

MPS まわりの流れ場の MHD 解析の現状について

Current Status of MHD Simulation for Magneto Plasma Sail

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磁気プラズマセイル (Magneto Plasma Sail; MPS) とは、探査機まわりに磁気圏を形成し、高速のプラズマ流である太陽風を「磁場の帆」で受け止め、太陽風の動圧を推力として利用する推進システムである。本推進システムにおける推力は「帆」に相当する磁気圏の大きさに比例するため、磁気圏を拡大するために、探査機周りに形成された磁場にプラズマを噴射することにより、効率よく磁気圏を広げる方法が検討されている。本報告では、探査機周りの流れ場がどのように形成されるかを調べるために、電磁流体方程式による数値シミュレーションを行い、噴射プラズマによる磁気圏の変化や太陽風と磁場の干渉の様子を調べた。その解析結果について報告する。

JAXA/JEDI Workshop (2006/10/3)

Current Status of MHD Simulation for Magneto Plasma Sail

Hiroataka Otsu (Shizuoka University)

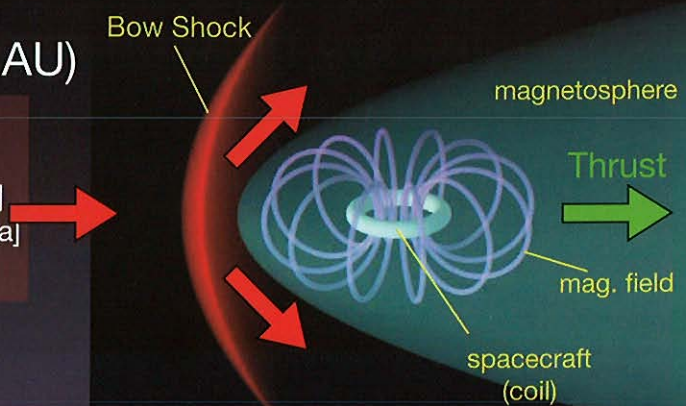
Contents

- What is Magneto Plasma Sail (MPS) ?
- Numerical Method
- CFD analysis for Mag Sail
- CFD analysis for MPS
 - Inflation of magnetic field
 - Thrust estimation
- Summary

Propulsion system utilizing the solar wind

- Solar wind(@1AU)

Gas : H^+, e^-
 Density : $5.0 [cm^{-3}]$
 Velocity : $300 \sim 500 [km/s]$
 Dynamic Pressure : $1 [nPa]$



- Thrust of Mag Sail and Magneto Plasma Sail

- Thrust is the drag force to the magnetosphere
- Thrust is transferred to spacecraft via electromagnetic effect
- Thrust = (dynamic pressure) x (size of magnetic field)

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Inflation of Magnetic Field

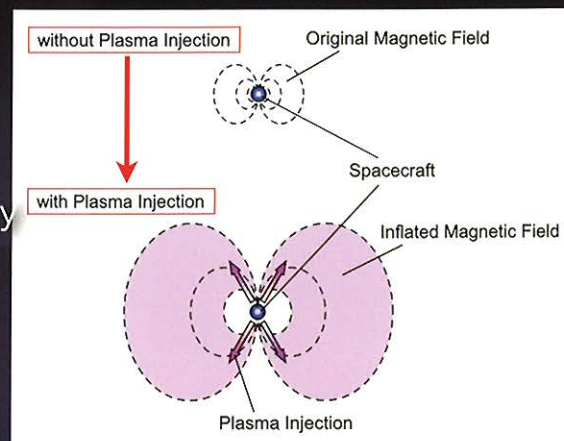
- Mag Sail

- Magnetic Field by Coil only
- Very large coil is necessary



- Magneto Plasma Sail

- Magnetic Field is inflated by injected plasma
- Large coil is not necessary



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Previous Works

MHD Simulation

- Interaction between solar wind and magnetic field for Mag Sail
- Inflation of magnetic field without solar wind

No results for interaction between
the solar wind
and
the **inflated** magnetic field

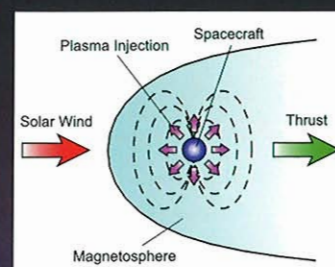
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Objective

- 3-dimensional MHD simulation for MPS
Interaction + Inflation



- Effect of Injected Plasma
 - Dimension of magnetosphere
 - Thrust estimation



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Governing Equation

- Ideal MHD equation
- Magnetic field is separated into two parts
 - Initial magnetic field B_0
 - Induced magnetic field B'
 - Total magnetic field $B = B_0 + B'$

$$\frac{\partial}{\partial t} \begin{bmatrix} \rho \\ \rho u \\ B' \\ E_t' \end{bmatrix} + \nabla \cdot \begin{bmatrix} \rho u u + (p + \frac{B' \cdot B'}{2})I - B' B' \\ u B' - B' u \\ (E_t' + p + \frac{B' \cdot B'}{2})u - (u \cdot B')B' \end{bmatrix} + \nabla \cdot \begin{bmatrix} 0 \\ (B_0 \cdot B')I - (B_0 B' + B' B_0) \\ u B_0 - B_0 u \\ (B_0 \cdot B')u - (u \cdot B')B_0 \end{bmatrix} = -\nabla \cdot B' \begin{bmatrix} 0 \\ B \\ u \\ u \cdot B' \end{bmatrix}$$

Density : ρ Velocity : u Pressure : p Heat Ratio : γ

time : t Energy : $E_t' = \frac{p}{\gamma - 1} + \frac{1}{2} \rho u \cdot u + \frac{B' \cdot B'}{2}$

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Numerical Method

- Numerical Flux
 - Lax-Friedrich Scheme
 - MUSCL (Cubic Limiter)
- Time Integration
 - Euler Explicit Method
 - Local Time Step
- $\nabla \cdot B = 0$ constraint
 - 8-wave Formulation
- Specific Heat Ratio $\gamma = 5/3$

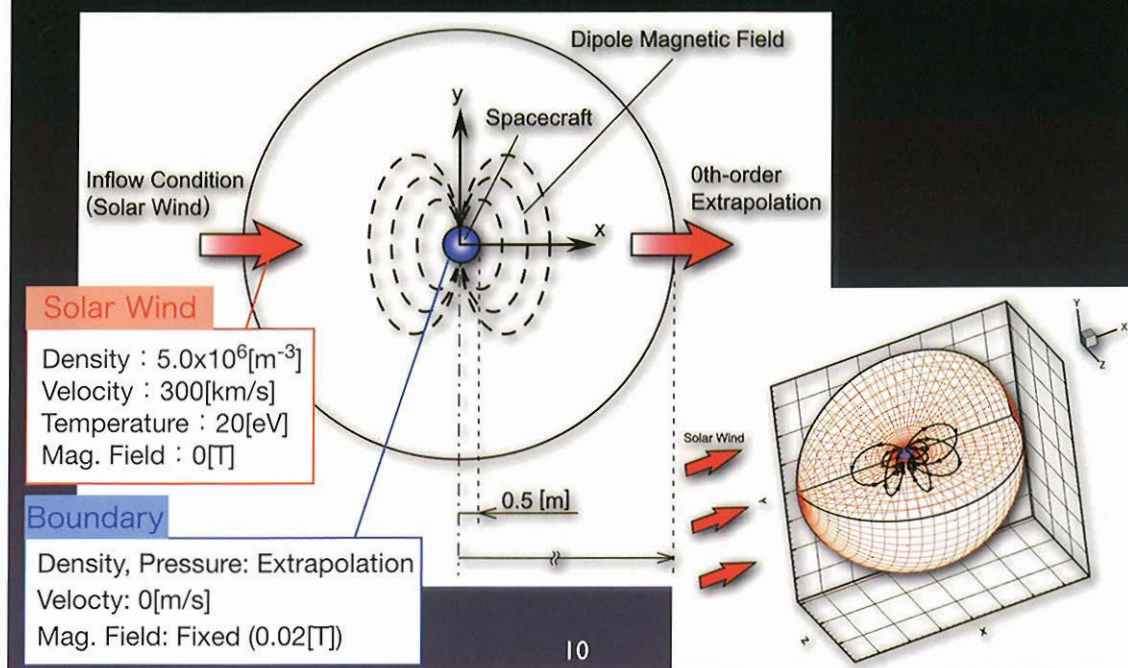
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without Plasma Injection

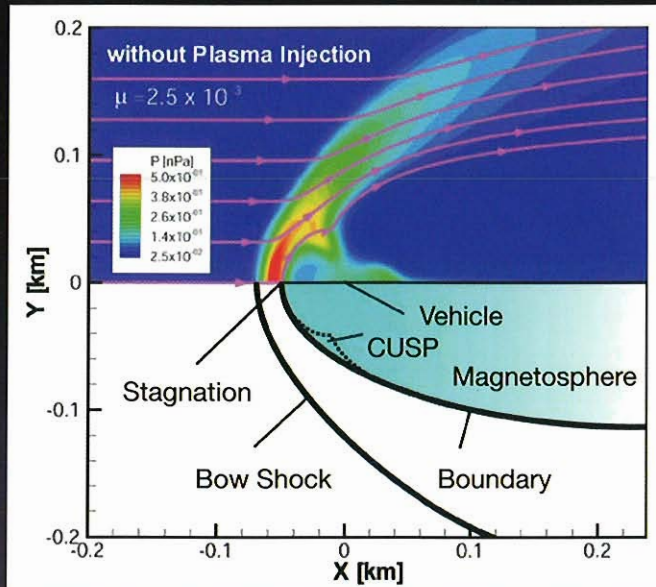
Flow field around Mag Sail (Assessment of Numerical Method)

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Calculation condition



Flow field around Mag Sail



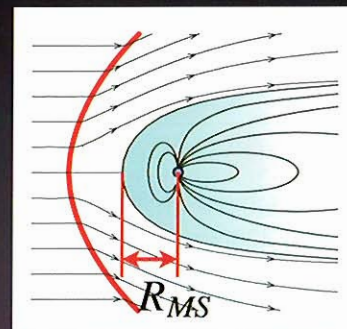
Flow field which is similar to the interaction between the Earth and the solar wind can be reproduced qualitatively.

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Quantitative Assessment

- Radius of Magnetosphere

	RMS [km]
CFD	0.0499
Theory	0.0486



Good agreement between CFD and theory!

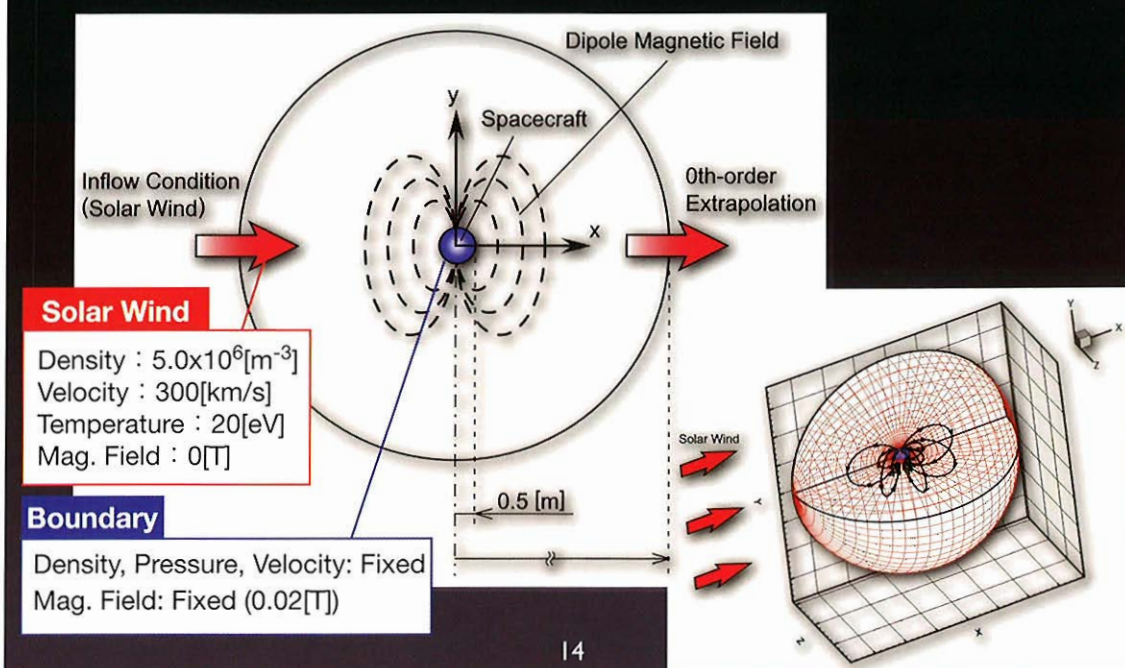
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with Plasma Injection

Flow field around Magneto Plasma Sail

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Calculation condition



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Injected Plasma

Ion	Ar ⁺
Velocity	4.0[km/s]
Temp.	20,000[K]
Mach	1.1
Beta	$10^{-10} \sim 10^0$

Mag. Field at Surface : 0.02[T]

$$\beta = \frac{\text{Dynamic Pressure}}{\text{Mag. Pressure}} = \frac{\frac{1}{2}\rho u^2}{\frac{B^2}{2\mu_0}} \propto \rho$$

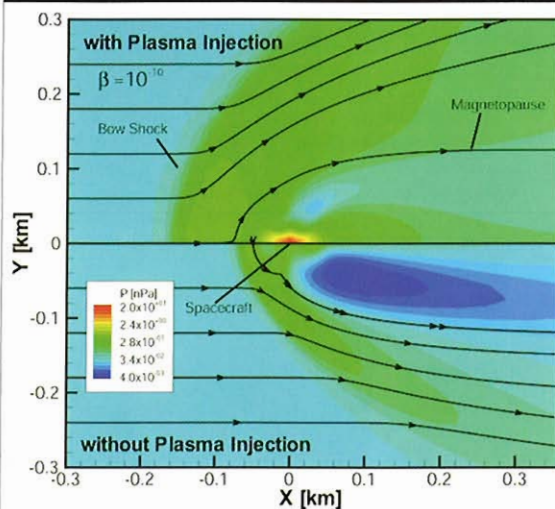
Beta value	10^{-10}	\sim	10^0
Density [m ⁻³]	3.0×10^{10}	\sim	3.0×10^{20}
Pressure [Pa]	1.6×10^{-8}	\sim	1.6×10^2

ρ : Density
 u : Velocity
 B : Mag. Field
 μ_0 : Permeability

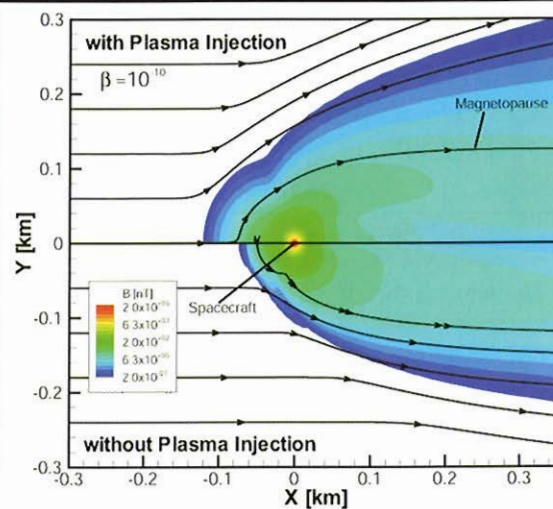
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Effect of Plasma Injection on Flow field

Pressure

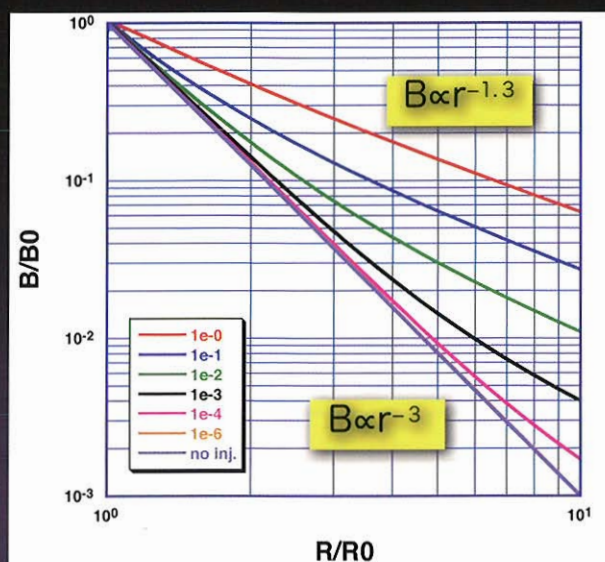


Magnetic Field



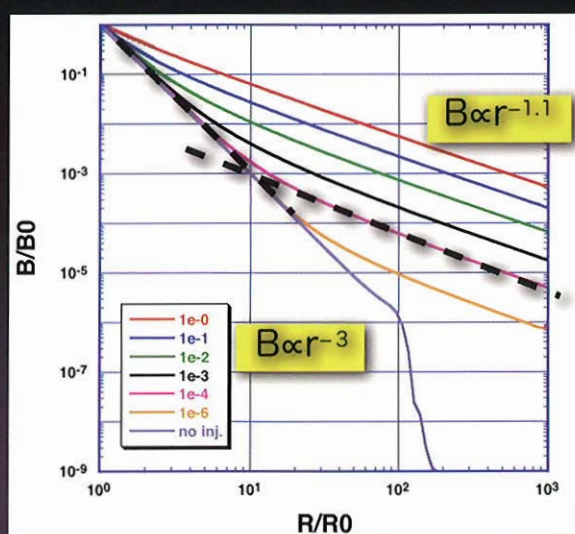
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B-Field Strength near spacecraft



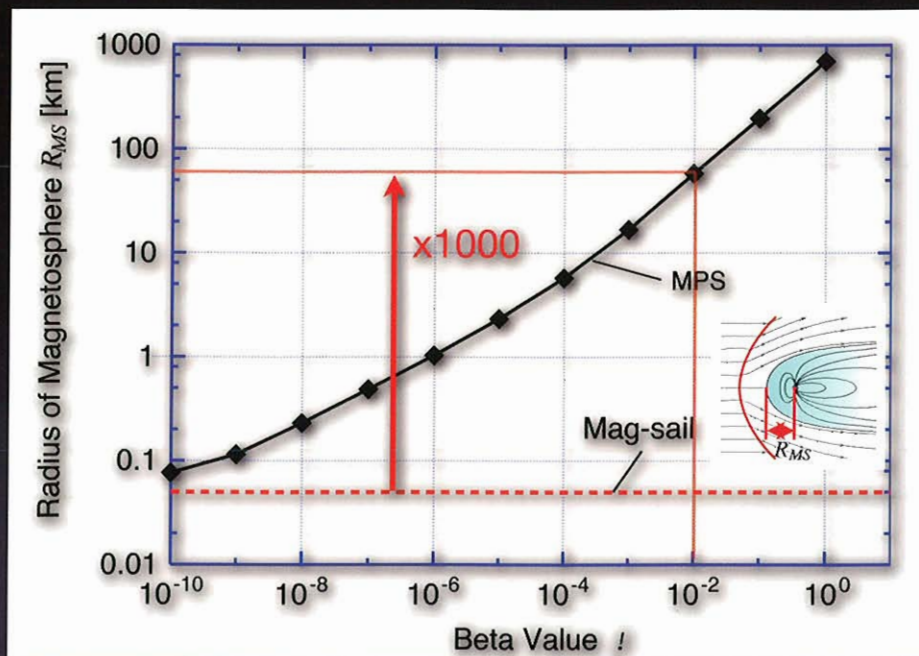
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B-Field Strength far from spacecraft



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Size of Magnetosphere



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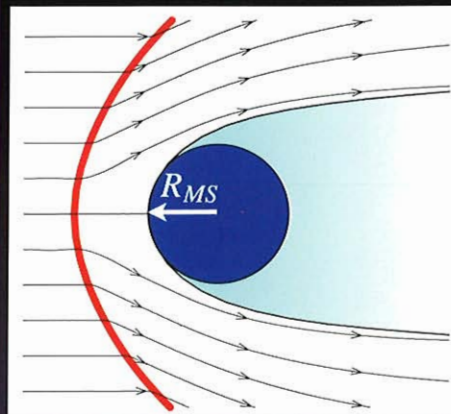
Thrust Estimation

Drag to the sphere

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

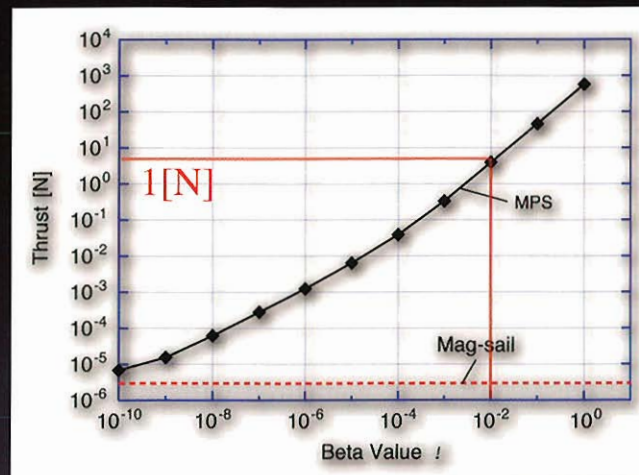
- Drag coefficient for sphere
 $C_D = 1.0$
- Frontal Area of magnetosphere
 $S = \pi R_{MS}^2$
- Dynamic pressure of solar wind

$$\frac{1}{2} \rho_{sw} u_{sw}^2 = 0.4 \text{ [nPa]}$$



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Thrust and beta value



Thrust of 1 [N] with $\beta=10^{-2}$ is achieved

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Summary

3 dimensional MHD simulation for MPS including inflation of the magnetic field by the plasma injection is performed and the thrust of MPS is also estimated.

- Our numerical method was assessed for the case of Mag Sail.
- Magnetosphere can be inflated by the plasma injection
- The size of magnetosphere is dependent on beta value of the injected plasma.
 - ▶ Rms ($\beta=10^{-2}$: x1000)
 - ▶ Thrust ($\beta=10^{-2}$: 1[N])

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