Jovian Trojan Asteroid Exploration by Solar Power Sail-craft

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The solar power sail can generate sufficient electric power to drive the high specific ion engine in the outer planetary region by thin-film solar cells attached to the entire surface of the spin-type solar sail. This paper proposes the direct exploration of the outer planetary region using solar power sail-craft. The target is an unexplored D/P-type Jovian Trojan asteroid. A lander is separated from the solar power sail-craft to collect surface and underground samples of the Trojan asteroid and perform in-situ analysis. The lander delivers samples to the solar power sail-craft for sample return to Earth as optional goal. Scientific observations during the interplanetary cruise are also implemented.

Key Words: Solar Power Sail, Trojan Asteroid, Round Trip, Lander, In-Situ Analysis

1. Introduction

Sample return missions from small celestial bodies, inspired by Hayabusa¹⁾, are being actively carried out.¹⁾ Hayabusa-2,²⁾ OSIRIS-REx,³⁾ ARM, Marco Polo-X⁴⁾ and Phootprint⁵⁾ can be mentioned as specific examples, shown in Fig. 1. Due to constraints of resources and orbital mechanics, the current target objects are mainly near-Earth asteroids and the Mars satellites, Phobos and Deimos. However, in the near future it can be expected that the targets will shift to higher primordial bodies, located farther away from the Sun.

In the primordial celestial exploration, it is required to scientifically investigate the internal structure of small celestial bodies by in-situ analysis of pristine underground samples which have not been exposed to space weathering. The exploration of primordial celestial objects has been enhanced by landing missions such as MINERVA,⁶⁾ MASCOT⁷⁾ and Philae.⁸⁾

In the navigation of the outer planetary region, ensuring electric power becomes increasingly difficult and ΔV requirements become large. It is not possible to perform landing or round trip missions to asteroids beyond the main belt with the combination of solar panels and chemical propulsion system, even with a large launch vehicle. Trojan asteroids exploration missions which are studied in Europe and the USA achieve only flyby and rendezvous.⁹⁾

The use of an ion engine should be adopted in order to decrease fuel mass. The higher the specific impulse of the ion engine, the larger the required electric power becomes. Besides the use of solar cells, a nuclear power source could be considered. However, adopting nuclear power is inefficient for small and medium-sized spacecraft from the perspective of weight. Thus the solar power sail can be a solution to this problem, since it can generate sufficient power from a large area thin-film solar cell to drive high specific impulse ion engines in the outer planetary region. IKAROS,¹⁰⁾ which was launched in 2010, demonstrated thin-film solar power generation as well as photon propulsion successfully.

Based on the above, we propose a mission to explore the higher primordial Trojan asteroids directly using the solar power sail-craft.¹¹⁾ At the Trojan asteroid, a lander is separated from the

Fig. 1. Overview of small celestial body exploration.

solar power sail-craft to collect surface and underground samples, and perform in-situ analysis. In addition, the lander delivers samples to the solar power sail-craft for sample return.

This paper shows a direct exploration mission of the outer planetary region by the solar power sail-craft in detail and presents an initial design for this spacecraft.

2. Direct Exploration Mission of Outer Planetary Region by Solar Power Sail-craft

2.1. Mission outline

A spin-type large solar sail with an area of 2500m^2 (10~15 times larger than that of IKAROS) can be an ultra-light power generation system (1kW/kg) and generate high electric power in the outer planetary region ($5\text{kW}@5.2\text{AU}$) by attaching thin-film solar cells on the entire surface of the sail membrane, as shown in Fig. 2(a). This electric-generating capacity is 10 times larger than that of the solar panels of JUNO⁽²⁾ ($486\text{W}@5.2\text{AU}$), shown in Fig 2(b). Even if using thin-film solar cell panels with a rigid-frame, the power generation system cannot achieve significant light weight and large sizes.

A high-performance ion engine with a specific impulse of 7000 seconds (2~3 times larger than that of Hayabusa) is driven by this high electric power, and is capable of achieving a large ΔV in the outer planetary region. This is much more than the ΔV by chemical propulsion of JUNO, but much less fuel mass is required because of the high specific impulse.

The mission sequence is shown in Fig. 3. The spacecraft is supposed to make the world's first trip to a Jovian Trojan asteroid around the L4 or L5 point of the Jupiter-Sun system using both Earth and Jupiter gravity assists. After arriving at the Trojan asteroid, a lander is separated from the solar power sail-craft to collect surface and underground samples and perform in-situ analysis. In addition, the lander delivers samples to the solar power sail-craft for sample return to Earth as an extra goal. In this mission, by probing the Trojan asteroids directly, it is possible to examine the planetary movement model of gas giants as the latest hypothesis of solar system formation theory empirically.

This mission also aims to provide several new innovative first-class astronomical science observations during the deep space cruising phase. Specifically, by measuring the spectra of the zodiacal light and the spatial distribution of the solar system dust, the generation rate and orbital evolution of dust, originating from the main belt, short period comets and Kuiper belt, is investigated. At the same time, by observation of the cosmic infrared background radiation in the region far from the main belt, without zodiacal light scattering, the first generation's stars which were formed in the creation of the universe are surveyed. It is also possible to carry out observations of the direction of gamma ray burst generation, by utilizing the distance between Earth and the spacecraft. These are first-class scientific observations that have not yet been realized, and greatly contribute to the progression of planetary science, astronomy and space physics.

The solar power sail-craft will carry out demonstrations of the following new technologies that will be required for future solar system exploration.

- 1) A large membrane space structure including spin deployment strategy: Area = 2500m^2 , Heat fused film
- 2) High power generation using Thin-film solar cells: Power = $5\text{kW}@5.2\text{AU}$, CIGS, the bending prevention by sputtering
- 3) Sail control using a reflectivity control device: Spin rate control, spin axis direction control
- 4) Hybrid propulsion using both solar sail and ion engines: Hybrid navigation using photon propulsion and electric propulsion
- 5) Ultra-high specific impulse ion engines: Specific impulse = 7000 seconds, service life = 4000 hours
- 6) Reaction control system capable of operation at very low temperatures: Ignition temperature = -40°C
- 7) Long-distance orbit determination: USO, ΔVLBI technology
- 8) Autonomous operation and landing of a lander
- 9) Surface and underground sampling, in-situ analysis
- 10) Rendezvous using an RF sensor, berthing and sample transfer from lander to solar sail spacecraft (optional)
- 11) High speed re-entry capsule (optional): Re-entry speed = $13\sim 15\text{km/s}$, $V_{\text{inf}} = 10\text{km/s}$

The main features of this mission are the following.

- 1) World's First Photon / Electric Hybrid Sail Propulsion
- 2) World's Highest Performance Ion Engines
- 3) World's First Background Emission Mapping
- 4) World's First Access to a Trojan Asteroid
- 5) World's First Sample Analysis of a Trojan Asteroid
- 6) World's First Round Trip to the Outer Solar System (optional)
- 7) World's Highest Re-entry Speed Capsule (optional)

(a) Solar power sail-craft (b) JUNO

Fig. 2. Spacecraft in the outer planetary region.

Fig. 3. Mission sequence.

2.2. Mission purpose

The purpose of this mission is to demonstrate the direct exploration in the outer planetary region using a solar power sail to lead the future of solar system exploration.

(1) Navigation technology: Navigation technology using a solar power sail-craft is demonstrated in the medium scale plan, in order to transport the payload needed for landing operations, to the outer planetary region, and in the round trip. (2) Exploration technique: The following exploration techniques which are necessary for achieving mission success are demonstrated together: rendezvous with a Trojan asteroid, surface and underground sampling, and in-situ analysis by the lander; optional sample return. (3) Scientific observations: Scientific observations during the deep space cruising phase and at the Trojan asteroid are implemented to the extent permitted by available resources.

2.3. Mission significance

(1) Navigation technology: Ensuring electric power is difficult and ΔV becomes large in the outer planetary region navigation. It is not possible to perform round trip missions including landing to asteroids beyond the main belt, even with a large rocket, with a combination of solar panels and chemical propulsion systems. Therefore, it is assumed that a system which drives an electric propulsion engine with nuclear power will eventually play an important role for large scale interplanetary transport in future. On the other hand, electric propulsion which utilizes the power generated by large solar cells without any frames will be adopted for small and medium-sized spacecraft because of the inefficiency and high weight of nuclear systems for spacecraft of this size. The solar power sail enables landing and round trip missions to celestial bodies within the distance of Saturn. As a consequence, Japan can secure superiority in sample return exploration, regarding frontier solar exploration missions (Fig. 4).

(2) Exploration technique: In the exploration of primordial celestial bodies, it is important to enhance landing missions by collecting pristine underground samples which have not been influenced by space weathering. When landing on celestial bodies larger than 10km in diameter, the fuel consumption increases. Therefore, it is necessary to investigate such asteroids by a separate lander. In addition, it is also required to obtain in-situ analysis because of the long duration of a round trip mission. Considering the above, in this plan, the technology demonstration is carried out in conjunction, to realize the following mission sequence: The solar power sail performs a rendezvous with a Trojan asteroid and lets a lander land on the surface. The lander then collects surface and underground samples, and carries out in-situ analysis. Sample return is also performed as an optional goal.

(3) Scientific observation: It can be considered that the targets for small celestial body exploration will shift to D/P-type asteroids, as higher primordial and farther small celestial bodies. In particular, unexplored D/P-type asteroids are predominant in the population of Jovian Trojan asteroids. In this mission, direct exploration which includes both landing on a Trojan asteroid and a round trip mission, can be achieved.

Furthermore, several astronomical science observations such as cosmic infrared background radiation mapping, in-situ

measurement of the solar system dust distribution, polarization detection of gamma-ray bursts during interplanetary cruise are expected to provide first-class scientific results in the early stages of this mission. It is also expected to provide a breakthrough of deep space based astronomy as a new scientific field.

Fig. 4. Frontier of solar system exploration.

2.4. Mission positioning

The relationship between Hayabusa, IKAROS, Hayabusa-2 and the solar power sail-craft is shown in Table 1. In regard to navigation technology, the solar power sail-craft is composed of a high-Isp ion engine and a large solar sail which have both been successfully demonstrated by Hayabusa and IKAROS respectively. In regard to exploration technology, Hayabusa landed directly on an asteroid to collect a surface sample. In addition to this, Hayabusa-2 will collect underground samples using a small carry-on impactor. On the other hand, the lander which is separated from the solar power sail-craft, lands on the asteroid to collect surface and underground samples and carries out in-situ analysis. Regarding scientific observations, the S-type asteroid Itokawa and C-type asteroid Ryugu (1999JU3) are the targets of Hayabusa and Hayabusa-2, respectively. For the solar power sail-craft, a D/P-type Trojan asteroid is selected as the target. In addition, the solar power sail-craft performs cruise science observations, like IKAROS.

Table 1. Mission positioning.

Spacecraft	Navigation	Landing	Sampling	Science
Hayabusa	Ion engine	Mother Spacecraft	Surface	Itokawa [S-type]
IKAROS	Solar sail	-	-	Cruising observation
Hayabusa-2	Ion engine	Mother Spacecraft	Surface	Ryugu (1999 JU3) [C-type]
Solar Power Sail-craft	High-Isp Ion engine Large solar sail	Lander	Surface and underground	Trojan asteroid [D/P-type] Cruising observation

3. Initial Design of Solar Power Sail-craft Mission

3.1. Trajectory design

If the diameter of the asteroid is more than 20km, there is a high probability of it being D/P type. From the point of view of landing, the gravity should be as small as possible. Therefore, Trojan asteroids with diameters between 20~30km

are selected as target candidates. The prerequisite of the trajectory design is as follows;

- Launch: 2021
- Initial mass at Earth departure/launch: 1300kg
- Initial mass at Trojan departure: 1100kg
- IES specific impulse: 7000 seconds
- IES thrust: 26.1mN per unit at 100% slot ring
- IES use power: 1600W per unit at 100% slot ring
- IES available power: max 2600W at 5.2AU, sun angle 0deg
- IES number of operating units: max 2 units during 1.4-year-EDVEGA and max 3 units during 2-year-EDVEGA
- IES operation rate: max 70%
- Sun angle: max 45deg
- Stay period at Trojan asteroid: min 1 year

Some examples of planned trajectories are shown in Fig. 5.

In case 1 the launcher configuration is H2A202; the target object is 2005EL140 (L5 point); the ion thrusters are mounted on the +Z plane, facing towards the sun, the outbound transfer period is 18 years including both a 1.4-year and 2-year-EDVEGA. The required fuel mass is decreased and inclination is changed by a Jupiter swing-by.

Phase	Start	End	IES dV[m/s]
1.4-year-EDVEGA	23/4/2021	10/10/2022	465
2-year-EDVEGA	10/10/2022	6/8/2024	1575
Earth to Jupiter	6/8/2024	7/1/2028	-
Jupiter to Asteroid	7/1/2028	1/4/2039	930
Rendezvous	1/4/2039	1/4/2040	-
Asteroid to Jupiter	1/4/2040	27/9/2051	1465
Jupiter to Earth	27/9/2051	23/8/2054	-

(a) Case 1

In case 2 the launcher configuration is H2A204; the target object is 2007RQ278 (L4 point); the ion thrusters are mounted on the +Z plane, the outbound transfer period is 15 years. The 1.4-year-EDVEGA is not required because of the increased launcher capability.

In case 3 the launcher configuration is H2A204; the target object is 2007RQ278 (L4 point); the ion thrusters are mounted on the -Z plane, facing away from the sun, the outbound transfer period is 11.7 years. The thrust of the ion engine can be increased because the spacecraft can fly closer than the distance of Jupiter in the forward path and can generate high electric power. Flight time to the asteroid can be shortened by using additional ΔV . In this case, the optional sample return is not performed.

Phase	Start	End	IES dV[m/s]
2-year-EDVEGA	17/8/2021	22/6/2023	1355
Earth to Jupiter	22/6/2023	10/12/2025	-
Jupiter to Asteroid	10/12/2025	1/7/2036	1757
Rendezvous	1/7/2036	1/7/2037	-
Asteroid to Jupiter	1/7/2037	1/9/2049	1685
Jupiter to Earth	1/9/2049	5/7/2052	-

(b) Case 2

Phase	Start	End	IES dV[m/s]
2-year-EDVEGA	9/8/2021	29/6/2023	983
Earth to Jupiter	29/6/2023	10/12/2025	-
Jupiter to Asteroid	10/12/2025	5/4/2033	4300

(c) Case 3

Fig. 5. Trajectory planning example.

3.2. System design

The initial design of the solar power sail-craft has been conducted. Wet mass, which includes a 100kg lander, is 1285kg. This means that the trajectory plan is feasible, as the estimated spacecraft mass is within the considered mass of 1300kg. Thus a solar power sail-craft, with a mass of about 1.3 tons will be able to transport a 100kg lander to the Trojan asteroid. On the other hand, Rosetta with its mass of 3 tons transported the Philae lander of the same 100kg mass to the comet 67P/Churyumov–Gerasimenko, which is located closer than the Trojan asteroids (Fig. 6). This difference indicates the superiority of the solar power sail.

Fig. 6. Rosetta and Philae.

The system block diagram of the solar power sail is shown in Fig. 7. The overview of each sub-system is as follows.

-Ion engine system (IES): 6 ion thrusters are mounted on either the -Z or +Z plane, depending on the target asteroid and trajectory. In order to spin up / down, three thrusters each are inclined towards the spin up / down direction. Four IES power processing units (IPPU) are equipped account for redundancy.

-Communication system (COM): Two X-band transponders are equipped. Low gain antenna (LGA-A, LGA-B) are used in the Earth neighborhood. The medium gain antenna (MGA) is mainly used during cruising phase. The high gain antenna (HGA) is mainly used during the rendezvous phase. HGA and MGA can be pointed to Earth by a despun platform. The communication rate of the HGA is aimed to provide a data transmission rate of 16Kbps by using the DSN in the Jupiter zone.

-Thermal control system (TCS): The -Z plane is set as the main radiating face and the IPPU is mounted on the -Z plane. In order to cope with the significantly changing thermal environment and to reduce the heater power, thermal louvers and the thermal switches are utilized.

-Electric power system (EPS): A Sub solar cell (SUBCELL) mounted on the +Z plane is used prior to deployment of the power sail. Since the voltage of the cells is significantly changed by the distance from the sun, it is equipped with a function to switch the series number.

-Reaction control system (RCS): A chemical propulsion system driven at ultra-low temperatures with much less heater power is adopted. The piping system is divided into two lines for redundancy.

-Attitude control system (ACS): Star tracker (STT), Spin type sun sensor (SSAS), inertial reference unit (IRU) and optical navigation camera (ONC) are equipped. The IES, reflectivity control device (RCD) and RCS are used to control attitude.

-Data handling unit (DHU): Each device is connected through a space wire router (SpW). Mission system equipment is connected to the mission processing unit (DE).

-Mission system (MS): Infrared observation equipment (IR), gamma-ray burst polarimeter (GAP), solar system dust detector (ALDN2), imaging spectrometer (IS), lander and re-entry capsule are carried.

The structural design and equipment layout of the solar power sail-craft is shown in Fig. 8. The entire structure is composed of octagonal side panels and upper / lower panels. A cylinder structure is equipped inside of the octagon. A path for transferring the sample from lander to re-entry capsule is provided in the cylinder. HGA, MGA and re-entry capsule are located on the +Z plane. Lander, ONC and observers (IR, GAP and IS) are located on the -Z plane. The IES is located on either the -Z or +Z side.

Fig. 7. System block diagram.

Fig. 8. Structural design and equipment layout of the solar power sail-craft (+Z IES configuration).

3.3. Mission Analysis at Trojan Asteroid

Since the solar power sail-craft has a large sail and spins, it is very risky for it to land on the asteroid itself. A lander is therefore separated and performs the landing, sampling, and in-situ analysis. As an optional mission, it delivers a sample to the solar power sail-craft by rendezvous and docking for sample return.

The operational policy after the arrival at the Trojan asteroid is as follows.

- 1) The solar power sail-craft is placed in a hovering home position above the asteroid, identical to Hayabusa. Since the size of the target asteroid is large, the home position altitude is 250~1000km to conserve fuel needed for maintaining this home position.
- 2) The solar power sail-craft performs global mapping and scientific observations from the home position. These are used for the landing site selection.
- 3) The solar power sail-craft performs a rehearsal of the lander deployment by descending to a lower altitude and ascending again. This makes it possible to investigate the asteroid surface around the selected landing point in detail.
- 4) The solar power sail-craft descends again, and separates the lander at an altitude of 1km.
- 5) The solar power sail-craft ascends to an altitude of 50km and waits for lander.
- 6) The landing method is not a free fall but a soft landing utilizing an RCS.
- 7) The lander collects the surface and underground samples. For the former, a sampler horn, similarly to that of Hayabusa is used. For the latter, a pressurized gas drill excavates a 1m regolith layer in advance. For each sampling, a bullet is fired to collect samples without depending on the condition of the asteroid surface.
- 8) The collected sample is conveyed to the mass spectrometer and in-situ analysis is performed.
- 9) The lander takes off to rendezvous with the solar power sail-craft. Navigation is supported by the solar power sail-craft. In particular, this is a new point to measure the relative direction between the solar power sail-craft and the lander by using the lander's phased array antenna as an RF sensor.
- 10) The lander docks with the solar power sail-craft and delivers the sample. Because the solar power sail-craft is spinning and the delay time is large, the docking should be conducted autonomously using an extendible boom as berthing point.
- 11) The lander is separated again and decommissioned. Meanwhile, the solar power sail-craft returns to its original home position.

The structural design and equipment layout of the lander is shown in Fig. 9. It is composed of a cylindrical shape (diameter: 650mm, height: 400mm) with legs at the bottom. Unlike the Philae, the lander is equipped with an RCS consisting of 12 cold gas thrusters. Since the sun distance of Trojan asteroids is about 5.2AU, significant power generation by solar cells cannot be expected. Therefore, the lander is exclusively driven by a battery. Science equipment is assigned a mass of 20kg, including sampling devices. The wet mass is 92.8kg, satisfying the mass of 100kg assigned to the lander.

Fig. 9. Structural design and equipment layout of the lander.

4. Conclusion

In this paper, a direct exploration mission of the outer planetary region by a solar power sail-craft was proposed. In regard to navigation technology, the transportation of a lander and a first trip to a Jovian Trojan asteroid is demonstrated. In regard to exploration technology, landing, surface and underground sampling, and in-situ analysis by a lander is demonstrated. Scientific observations during the interplanetary cruise as well as at a D/P-type Trojan asteroid are also implemented to the extent that resources permit.

With this mission, the solar power sail can lead future solar system exploration, as well as provide a breakthrough of space astronomy as a new scientific field.

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