# Research Status of Sail Propulsion Using the Solar Wind

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A spacecraft propulsion system utilizing the energy of the solar wind was reviewed. The first plasma sail concept was proposed by Prof. Winglee in 2000, and that was called M2P2 (mini-magnetospheric plasma-propulsion). However, the first M2P2 design adopting a small (20-cm-diamter) coil and a small helicon plasma source design was criticized by Dr. Khazanov in 2003. He insisted that: 1) MHD is not an appropriate approximation to describe the 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 plasma sail study in 2003, and it was shown that moderately sized magnetic sails in the ion inertial scale (~70 km) can produce sub-Newton-class thrust. Currently, we are continuing our efforts to make a feasibly sized plasma sail (Magnetoplasma sail) by optimizing its physical processes and spacecraft design.

Keywords: spacecraft propulsion, sail propulsion, plasma Sail, Magnetic Sail, M2P2, MPS

## 1. Introduction

In 2005, after a cruising of more than 25 years, it was reported that the Voyager 1 spacecraft has entered the solar system's final frontier, a vast, turbulent expanse where the Sun's influence ends. The Voyager 1 is now passing the termination shock where the solar wind first starts to slow down and reverse due to its first encounters with pressure from interstellar space. Although the Voyager successfully unveiled our solar system during its very long travel, future exploration to the outer planets, or even beyond the heliosphere should be conducted within several years to make such explorations attractive.

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 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[ 1 , 2 ]. Unfortunately, acceleration of the solar sails 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, Fig.1a) is proposed by Zubrin[3 ,4 ,5 ] because a magnetosphere around a spacecraft can capture the solar wind momentum without deploying a large (hence heavy) mast and sail.

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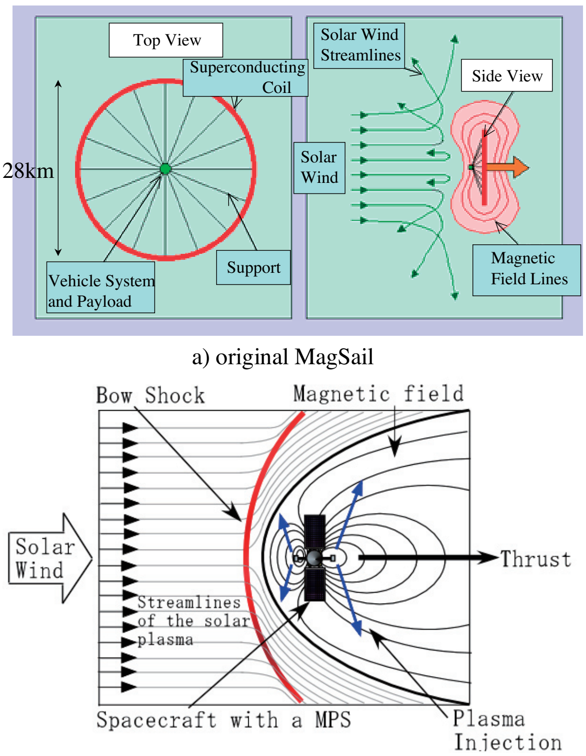
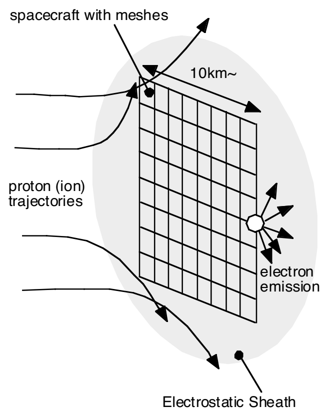
Although the MagSail requires a large hoop coil, Winglee proposed an idea to use a very compact coil to obtain a large MagSail; he proposed to inflate the original weak magnetic field by injecting a plasma jet from a spacecraft (Fig.1b)[6]. This idea, Mini-magnetospheric Plasma Propulsion (M2P2), is very attractive from the engineering point of view since no large structure is required.




a) original MagSail

b) plasma sail (M2P2/MPS)

Fig.1 Principle of solar wind sails.




c) electrostatic sail

Fig.1 Principle of solar wind sails (*cont*.).

In the following, starting from the original MagSail, several sail propulsion concepts using the solar wind energy are explained. Not only magnetic sails, electrostatic sail depicted in Fig. 1c) and other sails are also explained, and the research status of these sails is reviewed.

## 2. Catalogue of Solar Wind Sails

### 2.1.Original MagSail by Zubrin

Before the launch of a MagSail spacecraft, a loop of superconducting cable of millimeter in diameter on a drum is attached to the spacecraft. After the launch, the cable is released from the spacecraft to form a loop of tens of kilometers in diameter, then a current is initiated in the loop. Once the current is initiated, it will be maintained in the superconductor without further electric power. The magnetic field created by the current will impart a hoop stress to the loop for aiding the development and eventually forcing it to a rigid circular shape.

When the MagSail is in operation, charged particles approaching the current loop are decelerated/deflected according to the B-field they experience. If the interacting scale between the plasma flow and the magnetic field is large as in the cases of some magnetized planets like Earth and Jupiter, a magnetosphere (or a magnetic bubble) is formed around the current loop (Fig.2). In this case, the solar wind plasma flow and the magnetic field is divided by the magnetopause, at which ions entering the magnetic field are reflected except near the polar cusp region where the ions can enter deep into the magnetic bubble. Due to the presence of the magnetosphere, the solar wind flow is blocked, creating a drag force on the loop; thus the spacecraft is accelerated in the direction of the solar wind. The solar wind in the vicinity of the Earth is a flux of $10^6$ protons and electrons per cubic meter at a velocity of 400 to 600 km/s. The maximum speed available for the MagSail would be that of the solar wind itself.

Force on the current loop 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,

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

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[7]. 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 notice that about $L$=10 km is required to obtain 1 N, which will be suitable for a 1-t-class deep space explorer.

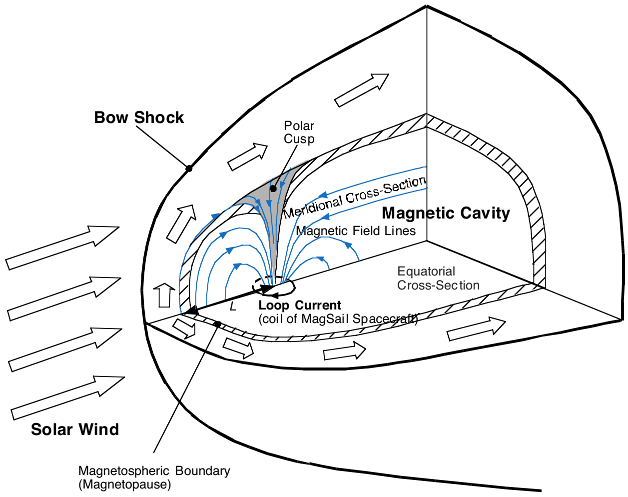



Fig.2 Solar wind flow and magnetic filed of MagSails.

Useful selection of $L$ is to set it to the distance from the center of coil current to a position where the plasma kinetic pressure equals the magnetic field pressure as,

$$\frac{B^2}{2\mu_0} = \rho u_{sw}^2 \qquad (2)$$

Assuming that the magnetic field around the spacecraft decays as

$$B = B_0 \left( \frac{a}{r} \right)^3 \qquad (3)$$

where $B_0$ is the magnetic flux density at $r=a$, and $r$ the distance from the center of the coil, $L$ is obtained from eqs.(2) and (3) as

$$L = \sqrt[6]{\frac{B_0^2}{2\mu_0 n m u^2}}\, a \qquad (4)$$

where $\mu_0$ the permeability in vacuum, $n$ the number density, and $m$ the mass of ions. Note that to enlarge the magnetosphere, a large coil is inevitable because the B-field quickly decays as $1/r^3$.

Among various parameters in eq.(1), if the solar wind parameters and the magnetic field parameters are all specified, only $C_d$ is the unknown parameter. $C_d$ for various $L$ is derived for various scales of MagSail[8,9,10].

### 2.2.M2P2 by Winglee

A new concept, Mini-Magnetospheric Plasma Propulsion (M2P2), was inspired by researchers in planetary magnetospheres[3]. M2P2 is sometimes called as plasma sail, or Magnetoplasma Sail (MPS). The M2P2/MPS sail uses an artificially generated magnetic field, which is inflated by the injection of a low-energy plasma (Fig.1b). This plasma injection allows the deployment of the magnetic field in space over large distances (comparable to those of the MagSail) with the B-field strengths that can be achieved with existing technology (i.e., conventional electromagnets or superconducting magnets). Additionally, one potential significant benefit of the M2P2 is its small size of the hardware (even though the magnetic bubble is very large); this would eliminate the need for the deployment of large mechanical structures that are presently envisaged for the MagSail or the solar sails[11]. Although these features are attractive, the feasibility of such a small M2P2 sail is denied by several researchers[12,13]. The details will be discussed afterwards.

### 2.3.Electrostatic sails

Electrostatic sail is a device capable of extracting momentum from the solar wind through electrostatic coupling rather than electromagnetic coupling used by the MagSails. An example is shown in Fig.1c)[14]. In Fig.1c), a mesh, which is made of thin conducting wires, is placed across the solar wind flow. If the mesh is kept at a positive potential with respect to the solar wind plasma, an outward electric field is set up around each wire whose spatial scale size is comparable to the Debye length of the plasma. Incoming solar wind protons see the mesh as a barrier if the mesh spacing is of the same order as the Debye length. To reflect the high-energy solar proton of about 1 keV, we should keep the spacecraft potential high enough value, say 6 kV; hence electrons must be continuously pumped out of the structure. The Debye length of the solar wind at 1 AU is about 10 m. Only in this electrostatic sheath region, electrostatic force can act between the ions and the electrostatic sail. As in the case of the MagSail, thrust is proportional to the mesh area, hence large mechanical structures like the original MagSail are required. Another electrostatic approach is to utilize the electric field as $\boldsymbol{E}=-\boldsymbol{u}_{sw}\mathrm{x}\boldsymbol{B}_{imf}$, where $\boldsymbol{B}_{imf}$ is the interplanetary magnetic field and $u_{sw}$ is the velocity of the solar wind[15]; but this system also demands a large structure to be biased to a large electric potential.

### 2.4.Other Sail Propulsion

Inspired by the ideas of the MagSails and the electrostatic sails, many new sail propulsion system are advocated. Khazanov and Akita proposed the usage of solar radiation for the MagSail[12,16]. Slough proposed a way to capture the solar wind momentum by using a rotating magnetic field, and the new system is called 'the plasma magnet'[17]. The plasma magnet is already accessed by laboratory experiment[18]. Another new idea is MagTether, which uses electrodynamics tether in interplanetary space in combination with the MagSail[19].

## 3. Research Status of Plasma Sail

### 3.1.Numerical Study

With an assistance of the plasma jet, an MPS spacecraft inflates the initial magnetic field produced by the coil to a position where the dynamic pressure of the solar wind balances the magnetic pressure. If the momentum change of the solar wind were obtained by the interaction between the enlarged magnetosphere and the solar wind and was transferred to the MPS spacecraft, the spacecraft could obtain a propulsive force. However, this momentum transfer process is considered skeptical by many researchers.

Two physical issues are addressed for the momentum transfer process of the MPS. The first issue is related to the momentum transfer process of the MPS in the MHD limit. Within the framework of the ideal MHD formulation, if the MPS spacecraft is surrounded by a radial super Alfvenic flow, it seems that no information is transferred toward upstream (i.e., to the spacecraft); this means that the Lorentz force cannot be transferred to the MPS spacecraft[20]. If this is true, the MPS could not obtain any thrust even if the magnetic cavity size were greatly enlarged. Another physical issue is associated with the ion kinetic effect. Kazhanov performed simulations of the M2P2 by using the MHD and hybrid models in the near field and the far field from the dipole center, respectively[12]. According to his study, the solar wind ions are not trapped in the magnetosphere produced by the coil because the ion Larmor radius is significantly larger than the representative length of the magnetosphere. Due to weak protons to magnetic field interaction, thrust obtained from the M2P2 system is negligibly small. He concluded that a considerably larger plasma sail than that was proposed by Winglee would be required.

Theoretical treatment of the idealized magnetic field inflation was conducted in Ref.[21]. As is discussed in the reference, the magnetic field inflation process is possible, but it is realized 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. In Refs.[22] and [23], paying attention to the MHD condition, Asahi carefully conducted an MHD analysis and clarified the structure of the inflated field. To drastically inflate the field, high-$\beta$ plasma injection is preferred, however, since the power required also increases, 'inflation efficiency" is not good for the cases of high-$\beta$ plasma injection. Asahi concluded that very low-$\beta$ plasma jet is preferred. To identify the finite Larmor radius effect in the magnetic field inflation, Winske[24] and Kajimura[25] are working on hybrid simulations, but their simulations are limited to low $\beta$

cases.

Assuming that 1) the inflated magnetic field will interface with the solar wind at a point where the magnetic and thermal pressure balance, and that 2) near-magnetic-field is not affected by the induced current at the boundary, thrust performance of resized MPS sails is predicted based on the analytical model by Asahi[23]. Thrust is increased by increasing the $\beta_0$ value ($\beta$ at the injection point), but the power input also increases, thus thrust to power ratio decreases with increasing $\beta_0$. Isp also degrades when $\beta_0$ increased. Hence the MPS sail should be operated for small $\beta_0$ values to achieve both high thrust to power ratio and high Isp.

From the above model used by Asahi, only low $\beta_0$ plasma injection seems feasible for the MPS. Due to numerical difficulty to treat the whole field of the MPS, so far, only moderate $\beta_0$ cases ($\beta_0$~$1$) are directly simulated by Winglee[ 26 ], Otsu[ 27 ], Asahi, and Nishida[20]. Nishida showed the dependence of thrust characteristics on various $\beta$ values. To clarify the minimum/maximum allowable $\beta_0$ and the coil size for inflation, we are still working on the MHD simulation.

Although hybrid simulation is required to address the ion kinetic effect on the plasma sail, results available so far are limited to only a few cases. Among them, Khazanov and Omidi conducted hybrid simulation for the same condition as Winglee, and indicated that the results deviate from the MHD simulation; to enlarge momentum coupling to the sail, it was pointed out that the size of the system should be tremendously increased[12]. This statement qualitatively agrees with that of Asahi. In spite of many hybrid simulations, effective thrust production was never obtained, so some researchers including our group are actively working on the hybrid simulations[28,29].

## 3.2.Experimental Study

Winglee and his group conducted an interesting demonstration of the magnetic field inflation[30,31,32,33,34,35,36]. A high-density helicon or an arc plasma source is located in a drum-like solenoid to observe the inflated. The demonstration was conducted in a space chamber of 1 m in diameter, so the change of the field was measured only in a pulse mode but the far-field feature was not established. A large chamber experiment would be important to characterize the far-field plasma and the stability of the inflated magnetic field. He also tried full demonstration of M2P2. Due to the large M2P2 source and corresponding difficulty in obtaining large-scale solar wind source, they cannot demonstrate the important features of the M2P2; for example, 1) how far is the inflated magnetic field expanded for a specific condition, and 2) what amount of momentum transfers from the solar wind to the spacecraft (coil), are not validated.

Scaled down model approach by our group with a very small plasma emission from the center of the coil seems reasonable to simulate the whole system of the M2P2/MPS sail. When Magnetic sail (MagSail) spacecraft is operated in space, the supersonic solar wind plasma flow is blocked by an artificially produced magnetic cavity to accelerate the spacecraft in the direction leaving the Sun. To evaluate the momentum transferring process from the solar wind to the coil onboard the MagSail spacecraft, we arranged a laboratory experiment of MagSail spacecraft[37]. Based on scaling considerations, a solenoidal coil was immersed into the plasma flow from a magnetoplasmadynamic arcjet in a quasi-steady mode of about 1 ms duration. In this setup, it is confirmed that a magnetic cavity, which is similar to that of the geomagnetic field, was formed around the coil to produce thrust in the ion Larmor scale interaction[38]. Also, the controllability of magnetic cavity size by a plasma jet from inside the coil of MagSail is demonstrated, although the thrust characteristic of the MagSail with plasma jet[39] is to be clarified in our next step.

## 4. 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 condition of $r_{Li}<<L$. Since the optimum thrust performance available for the M2P2/MPS sail has not been established yet, further research is required.

Flight system study and mission analyses are also important to show the feasibility of plasma sail. In addition to the spacecraft guidance method in a radial acceleration[40], electromagnet system should be studied in detail; until now, only rough estimations are conducted[41,42].

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