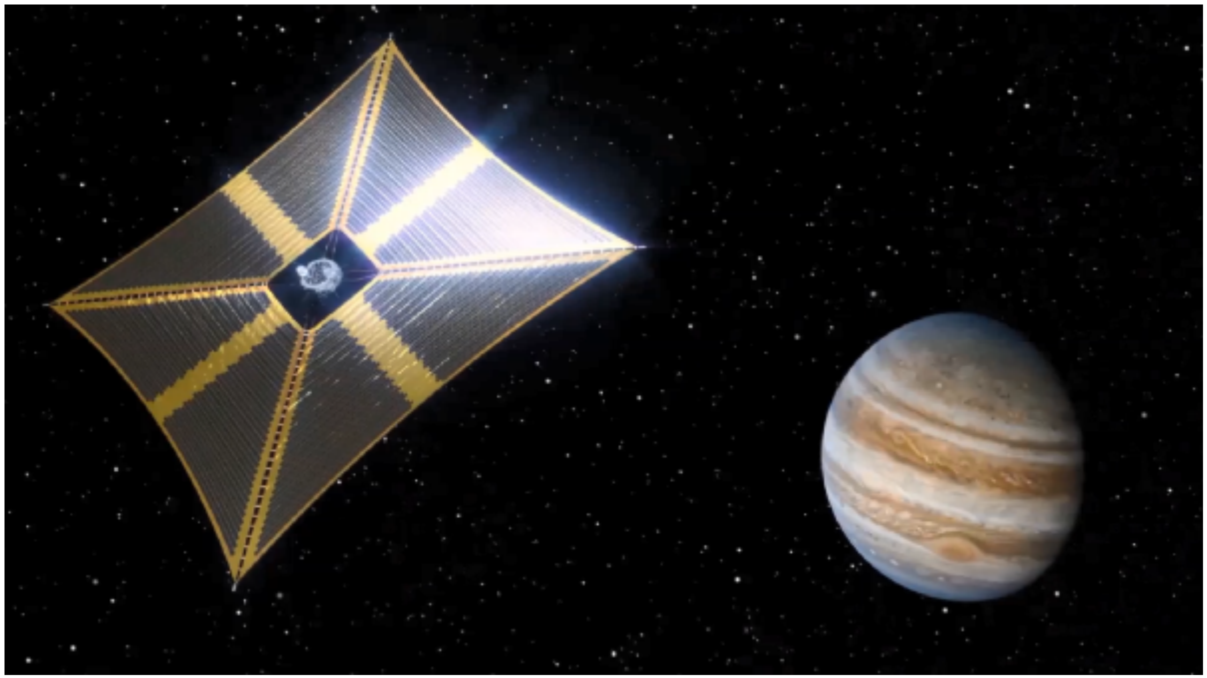
Direct Exploration of Outer Solar System using Solar Power Sail OKEANOS



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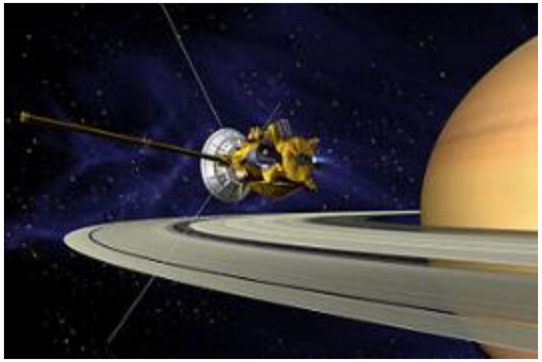
Exploration Missions: Past Trends
1. RTG with Chemical Propulsion

Due to two factors, sample return missions beyond the asteroid belt is difficult.
- The power obtainable through solar panels reduce drastically beyond the asteroid belt.
- Larger ΔV is required to reach these distances.

Galileo, Cassini and New Horizons have relied on RTG to generate the electric power, while chemical propulsion was used to generate ΔV.

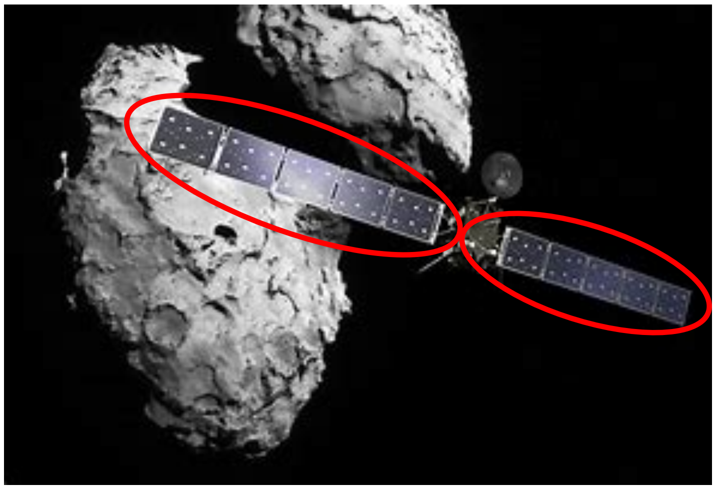


Spacecraft power and propulsion systems

Power subsystem	Propulsion subsystem	Mission
RTG	**Chemical propulsion**	**Galileo, Cassini, New Horizons**
Solar panel		Rosetta, Juno
	Ion thrusters	Hayabusa, Hayabusa2
Solar power sail	High-Isp Ion thrusters	OKEANOS
Nuclear power generator		

Exploration Missions: Past Trends
2. Solar Panel with Chemical Propulsion

As the performance of solar cells improved, Rosetta and Juno were able to instead rely on solar panel.



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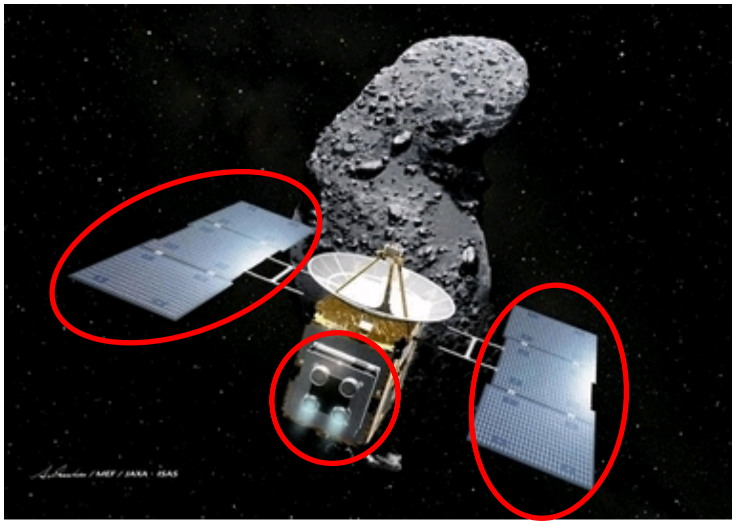
Solar panel	**Chemical propulsion**	**Rosetta, Juno**
Solar panel	Ion thrusters	Hayabusa, Hayabusa2
Solar power sail	High-Isp Ion thrusters	Solar power sail-craft
Nuclear power generator	High-Isp Ion thrusters	

} Not sample return (Galileo, Cassini, New Horizons; Rosetta, Juno)

Exploration Missions: Past Trends
3. Solar Panel with Ion Thrusters

Hayabusa and Hayabusa2 were able to generate enough power to operate their ion thrusters, generating ΔV for a return trip to NEAs.



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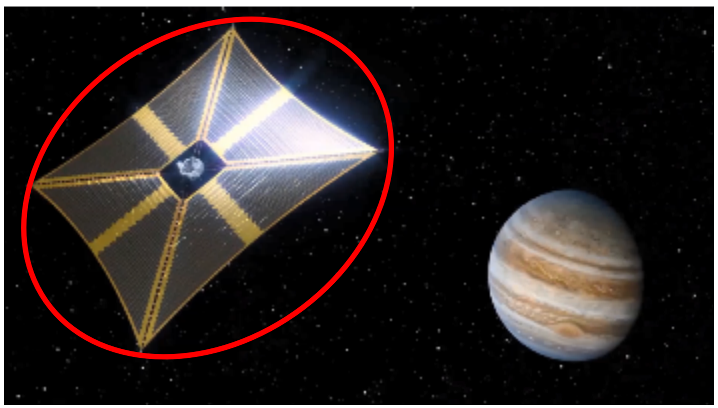
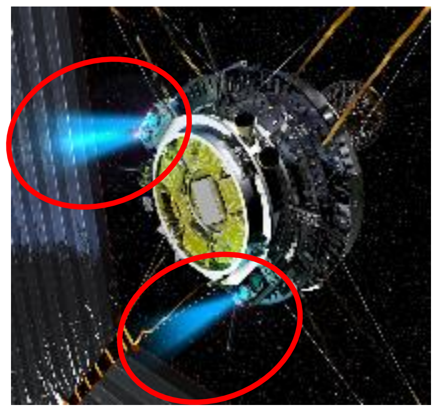
Nuclear power generator		

Not outer solar system

Next Generation Outer Solar System Exploration
Solar Power Sail with High-Isp Ion Thrusters

Solar power sail-craft is equipped with a large number of thin-film solar cells attached on a solar sail, generating enough power to operate high-Isp ion thrusters at Jovian and Saturnian distances.
(Solar power sails are distinct from solar sails in that the majority of the thrust is generated through the high-Isp ion thrusters, and not from the sail itself.)





Spacecraft power and propulsion systems

Power subsystem	Propulsion subsystem	Mission
RTG	Chemical propulsion	Galileo, Cassini, New Horizons
Solar panel		Rosetta, Juno
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Solar power sail	**High-Isp Ion thrusters**	**Solar power sail-craft**
Nuclear power generator		

to Jupiter/Saturn zone

Next Generation Outer Solar System Exploration
Nuclear Power Generator with High-Isp Ion Thrusters

As the next step, nuclear power generator can generate enough power without depending on the distance of the sun. A round trip to anywhere can be achieved.

Spacecraft power and propulsion systems

Power subsystem	Propulsion subsystem	Mission
RTG	Chemical propulsion	Galileo, Cassini, New Horizons
Solar panel		Rosetta, Juno
	Ion thrusters	Hayabusa, Hayabusa2
Solar power sail	**High-Isp Ion thrusters**	Solar power sail-craft
Nuclear power generator		

to anywhere

Sample Return to beyond the Asteroid Belt

Status of outer solar system exploration

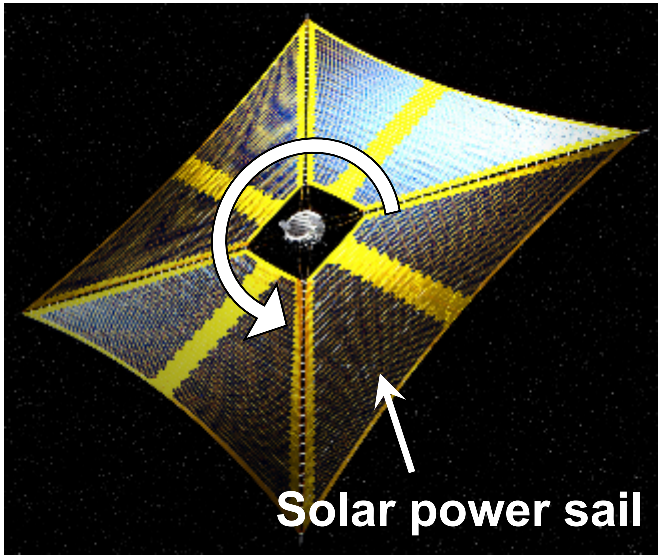
	Jupiter zone	Saturn zone	Uranus	Neptune	Pluto, EKBO
Flyby	●U ■U:Lucy ■J:OKEANOS	●U	●U	●U	●U:New Horizons
Orbiter/ Rendezvous	●U:Galilleo, Juno ■E/J:Juice ■U:Europa Clipper	●U	■U		
Landing	●U ■J:OKEANOS	●E:Cassini	■U		
Sample return	■J:OKEANOS				

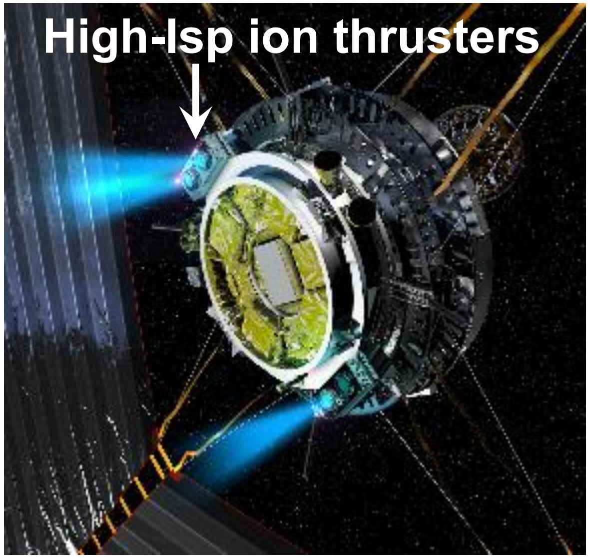
● Achievements
▲ Under operation
■ Under development / Under investigation

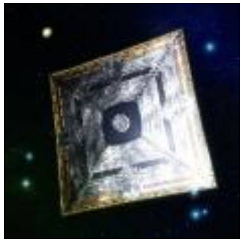
J = Japan;
U = USA;
E = ESA;

Solar power sail-craft OKEANOS aims to sample return in Jupiter zone.

Solar Power Sail and High-Isp Ion Thrusters of OKEANOS







<Solar power sail>

Sail is covered with thin-film solar cells

- Spin-type large sail: 2000 m^2 (10 times larger than that of IKAROS)
- Ultra-light power generation system: 1 kW/kg (20 times larger than that of Juno)
- Large electric power in the outer planetary region: 5 kW @ 5.2 AU (10 times larger than that of Juno)

<High-Isp ion thrusters>

- Isp: 6800 seconds (2 times higher than that of Hayabusa or Hayabusa2)
- Large ΔV in the outer planetary region: 6000 m/s (3 times larger than that of Juno)

Trade-off: Power Subsystem

<Four power generator types>

1) RTG (Radio-isotope Thermal Generator)
   $Mp = P/\alpha$
   α = 5.0 W/kg (from GPHS-RTG)
   Note that $P \leqq 700W$ (Output power is limited to several hundred watts.)

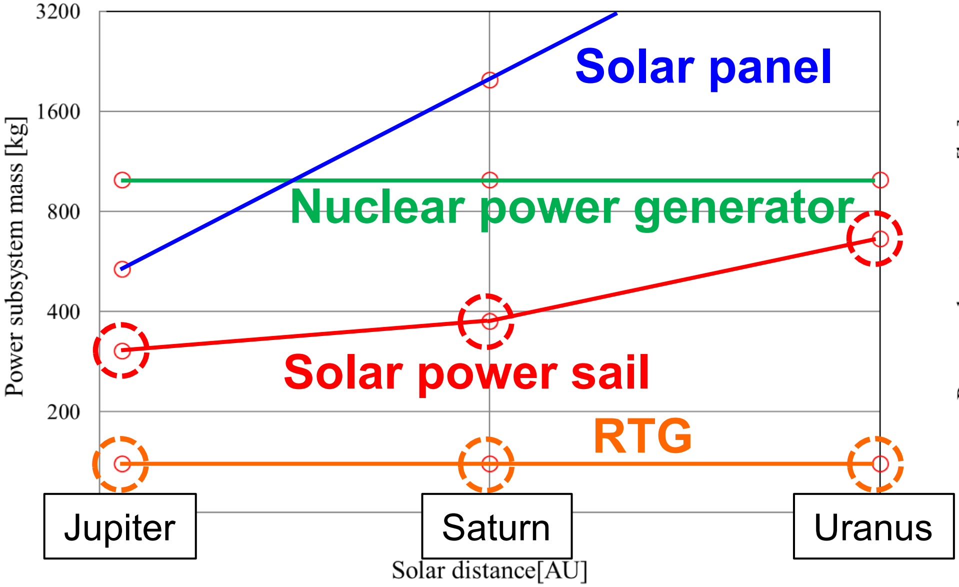
2) Light solar panels
   $Mp = P/\alpha$
   for α = 1.3 W/kg at 5.2 AU. (from Juno)

3) Solar power sail
   $Mp = P/\alpha + Mm$
   for α = 27 W/kg at 5.2 AU, Mm = 280. (both from OKEANOS)

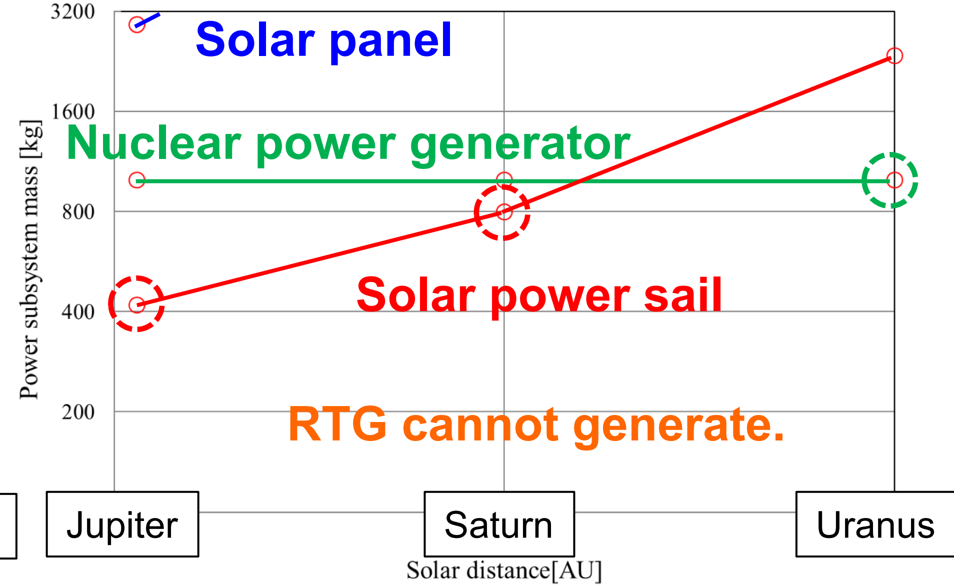
4) Nuclear power generator
   Mp = 1000 kg (from TOPAZ reactors)

Mp: power subsystem mass, P: generated power, α: efficiency, Mm: mechanism mass

Trade-off: Power Subsystem



P = 700 W
(bus and chemical propulsion)



P = 3800 W
(bus and high-Isp ion propulsion)

Mp (power subsystem mass) for the four generator types

In case of P = 700 W,
Mp (power subsystem mass) for RTG is the lightest, followed by solar power sail.

In case of P = 3800 W, RTG cannot generate.
We find the solar power sail option to be the lightest in Jupiter and Saturn zones, while the nuclear power generator becomes the lightest option in Uranus zone.

Trade-off: Propulsion Subsystem

Ms (spacecraft mass) is related to the total ΔV, Mp (power subsystem mass) and Mb (bus mass) as follows

$$Ms = (Mb+Mp) \times \exp[\Delta V/(9.8 \times Isp)]$$

Mb = 900 kg (It corresponds to a medium-sized probe.)

<Two thrusters>

a) Chemical propulsion

Isp = 300 s

The required fuel mass is very large.

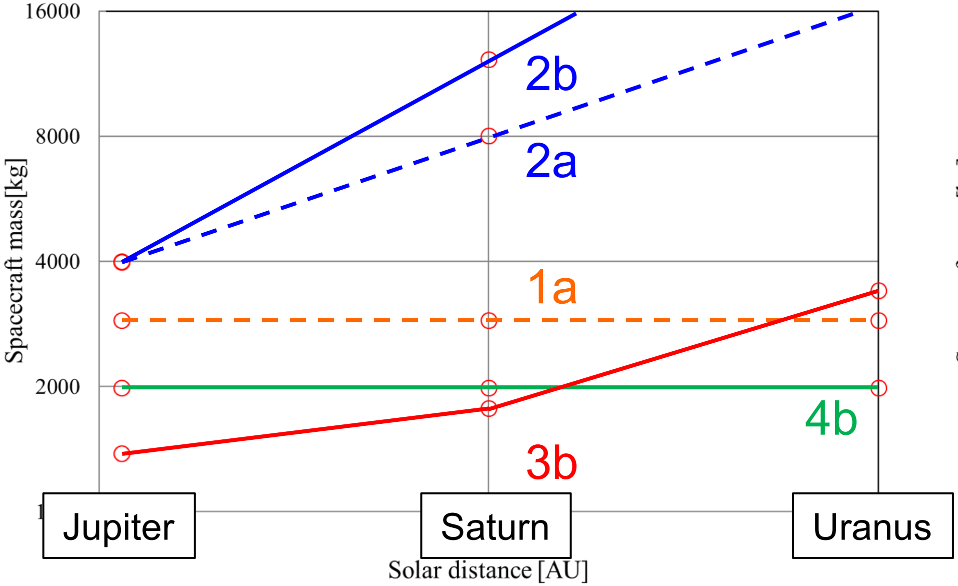
b) High-Isp ion propulsion

Isp = 6800 s

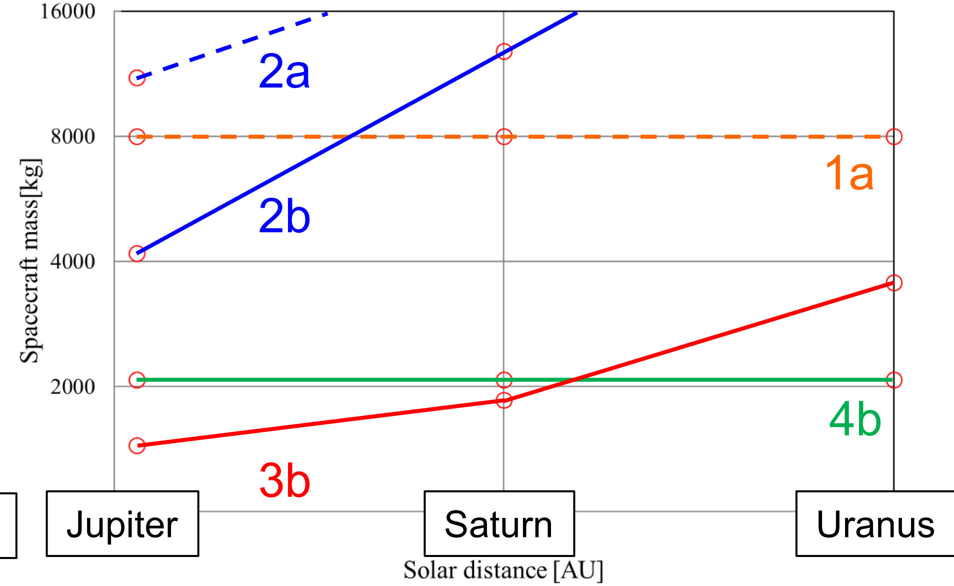
The required fuel mass can be minimized.

However, Mp becomes dominant to drive high-Isp ion propulsion.

Trade-off: Propulsion Subsystem



ΔV = 3 km/s (one way)

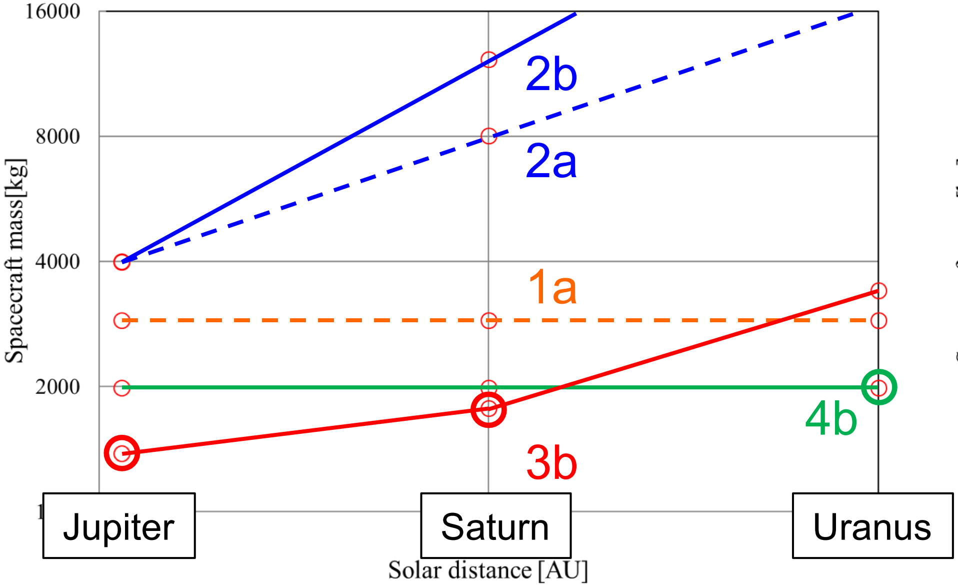


ΔV = 6 km/s (round trip)

Estimated Ms (spacecraft mass)

1a) RTG with chemical propulsion,
2a) light solar panel with chemical propulsion,
2b) light solar panel with high-Isp ion propulsion,
3b) solar power sail with high-Isp ion propulsion, and
4b) nuclear power generator with high-Isp ion propulsion.

Spacecraft Mass using Ion Propulsion



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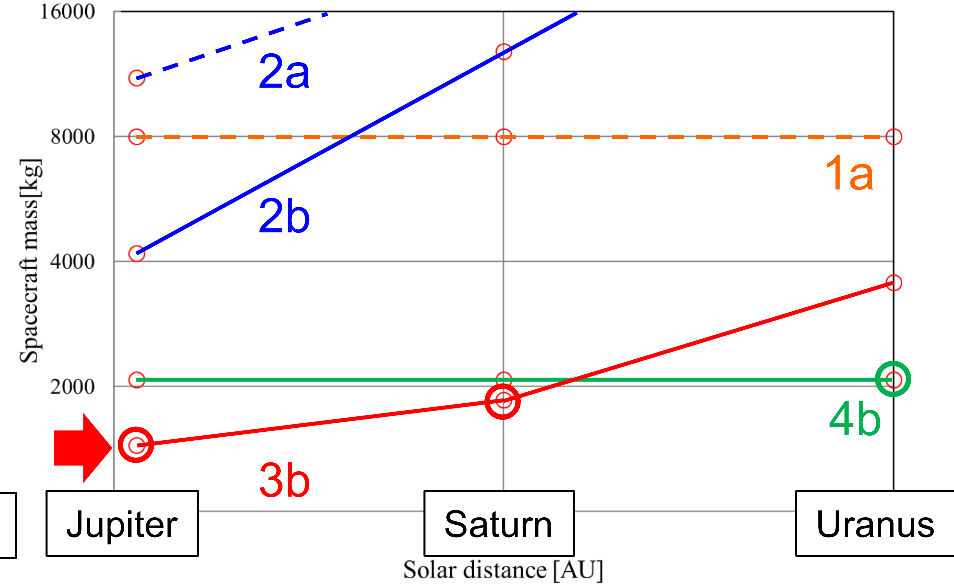
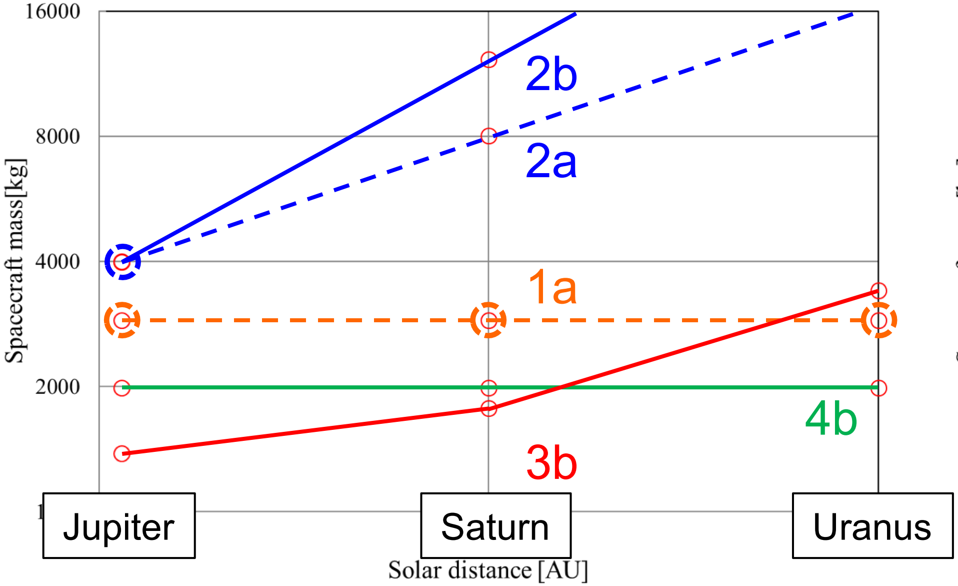


ΔV = 6 km/s (round trip)

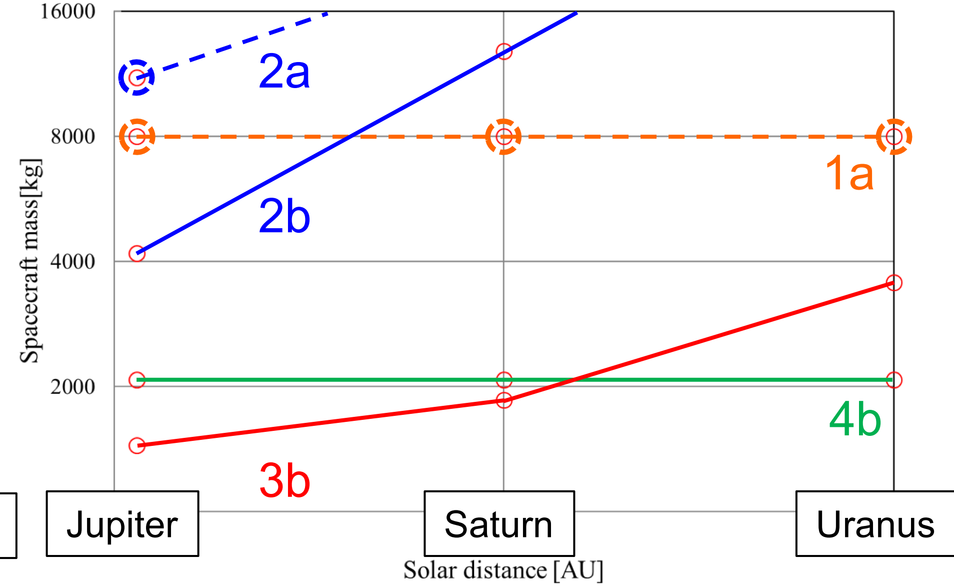
In Jupiter and Saturn zones,
3b (solar power sail with high-Isp ion propulsion) is the lightest option for one way and round trip. -> OKEANOS mission (Ms = 1.4 ton)

In Uranus zone,
4b (nuclear power generator with ion propulsion) is the lightest option for one way and round trip.

Spacecraft Mass using Chemical Propulsion



ΔV = 3 km/s (one way)



ΔV = 6 km/s (round trip)

In case of one way,
1a (RTG with chemical propulsion) in Jupiter, Saturn and Uranus zones and
2b (light solar panel with chemical propulsion) in Jupiter zone are still workable.

In case of round trip,
Ms for these options jump, because the Isp of chemical propulsion is low.

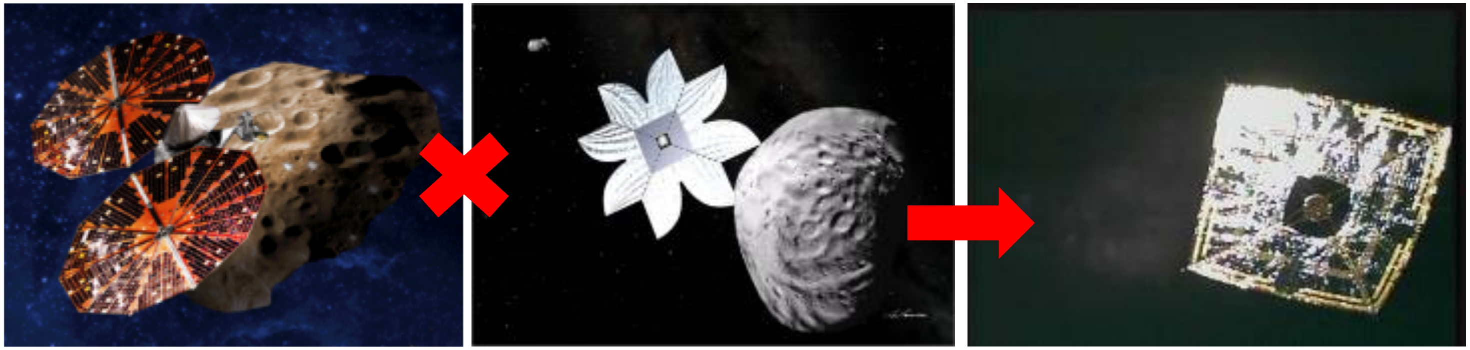
Lucy and Solar Power Sail Missions

In 2017 NASA has selected Lucy (multiple flybys for Jupiter trojan asteroids) for its Discovery Program.

The Lucy project is very similar to the solar power sail project proposed in 2005 by our solar sail working group to Jupiter trojan asteroid multiple flyby mission (plus observation of Jupiter).

This solar power sail project, unfortunately, was not selected, since key solar power sail technologies had not been demonstrated at that time.

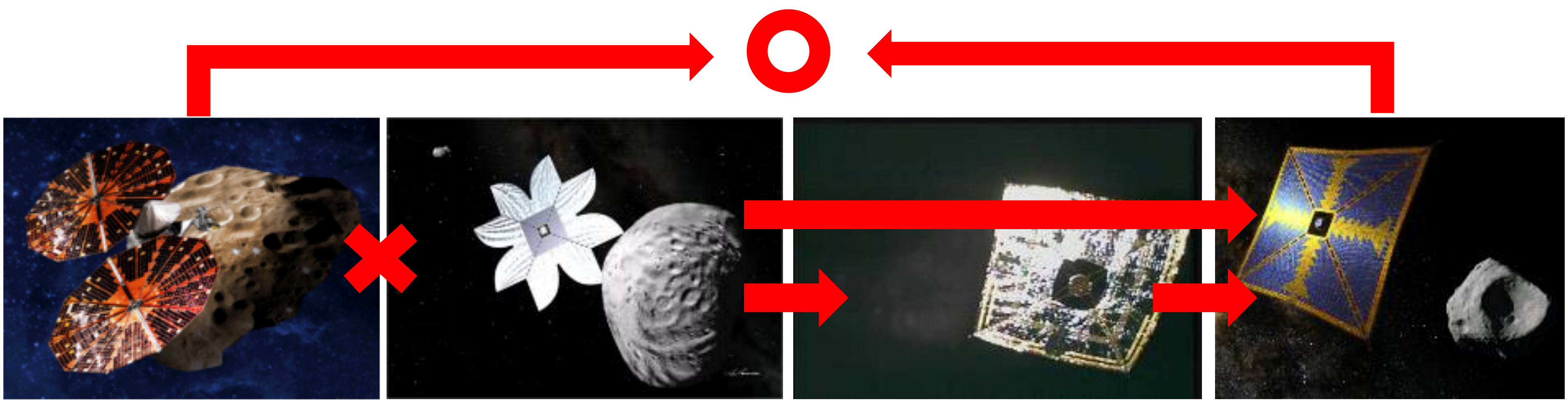
In order to demonstrate solar sail and solar power sail technologies for the first time in the world, IKAROS mission was later proposed and selected, leading to its launch and technology demonstration in 2010.



Lucy and Solar Power Sail Missions

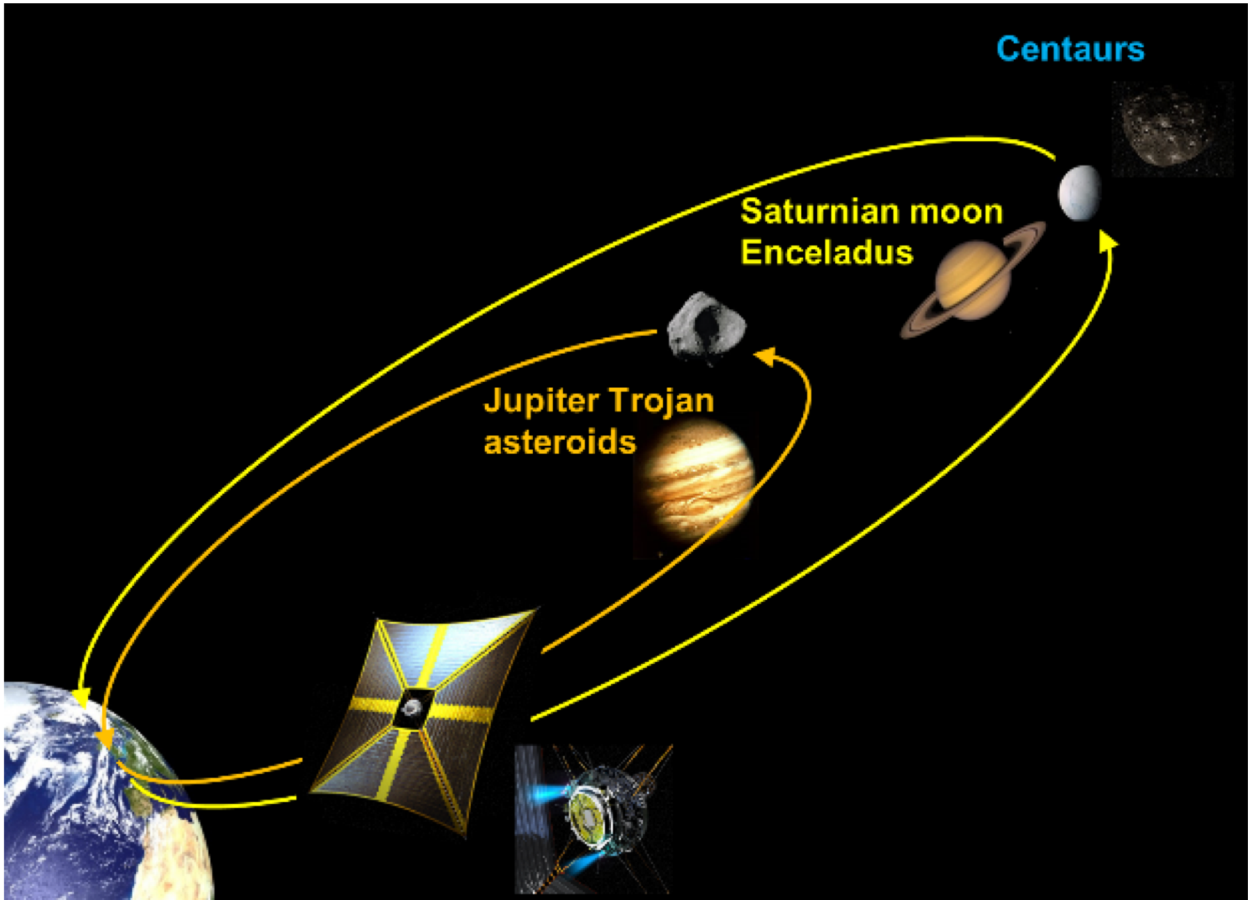
Following this success, we have now further developed the concept for the much larger H3 launch vehicle, to perform direct observation on Jupiter trojan asteroids.

Since Lucy is a flyby mission to these asteroids, combining its observations with the more detailed observations of the solar power sail probe will maximize scientific output. In other words, the two projects are complementary endeavors, and key members of the two projects are in agreement with this direction.

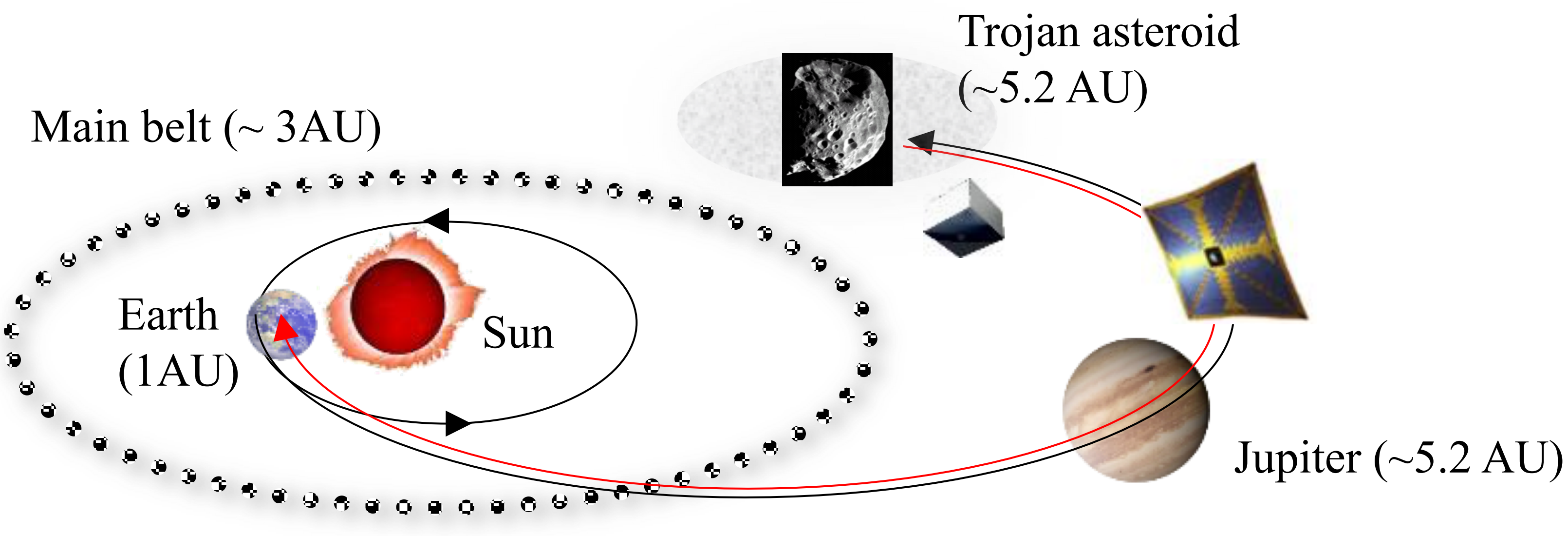


Solar Power Sail Missions

Potential target bodies of solar power sail missions include the Jupiter trojan asteroids, as well as Saturnian moon Enceladus and Centaurs.
The large cargo capacities of solar power sails can be also used to transport and deploy multiple lander and explorer nanosatellites.



OKEANOS Mission Sequence



EDVEGA, as well as Jovian gravity assist are used to achieve the world's first rendezvous with a Jupiter trojan asteroid.

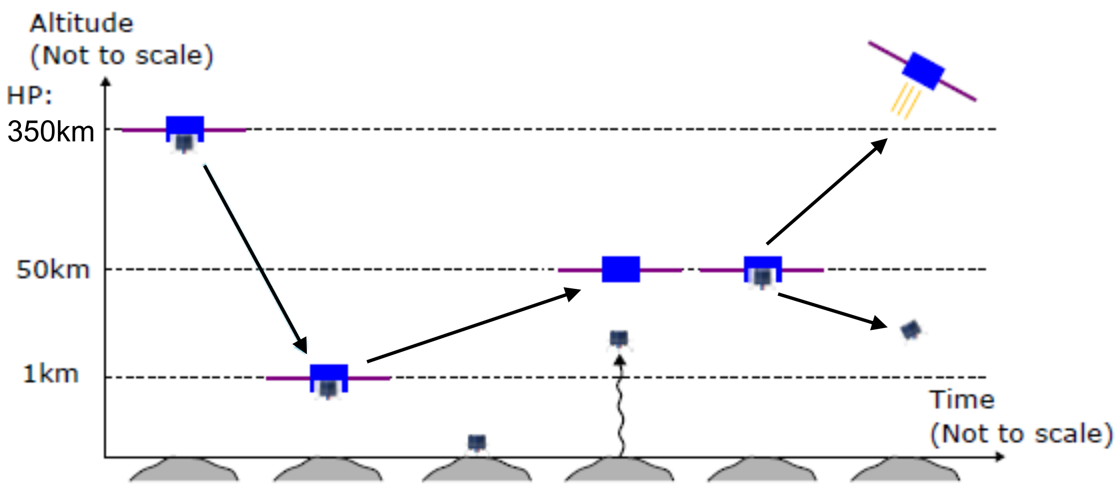
At the asteroid, a lander is deployed to obtain samples for analysis.

The lander leaves the asteroid surface and docks with OKEANOS, delivering the collected samples.

OKEANOS returns to Earth.

Operational Policy at the Trojan Asteroid

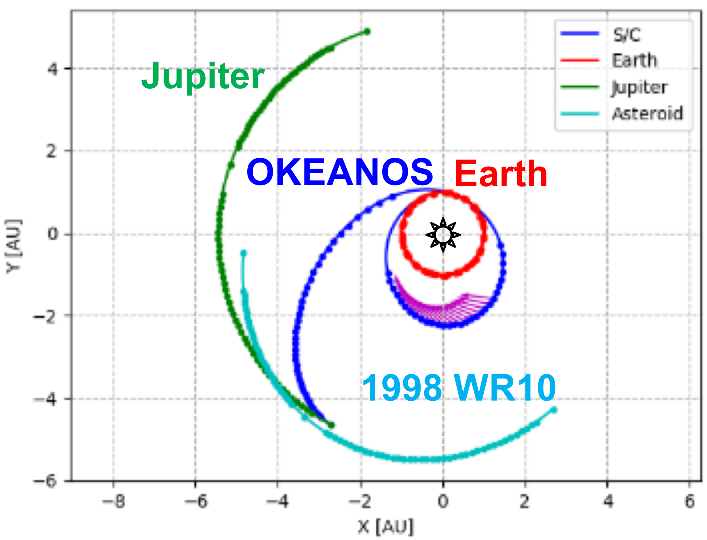
Upon asteroid rendezvous (proximity phase), OKEANOS maintains the HP (Home Position) at 350 km altitude in the same manner as Hayabusa and Hayabusa2.
Since OKEANOS has a large sail that spins, it is highly risky for itself to land on the asteroid. Therefore, OKEANOS separates a lander at 1 km.
After landing, the lander conducts sampling and in-situ analysis.
OKEANOS ascends to 50 km and keeps that position until rendezvous docking with the returning lander is completed.
After the samples are transferred, the lander is again separated from OKEANOS.



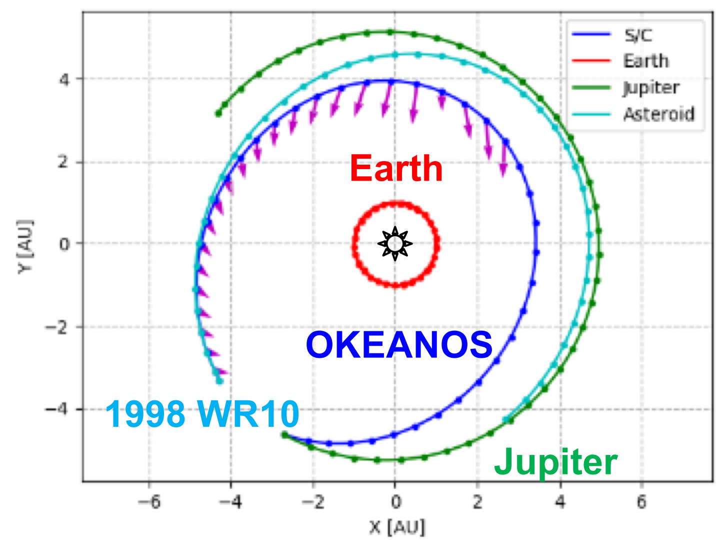
Outbound Trajectory

Target candidates are 20-30 km Trojans at L4 point.
There are two or three target asteroids for every launch year.

Phase	Start	End	IES ΔV [m/s]
2-year EDVEGA	20/1/2026	4/11/2027	954
Earth to Jupiter	4/11/2027	15/8/2030	-
Jupiter to 1998 WR10	15/8/2030	20/1/2039	2498



2-year EDVEGA + Earth to Jupiter

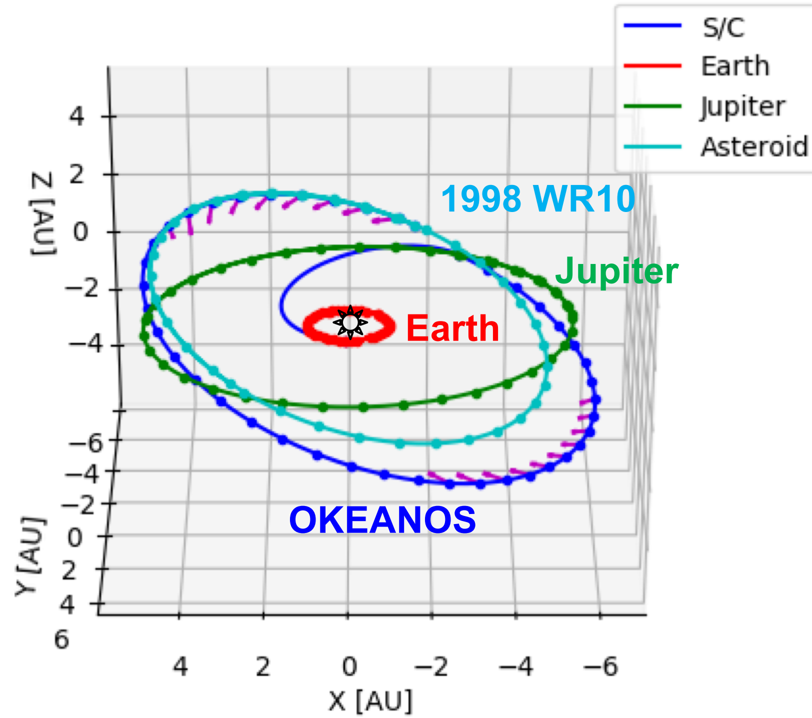


Jupiter to 1998 WR10

The duration is 13 years.

Return Trajectory

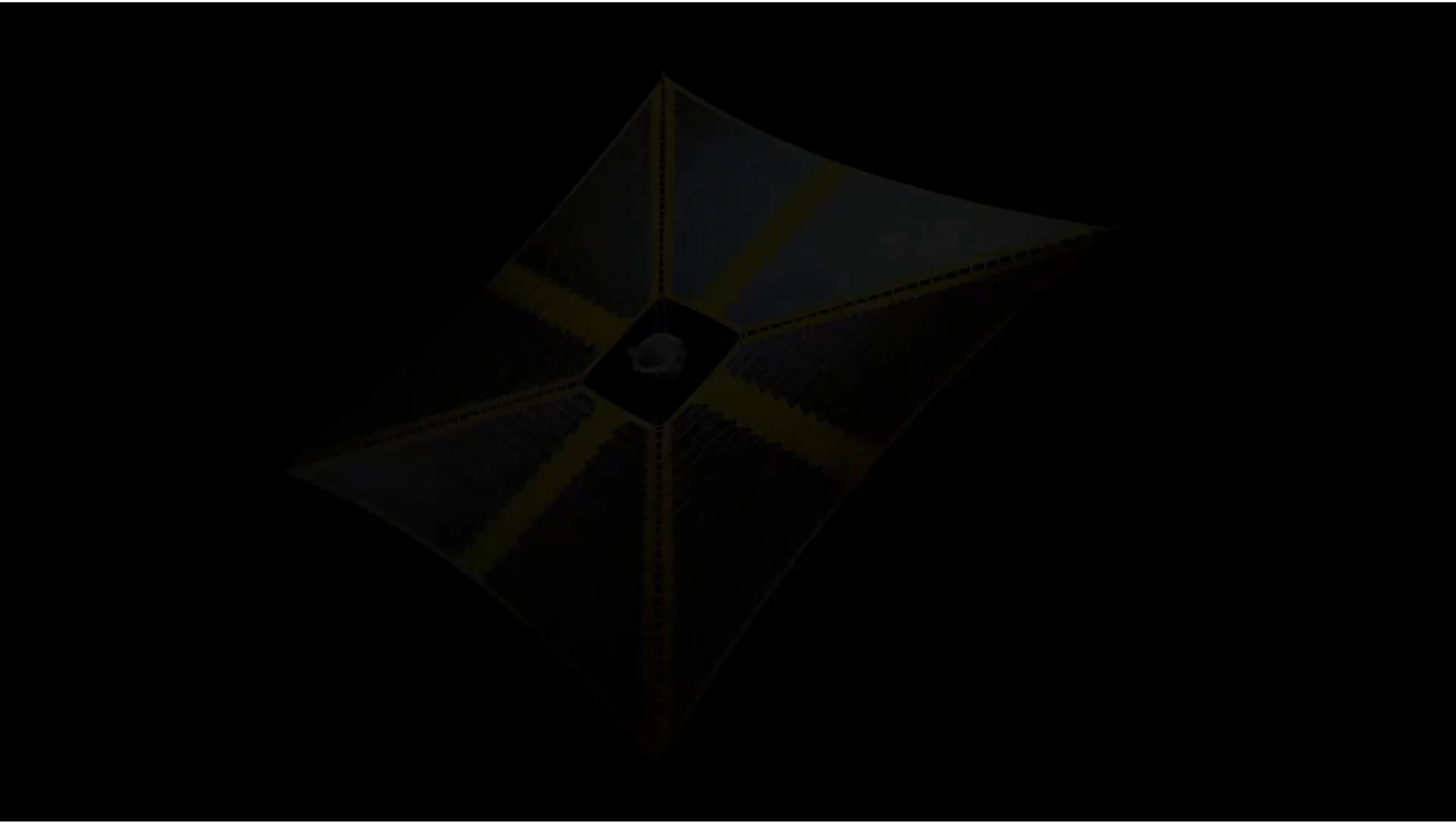
Phase	Start	End	IES ΔV [m/s]
1998 WR10 to Jupiter	20/7/2040	6/5/2054	2209
Jupiter to Earth	6/5/2054	19/12/2057	-



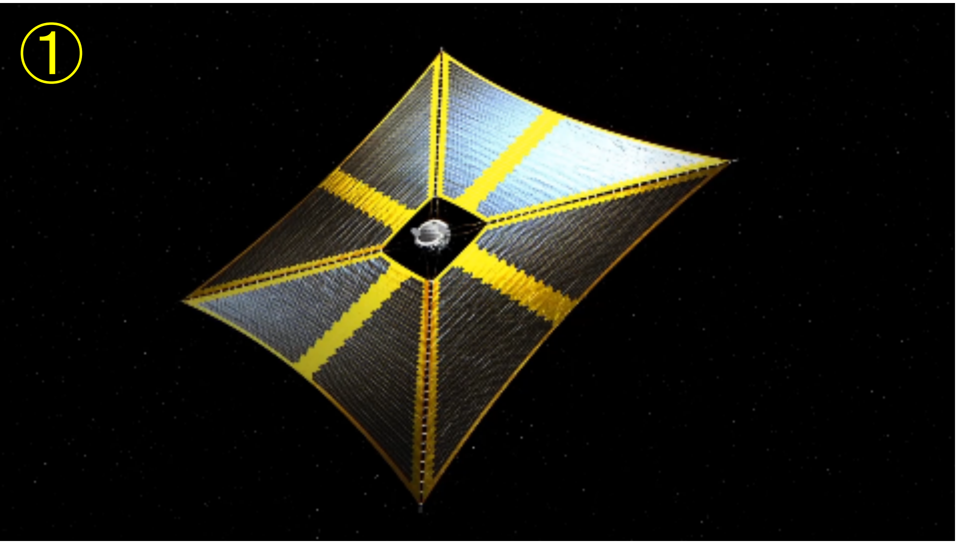
1998 WR10 to Jupiter + Jupiter to Earth

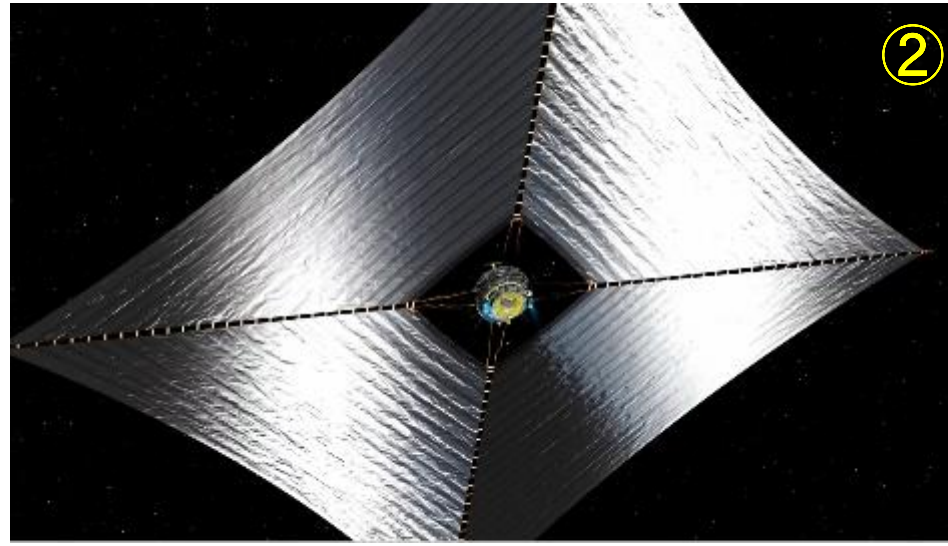
The duration is 17 years.
The total period is longer than 30 years.

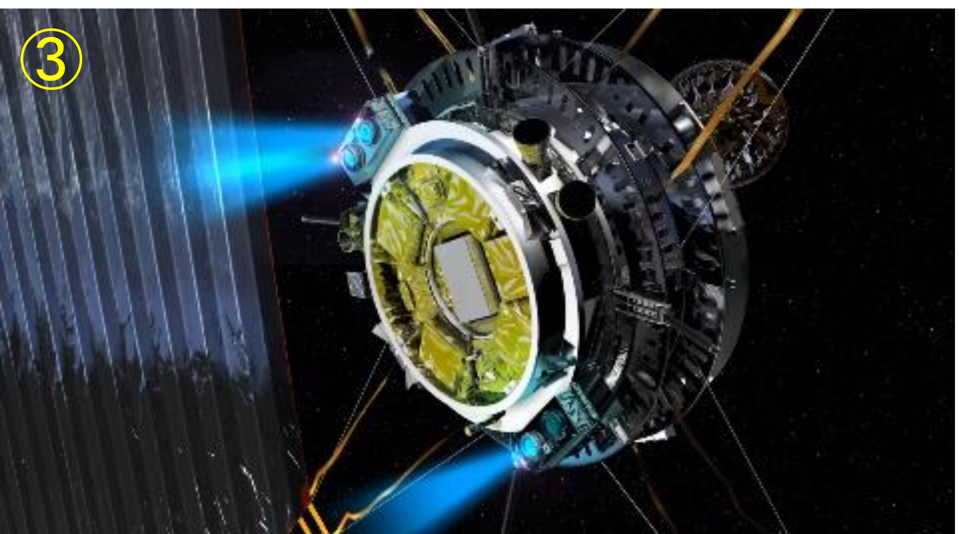
OKEANOS Mission Image

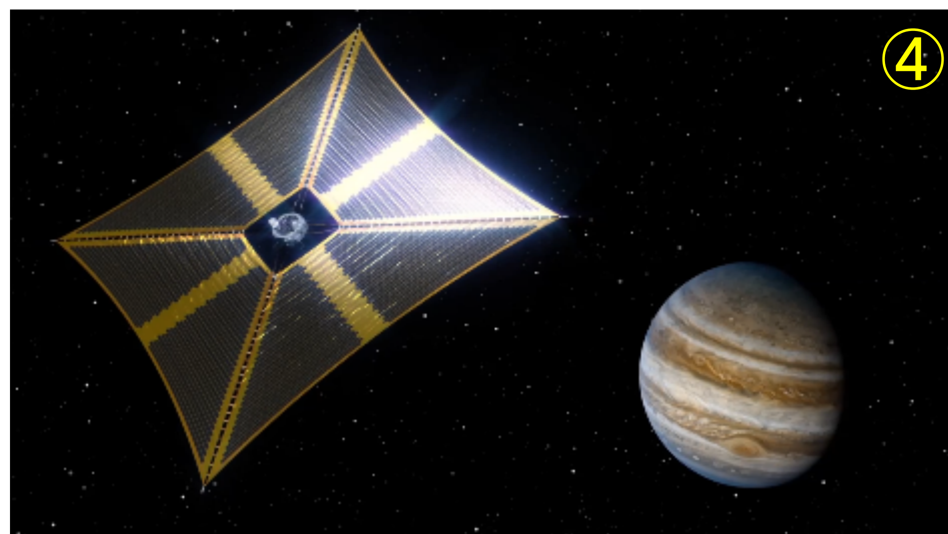


OKEANOS Mission Image (1/3)









OKEANOS Mission Image (2/3)

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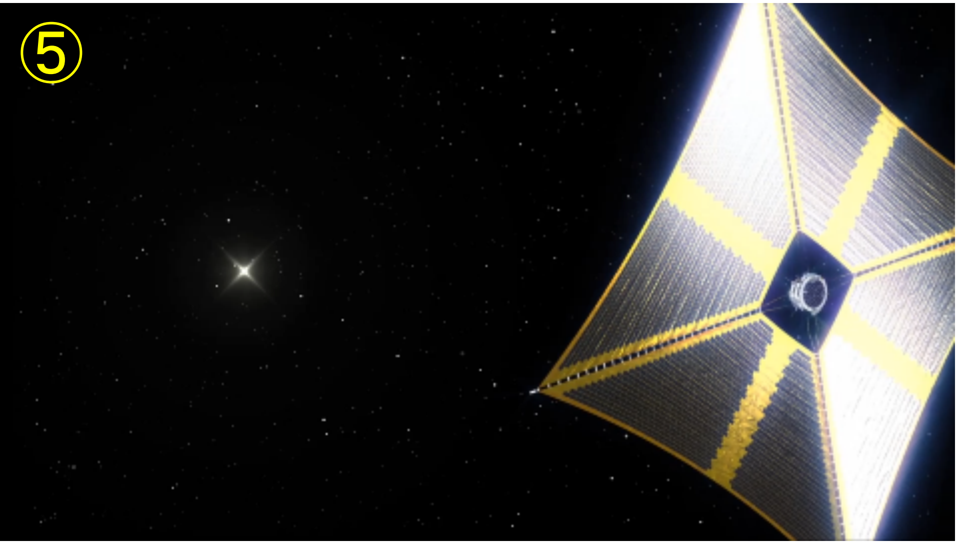

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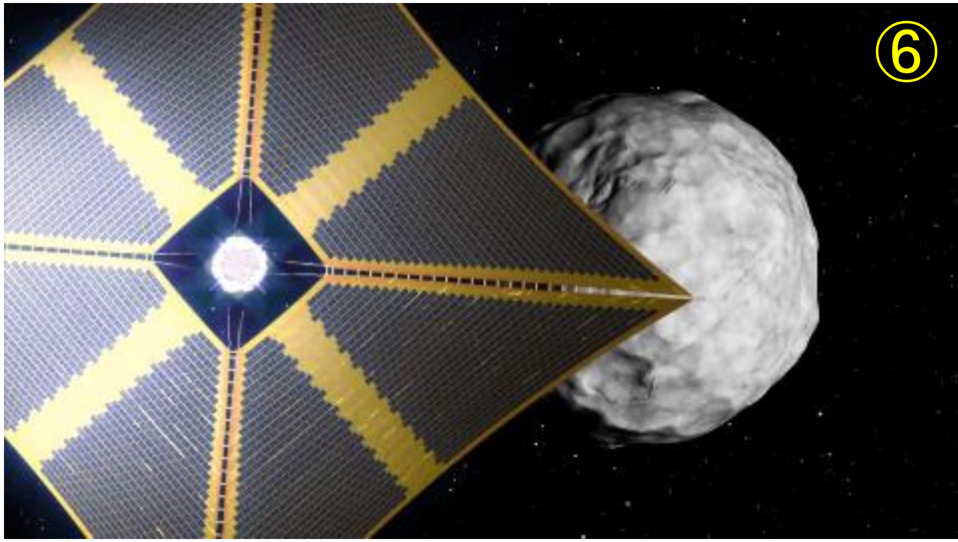

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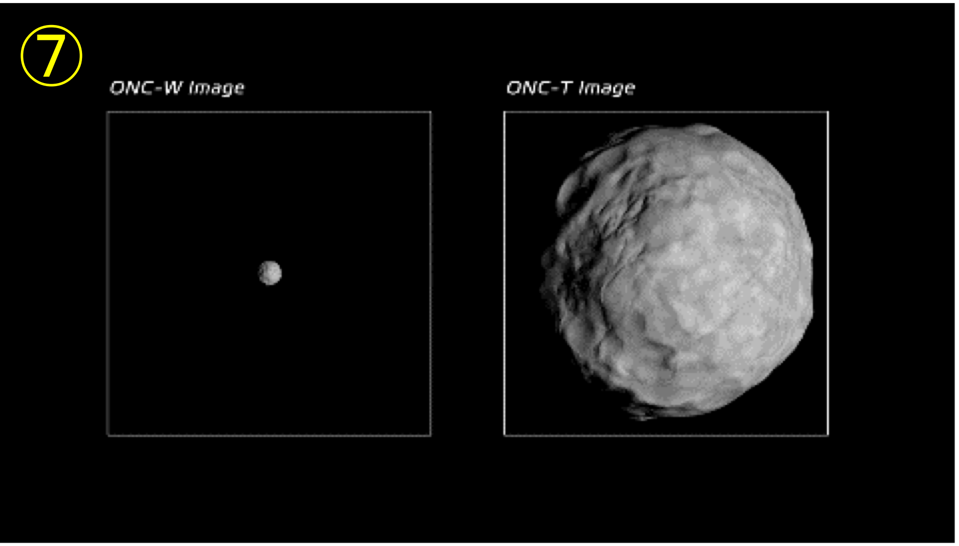

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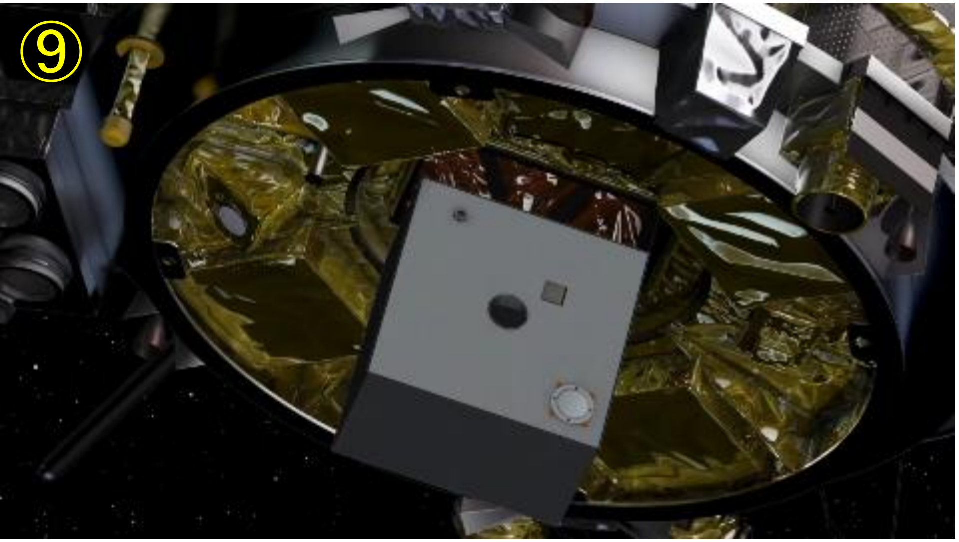
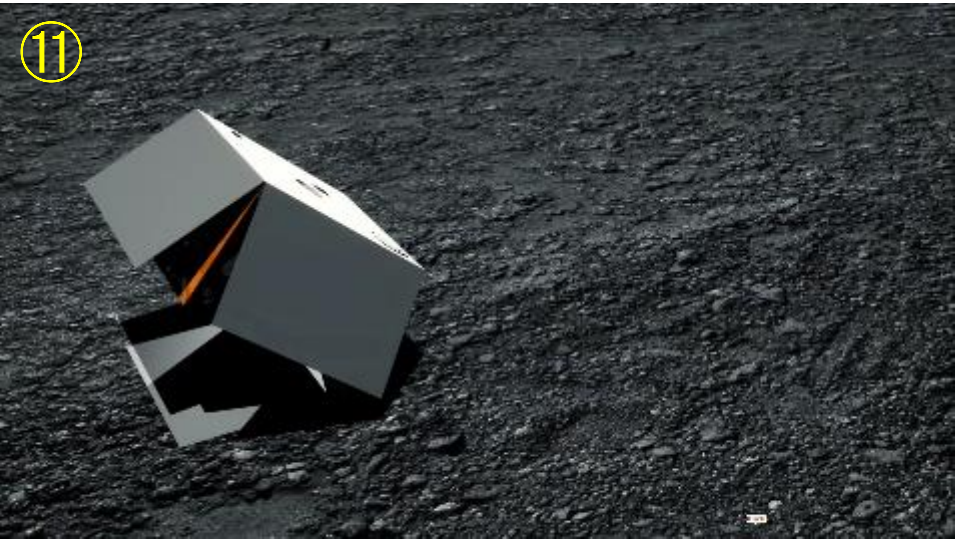
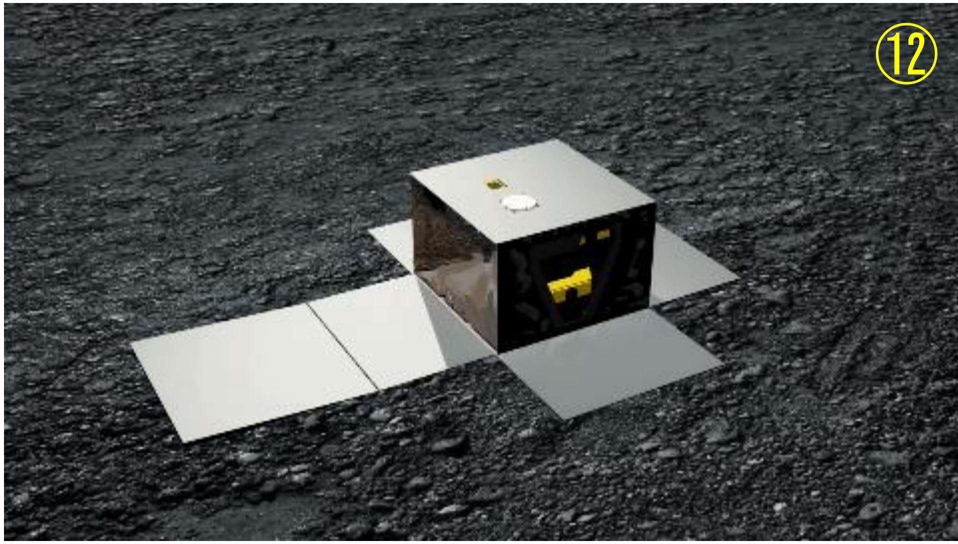
OKEANOS Mission Image (3/3)







Conclusion

- A trade-off analysis has been performed between various available power subsystems and propulsion subsystems for outer solar system exploration. The study has found that up to Saturn (10 AU), the combination of solar power sail and high-Isp ion propulsion leads to overall lightest spacecraft.
- The mission sequence of solar power sail-craft OKEANOS have been proposed for Jovian trojan exploration and suitable trajectories have been designed.

The solar power sail-craft leads the future solar system.