# Research of Magnetoplasma Sail (MPS): A Quick Review

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A quick review of plasma sail propulsion is provided to close up the technical and physical issues of plasma sail. A spacecraft propulsion system utilizing the energy of the solar wind was firstly proposed by Prof. Winglee in 2000. Although Winglee proposed an M2P2 (mini-magnetospheric plasma-propulsion) design with a small (20-cm-diamter) coil and a small helicon plasma source, it was criticized by Dr. Khazanov in 2003. He insisted that: 1) MHD is not an appropriate approximation to describe M2P2 design by Winglee, and with ion kinetic simulation, it was shown that the M2P2 design could provide only negligible thrust;2) considerably larger sails (than that Winglee proposed) would be required to tap the energy of the solar wind. We started our study in 2003, and it is shown that moderately sized magnetic sails can produce sub-Newton-class thrust in the ion inertial scale (~70 km). We continue our efforts to make a feasibly sized plasma sail (Magnetoplasma sail) by optimizing the magnetic field inflation process Winglee proposed. However, several physical issues (action and reaction force of the MPS, finite Larmor radius effect in the far region of the MPS, and so on) were shown to remain to be solved before we proceed to a system design of a spacecraft propelled by MPS.

JAXA/JEDI Workshop on Plasma Simulation (2006.10.2-3)

# Research of Magnetoplasma Sail (MPS): A Quick Review

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**and**
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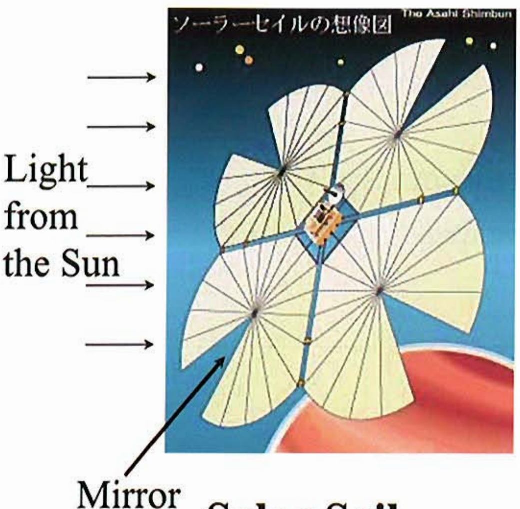
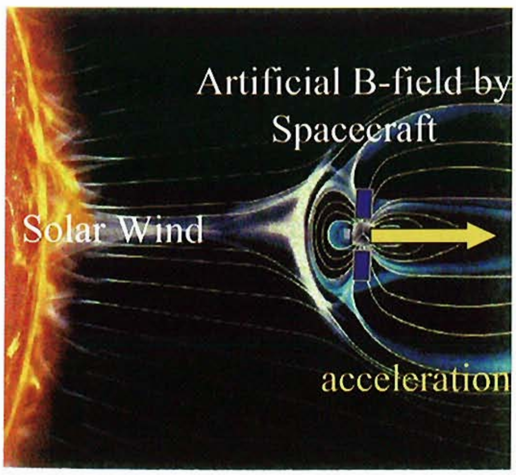
## Outline

1. Backgroud
   - Principles of MagSail and MPS (Magnetoplasma Sail)
   - Status of M2P2 (Mini-Magnetospheric Plasma-Propulsion by Winglee)
2. Goal of our MPS Research
3. Status of MPS Research in Japan
   - Numerical Simulations
   - Experiment in Vacuum Chamber
4. Summary

# 1. Background

## Spacecraft Propulsion Using Solar Energy




**Solar Sail**

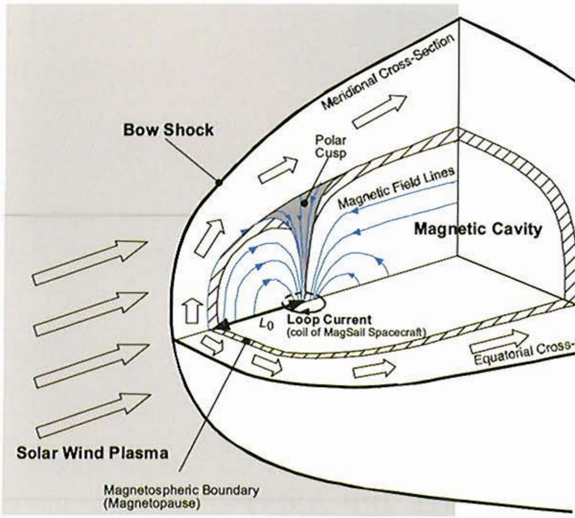
- Thrust production by light pressure
- low acceleration

**Magnetic Sail (MagSail)**

- Thrust production by the solar wind
- high acceleration for M2P2?

inflation B-field with plasma jet

# Plasma Flow of Pure MagSail and its Thrust




**Plasma Flow and B-field of MagSail**

Characteristic Length of MagSail
(Stand-off distance, $L_0$)

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

$M$:dipole moment
$nm_i u^2$:solar wind dynamic pressure

$L_0$ is derived from pressure balance:

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

Thrust of Magsail (Drag Force)

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

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

$\frac{1}{2}\rho u_{sw}^2$: solar wind dynamic pressure
$C_d$: non-dim. Thrust coefficient (a function of $L_0$, $\rho$, $u_{sw}$)

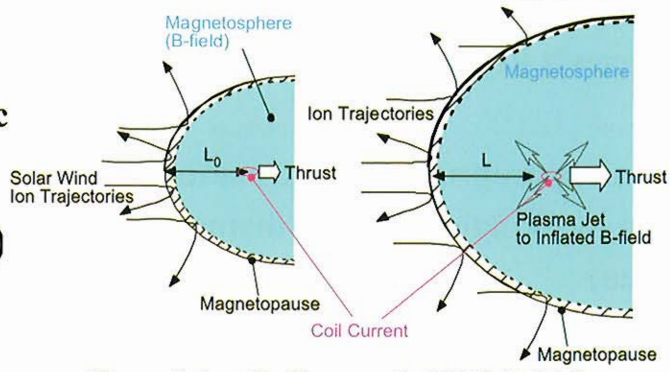
# MagSail with Plasma Jet (M2P2/MPS)

Mini-Magnetospheric Plasma Propulsion
MagnetoPlasma Sail

**Schematics of Magnetic Field Inflation:**

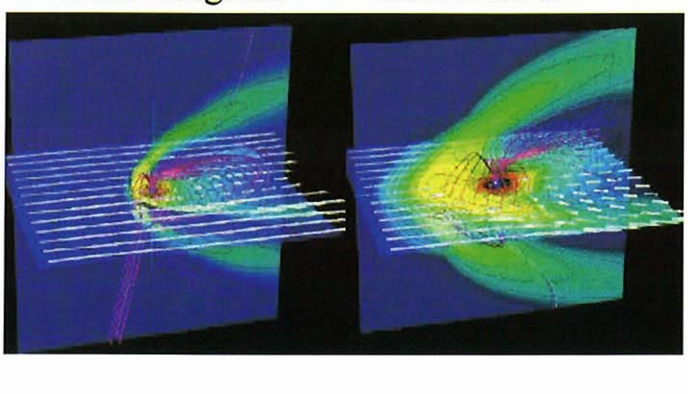
Large $F = C_d \frac{1}{2}\rho u_{sw}^2 \left(\pi L^2\right)$

by enlarging $L$



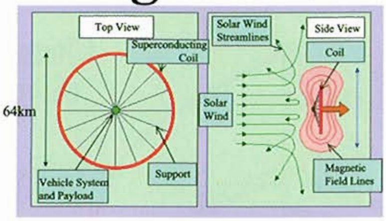

Pure MagSail M2P2/MPS

**MHD Simulation**
by Winglee (SATIF2000)

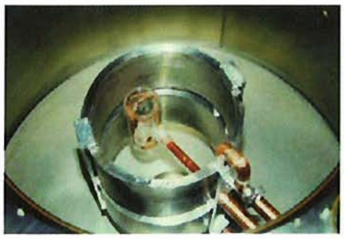


# Research History of Magnetic Sails

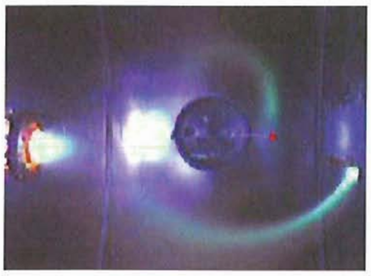
**Zubrin**(JSR1990)
First proposal of Magnetic Sail (MagSail)
20-N pure MagSail using 64-km-diameter coil




**Winglee**(JGR 2000)
Mini-Magnetospheric Plasma Propulsion (MagSail with Plasma Jet)
using 20-cm-diameter coil and high-density plasma source



**Winglee**(AIAA Conf. 2001, 2003)
Ground experiment on M2P2 prototype



**Khazanov**(AIAA Conf.2003, JPP 2005)
From numerical simulations (MHD+Hybrid)
M2P2 (Winglee's design) was denied because of its negligible thrust production.

**Slough**(AIAA Conf., 2005)
New concept: Plasma Magnet

# Controversy of Winglee's M2P2 Concept

Khazanov's Report (J. Propul. Power, 2005)

•MHD is not an appropriate approximation to describe M2P2 design by Winglee (10-cm-diameter coil with plasma source)

•With ion kinetic simulation, it was shown that the M2P2 design could provide only negligible thrust.

• *L* (stand-off distance of magnetic cavity) >> ion inertial scale (70 km), hence, considerably larger sails (than that Winglee proposed) would be required to tap the energy of the solar wind.

# 2. Goal of Our MPS Research

Design a sub-Newton-class MPS for 1000-kg-class deep space spacecraft that is suitable for a H-IIA launch by:

1. finding $L$ (stand-off distance of magnetosphere) for $F$=0.1~1N

2. clarifying thrust production mechanism of MPS

3. optimizing the magnetic field inflation process

# 3. Status of MPS Research

# Status of MagSail/MPS Research

○=Finished, △= Going on, ×= Not started yet

| Cases | Input and Output for Simulation | Numerical Simulation | | Experiment |
|---|---|---|---|---|
| | | MHD | Hybrid (ion particle, electron fluid) | Scale-model Experiment |
| Pure MagSail | $F$ for various $L_0$ ($C_d$ for various $r_{Li}/L$) | ○ | ○ | △ |
| MPS | $F$ and $L$ for various plasma jet and $L_0$ ($C_d$ and $r_{Li}/L$ for various $r_{Li}/L_0$ and $\beta_0$) | △ | × | △ |

$$F = C_d \frac{1}{2}\rho u_{sw}^2 \left(\pi L_0^2\right) \quad \text{for pure MagSail}$$

$$F = C_d \frac{1}{2}\rho u_{sw}^2 \left(\pi L^2\right) \quad \text{for MPS with } L=L(L_0, \beta_0),\ \beta_0 = \frac{1}{2}\rho_0 u_0^2 \Big/ \frac{B_0^2}{2\mu_0}$$

# Why MHD and Ion Hybrid Simulation?

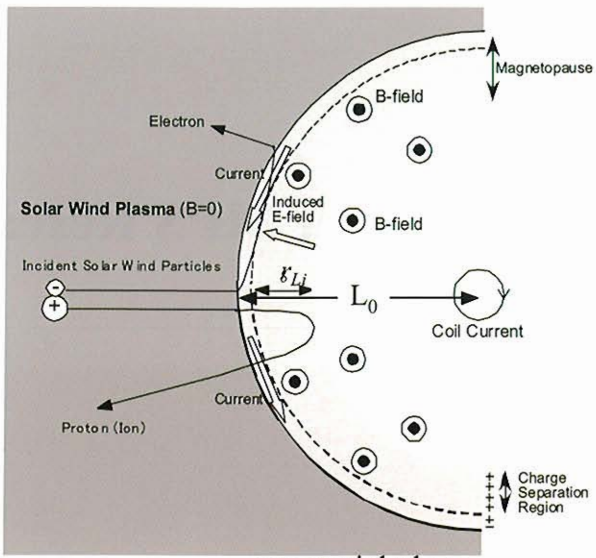
Because the solar wind and the B-field interaction is in transitional regime

Characteristic length:

1) Cavity (magnetopause) size: $L_0$
2) Skin depth of magnetopause:
$$\delta = c/\omega_p$$
3) Ion Larmor radius at magnetopause: $r_{Li} = \frac{m_i u_{sw}}{e \cdot 2B_{mp}}$ ~70 km

Non-dimensional parameters and conditions for $L_0$=10~70km:

1) $\delta/L_0 < 0.1$
2) $1 < r_{Li}/L_0 < 7$
3) Mag. Reynolds No.
$$Rm = \sigma \mu_0 u_{sw} L_0 >> 1$$
4) Mach No. $M_i = \frac{u_{sw}}{\sqrt{\gamma R T_{sw}}}$ ~8



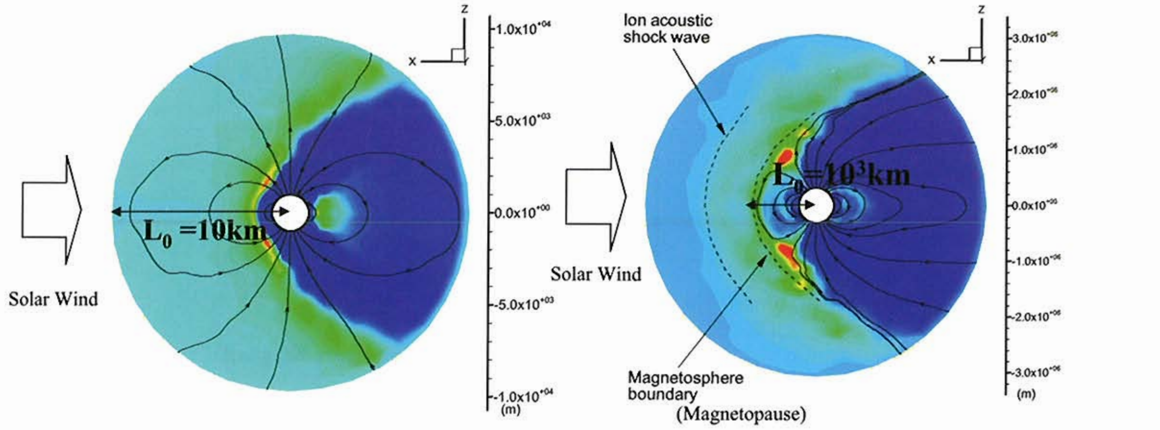

equatorial plane

**Flow around MagSail (coil current)**

charged particle behavior near magnetopause

# Plasma Flow around Pure MagSail

Hybrid plasma simulation: ion particle/electron fluid **(by K.Fujita, JAXA)**




***m*=4x10⁴ Tm³, $L_0$=10km, $r_L/L_0$=10** (at $L_0$) ***m*=4x10¹⁰ Tm³, $L_0$=10³km, $r_L/L_0$=0.1**(at $L_0$)

$r_L$: ion Larmor radius

**Distribution of Ion Number Density and Magnetic Field Lines**

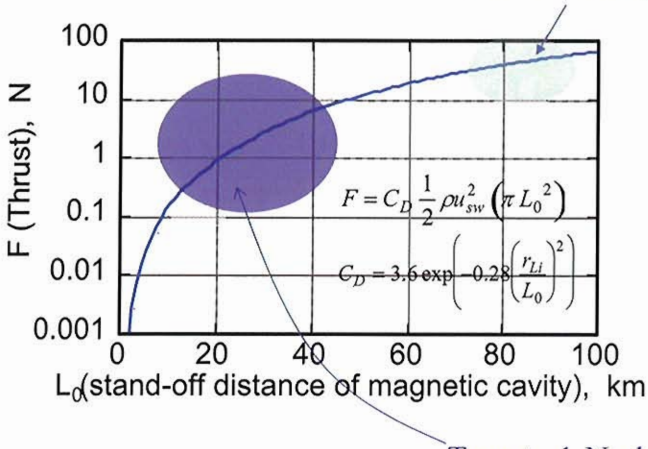
- ion trajectory deformation by **u×B**
- small interacting area << $L_0^2$
- $C_d$~ 0.5

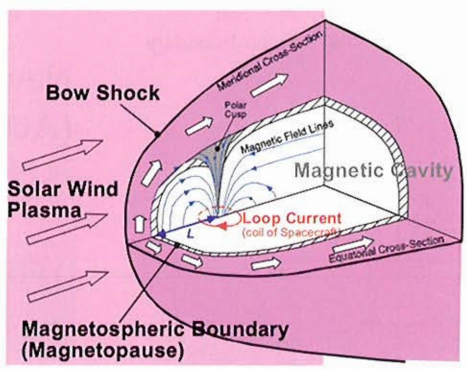
- MHD-like interaction with a shock
- interacting area ~ $L_0^2$
- $C_d$~ 3.6

# Thrust Characteristics of Magsail

**Effect of Stand-off Distance($L_0$) on Thrust($F$)**

20-N-class (Zubrin)




Definition of $L_0$

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

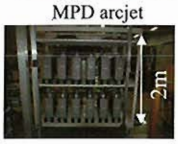
**Empirical relation between $L_0$ and thrust of MagSail ($F$)**

$C_D$ *formulation by* Fujita, J. Space Science and Technol., 2004

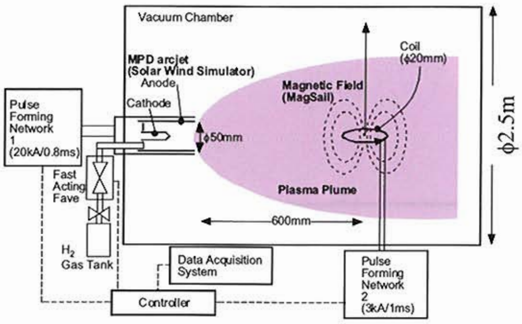
# Magnetic Sail Experimental Simulator

- scale-model experiment of 0.1-N-class pure MagSail in a vacuum chamber
- whole MPS system may be demonstrated in the future

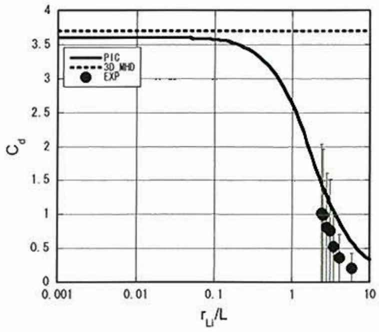

MPD arcjet



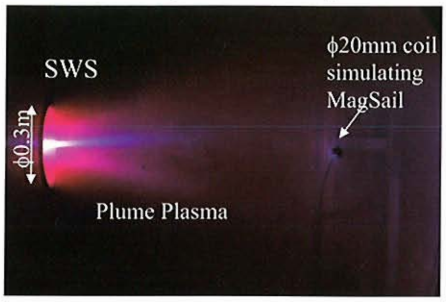

Capacitor Bank (PFN1)



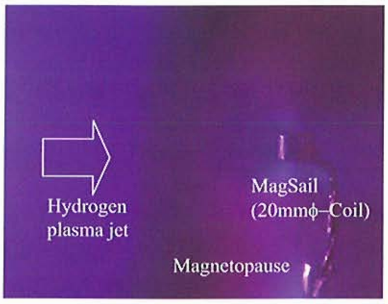

**Experimental Setup**




**$C_d$ for 0.1–1Nclass pure MagSail**



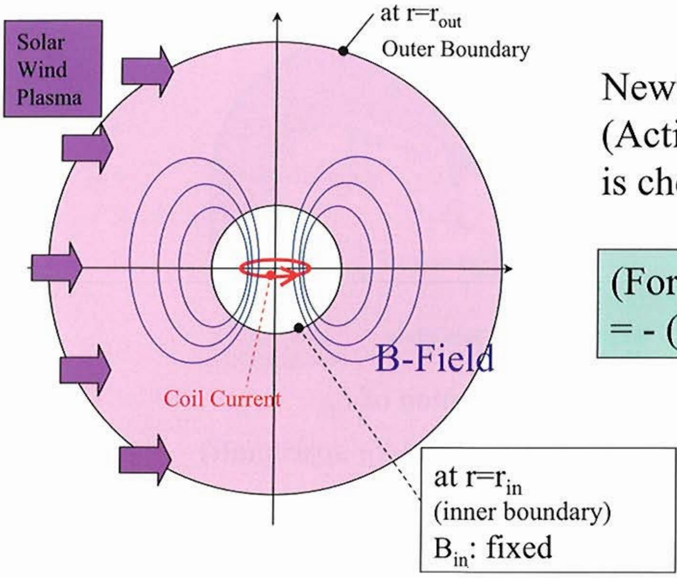

**Operation of Solar Wind Simulator and MagSail**




**Close-up view of a Plasma Flow around Coil**

$H_2$ 0.4g/s, PFN1:4.0kV, 1.9T at the coil center (plasma duration:0.8ms, density; $10^{18}$ /m$^3$, velocity: 50 km/sec)

# Calculation Region, Boundary Conditions, and Thrust Evaluation for Pure MagSail




**Region for Pure MagSail**

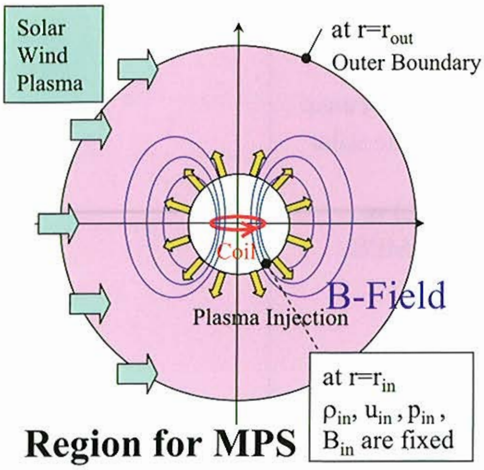
Newton's 3rd Law
(Action and Reaction Force)
is checked:

Lorentz force

(Force exerting on Coil)
= - (Force on solar wind plasma)

Drag force

## Calculation Region, Boundary Conditions, and Thrust Evaluation for MPS

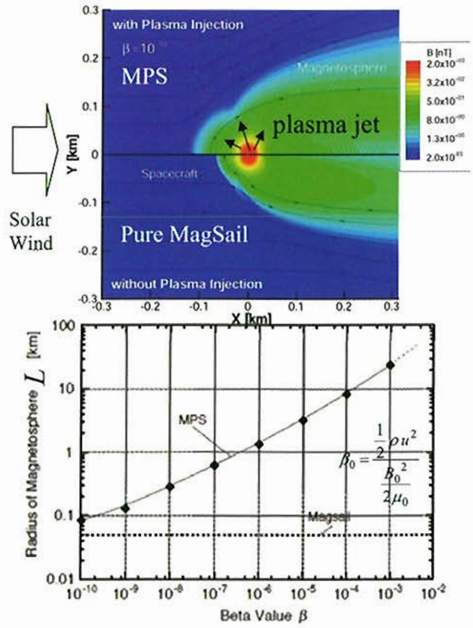



**Region for MPS**

(Force exerting on Coil)
≠ – (Force on solar wind plasma)

Newton's 3rd Law (Action and Reaction Force) is violated??

- boundary condition problem?
- divB>0 trouble?



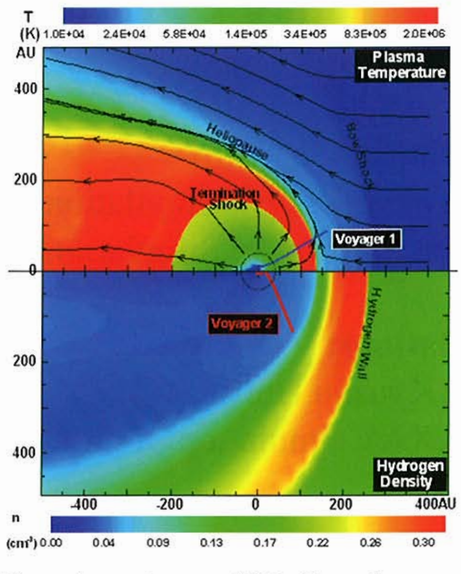

**Simulation Results of MPS and Pure MagSail (by Otsu, Shizuoka Univ.)**

## Remaining Issues of MPS Simulation

1. In our current MHD simulation, force of MPS is evaluated by the momentum change of the solar wind. "How thrust exerts on the coil current" should be answered (by precisely analyzing the magnetic field near the coil).

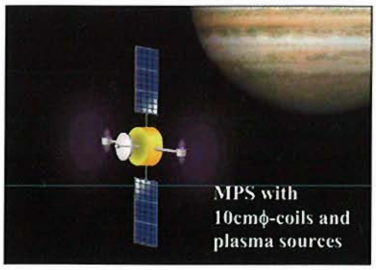
2. Far from the coil, an MHD-scale flow will transit to an ion kinetic scale. Hybrid simulation is required at least at this region far (> 1 km) from the coil.

3. Efficient and low cost way to inflate the magnetic field are under survey.




**The structure of Heliosphere:** MPS field may be analogous to Heliosphere except its small pause size ($L$~10km).

# 4. Summary

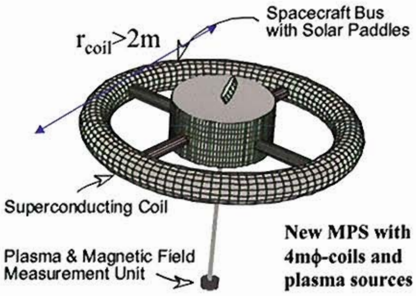



**MPS (2003) started with small coil:**

- produces only 1-mN-class thrust because of very weak coupling between the solar wind and the B-filed.
- ~10-km-radius magnetopause (*L*) is necessary for 0.1- to 1-N-class MPS.

**New MPS design (2005) with 4m-diameter coil:**

- will produce > 0.5 N for 10kW
- efficient and low-cost B-field inflation strategy is surveyed.
- two important physical issues:Newton's 3rd Law, effect of ion inertial scale physics on thrust production




# Today's Presenters

**MHD simulations:**

Mr. Nishida (Tokyo Univ.): Simulation of pure MagSail
Dr. Otsu (Shizuoka Univ.): Simulation status of MPS

**Hybrid Simulations:**

Dr. Kajimura (Kyushu Univ.):
(Dr. Fujita (JAXA): simulation of pure MagSail (when requested))