Feasibility Study of Magnetoplasma Sail

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Abstract: To propel a spacecraft in the direction leaving the Sun, a magnetic sail (MagSail) produces a large-scale magnetic field to block the hypersonic solar wind plasma flow. Based on some theoretical evaluations, a MagSail with plasma jet, consisting of a 10-m-diameter coil and a high-density plasma source, can efficiently increase the size of the magnetic field of the MagSail; hence this concept, what we call Magnetoplasma sail, is shown feasible from both theoretical and engineering point of view. Ultimate performance of the MPS spacecraft and necessary resources to construct it, however, are still under discussion. Accordingly, magnetoplasmadynamic thrust production process as well as spacecraft design should be optimized to realize a fast trip to the outer planes, which requires both high specific impulse and large thrust to power ratio.

I.   Introduction

To drastically shorten the mission trip time to deep space, some new in-space propulsion systems are proposed. High priority candidates are: 1) next generation ion thruster which features high specific impulse (*Isp*) of more than 5,000 s, 2) sail propulsion utilizing the energy of the Sun, and 3) aerocapturing/breaking systems, which are expected to be used in combination with high-performance ion thrusters or the sails if you want to put an orbiter to the outer planets. Among the sail propulsion systems, solar sails are intensively studied by both NASA and JAXA targeting at future deep space missions.(Ref.1,2) Unfortunately, acceleration of the solar sail is usually small due to heavy materials used for the sail, hence it is difficult to shorten the mission trip time in particular for the missions within our solar system. To overcome this difficulty, a magnetic sail (usually abbreviated as MagSail) is proposed by Zubrin(Ref.3,4,5) because it is expected to achieve high thrust per weight by capturing the momentum of the solar wind. After deploying large but thin wires, the MagSail captures the solar wind momentum by a magnetic field artificially produced around a spacecraft as in Figure 1 a). Although the MagSail requires a large

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hoop coil, Winglee proposed an idea to use a very compact coil to obtain a large MagSail; he proposed to inflates a weak original magnetic field made by a small coil of about 0.1 m in diameter with an assistance of a high-density plasma jet. (Figure 1b, Ref.6) This idea, Mini-magnetospheric Plasma Propulsion (M2P2), is very attractive from the engineering point of view since no large structure is required.[7]

Although the feasibility of this compact M2P2 design is denied by several researchers, we revised the M2P2 design by changing the coil to moderate sizes of 10 to 100 m in diameter to efficiently enlarge the blocking area.[8] Such revised systems, which we call Magnetoplasma Sail (MPS), still has some both technical and physical issues to be clarified; some of them are discussed in this article, and based on the following performance estimation model, we derived a hopeful magnetic and plasma jet configuration suitable for MPS.
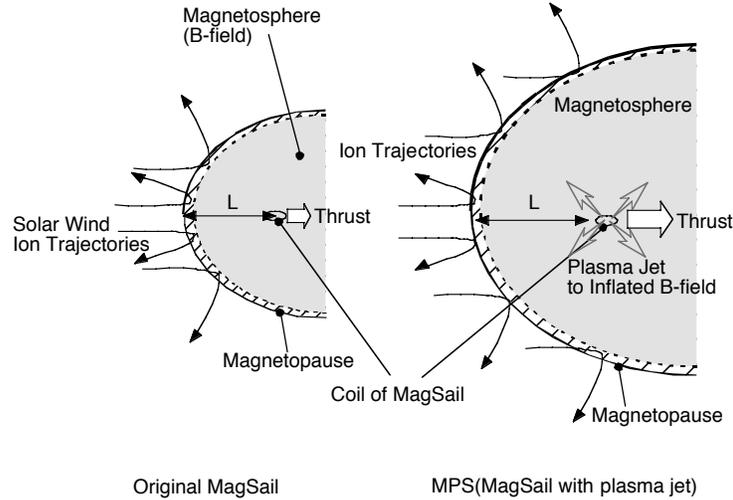
Figure 1. Schematics of Magnetic Sail (MagSail) and Magnetplasma Sail (MPS)

II.   Principle of Magnetoplasma Sail and its Technical Problems

Force on the current loop of a Magsail or an MPS depends on the area blocking the solar wind. By increasing the size of the magnetosphere, large blocking area hence large thrust is available. Force on the MagSail is therefore formulated as,

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

where C_D is thrust coefficient, $1/2\rho u^2$ is the dynamic pressure of the solar wind, and S is the representative area of the magnetosphere. In Eq.(1), $\rho=mn$ is the density of the solar wind, u_{sw} the velocity of the solar wind. Defining characteristic length of the magnetosphere, L, so that $S=\pi L^2$, correlation between L and F is derived. One may calculate that for $C_D=0.5$, about $L=10$ km is required to obtain 1 N, which will be suitable for a 1-t-class deep space explorer.

A. The Effect of Magnetopause Dimension on Momentum Transfer from the Solar Wind to MagSail

The schematics of interactions between the magnetic field around a spacecraft and the solar wind was depicted in Figure 1. Owing to very low-density solar wind plasma flow, the plasma behaves as collision-less particles, whose movement separates the region between the plasma and the magnetic field (Figure 2). A close-up view of a magnetospheric boundary is plotted in Figure 2a. If a stream of solar wind electrons and ions impinges on a plane magnetic boundary, the ions will penetrate more deeply into the magnetosphere than the electrons because of the greater mass. This produces charge separation, and because a plasma tends to maintain neutrality, a polarization electric field is set up, thus restraining the ions. Ions are returned by this strong polarization electric field before the ions are deflected by the magnetic field. The electrons, however, experience the Lorentz force and gain energy in the polarization field.

The thickness of charge separation, δ, is an important parameter to describe the scaling law of the magnetic sail. Here, δ is expressed as,

$$\delta = \frac{c}{\omega_p} \qquad (2)$$

where c is the light velocity, and ω_p the plasma frequency. The size of the magnetic cavity, L, can be controlled by changing a or B_0 in eq. (4); hence, the parameter δ/L can also be controlled.

Using Figure 2a, another scaling parameter r_{Li}/L, ratio of ion Larmor radius to L is also explained. The ion Larmor radius, r_{Li} is defined as

$$r_{Li} = \frac{m\, u_{sw}}{e B_{mp}} \qquad (3)$$

where B_{mp} is the magnetic flux density at the magnetospheric boundary, and e is the electronic charge. Figure 2b shows the scaling parameters for various L at 1 AU (plasma density, 10^6 m^{-3}, velocity, 400 km/s). For small L values around 1 km, thick magnetopause develops and δ is comparable to L. In this thick magnetopause mode, the effective area that reflects ions is smaller than L as illustrated in Figure 3. Only part of the ion's momentum will be transferred in the thick magnetopause mode, so small C_D values are expected. To efficiently reflect the incident ions, the magnetopause should be thin, hence $\delta/L << 1$ is required for the MagSail. In this thin magnetopause mode, all the ions are reflected back at very thin magnetopause by the induced electric field. Numerical hybrid simulations support this discussion, and relatively large C_D values are available for thin magnetopause mode(Figure 4). In contrast, if the magnetopause develops, almost all ions enter into the field near the coil (Figure 3b, left); in this case, the ions exchange momentum only by the Lorentz force, $u \times B$. For $L >> r_{Li}$, the field is expected to behave like a fluid, and Semi-MHD mode is defined in Figure 2b.

a)microscopic view of the magnetopause

b) scaling parameters for various L at 1 AU
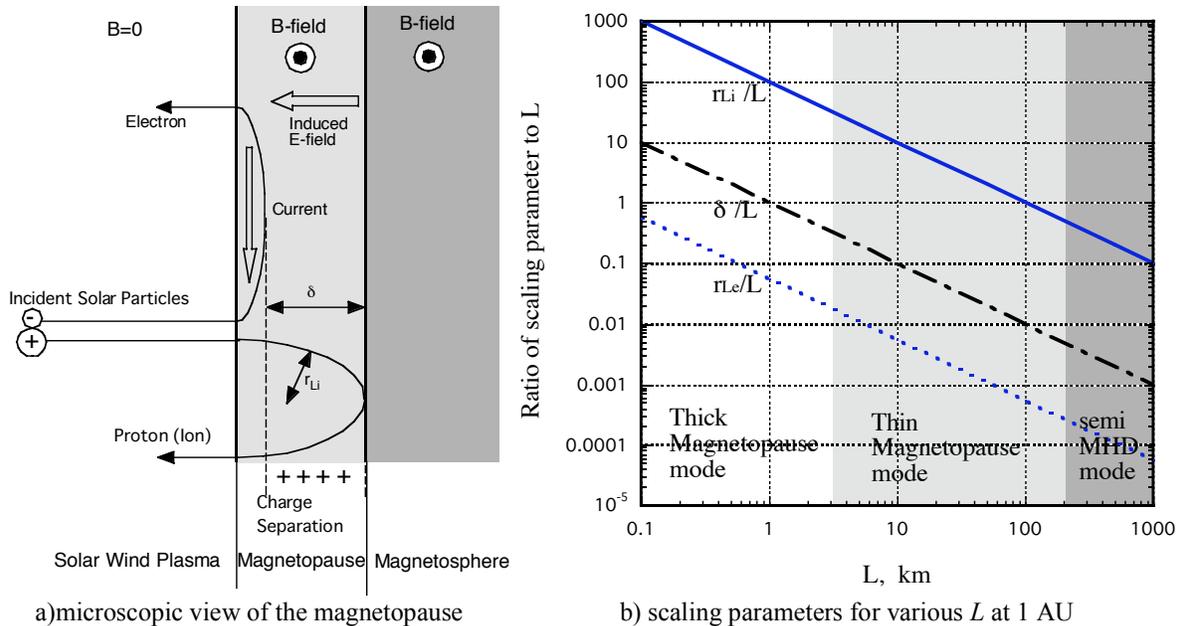
Figure 2. Scaling parameters of MagSail.
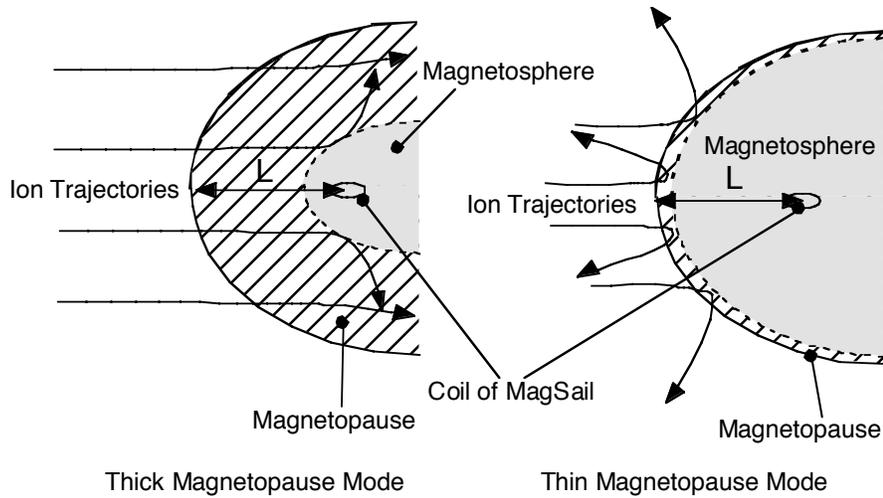
Figure 3. Operational modes of the original MagSail.

Thrust coefficient, C_D, is quantitatively obtained by hybrid simulation. In Ref.9, the thrust coefficient was found to be fitted by

$$C_D = 0.36 \exp\left(-0.28 R_L^2\right) \text{ for } R_L < 1 \tag{4a}$$

or

$$C_D = \frac{3.4}{R_L} \exp\left(-\frac{0.22}{R_L^2}\right) \text{ for } R_L \geq 1 \tag{5b}$$

where $R_L = r_{Li}/L$ is the ratio between the ion Larmor radius at the magnetopause and the magnetopause size. In Figure 4, the drag coefficient is plotted using above formula. The drag coefficient is found to decrease to 0.5 at r_c =15 km, and to 0.1 at r_c=3 km approximately.
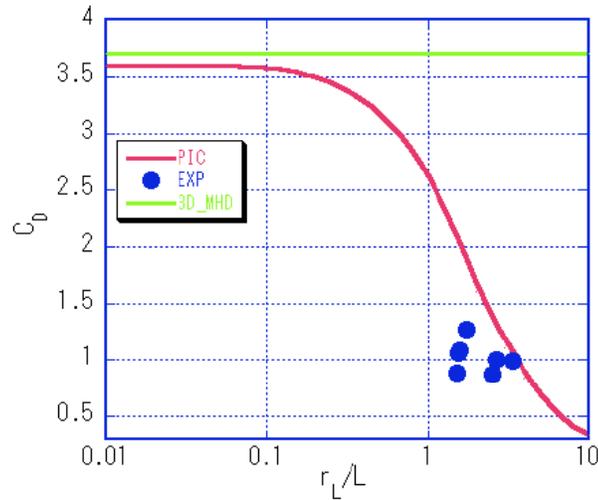
Figure 4. Thrust coefficient C_D of MagSail; C_D obtained by MHD code,[10] hybrid code,[9] as well as experiment[11,12] are plotted.

B. Enhancement of Thrust by Magnetic Field Inflation

To complement the weak B-field produced by a coil, plasma jet from near the coil is effective. This is demonstrated by some numerical investigations. For example, Figures 5 and 6 showed the B-field was successfully inflated to enlarge the magnetopause size, L, resulting in increased thrust.

However, before practical application of this B-field inflation technology, we need to obtain the maximum performance of MPS, that is, to clarify the limit of thrust to power ratio (T/P) and Isp available by MPS. In spite of many numerical investigations, a configuration that can obtain both high T/P and high Isp is not proposed yet. In the next chapter, establishing a performance model of MPS, we try to find a better design point of an MPS configuration.
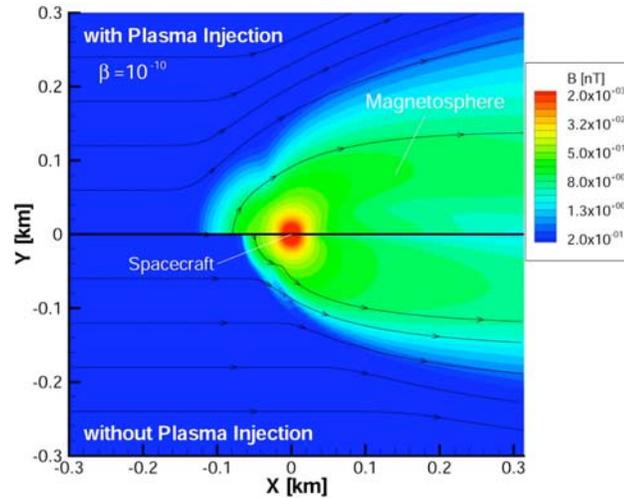
Figure 5. MPS analysis[7]; Distribution of the streamlines of the solar wind and the static pressure around the MPS spacecraft.

a)   b)
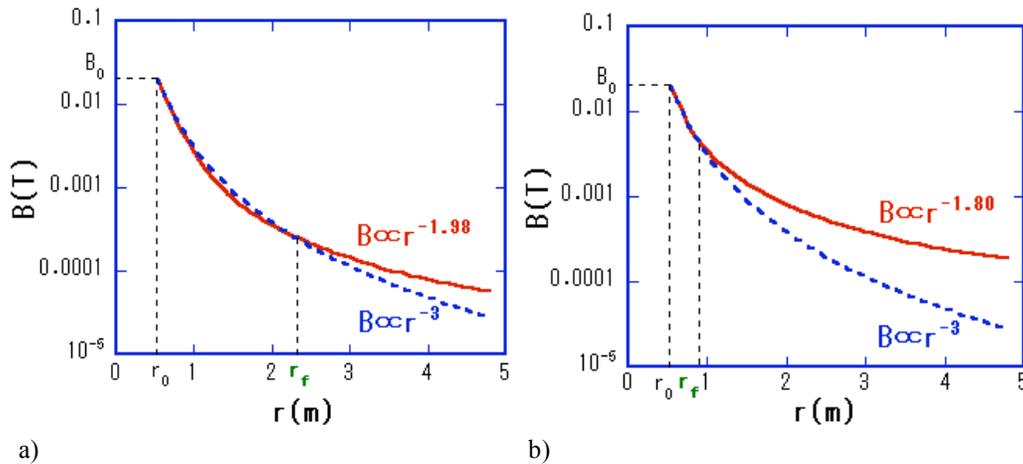
Figure 6. Near-field analysis of inflated B-field; (β_0=10^{-3},B_0=0.02T (a), β_0=10^{-1},B_0=0.02T (right), dotted lines are original b-field, and r_f is where the inflated field will depart from the original field

III.   Model Analysis of Magnetoplasma Sail Performance

A. Model of Inflated B-Field and its Interaction with the Solar Wind

The limitation of the magnetic field inflation is due to the pressure equilibrium between the magnetic pressure and the solar wind static pressure. Defining the position of the pressure equilibrium as r_b and the magnetic flux density at $r=r_b$ as B_b, the ultimate size of the magnetic field can be derived from the equation of pressure balance (6) and the equation of inflated magnetic field (7) and (8) by substituting n and r_f calculated in Ref.13,

$$\frac{B_b^2}{2\mu_0} = n_{sw} k T_{sw} \tag{6}$$

$$B_b = B_f \left(\frac{r_f}{r_b}\right)^n \tag{7}$$

$$B_f = B_0 \left(\frac{a}{r_f}\right)^3 \tag{8}$$

where n_{sw} and T_{sw} are the solar wind number density and temperature, respectively. k is the Boltzmann's constant. r_b calculated from equation (6) to (8) is the maximum radius of the magnetic field, hence the maximum cross section of the magnetic field can be written as follows.

$$S = \pi r_b^2 \tag{9}$$

Thus the thrust can be conducted from (1) and (9) by substituting C_D calculated in the previous chapter.

In addition, the electrical power to produce the injected plasma cam be calculated from the plasma parameters using the following equation.

$$\eta P_{wr} = \left(\frac{1}{2}\rho_{in}U_{in}^2 + \frac{n_{in}kT_{in}}{\gamma - 1}\right)U_{in}A \tag{10}$$

where η is the efficiency of the plasma production and acceleration, γ the Specific Heat Ratio, A the area of the plasma injection. ρ_{in}, U_{in}, n_{in}, and T_{in} represent the injected plasma density, velocity, number density, and temperature, respectively. Therefore, the other performance value of the MPS, thrust to power ratio, can be obtained from F/P_{wr}.

B. Derivation of MPS Performance

Magnetic field inflation is possible, but it is only in the framework of the ideal MHD model. If the MHD condition breaks down, and the radius of ion gyration becomes large, the injected plasma flow leaves the magnetic field of the MPS sail without inflating the magnetic field because the coupling between the magnetic field and the plasma is weak. Paying attention to this MHD condition, we carefully conducted an MHD analysis and clarified the structure of the inflated field. As shown in Figure 6, to drastically inflate the field, high-β plasma injection is preferred, however, since the power required to inflate the B-field also increases, 'inflation efficiency' are not good for the cases with high-β plasma injection. This is clearly seen in Figure 7; low-β plasma jet is preferred as long as thrust performance is concerned.

Another important characteristic of MPS is its dependence on the reference size, r_0. At a point of the reference size, a moderate B-field of about 0.02 T is required because weaker B-field as 0.002 T result in very high Isp and T/P but only small thrust below 10 mN. To make the 0.02-T-classs B-field at the reference point, r_0, a coil of 10-m-diameter or large should be located at the center of the MPS spacecraft. To simultaneously obtain Isp>3,000 s and T/P>100 mN/kW, r_0>10m is necessary; to suppress the size of the coil, a superconducting coil of about 1 T at its surface will be required.
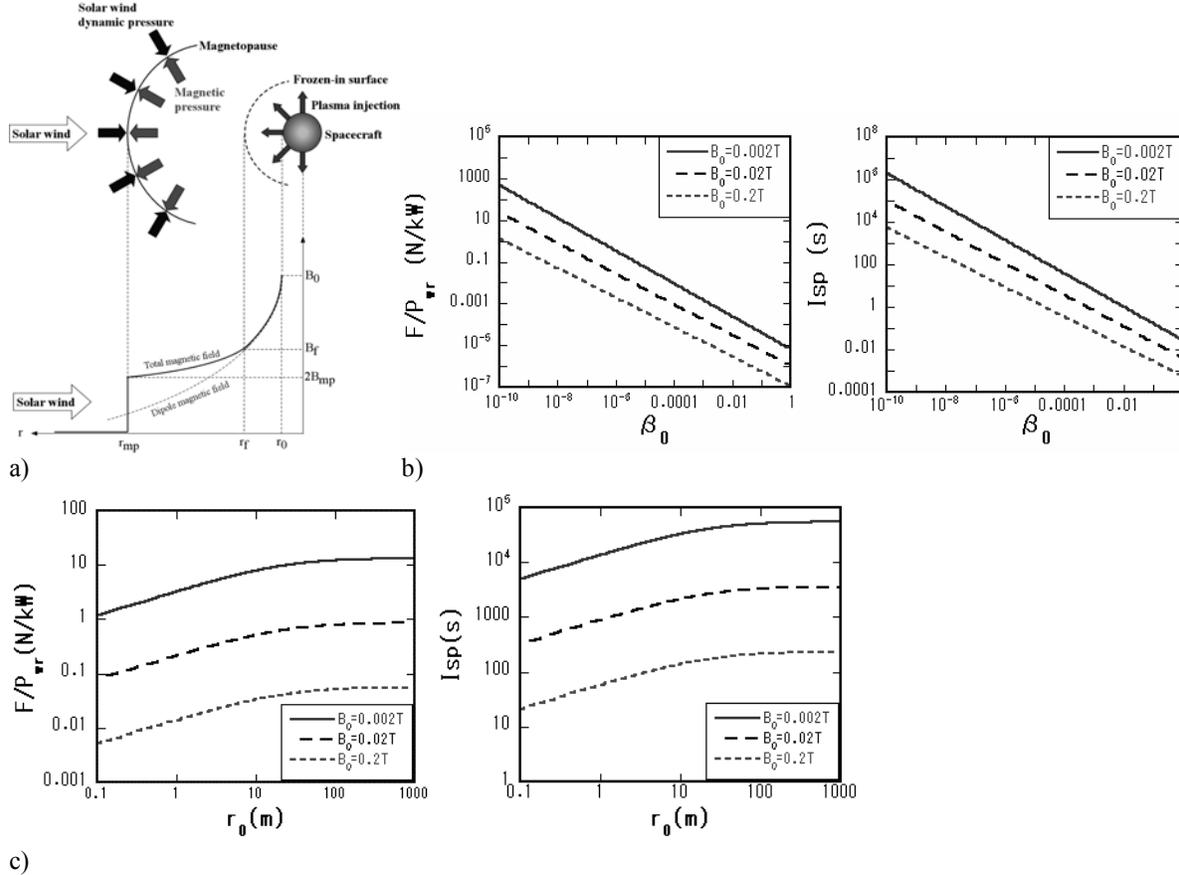
Figure 7. Performance estimation of MPS; a) configuration, b) *Isp* and *T/P* dependencies on β_0, c) effect of the reference size, r_0 ($\beta = 10^{-8}$ at r_0).

IV. Summary

The original M2P2 concept advocated a very compact configuration with a coil of 0.1m in diameter and a 3-cm-diamter helicon plasma source. Although many papers insist that the magnetic field inflation based on such a weak magnetic field generates only negligible thrust, the analyses derived by Asahi indicate that the revised M2P2 (MPS) with a over 10-m-diameter coil can produce a strong interaction between the inflation plasma and the magnetic field under the satisfied condition of $r_{Li} << L$.

Acknowledgments

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