 12-mN thrust, the power setting was changed to the 220-mA constant current extraction mode and the durability test is continuing.

In addition to improving the ignitability of the ion source and extending the life of the neutralizer, small design changes have been made, such as the arrangement of the xenon gas injection ports in the ion source and the optimization of flow distribution between gas ports, and adjustment of the accelerator grid hole diameter and screen-grid thickness for ion acceleration. As a result, the upper limit of thrust at variable flow rate was increased from 8 mN to 10 mN. Thanks to this, it is possible to give the same acceleration to the Hayabusa2, which has about 20% more mass than Hayabusa. Figure 2 shows the appearance of one of the four flight model ion engines during the acceptance test, and Fig. 3 shows the appearance of Hayabusa2 and Hayabusa as seen from the ion engine system mounting surface.

Hayabusa2 made a successful earth swing-by on December 3, 2015, one year after its launch. After swing-by, the ion engines were operated in three periods, and the outbound operation before the arrival of the asteroid Ryugu was completed on June 3, 2018. So far, the total delta-v has been about 1015 m/s and the space powered flight time has reached 6515 hours. 24 kg of propellant xenon was consumed, and 42 kg remained. All three thrusters finished the outbound trip with a maximum thrust of almost 10 mN.  

![Figure 2. Microwave discharge ion thruster µ10 for Hayabusa2.](Image)
B. BepiColombo Mercury Explorer

BepiColombo was blasted off on an Ariane 5 from Kourou at 20 October 2018 on its exciting mission to study the mysteries of the Solar System's innermost planet, Mercury. The mission comprises two spacecraft: the Mercury Planetary Orbiter and the Mercury Magnetospheric Orbiter Mio, latter of which was provided from JAXA. QinetiQ T6 ion engines are accelerating BepiColombo aiming to arrival in 2025. JAXA has another duty to track BepiColombo by Misasa Deep Space Antenna with 54m diameter under construction as a successor to Usuda Deep Space Antenna with 64m as seen in Fig.4.

III. Future Projects in Deep Space

A. DESTINY+

DESTINY+ (Demonstration and Experiment of Space Technology for lNterplanetary voYage, Phaethon fLyby and dUst Science), adopted by ISAS's “FY2015 Epsilon Space Science Mission Call for Proposals”, is a joint mission of science and engineering that conducts flyby exploration of the near-earth asteroid 3200 Phaethon, which is the parent body of the Gemini meteor shower. The significance of this project as an engineering mission is the acquisition of deep space probe technology for small-class project in ISAS. In order to realize deep space exploration as a small-class project of ISAS, the purpose of DESTINY+ is to expand space flight technology by electric propulsion and expand the scope of use of electric propulsion, and to acquire fly-by exploration technology and expand opportunities for exploration of small bodies. It also has political significance as an anchor tenancy for launching low-cost Epsilon launchers through the continuous creation of scientific missions. By proving the technology of the small high-performance deep space probe platform, it is expected that Japan will be able to carry out various deep space exploration at low cost and high frequency in near future. The electric propulsion, the core of the platform, consists of four µ10 ion thrusters that will be developed following the achievements of Hayabusa2.

DESTINY+ will be launched into a highly elliptical orbit by the Epsilon rocket in 2022, and then will gradually increase its altitude by ion engines, and then will escape from the Earth in 2024 by a sequence of moon gravity assists. Deep space powered flight will be carried out while analyzing interplanetary dust environment, and in 2026, Phaethon will be explored by fly-by with a relative velocity of 33 km/s at a closest approach distance of 500 km. The total delta-v by the ion engines is assumed to be 4 km/s, which is about twice that of Hayabusa's achievement by 2010. Increase in the thrust per µ10 thruster to 12mN and increase in the number of simultaneously operating thrusters from 3 in the Hayabusa 2 spacecraft to 4 in DESTINY+ is planned 3). Figure 5 shows an artistic image of the spacecraft.
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Figure 5. DESTINY+ flyby mission to asteroid Phaethon.

B. OKEANOS

ISAS has been investigating Jupiter Trojan asteroid exploration by solar power sail as a medium-class project, and this is called Oversized Kite-craft for Exploration and AstroNautics in the Outer Solar system (OKEANOS). OKEANOS is a spacecraft with a large area (2000 m$^2$) of sail film surface that is equipped with many thin-film solar cells, and can supply power necessary for driving the ion engine even in the outer planetary region \textsuperscript{4). This sail is specialized for spin-stabilized spacecraft and can be lighter (1 kW/kg) by an order of magnitude compared to ordinary solar cell paddles. The new ion engine $\mu 10$HIsp is based on the Hayabusa2’s $\mu10$, and the ion beam voltage will be increased to 7500 V, which is five times higher than that of the conventional model. It aims to drastically reduce xenon propellants thanks to the higher specific impulse of 7000 s. A rendezvous to the Jupiter Trojan asteroid will be performed, and landing, sampling, and in-situ analysis will be performed by a small lander. Combining Japan's unique solar power sail with a high-specific-impulse ion engines makes it possible to reach the outer planetary region with a payload sufficient for remote sensing and landing exploration of small bodies. OKEANOS was defeated in the down-selection at ISAS held in May 2019, and the plan has just begun to rebuild, including the launch year.

Figure 6. OKEANOS rendezvous mission to a Jupiter Trojan asteroid. Left represents a full view including the membrane solar array. Right shows a center core spacecraft.

IV. Satellite Applications

A. Super Low Altitude Test Satellite (SLATS)

Super Low Altitude Test Satellite (SLATS) nicknamed “TSUBAME” (Fig.7) was successfully launched on December 23, 2017. The demonstration purposes in orbit are 1) to keep precisely by an ion engine at planed orbits from 271.5km to 180km where high atmospheric drag acts a satellite, 2) to acquire data related to atmospheric density and atomic oxygen, and 3) to obtain high resolution satellite images. The ion engine was designed and improved from the lessons and learned of Kiku-8 (Fig.8). SLATS is right now controlling successfully the orbits from April to September, 2019 by using the ion engine at 11.5mN thrust, in parallel with attaining atmospheric data and high resolution images.
B. Engineering Test Satellite 9 (ETS-9)

To satisfy the growing demand for all-electric propulsion satellite, JAXA is working on the Engineering Test Satellite 9 (ETS-9) program. In the program, a newly designed 5-ton class GEO satellite is going to demonstrate key technologies to enable high power (25 kW) and high payload ratio satellite. Its xenon electric propulsion subsystem (XPS) consists of both flight-proven Hall thrusters (SPT-140) as main propulsion and a Japanese xenon Hall thruster for flight experiment. Figure 9 shows the illustration of the ETS-9 satellite with four main thrusters on arm gimbals whereas the Japanese Hall thruster being located on the bottom of the satellite body. The Japanese Hall thruster in Fig. 10 executes part of orbit raising maneuver to demonstrate 359 mN and 1,710s at 6 kW (maximum power). In addition, limited lower power operation during the OR maneuver or in GEO is under planning. This flight opportunity for the Japanese Hall thruster enables not only more efficient all-electric propulsion satellite but also paves the way to near-future high power space transportation and exploration missions.

The ETS-9 project is currently producing and testing engineering models (EM) of some components in key subsystems. In the case of Japanese Hall thruster, EM fabrication and testing are prepared for a Hall thruster unit (HTU) and a power processing unit (PPU) to check the interfaces between HTU, PPU, and satellite system by executing performance evaluation, shock/vibrational test, and some coupling tests. The design is based on studies using breadboard models so far, including performance evaluation, preliminary life tests, and a compatibility test between a BBM thruster unit and a breadboard model PPU (BBM/PPU). Performance test using a breadboard model (BBM4) obtained 393 mN and 1,940s at the beginning of life, and as a result of preliminary life test, it is found that the thrust value slowly decreased from 393 mN to reach a constant value of about 384 mN at around 500 to 600 hours of accumulated operation, resulting in the same trend for Isp and thrust efficiency; they decreased from 1,940 s and 62.9% to reach the constant values of about 1,900s and 60%. During accumulated operation from 1,012 to 4,048 hours, nearly constant performance continued. The test is to be continued to check the feasibility of low-power operation for station keeping before full qualification processes starts in the prototype model (PM) phase.
C. 1kW Hall Thruster for debris removal satellites

In 2020’s, a technological demonstration satellite for removing space debris is planned in Japan. For the mission, the research and development of a 1 kW class Hall thruster has started since 2018. Figure 11 shows the schematic of the satellite and the laboratory model of the 1 kW Hall thruster. The first experiment campaign of the thruster was conducted in Aug 2019 at ISAS/JAXA. It achieved 52% of the total efficiency with 50 mN of thrust and 1600 sec of specific impulse, which features the center mounted cathode and the magnetic shielding topology. The further activities, such as PPU development, cathode development and the propellant controller development are ongoing to increase TRL.

![Figure 11. The schematic of the debris removal satellite (Left) and the photograph of the laboratory model of the 1 kW Hall thruster with a center mounted hollow cathode (right).](image)

References


