Dec.14, 2015
Lecture in “Propulsion and Energy Systems”
Tokyo University

Overview of Sail Propulsion for Space Flight

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Abstract

Currently, three kinds of sail propulsion concepts are studied and they are called as solar light sail, magnetic sail, and electric sail. Since these sail propulsion concepts do not require propellant, but instead, the momentum of the solar radiation or the solar wind is used to accelerate a spacecraft. Such propellant-less propulsion system may be the dream for spacecraft engineers because spacecraft propulsion engineers are willing to improve maneuverability by increasing specific impulse (Isp), but propellant-less propulsion may provide *infinite* Isp!

In this lecture, research status of sail propulsion for space flight is overviewed.

Outline

1. Introduction

2. Solar Light Sail (Solar Sail)

3. Solar Wind Sail (Magsail)

4. Another Solar Wind Sail (Electric sail)

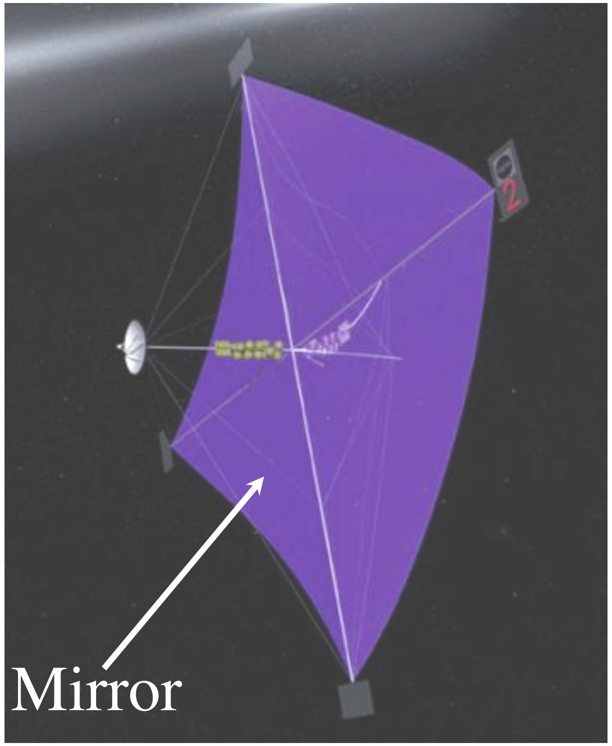
5. Future Evolutions of Sail Technology

6. Summary

1. Introduction

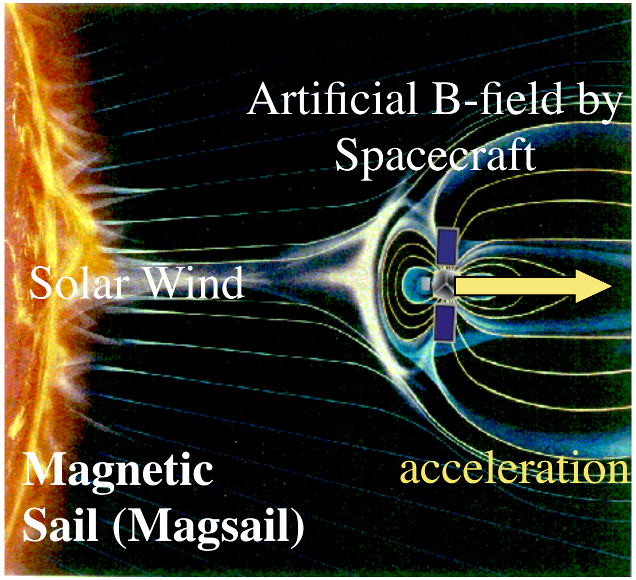
Deep Space Propulsion Using Solar Energy

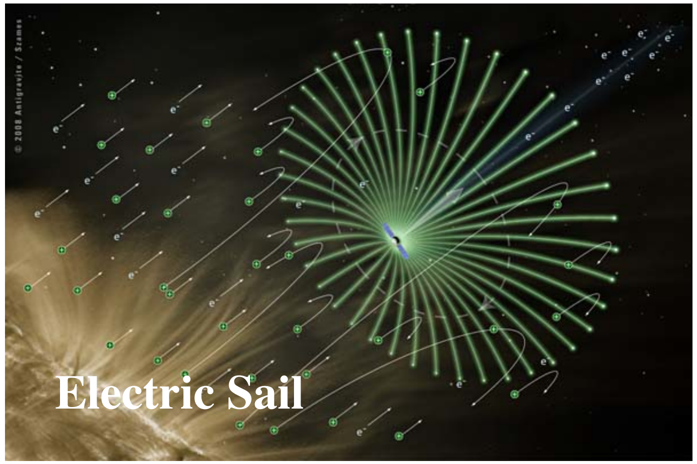
Light from the Sun



Solar Ligh Sail

Thrust production by light pressure



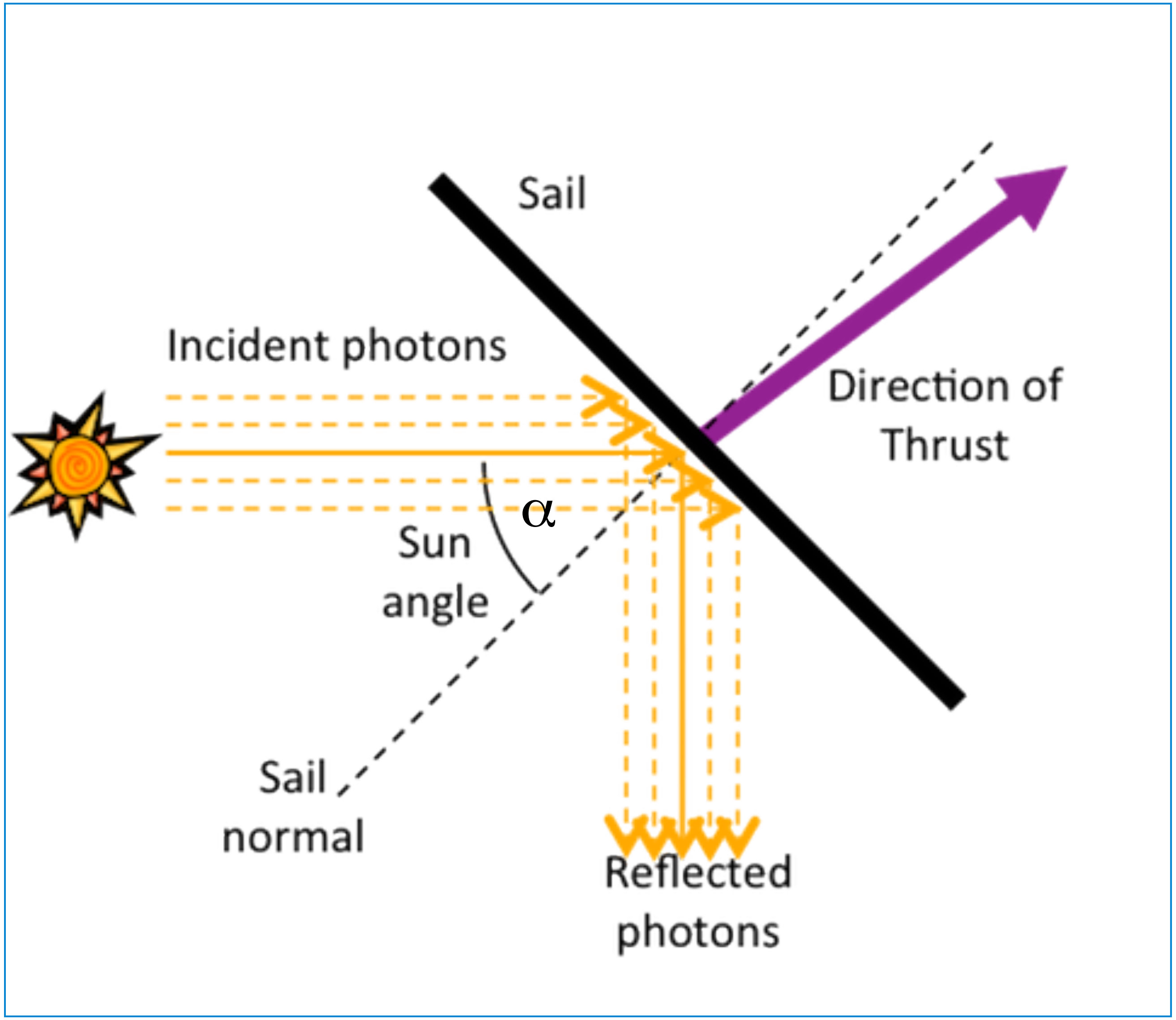


Solar Wind Sail

Accelerated by the solar wind dynamic pressure

2. Solar Light Sail
(Solar Sail)

Principle of Solar Light Sail



Thrust per unit area (pressure): P

Maximum Pressure for perfect reflection:

$$P_0 = 2\frac{W}{c} \qquad (2.1)$$

$$\approx 2\frac{1368\,[W]}{3\times10^8\,[m/s]}$$

$$\approx 9.12\,[\mu N/m^2]$$

The solar intensity W at 1 AU is 1368 [W/m^2], and c is the speed of light.

Theory of Solar Light Sail

- The pressure P on a flat perfect reflector is given by:

$$P = P_0 \frac{\cos^2 \alpha}{R^2} = 9.120 \frac{\cos^2 \alpha}{R^2} \quad \mu N/m^2 \qquad (2.2)$$

where R the distance from the Sun's center in AU, and α is the angle between Sun and sail normal.

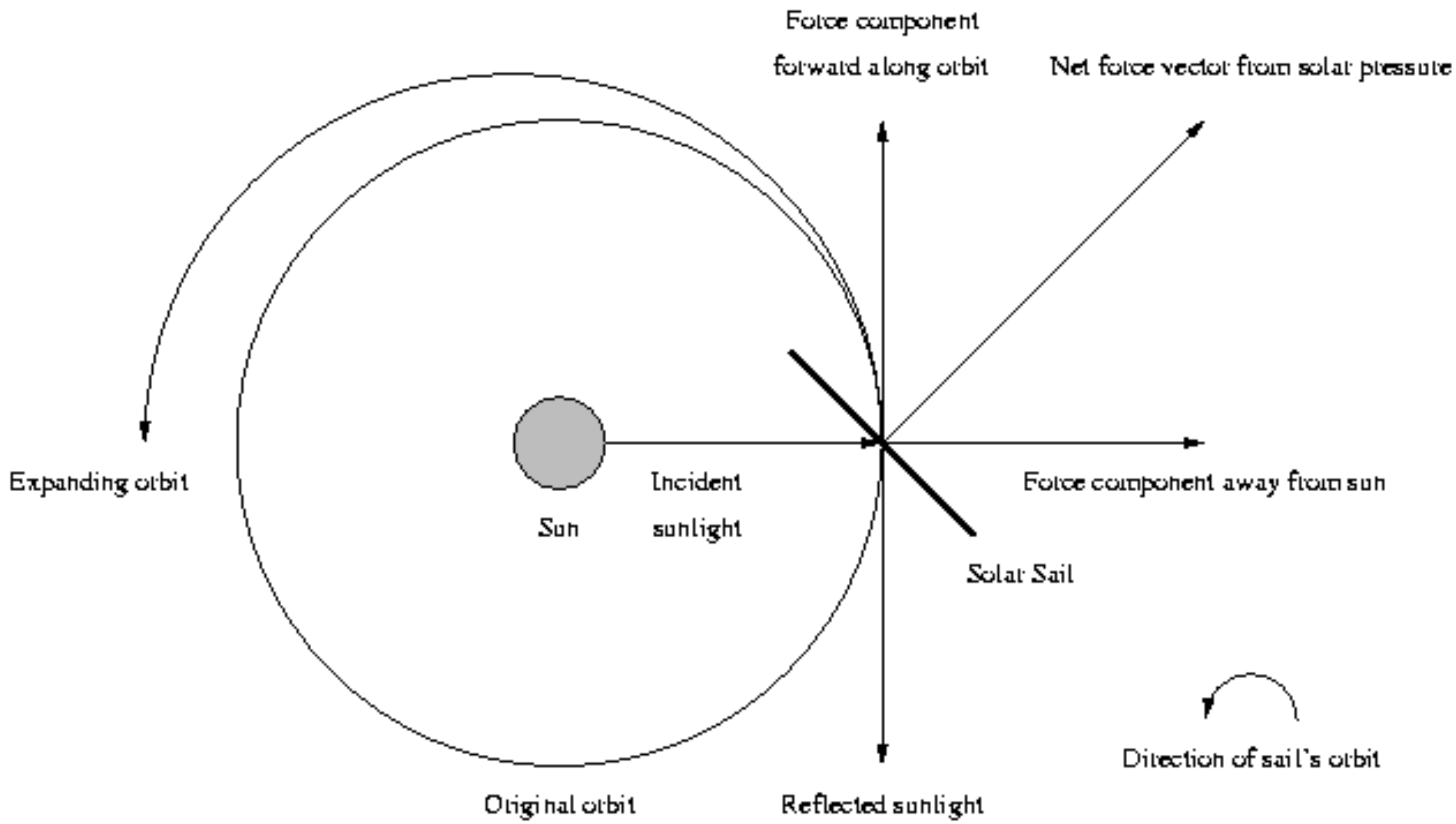
- Using an efficiency factor, η, of typically about 0.90, pressure, characteristic acceleration (a_c), and sail loading, σ, are related by:

$$a_c = \frac{P_0 \times \eta}{\sigma} = \frac{9.120 \times \eta}{\sigma} = \frac{8.28}{\sigma} \quad mm/s^2 \qquad (2.3)$$

Sail loading σ is total mass divided by sail area, and σ is given in [g/m^2].

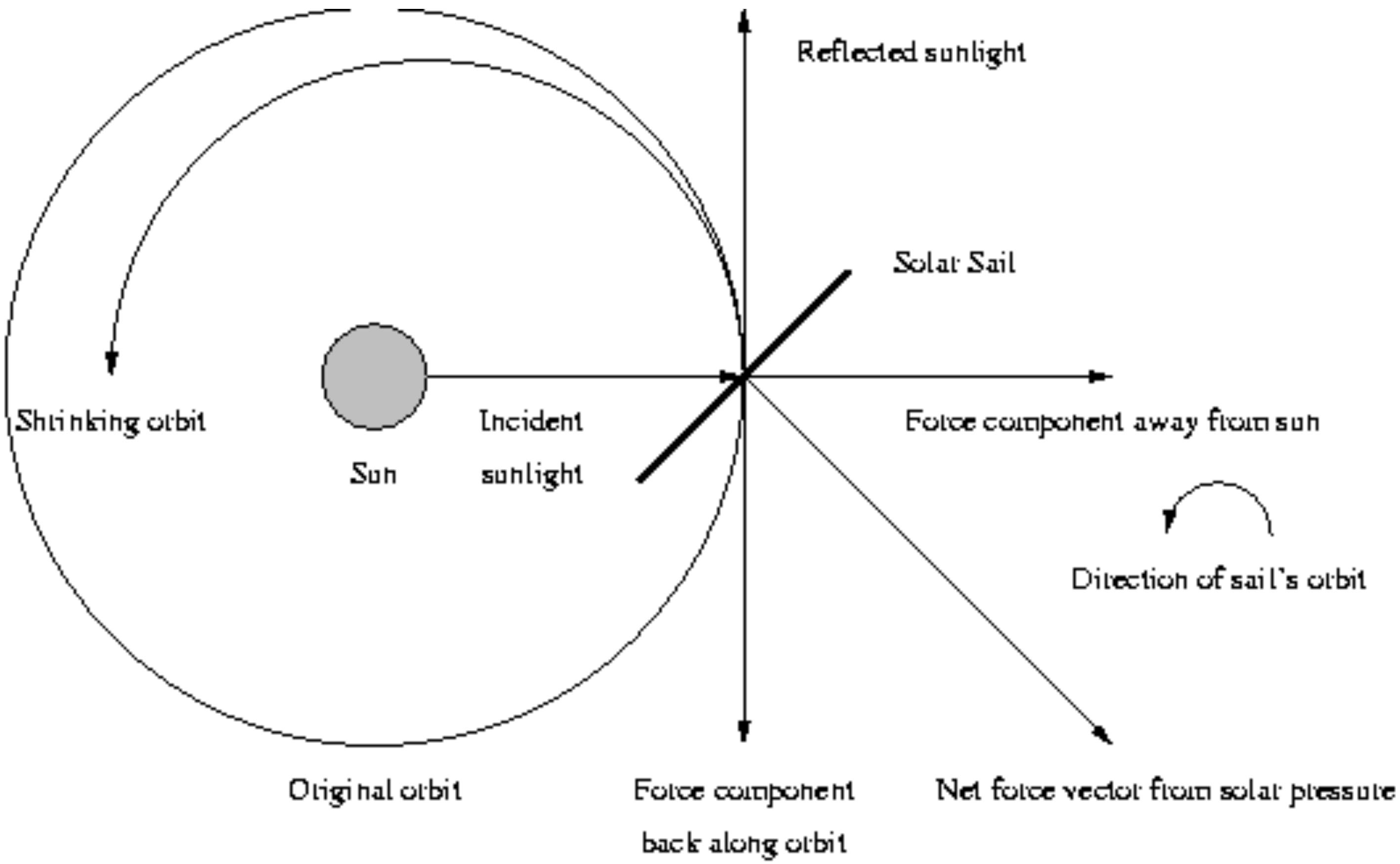
Orbital Transfer by Solar Light Sail

(1) **Outward** Spiral Case



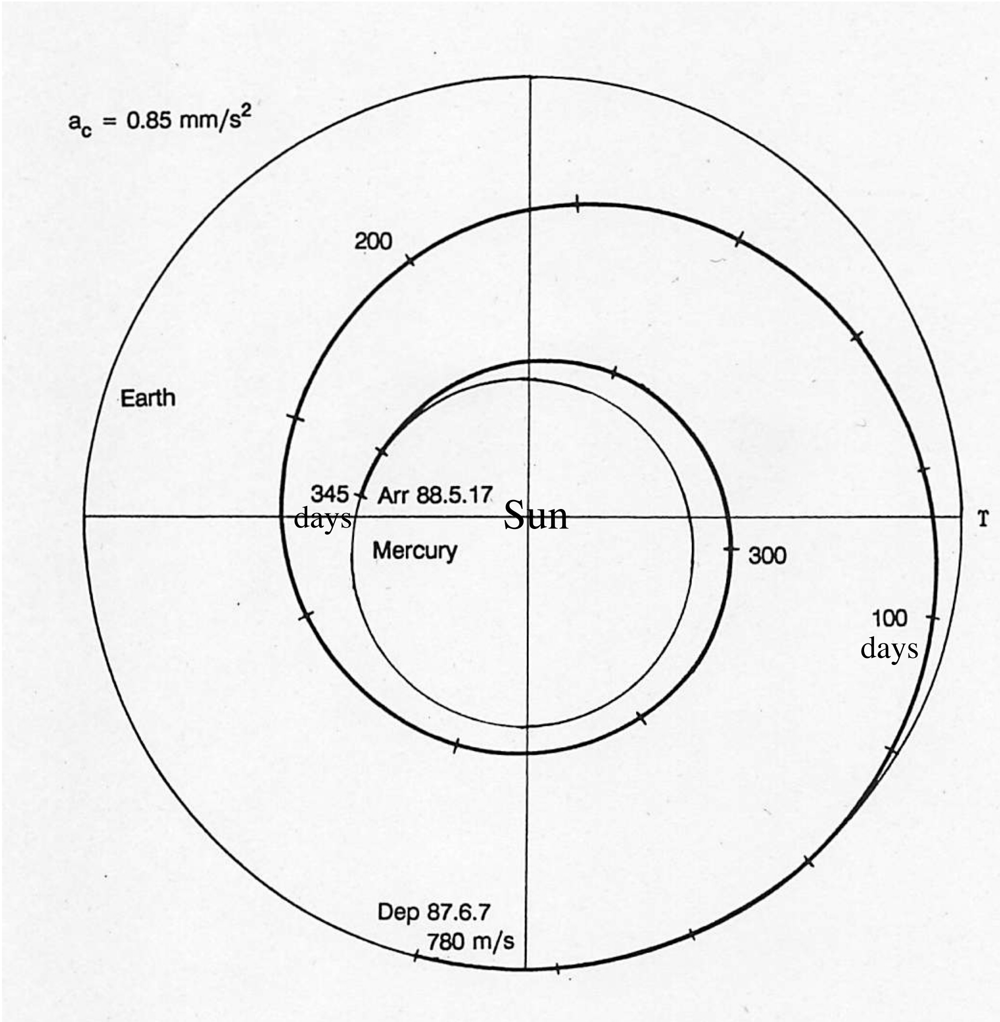
Orbital Transfer by Solar Light Sail

(2) **Inward** Spiral Case



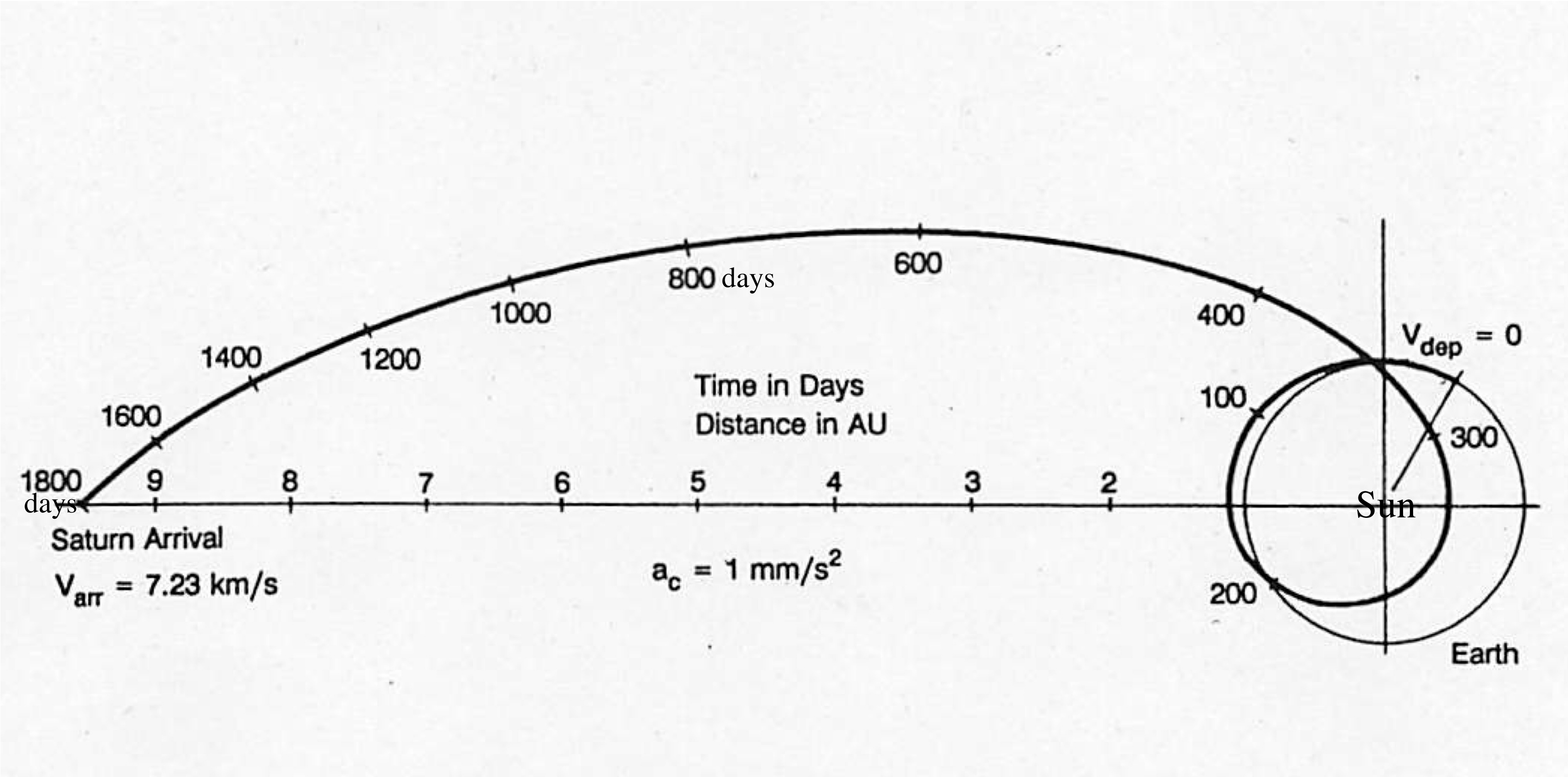
Orbital Transfer by Solar Light Sail

(3) Mercury Orbiter Trajectory



Orbital Transfer by Solar Light Sail

(4) Saturn Flyby Trajectory



History of Solar Light Sail

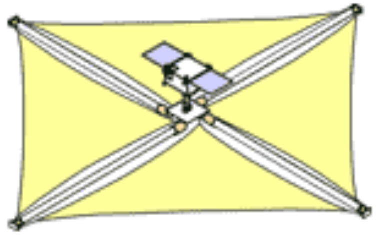
- **Svante Arrhenius** predicted in 1908 the possibility of solar radiation pressure distributing life spores across interstellar distances, the concept of panspermia. He apparently was the first scientist to state that light could move objects between stars.
- **Friedrich Zander** (Tsander) published a technical paper that included technical analysis of solar sailing. Zander wrote of "using tremendous mirrors of very thin sheets" and "using the pressure of sunlight to attain cosmic velocities”.
- **J.D. Bernal** wrote in 1929, "A form of space sailing might be developed which used the repulsive effect of the sun's rays instead of wind. A space vessel spreading its large, metallic wings, acres in extent, to the full, might be blown to the limit of Neptune's orbit. Then, to increase its speed, it would tack, close-hauled, down the gravitational field, spreading full sail again as it rushed past the sun.”
- The first formal technology and design effort for a solar sail began in 1976 at Jet Propulsion Laboratory for a proposed mission to rendezvous with Halley's Comet.

Key Technologies of Solar Light Sail

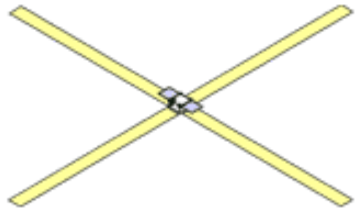
- Sail deployment
  - 33m x 33m sail is required for 10mN thrust
  - 105m x 105m sail is required for 100mN thrust

  Usually, 100m-sq sail or larger is necessary for 1,000-kg interplanetary spacecraft.
- Sail material

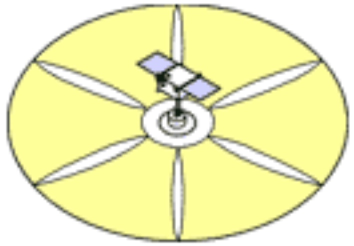
  lightweight, therefore ultra thin (~μm) film is necessary
  - $\sigma \sim 8$ g/m^2 is required to obtain $a_c \sim 1$ mm/s^2. In this case, weight is 80 kg for 100m-sq sail.
  - So far, 5 μm thick Mylar sail material achieves mass ~ 7 g/m^2, aluminized Kapton films have a mass as much as 12 g/m^2.
- Attitude control
  - achieved by a relative shift between the craft's center of pressure and its center of mass



Square Sail (not to scale)



Heliogyro (not to scale)



Spinning Disk Sail (not to scale)

Sail Configurations

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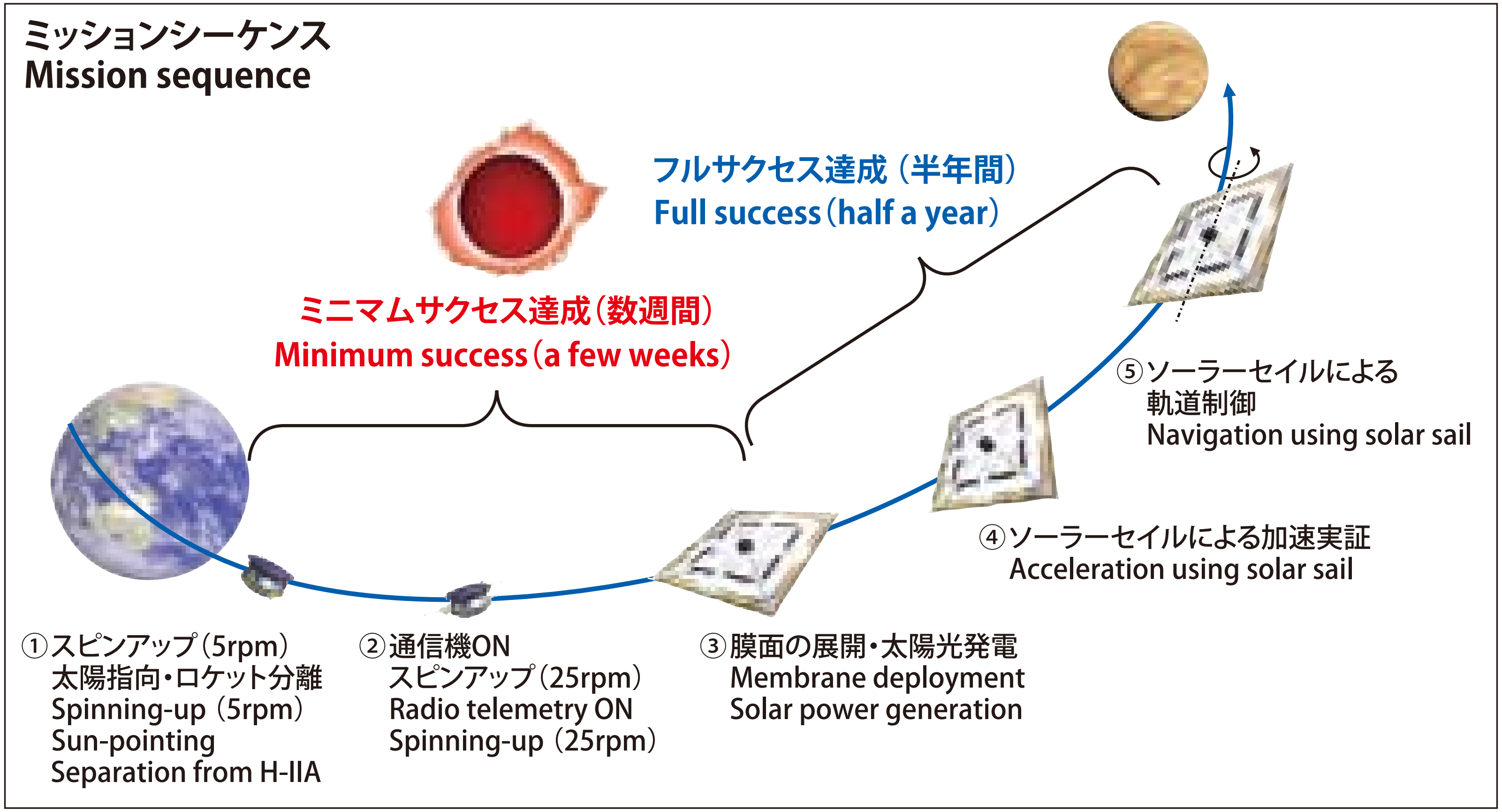
Flight Tests of Small-scale Solar Sails

Year	Country	Flight Goal	Result
1993	Russia	Znamiye -- Deployment of "shade" outside of Mir	Success – but not a sail
1999	Russia	Znamiye-2 Deployment test from Progress	Collided with s/c antenna during deployment
2002	TPS	Sub-orbital deployment test	Rocket 3rd stage failed to separate
2004	Japan	Sub-orbital deployment tests	Success
2006	Japan	Deployment test in Earth orbit on Astro-F	Did not fully deploy
2005	TPS	COSMOS 1 – Fully controlled flight in Earth orbit	Rocket failed during 1st stage
2008	U.S.	Nanosail-D: Sail orbital deployment in atmosphere as a drag brake	Rocket failed to deliver to orbit
2010	Japan	IKAROS: interplanetary flight	June – successful deploy first solar sail in space

TPS: The Planetary Society

JAXA IKAROS

IKAROS : Interplanetary Kite-craft Accelerated by Radiation Of the Sun



Piggybacked on the Venus Climate Orbiter (Planet-C) Mission: June 2010

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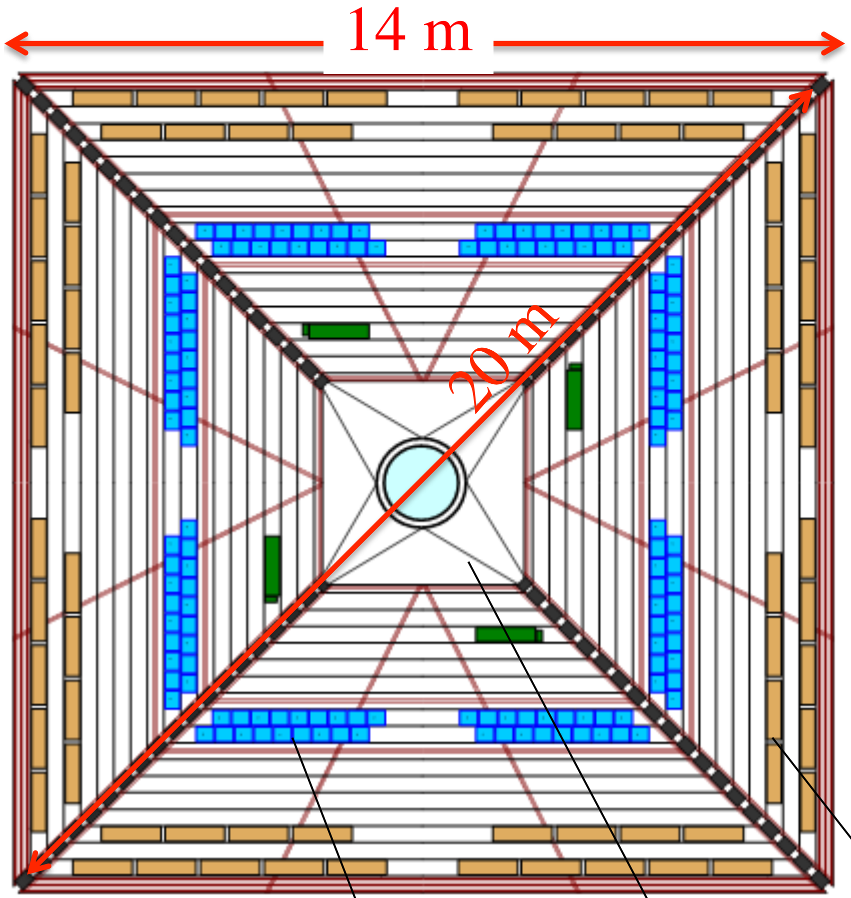
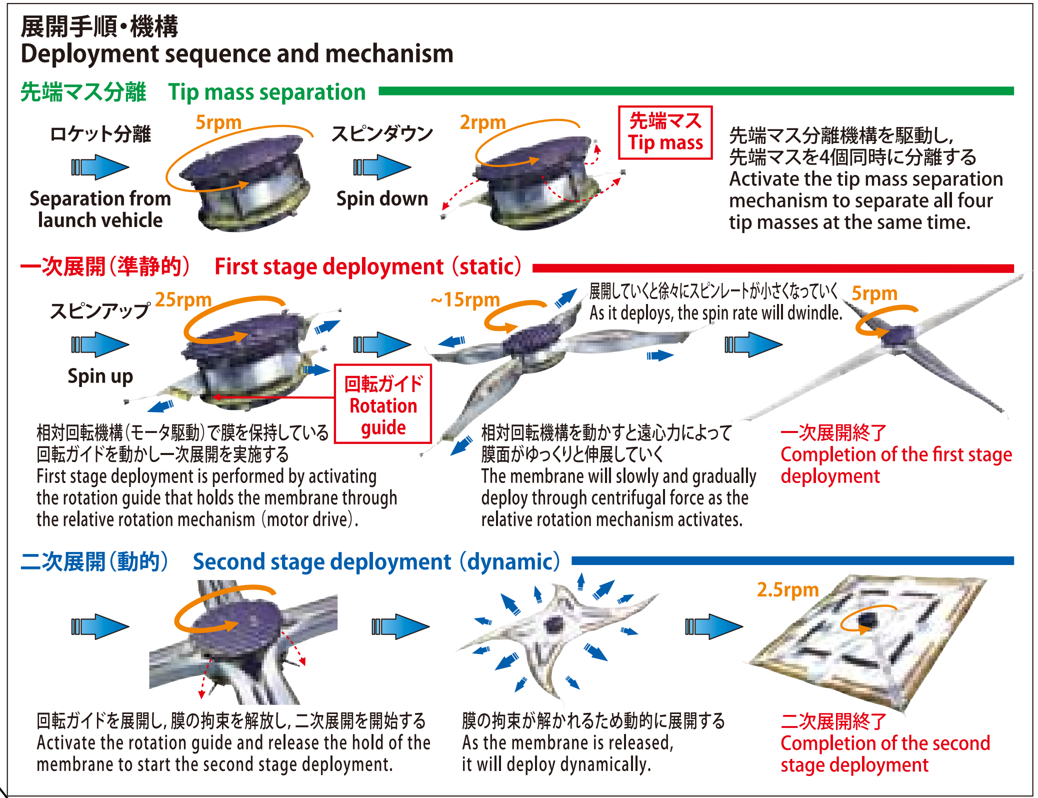




Deploying Sequence

Tip Mass　Solar Cell　Tether　Steering Device

Vary reflectance

Future Plans for Solar Light Sail

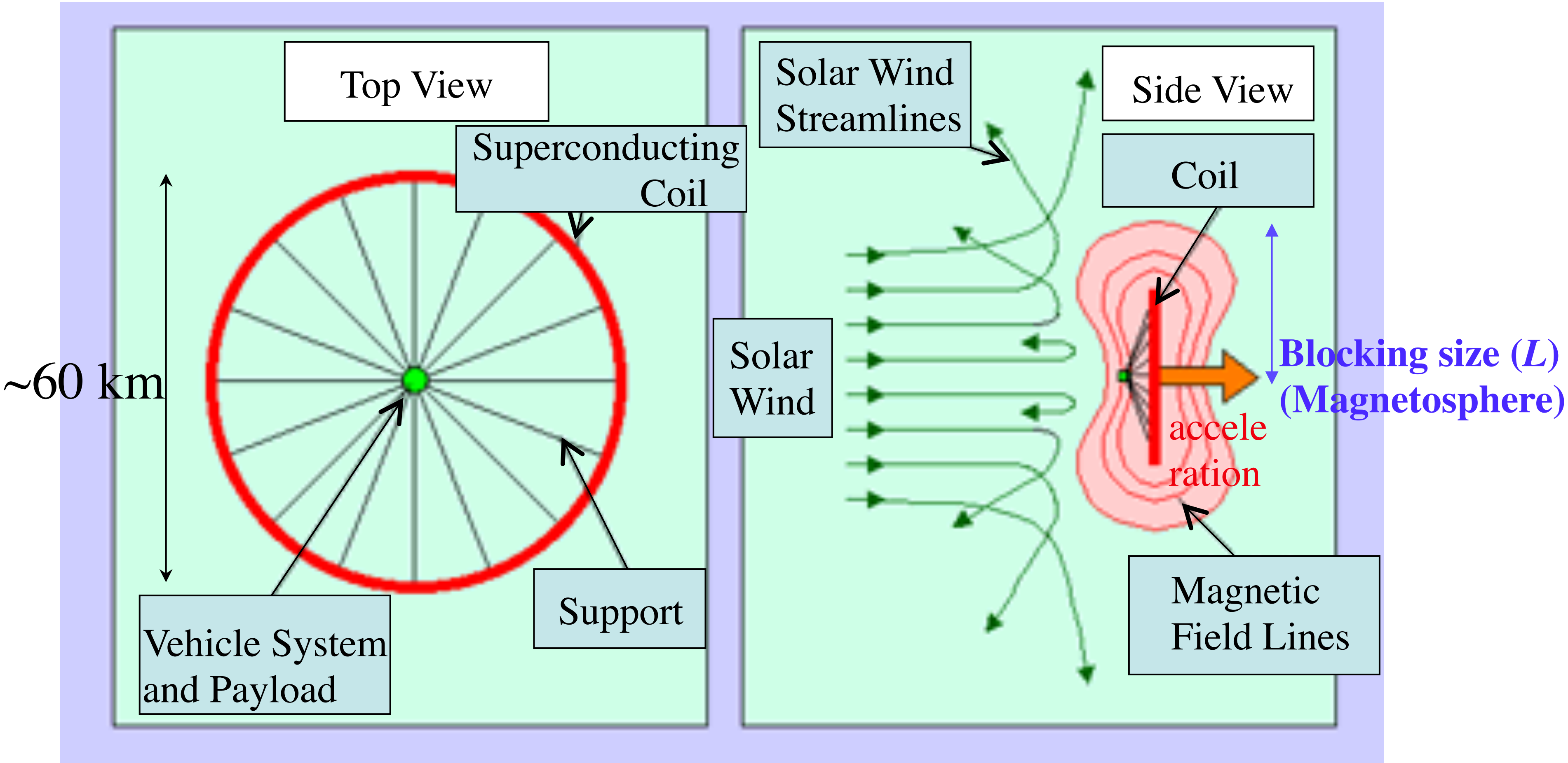
Mission	Who	Size	Status	Mass	Launch
COSMOS 1	TPS	150 sq m	Launch failure	130 kg	2005
Nanosail D	MSFC	9 sq. m	Launch failure	4.5 Kg	2008
IKAROS	JAXA	200 sq. m	In orbit – success		2010
Nanosail D-II	MSFC	20 sq. m	In orbit – partly success	4.5 kg	2010
Lightsail – 1	TPS	32 sq. m	In development	4.5 kg	
Cubesail	EADS - Surrey	25 sq. m	In planning/dev.	5 kg	
Cube Sail	CU Aerospace	20 sq. m	In planning	5 kg	
Lightsail - 2	TPS	100 sq. m	In planning	10 kg	
Ultra Sail	CU Aerospace	100 sq. m	In planning	20 kg	
Sunjammer	MSFC	1,208 sq m (38mx38m)	In development	32 kg	2015

TPS: The Planetary Society
MSFC: NASA Marshall Space Flight Center

3. Solar Wind Sail (MagSail)

The Idea of Solar Wind Sail, Magnetic Sail

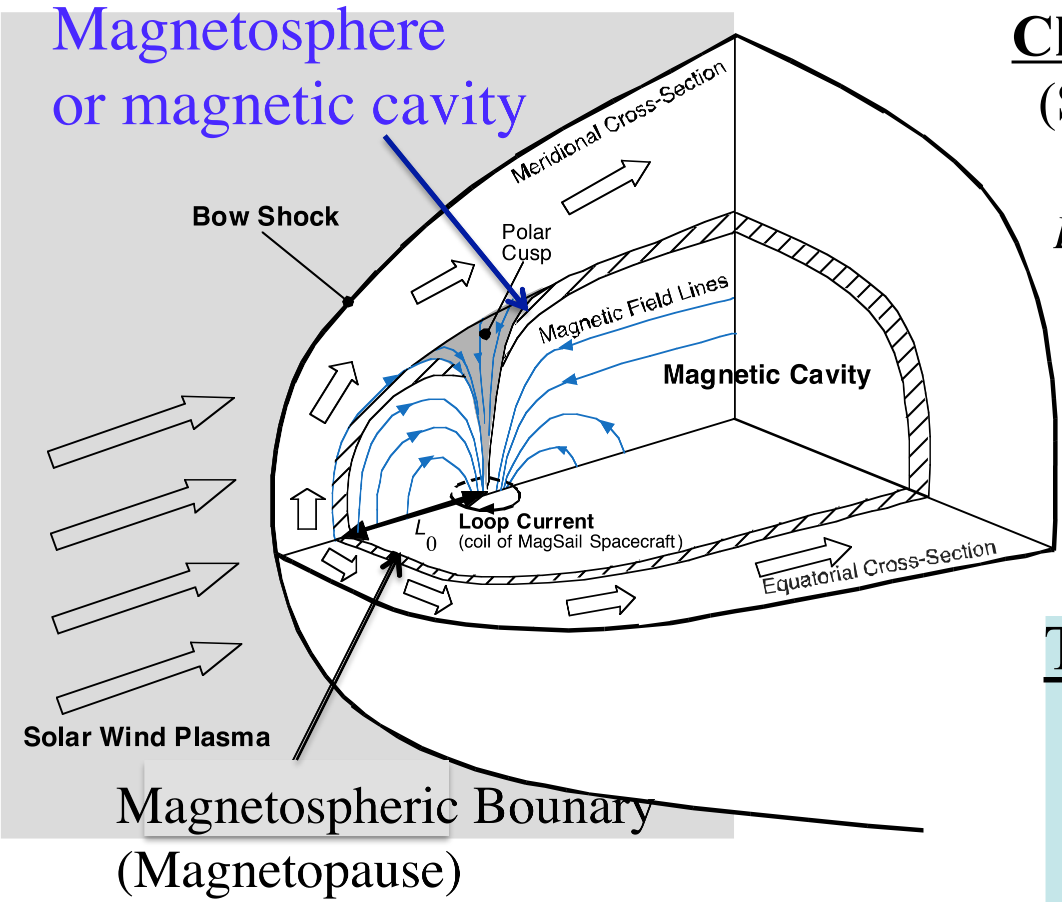
(=Magsail)



History and Status of Magsail Research

- R.M. Zubrin and D.G. Andrew proposed Magnetic sail for earth escape, interplanetary travel, and interstellar flight in 1989-1991.
- Due to some technical issues, Magsail never flew in space.
- In 2001, R. Winglee and his colleagues started Mini-magnetospeheric Plasma Propulsion (M2P2) as an way to compactly implement the concept of Magsail.
- From 2006, JAXA, in collaboration with Japanese universities, continues theoretical and experimental investigations on Magsail and its derivatives. The first laboratory experiment of Magsail was conducted to confirm theoretically derived thrust formula. Also, small flight demonstration of Magsail is being proposed.

Plasma Flow and Thrust of MagSail



Plasma Flow and B-field of MagSail

<u>Characteristic Length of MagSail</u>

(Stand-off distance, L_0)

$$L_0 = \sqrt[6]{\frac{\mu_0 M^2}{8\pi^2 n\, m_i\, u^2}} \qquad (3.1)$$

M:dipole moment

nm_iu^2:solar wind dynamic pressure

L_0 is derived from pressure balance:

$$n m_i\, u^2 = \frac{(2B_{mp})^2}{2\mu_0} \quad \text{and} \quad B_{mp} = \frac{\mu_0 M}{4\pi L_0^3}$$

<u>Thrust of Magsail (Drag Force)</u>

$$F = C_d \frac{1}{2}\rho_{sw} u_{sw}^2 S$$

characteristic area

solar wind dynamic pressure

non-dim. Thrust coefficient
(a function of L_0, ρ_{sw}, u_{sw})

$$= C_d \frac{1}{2}\rho_{sw} u_{sw}^2 \left(\pi L_0^2\right) \qquad (3.2)$$

Thrust by Magsail and Solar Light Sail

- The dynamic pressure *P* of a solar wind at 1 AU is given by:

$$\begin{aligned} P_0 &= \frac{1}{2}\rho u^2 \\ &\approx \frac{1}{2}\left(1.67\times10^{-27}\times5\times10^{6}\right)\times\left(5\times10^{5}\right)^2 \quad Pa \\ &\approx 1 \quad nPa \end{aligned} \qquad (3.3)$$

  when solar wind number density $5\text{x}10^6$ particle/m^3 and velocity 500 km/s are assumed.

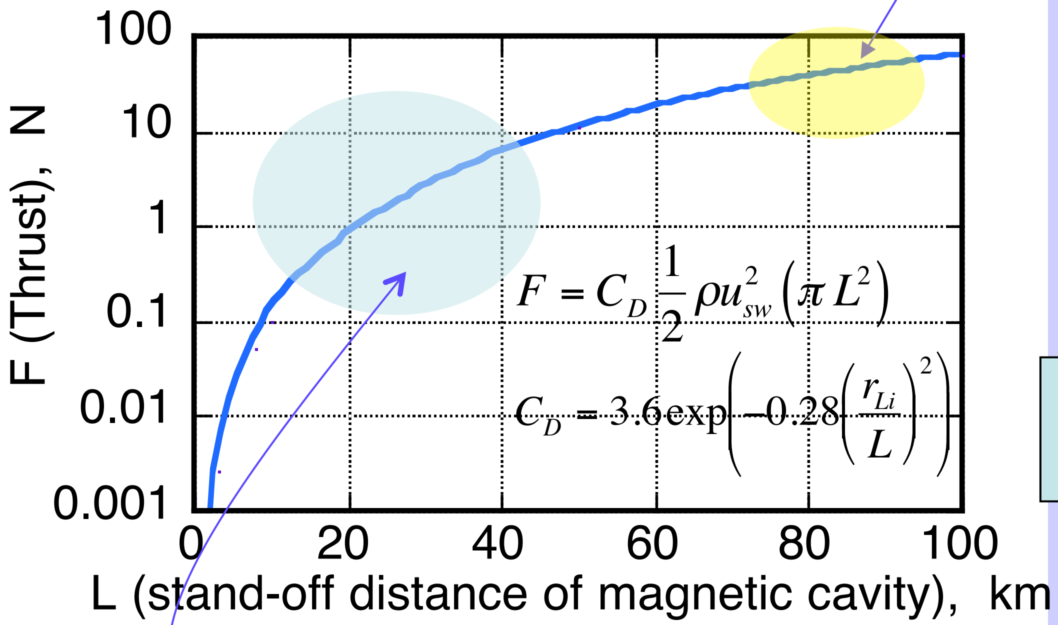
- P_0 by the solar wind (~1 nPa) is very small in comparison with the solar light pressure (~9 μPa at 1 AU). Hence, sunlight has thousands of times more momentum (per unit area) than the solar wind. Therefore, a magnetic sail must deflect a proportionally larger area of the solar wind than a comparable solar sail to generate the same amount of thrust.
- However, Magsail need not be as massive as a solar sail because the solar wind is deflected by a magnetic field instead of a large physical sail. So, in some cases, Magsail might have competitiveness against solar light sail.

Theory of Magsail (cont.)

Effect of *L* (Stand-off Distance) on Thrust (*F*)

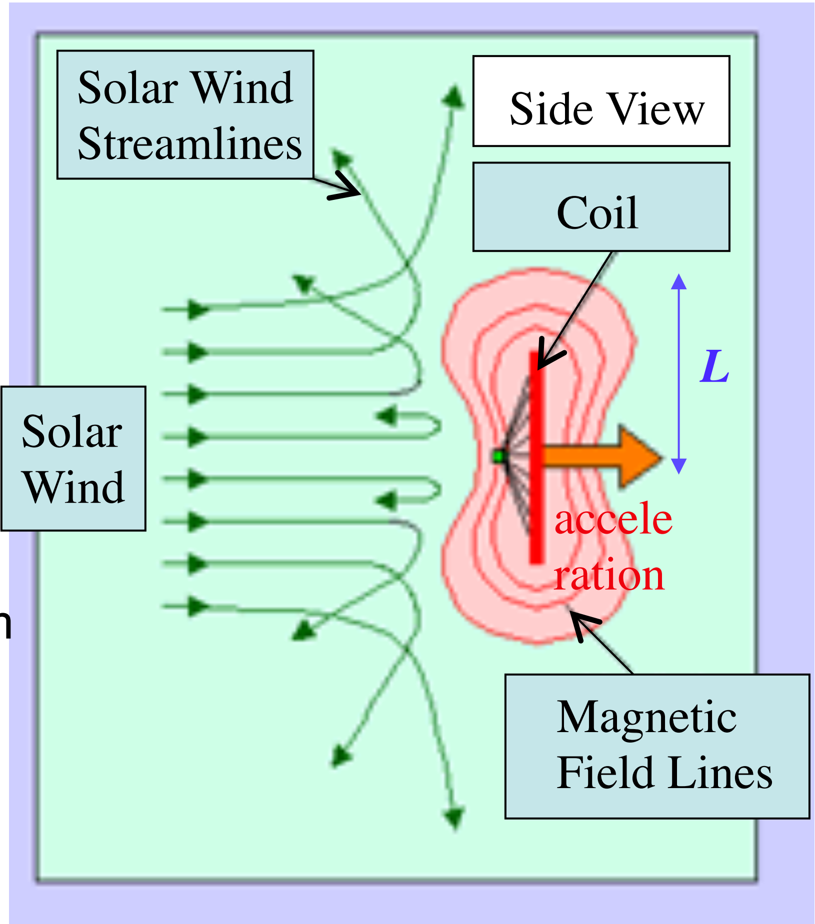
R. Zubrin proposed 20-N-class Magsail (for 100-km-diameter magnetosphere) that is obtained with B-field by superconducting coil of 5mm in diam., 5000 kg weight.

20-N-class (Zubrin)



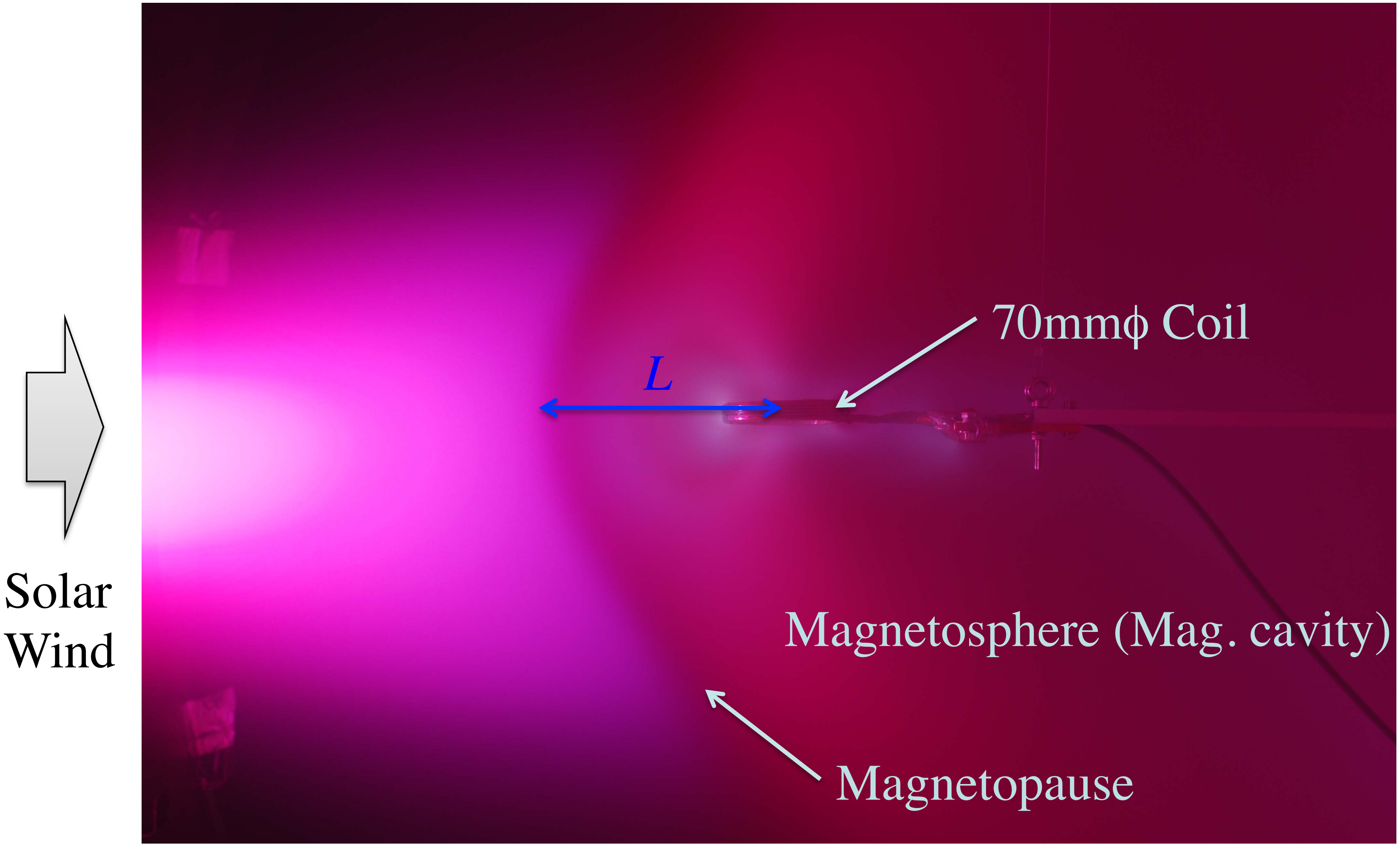
Thrust of Pure MagSail

Design Target: 1-N-class Sail
(for 1,000-kg-spacecraft)



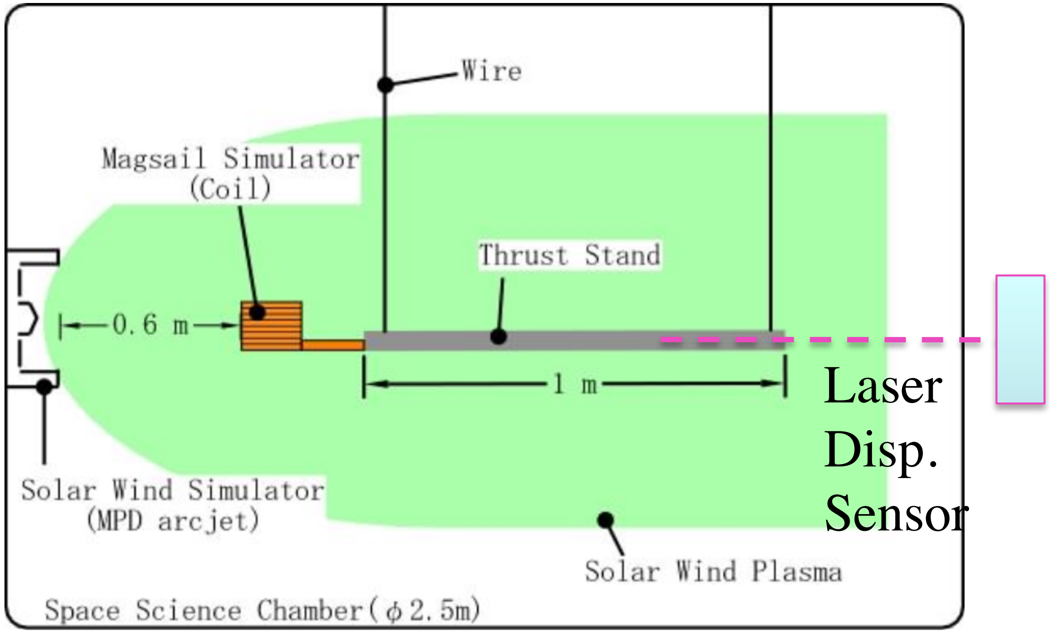
Definition of *L*

Typical MagSail Experiment in Laboratory



Hydrogen 0.4g/s,
PFN1: 4kV, 1T at the center of the 70mmϕ coil

Direct Thrust Measurement of MagSail in Laboratory

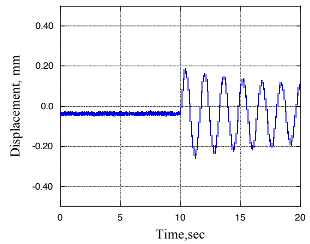


MagSail Operation in Laboratory

- Hydrogen 0.4g/s, PFN1: 4kV
- 1.9T at the center of the coil
- Discharge duration:0.8 ms,
- Time resolution:5 μs

Thrust Stand

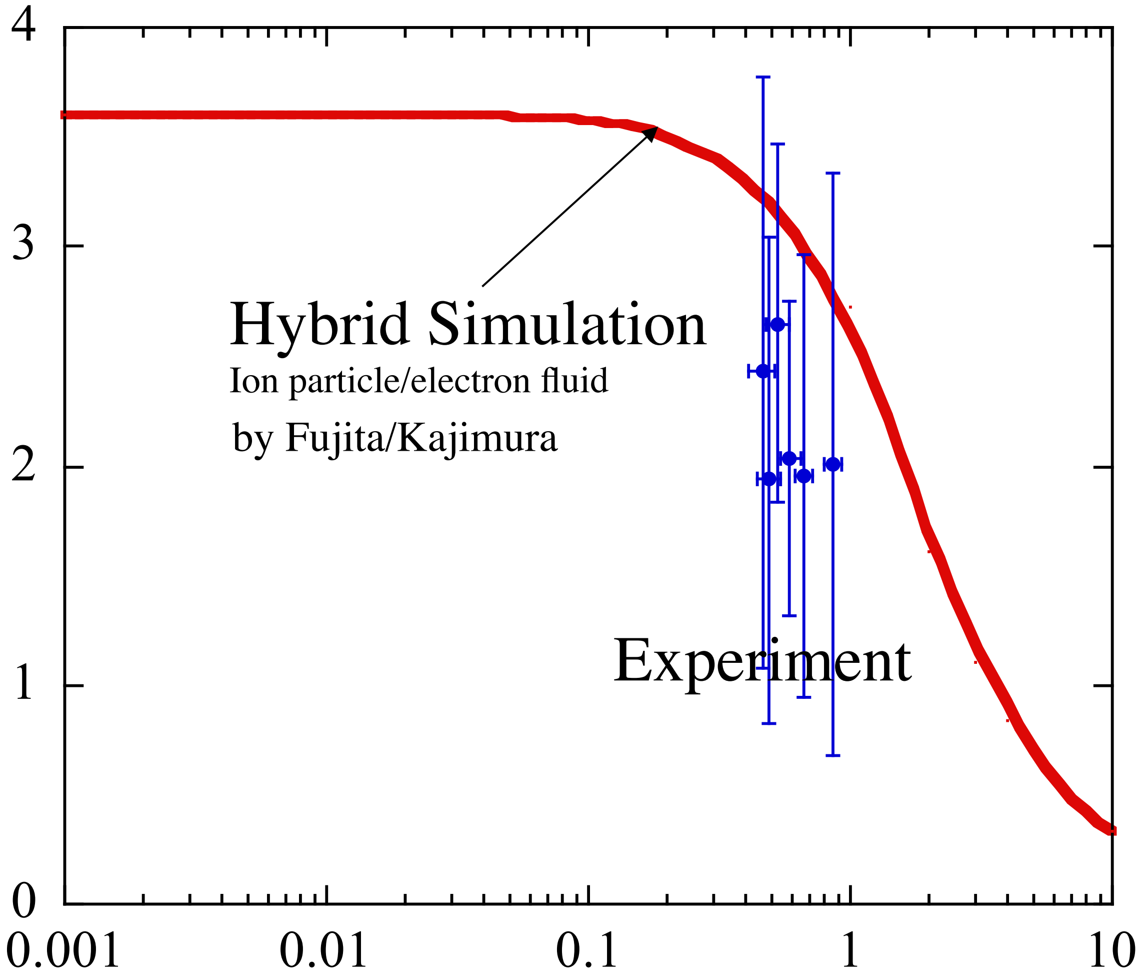
- ballistic pendulum method
- supported by 4 wires
- laser displacement sensors



Thrust Characteristics of MagSail

$$C_d = \frac{F}{\frac{1}{2}\rho u_{sw}^2 S}$$

non-dimenaional thrust coef.



$$\frac{r_{Li}}{L} = \frac{m_i u_i}{e B_{mp} L}$$ ***=(non-dim. ion Larmor radius at magnetopause)***

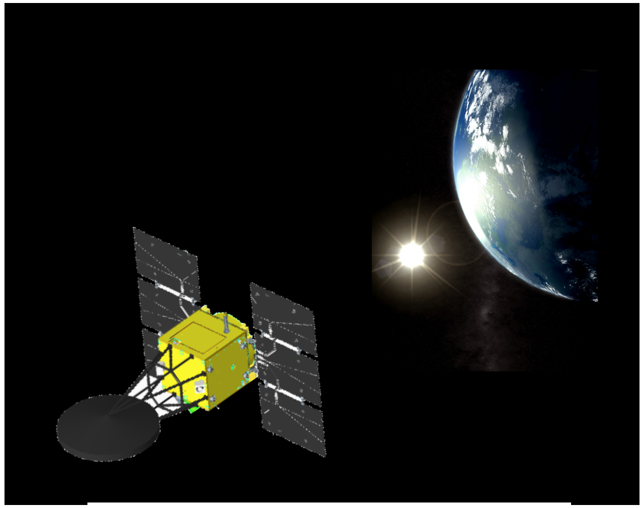
Small Magsail Demonstration Plan

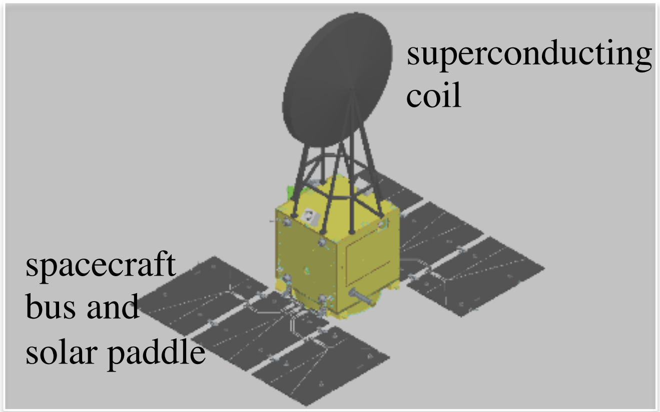
<u>Outline:</u>

- 300kg(wet) class small engineering spacecraft
- inserted into Earth escape orbit at C3≒0 by Japanese Small Launcher (Epsilon) or as a secondary payload of heavy launch vehicle (H-IIA)

<u>Objectives:</u>

- Cooling and start-up of superconducting coil in an orbit departing the Earth
- 1mN-class thrust production when operating the superconducting coil, as a result of solar wind to magnetosphere interaction
- Testing attitude control and guidance of Magsail in deep space

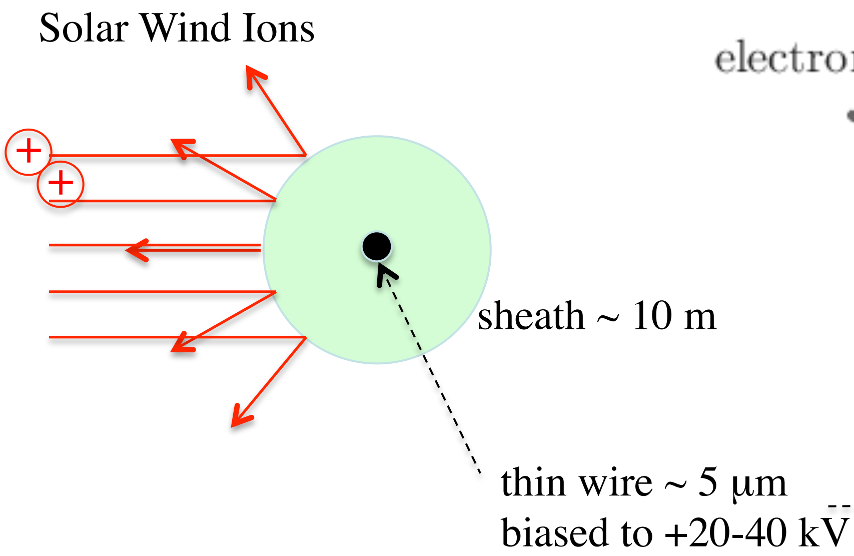




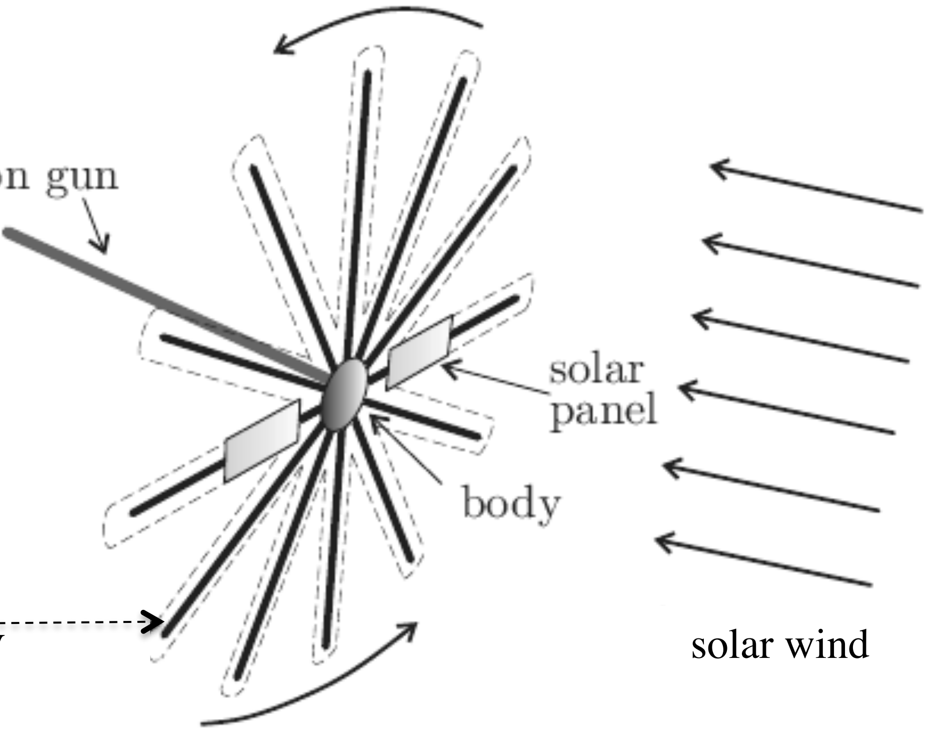
Spacecraft and Mission Image of Magsail Demonstration Mission

4. Another Solar Wind Sail
(Electric Sail)

Principle of Another Solar Wind Sail, Electric Sail



Solar Wind Repelling Scheme



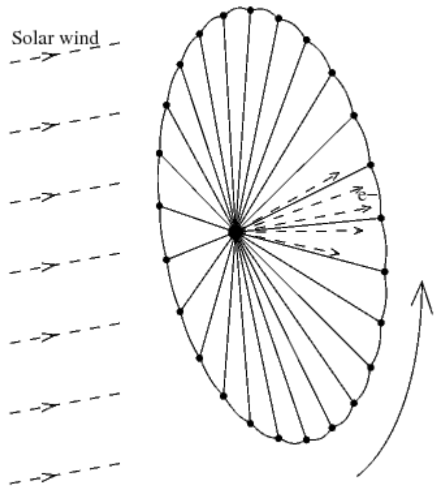
Electric Sail Spacecraft Concept

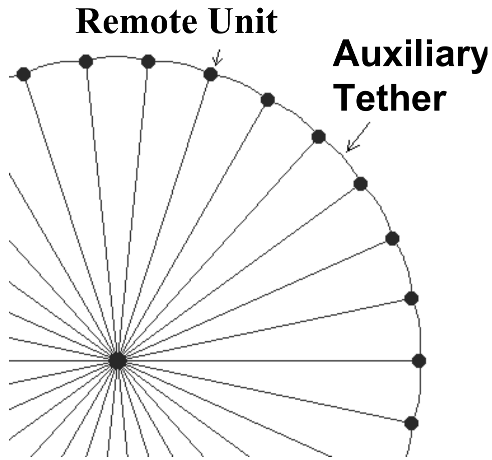
The electric sail consists of a number of thin, long and conducting tethers which are kept in a high positive potential by an onboard electron gun. The positively charged tethers repel solar wind protons, thus deflecting their paths and extracting momentum from them.

Janhunen, Electric Sail HP

Principle of Electric Sail (cont.)

- To capture solar wind momentum, Coulomb interaction between solar wind and long, thin, positively charged tethers (10-20 km, 25-50 μm wire, +20-40 kV) is used.
- Thrust per unit length is 500 nN/m. Up to 1 N thrust (scales ~ 1/r) is expected for 100-200 kg unit
- A way to deploy the tethers is to rotate the spacecraft and have the centrifugal force keep them stretched.
- By fine-tuning the potentials of individual tethers and thus the solar wind force individually, the attitude of the spacecraft can be controlled.





Status of Electric Sail Research

- P. Janhunen (Kumpula Space Centre, Finland) proposed the concept in 2004.
- Until recently, theoretical model and spacecraft design were studied by Janhunen's group.
- E-sail effect in low Earth orbit is to be demonstrated onboard ESTCube-1 satellite, which was launched on May 7 2013.
  - ESTCube-1 will deploy a 10 m long tether and charge it up which allows us to measure the E-sail force exerted on the tether by the ionospheric ram flow acting on the satellite.

ESTCube-1 (1-kg nano-sat) was the first satellite to test electric sail.

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5. Future Evolutions of Sail Technology

Solar Sails: Limitations and Future Prospects

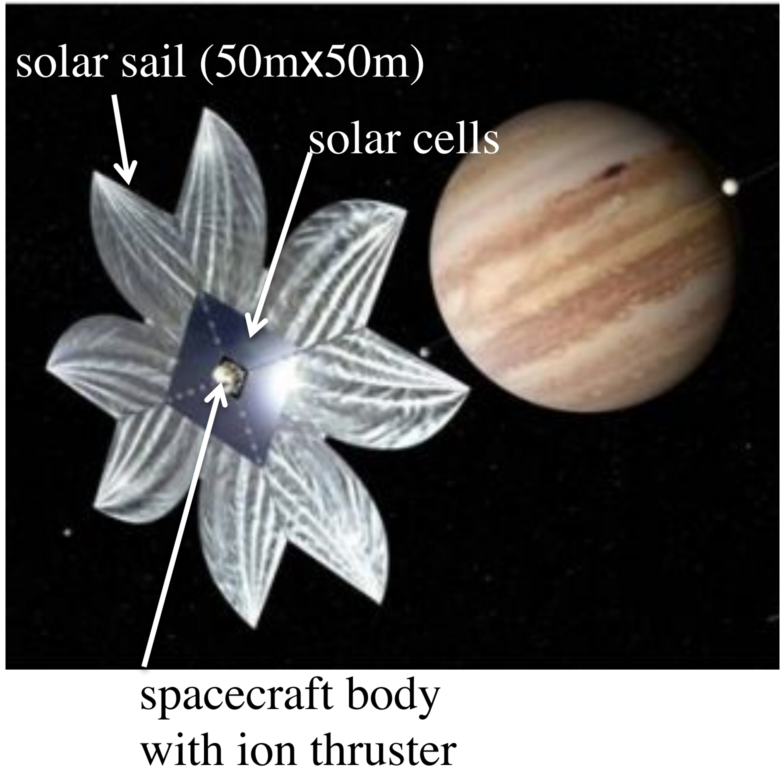
1. Thrust is produced only near the Sun
   - Large acceleration is possible for inner solar system exploration. Therefore, spacecraft can be put into an orbit of Mercury, Venus and Mars via solar sails.
   - Acceleration is NOT enough for orbital transfer in the outer solar system beyond Jupiter. This means that solar sail propulsion is effective for 1) flyby missions targeting at outer planets in the solar system, or 2) for solar system escape (with nuclear power source) when enough acceleration is provided in the inner solar system region.

Solar Sails: Limitations and Future Prospects (cont.)

2. Solar sails' thrust as well as electric power are severly limited. To overcome electric power limitation, in particular in the outer solar system, the usage of solar power sail (SPS) is planned for future Jupiter-Trojan mission. To overcome thrust limitation for outer planet exploration, aeroassist maneuver or the usage of electric propulsion (in combination with SPS) may be effective.
3. Rapid solar system escape would be another target mission with solar sails. Drastic acceleration in the inner solar system may be possible by Magsail's derivatives (MPS) or by Electrostatic sail.
4. The usage of sail technology for far future long-distance missions is also discussed.

JAXA Solar Power Sail (SPS) Concept

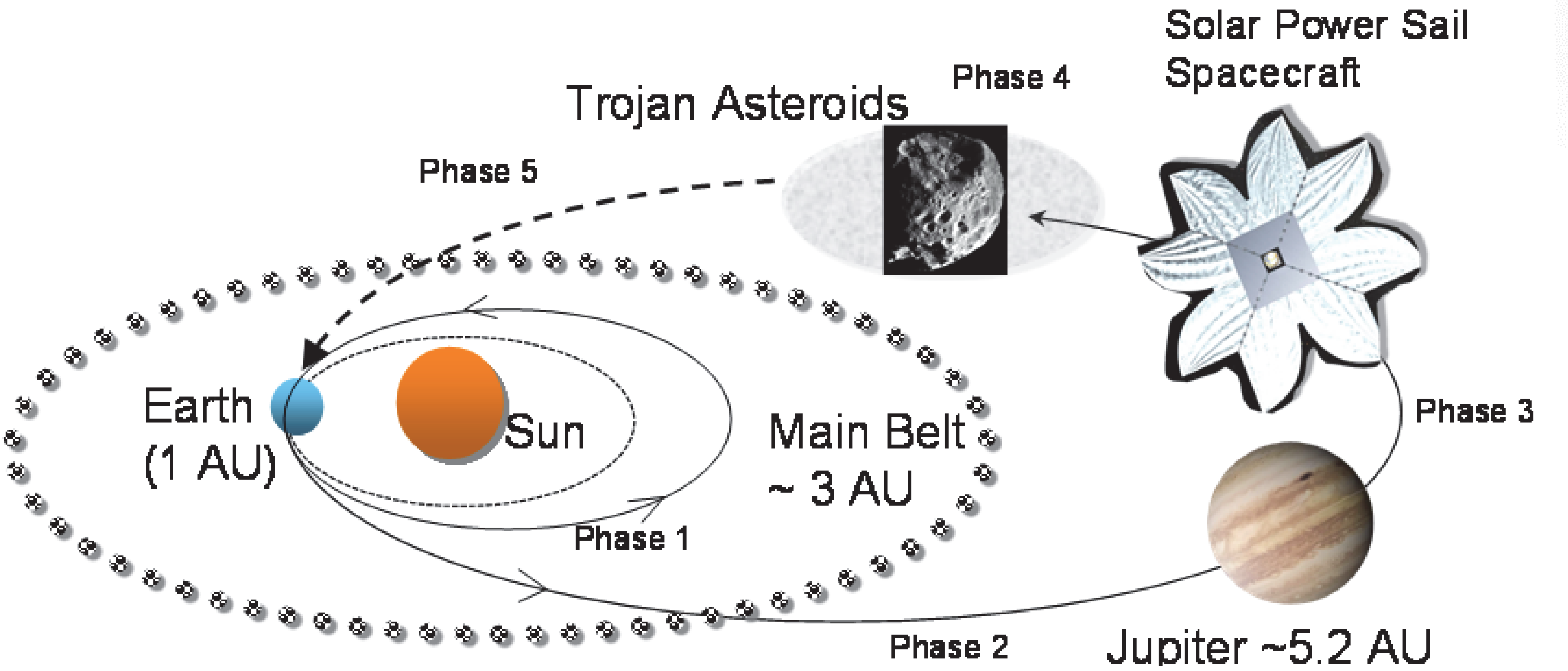
A solar power sail combines a solar sail (photon propulsion) with additional electric power generation capability of flexible solar cells attached to the sail membrane. Solar power sail spacecraft is powered by the hybrid propulsion of solar photon acceleration and highly efficient ion engines driven by the large electric power supply from the flexible solar cells. This in turn, leads to flexible and efficient orbital control capability.



Solar Power Sail Spacecraft Concept

JAXA JSPEC HP

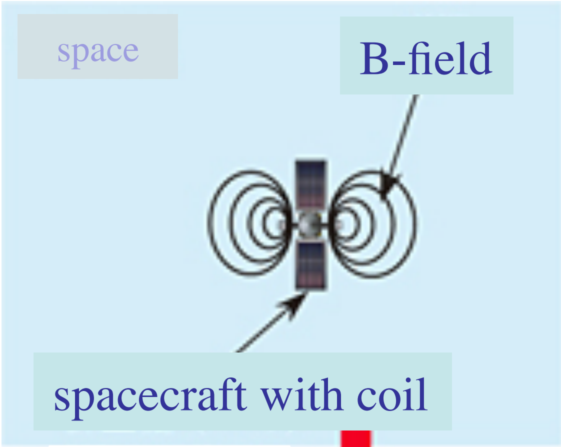
JAXA Solar Power Sail Mission Proposal



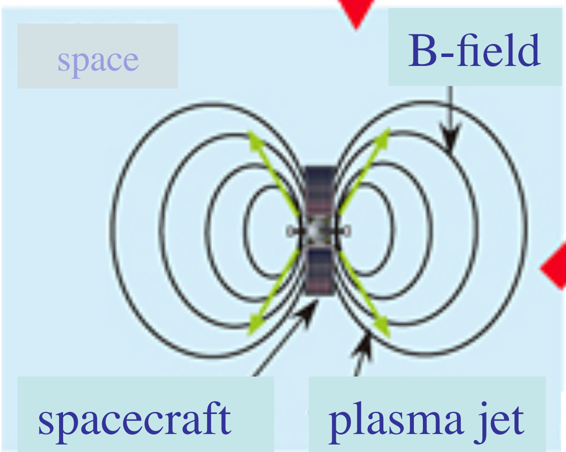
Jupiter-Trojan Sample Return Mission (2020~)

R. Funase, O. Mori, et al., ISTS2013-d-20

JAXA Magnetoplasma Sail (MPS) Concept

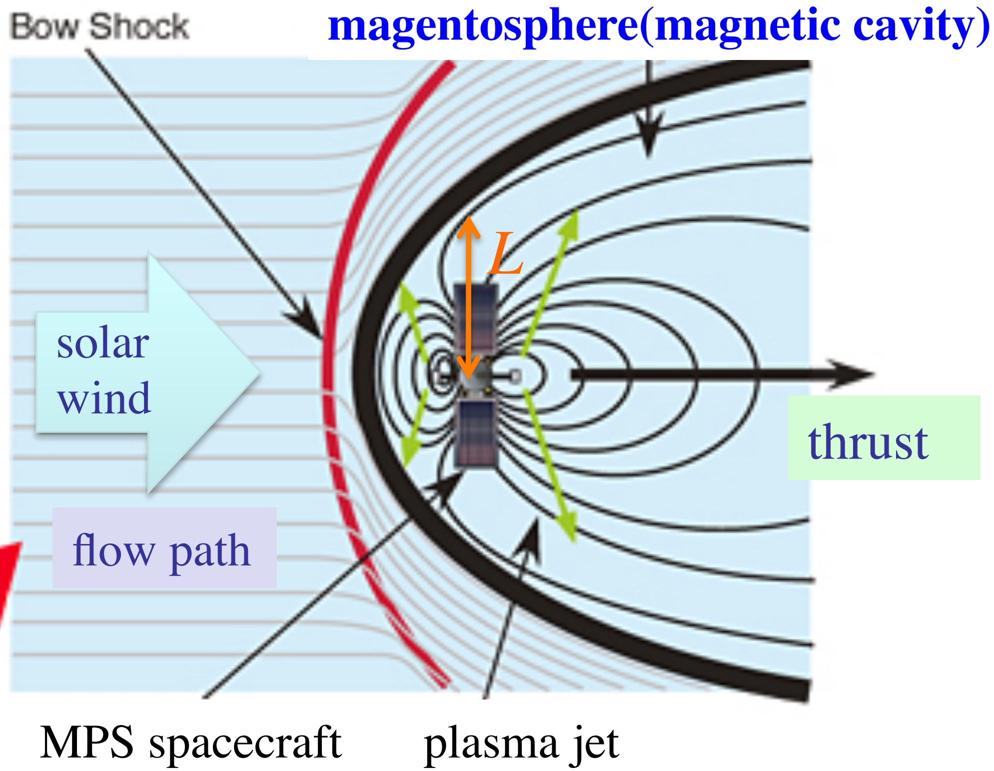


(1) B-field by coil



(2) plasma is released to inflate the magnetic field

(3) magentosphere (MPS spacecraft) is accelerated



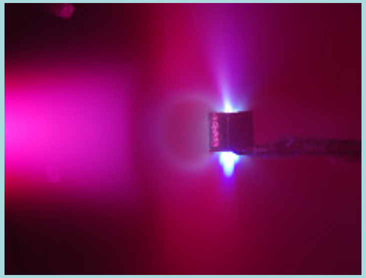
$$\text{Thrust by MPS: } F \approx C_d \frac{1}{2} \rho_{sw} u_{sw} \pi L^2 \tag{6.1}$$

Magnetoplasma Sail (MPS) Research at JAXA

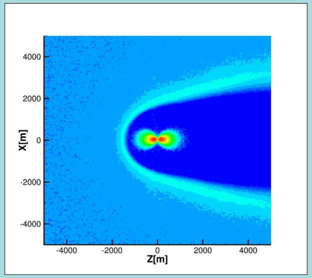
2007 2015 ~2020 ~2025

Fundamental Research ⟷ **Space Demonstration of Magsail/MPS** **Future Missions by Magsail/MPS**

1. Thrust Control Technology

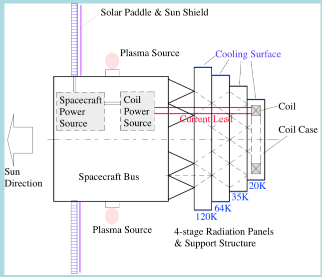


Scale-model experiment

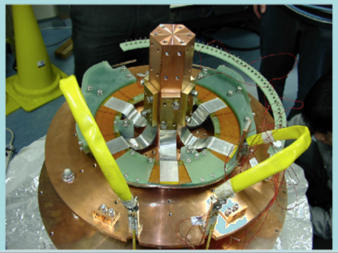


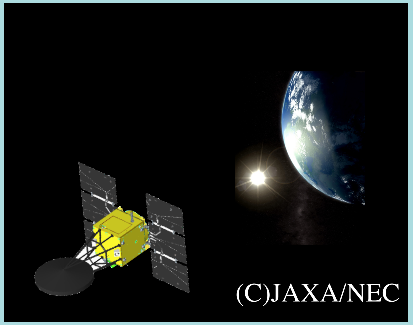
Numerical simulation

2. Conceptual Study of MPS Spacecraft



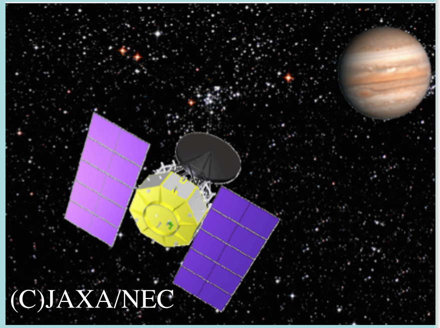
3. R&D of Superconducting Coil System





MPS Technology Space Demonstration

- Spacecraft wet mass ~300kg
- In-space testing of
  - Magsail (coil) technology
  - MPS technology thrust production capability



Deep space Mission based on Plasma Sail, 2025 or later)
–rapid Jupiter/Saturn Flyby
–rapid Solar system escape

Far Future Interstellar Mission by Sails

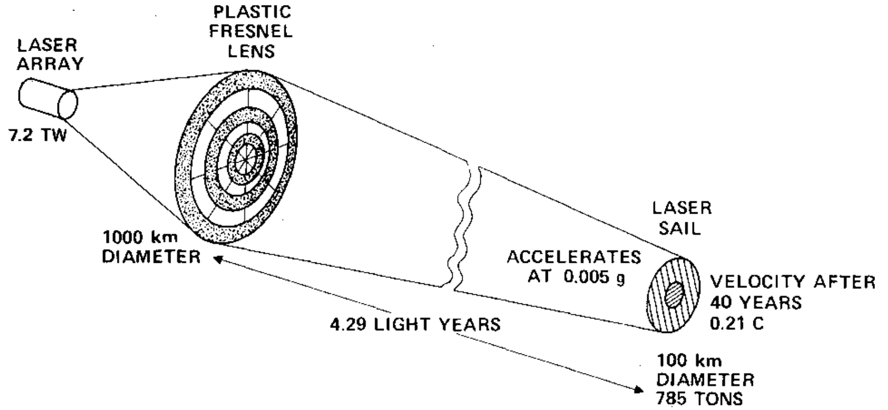


Fig. 3 Interstellar rendezvous mission-acceleration phase.

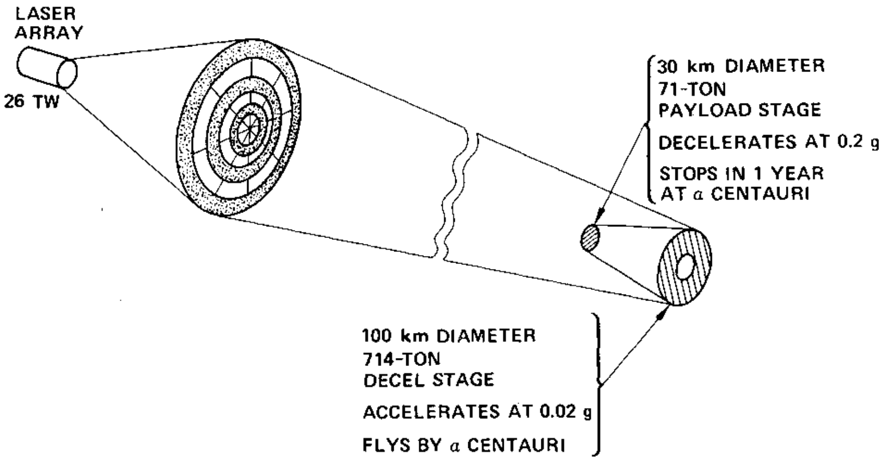
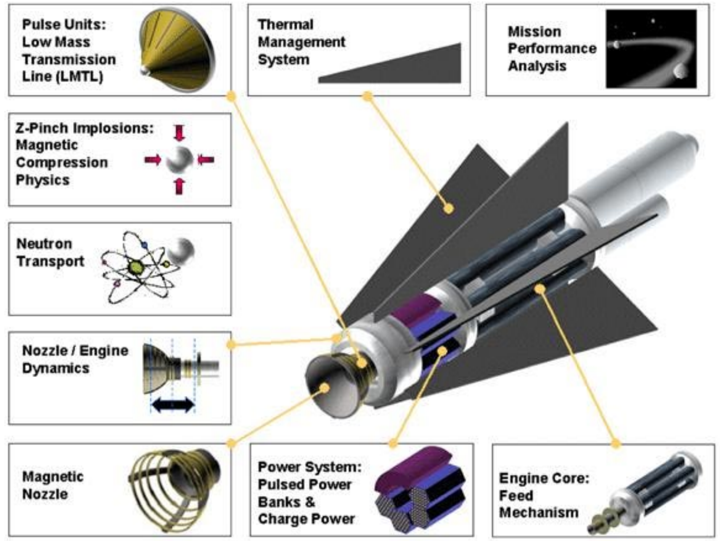
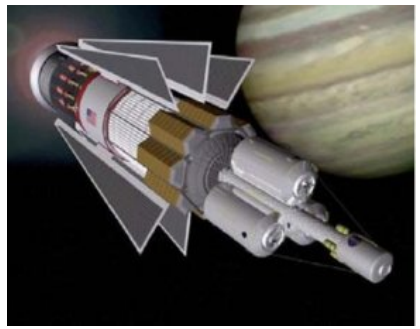


Fig. 4 Interstellar rendezvous mission-deceleration phase.

Interstellar rendezvous mission to a-Centauri using laser-pushed lightsail





The Mini-Mag Orion interstellar concept, a hybrid starship accelerated by beamed pellet propellants, and decelerated with a magnetic sail.

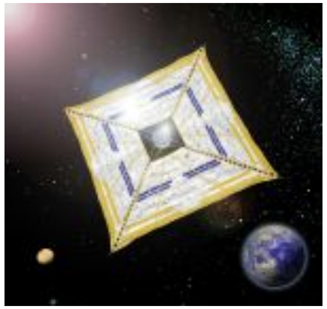
R. L. Forward (1984)

D.G. Andrew (2003/2007)

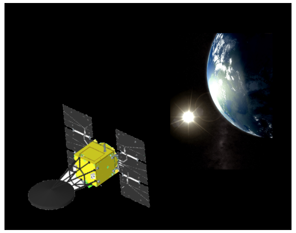
6. Summary

Sail Propulsion for Deep Space Flight is overviewed.

- **Solar Sail (thrust based on light pressure)**
  - firstly demonstrated as IKAROS by JAXA
  - Further increase in size is required for practical deep space mission
- **Magsail (thrust based on solar wind pressure)**
  - Never flew, no feasible design was shown
  - small demonstration is being proposed
  - magnetosphere deployment (or expansion) should be further studied to obtain large acceleration
- **Electric Sail (thrust based on solar wind pressure)**
  - a new concept recently proposed
  - small demonstration is in progress



IKAROS



Magsail

Electric Sail

Some hybrid/future concepts are also studied for future deep space missions