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Study of a Plasma Sail for Future Deep Space Missions

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Abstract

If a dense plasma were exhausted near the center of a mageetic sail, the magnetic field could be expanded far away from the spacecraft, thus the energy of the solar wind can be captured by this huge magnetic field in spite of very low-density solar wind. Then the magnetic sail can propel a spacecraft by the solar wind in the inerplanetary space. Such a magnetoplasma sail was analytically studied, and large thrust to power ratio as much as 250mN/kW was explained. When applied to short-term deep space missions, the magnetoplasma sail has great advantage against other electric propulsion systems because of its ability to achieve larger thrust to power ratio.

1. Introduction

A magnetic sail is the way to propel a spacecraft by the solar wind in the inerplanetary space. As in Fig.1, the magnetic sail consists of a magnetic field produced by a loop coil. Because the produced magnetic field deflects the flow of the solar wind, a drag force will appear to propel the spacecraft. Although original concept of the magnetic sail relies on a huge superconducting coil of several tens of kilometers in diameter, which is practically impossible in our current technology level, in 2001, Winglee et al. proposed an efficient method to realize a large magnetic field around a spacecraft with an assistance of plasma emission (Fig.2).[1] From their theoretical analysis of what they call as mini-magnetospheric plasma propulsion (M2P2), it was shown that if a dense plasma were exhausted near the center of the dipole magnetic field, the magnetic field can be expanded far away from the spacecraft, thus the energy of the solar wind can be captured by this huge magnetic field as shown in Fig.1. If the magnetic field can be inflated to several tens of km, a large thrust of a few N is available in spite of very low-density solar wind. Following the obtained performance, M2P2 system has an advantage against other propulsion system in particular for a short-term deep space mission that requires a considerable amount of ΔV.[2]

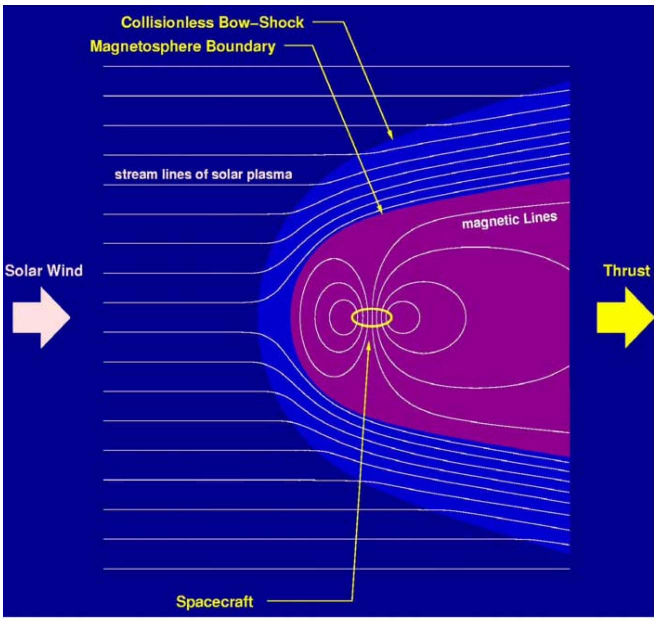


Fig. 1 Magnetic sail.

In spite of many theoretical and experimental activities on M2P2, technical issues of the M2P2 system are not completely solved, and the thrust formula of M2P2 is not established yet. This is mainly because the system includes a large-scale interaction between the solar wind plasma flow and the magnetic field, which is hard to realize in the ground test chamber. So far, direct demonstration of the M2P2 system is not conducted, but only some preliminary experiments of plasma expansion process were conducted by Washington University.[3] Difficulty of experimental demonstration limits the current activities to theoretical research; Winglee uses an idealized MHD model to depict the interaction, and his group is preparing a particle-fluid hybrid model to accurately predict the plasma field of the M2P2 system.

Since the flowfield around the M2P2 system (typical lenght: several meters) cannot be treated by an ideal MHD model (typically dealing with a large scale of several kilmeter) as was originally studied by Winglee. In this sense, the thrust formula shown by Winglee et al. is doubtful. Hence, extension of the model to practical model is necesary to clarify the thrust production process of the M2P2 system.

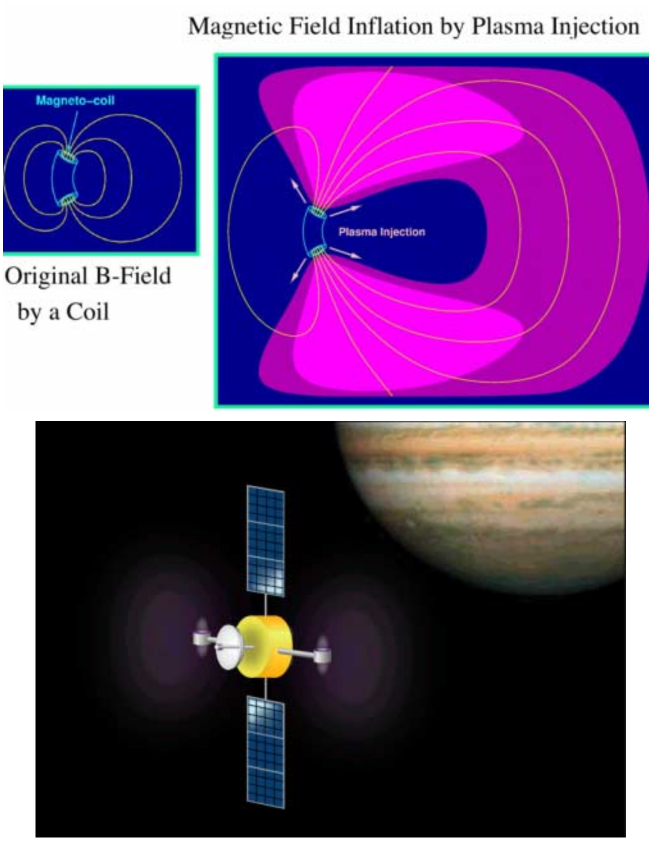


Fig. 2 Principle of magnetoplasma sail and image of a spacecraft propelled by magnetoplasma sail.

Under these circumstances, we started a study of a M2P2 system as a way to realize short-term deep space missions. We call such a system as "magnetoplasma sail" since magnetoplasmadynamically expanded plasma will enhance the ability of the magnetic sail. This paper firstly deals with a process of the magnetic field inflation accompanied by plasma emission from the spacecraft. After deriving an energy balance model that describes electric power necessary to inflate the plasma and achieve a thrust, two-dimensional numerical simulation is also discussed to find a practical method to inflate the magnetic field. Next we studied deep space missions targeting at some outer planets to quantify the advantage of the plasma sail against other electric propulsion systems. Although these studies show the possibility of the magnetoplasma sail, there still remains some problems to be considered; these issues are listed and discussed with some future plans to reveal these problems.

2. Analysis of Magnetoplasma Sail

a.Thrust prediction model

In order to expand the magnetic field around a spacecraft as in Fig.2, collisionless plasma flow should be realized. Then the magnetic field is carried away to a far field until the magnetic pressure balances the dynamic pressure of the solar wind. This is the idealized case that corresponds to the maximum (theoretical limit) thrust produced by the magnetopalsma sail. However, in reality, transition collisional- to collisionless-plasma occurs during the expansion, hence only part of the energy of the plasma is converted. How to optimize the energy conversion process from the plasma to the magnetic field is the most important topic for the magnetoplasma sail.

As is shown in the following discussion, the energy required to inflate the magnetic field is small. Suppose a plasma source in 200-mm diameter with 0.02 T magnetic field at the surface, and assume that the frozen field is realized during plasma expansion at r=2 m, where r is the distance from the plasma source. In this case, electric power of 100 W is required to expand the magnetic flux density of the dipole,

$$B \propto r^{-3}$$

to the field,

$$B \propto r^{-1.52}$$

As an example of thrust calculation, a weak magnetic field of 50 nT, which is strong enough to support the solar wind plasma flow, is expanded to a radius of 26 km. The thrust of a magnetoplasma sail F is approximated by

$$F = (1/2)\rho u^2 \times S_{eff}$$

where the term $1/2\rho u^2$ represents the dynamic pressure of the solar wind, and S_{eff} is the effective area that deflects the plasma flow of the solar wind. Using typical parameters of the solar wind, the thrust for this case is obtained as F=1 N. If conversion efficiency from plasma energy to the magnetic field energy is assumed to be 20%, approximately 4 kW electric power is needed to produce and supply a plasma of 5 eV.

Here the efficiency to produce plasma is set to 80%. If the above scenario is possible, thrust to power ratio of 250 mN/kW is possible. The obtained performance is plotted in Fig.3, in which the performance is compared with other electric propulsion systems. As shown in the figure, by acquiring energy of the solar wind, the magnetoplasma sail achieves a large thrust to power ratio. Also, specific impulse, which is calculated from a thrust divided by required mass flow rate, is as high as ion thrusters, hence both large thrust to power ratio as well as large specific impulse are possible if a magnetoplasma sail is employed.

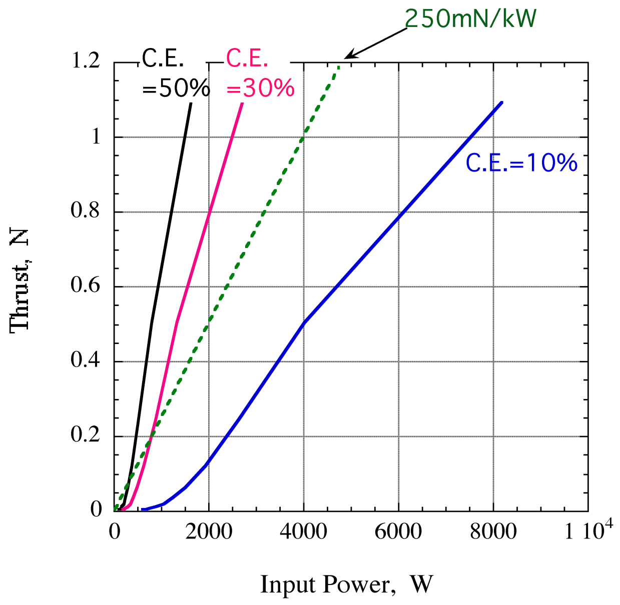


Fig. 3 Thrust to power ratio of magnetoplasma sail obtained from the electric power required to expaned the magnetic field.

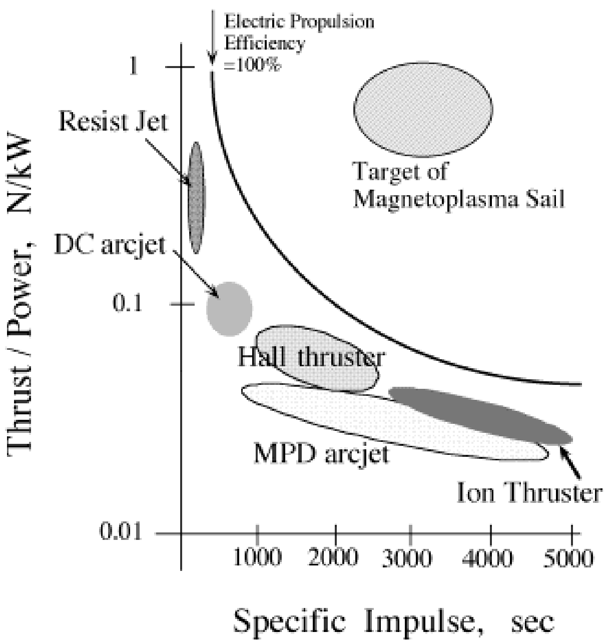


Fig. 4 Performance of magnetoplsama sail.

b.Two-dimensional simulation of Inflated Magnetic Field by Plasma Injection

The above model cannot predict how far the magnetic field are carried away by the plasma, which must be determined from an MHD analysis. For the MHD analysis, following equations are used and solved by an MHD code NIRVANA.[4]

Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{u}) = 0$$

Equation of Motion

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla\left(\rho |\mathbf{u}|^2 + p\right) = \mathbf{j} \times \mathbf{B}$$

Energy Equation

$$\frac{\partial e}{\partial t} + \nabla\left[(e + p)\mathbf{u}\right] = \mathbf{j} \cdot \mathbf{E}$$

$$e = \frac{p}{\gamma - 1} + \frac{1}{2}\rho |\mathbf{u}|^2$$

Induction Equation

$$\frac{\partial B}{\partial t} = rot\left[\mathbf{u} \times \mathbf{B} - \frac{1}{\sigma\mu} rot\, \mathbf{B}\right]$$

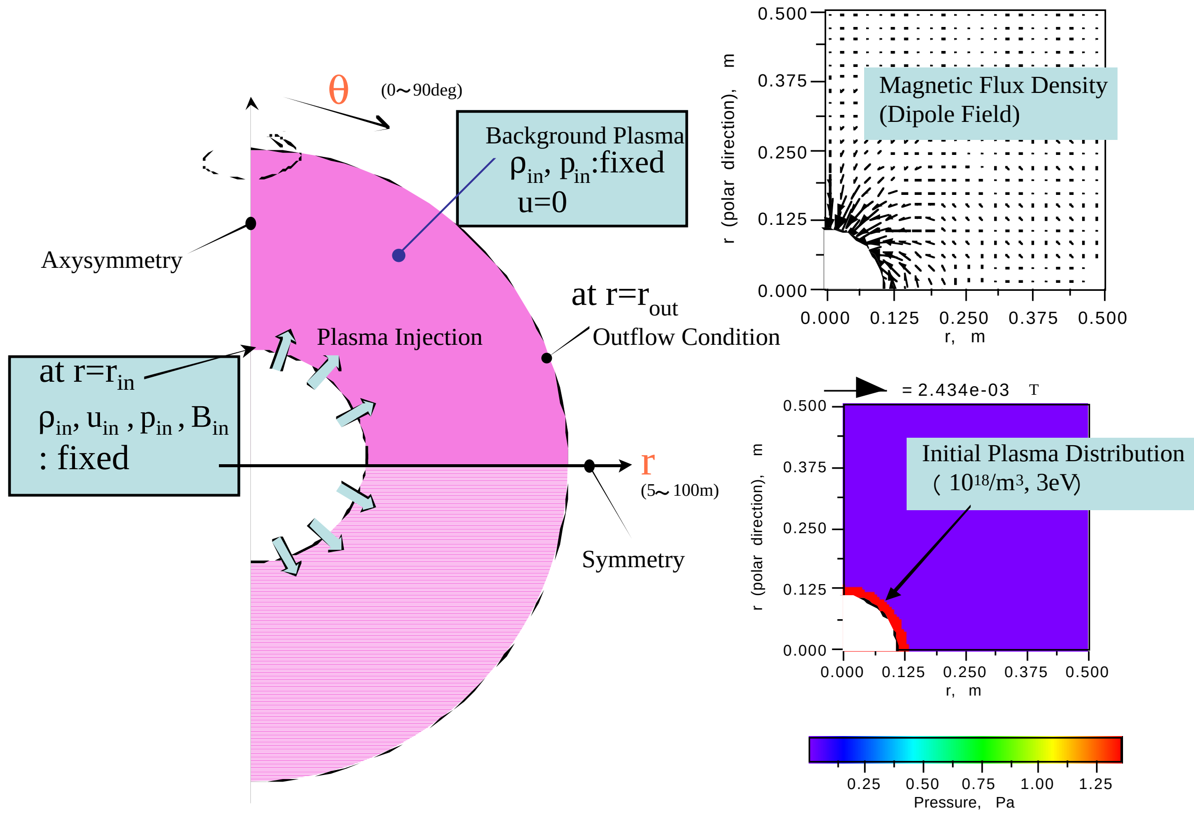
Figure 5 shows two-dimensional model. At the origin of the polar coordinate, dipole magnetic field is located. All the calculation region was filled with background plasma without velocity at t=0, then a dense plasma is set near the origin, r=100 mm, from which the plasma will expand. The analysis was conducted only near the dipole, hence the plasma and magnetic field evolution only the near-field is considered in this simulation.

As in Fig.6, the magnetic field is inflated during the initial period. Since the waves in this MHD field propagate in different velocities in different directions as one can see in the velocity distribution in Fig.7. The shape of the magnetic field in Fig.6 is correspondingly distorted as the time step goes on. The fastest wave in Fig.7, first magnetosonic wave, penetrates into the background plasma, and strong Joule heating occurs. By this large heat addition, local Magnetic Reynolds number, Rm, becomes large at the shock front. Large Rm usually represents strong interaction between the plasma flow and the magnetic field, hence the magnetic field is conveyed by this surface, as the image of plasma to magnetic field coupling is depicted in Fig.8. Here Rm is defined as,

$$Rm = \sigma \mu_0 u r$$

where σ is the conductivity, μ_0 is permeability in vacuum, u local speed of the plasma, and r the distance from the origin. Inside the region behind the front shock in Fig.7, plasma expansion is accompanied by deceleration at the second shock, where strong heat addition is again found. Expansion of plasma into the background field is hence rather complicated during the initial evolution phase.

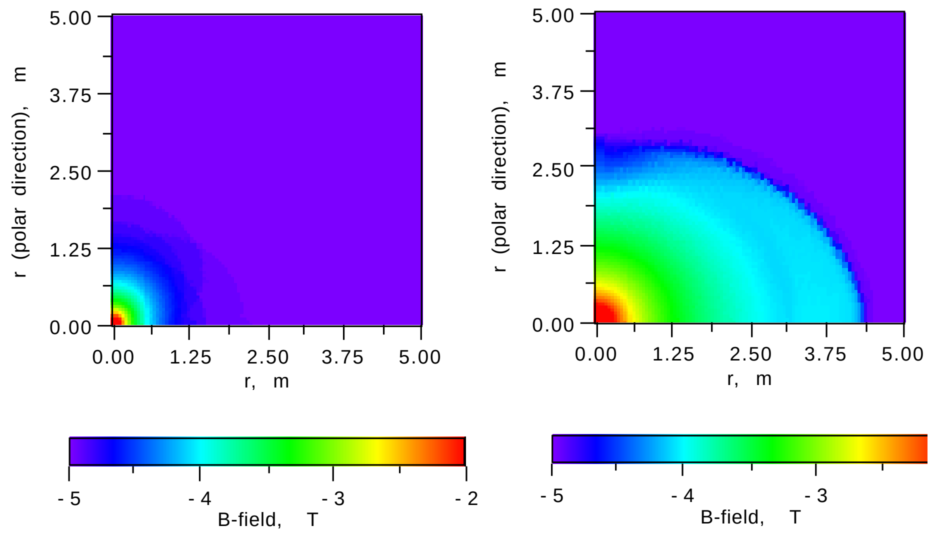
Our interest now is to achieve a steady state after the above discussed initial expansion phase. With an assistance of the shock wave, the magnetic field inflates to a far-field, until the dynamic pressure of the solar wind will balance the magnetic pressure. After some bouncing oscillation by shock waves, an equilibrium state is



r-θ Calculation Region

Initial Conditions

Fig.5 Numerical model..



a) without plasma injection

b) with plasma injection

Fig.6 Inflation of magnetic field; magetic flux density distribution at t=0.22ms after plasma injection; logarithmic scale.

possible if we use an ideal MHD mode.[5] To simulate the complicated near-field and the far-field with a full MHD code is our next step.

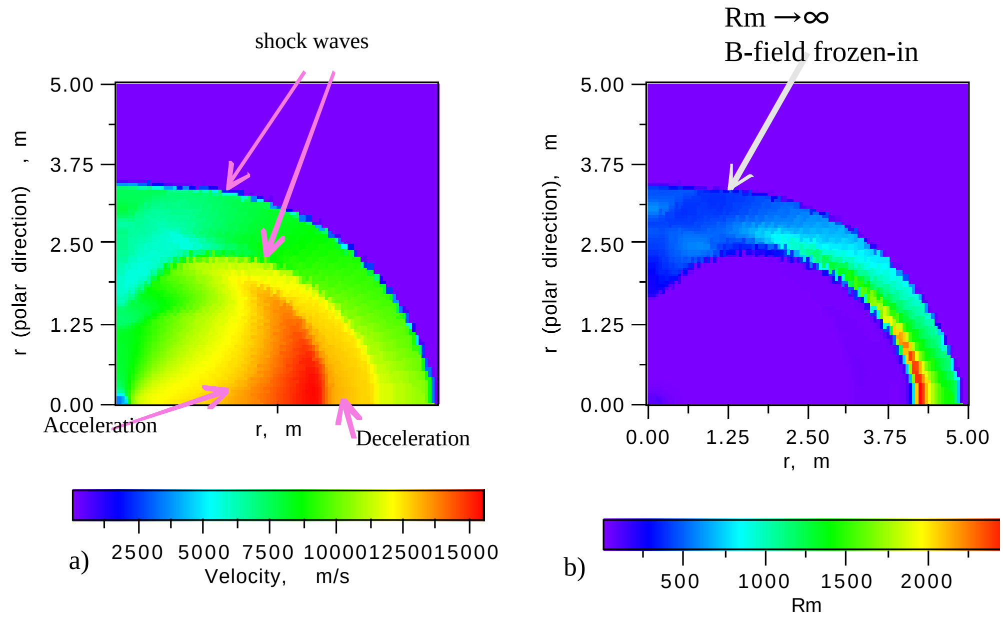


Fig.7 Evolution of plasma; a) velocity distribution, b) magnetic reynolds number distribution..

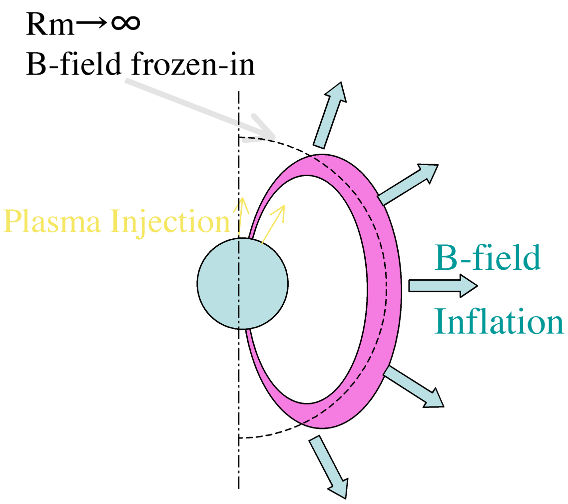


Fig. 8 Image of frozen magnetic field

3. Application of Magnetplasma Sail to Deep Space Missions

Application to Planetary Exploration

Table 1 summarizes the application of magnetoplasma sail to the outer planet exploration.[6] The high thrust/power ratio is assumed as 1N/4kW. The electric power for plasma supply is from the solar cell paddle, and 8.0kW is generated at 1.0AU. The thrust is 1.8N at 1.0AU. C3 (the square of the hyperbolic excess velocity with respect to the Earth) is assumed 0 km2/s2 at Earth departure. This corresponds to the marginal escape from the Earth's magnetosphere followed by the activation of the magnetic sail engine. The thrust direction angle (i.e. steering angle) is the parameter, which is the thrust angle from the opposite direction of the sun. For the outer planets, it is designed to lean to the direction of orbital velocity for acceleration. By changing the steering angle to 5 deg, 15 deg and 20 degree, Jupiter, Saturn and Uranus can be reached. It is not listed in Table 1, but if we could make the steering angle or the power generation slightly larger, even the escape from the solar system is possible. Since the thrust magnitude is larger compared with the other low-thrust propulsion systems, required acceleration for transfer is achieved in a shorter flight time, which may remove the use of the planetary gravity assist. The compromise due to the use of planetary gravity assist between longer flight time and payload increase is the topic for the future study.

Table 1. Application to Outer Planets Exploration (Power Generation by Solar Cell)

Thrust/Power ratio	1N/4kW
Propellant flow rate	0.5kg/day/kW
Solar paddle power	8.0kW@1AU (ÅÂ1/r**2)
Bus power	0.5kW
Thrust	1.8N@1AU
Initial spacecraft mass	1000 kg

Steering Angle	Max Aphelion Distance	Final Mass
+ 0deg	3.9 AU	498 kg
+ 5deg	5.0 AU (Jupiter)	545 kg
+10deg	6.9 AU	572 kg
+15deg	10.5AU(Saturn)	591 kg
+20deg	20.0AU(Uranus)	605kg

Table 2 shows the cases where the generation of kW-class power is supplied not by the solar cell, but by RTG (Radioisotope Thermoelectric Generator). Due to the constant power supply regardless of the solar distance, it makes the power system smaller, and the operation time of magnetoplasma sail engine shorter.

Table 2. Application to Outer Planets Exploration (Power Generation by RTG)

Thrust/Power ratio	1N/4kW
Propellant flow rate	0.5kg/day/kW
Bus power	0.5kW
Initial spacecraft mass	1000 kg

Steering Angle	Power	Max Aphelion	Final mass
+ 5deg	8.0 kW	4.6 AU	591 kg
+ 5deg	4.0 kW	5.2 AU	523 kg
+10deg	4.0 kW	5.7 AU	571 kg

Application to the Jupiter Exploration

In this chapter, a preliminary spacecraft design is shown based on the concrete orbit plan taking the Jupiter mission as an example. Table 3 and Fig.9 show the Earth-Jupiter transfer trajectory and its main parameters. As the trajectory is direct transfer from the Earth to Jupiter without planetary swing-by, the flight time is only 2 years and 3 months, which is shorter comparing with other Jupiter explorers such as Galileo. In this example, the magnetic sail is turned on up to the distance of 4AU from the sun.

Table 3. Specifications of the Earth-Jupiter Direct Transfer Trajectory by Plasma-Assisted Magnetic Sail

Mass	Launch Mass	1000 kg
	MPS fuel	410 kg
Power	Solar Power	8 kW@1 AU
	Bus Power	0.5 kW
Epoch	Earth departure	15 Aug. 2011
	Jupiter arrival	10 Nov. 2013
	Flight time	818 days
Delta-V	MPS delta-V	22.77km/s
C3 at Earth		0.0 km2/s2
Jupiter V infinity		7.64km/s

Table 4 shows the spacecraft mass budget whose initial value is 1,000kg at launch. The fuel mass (Xe) is 450 kg. Fig.2 in introduction shows an artistic image of the magnetic sail explorer. The high gain antenna is pointed toward the earth for communication, and the solar cell paddle is mounted on a single-axis gimbal and pointed to the Sun to get enough electric power. The plasma is supplied from two plasma sources. By changing the attitude of spacecraft with respect to the Sun, the direction of generated thrust (steering angle) will be controlled. The deceleration method at Jupiter arrival (chemical and electrical propulsion usage, reentry capsule) is the topic for future study.

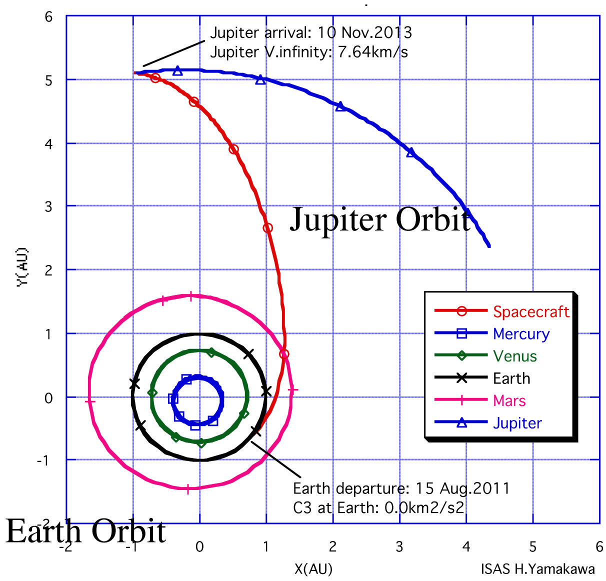


Fig. 9 Application of a mangetoplasma sail to a deep space mission; trajectory to Jupiter.

Table 4. Magnetoplasma SailSpacecraft Mass Budget

M2P2 propulsion system	120kg
(thruster, Xe tank, RF, PPU, feeder, boom)	
Power	160kg
(8kW paddle 150kg, 15AH battery 10kg)	
RCS (attitude control)	20kg
AOCS	20kg
Communication	20kg
DHU	7kg
Structure	110kg
Thermal control	35kg
Cable	20kg
Science Instruments	13kg
(solar wind detection system)	
M2P2 Fuel	450kg
(Xe with 10% margin)	
RCS Fuel (Hydrazine)	15kg
Margin	10kg
Total	1000kg

4. Future Plans

Magnetoplasma Sail Engineering Satellite

For the outer planet exploration in the future, here is proposed an engineering validation satellite, which confirms the propulsion system specification and operation methodology. The main features are as follows:

1) The satellite is around 200kg such that its launch is possible by H-IIA piggyback or M-V Lite,.

2) Since the magnetopause of the Earth magnetosphere is about 10Re at Sun side and the bow shock is located at about 13Re from the Earth, the satellite is injected into an orbit with 250km perigee altitude and 20 Re apogee distance where apogee is located at the Sun side.

3) In case of H-IIA piggyback, solid motor should be used for apogee raise from 36000km to 20Re.

4) The magnetic sail is turned on only in the vicinity of apogee outside the Earth's magnetosphere. The thrust is estimated by the orbit determination result. A plasma wind monitor is installed on the satellite to get the knowledge of the interaction between the solar wind and thrust force.

5) A guidance law is indispensable for the planetary explorer under the variable solar wind circumstance. This requires a detailed solar wind prediction model and the simultaneous use of electric propulsion for guidance maneuver.

Validation Experiment

The above-mentioned engineering satellite is the final step towards the verification of the principle of the plasma assisted magnetic sail. Prior to this, there are a lot of problems to be verified through ground experiments.

One of them is the verification of magnetic field inflation mechanism. In our experiment, we will have a small size microwave plasma source of 2-cm-diameter inside the space chamber of 2-m-diameter. Then the dipole magnetic field of the plasma source itself will be inflated by the plasma injection. To confirm the magnetic field inflation in a limited region inside the space chamber, a pulse mode operation is inevitable. This can be realized by the microwave plasma source, which is suitable for observing the transient magnetic field inflation after the plasma ignition. It will be also useful to design the plasma assisted magnetic sail, because the plasma density can be changed by three orders of magnitude by varying the supplied power. To measure the magnetic field inflating with aÅ@high speed as much as Alfven velocity, a high-speed camera and a magnetic probe will be used. During the magenetic field inflation, whether excessive heating caused by the instability of the plasma exists or not shall also be checked in the high-speed plasma flow simulating the solar wind. Also we need to check if the energy of the solar wind is transmitted to the magnet field, and for this purpose the thrust force measurement methodology shall be established.

The second problem is the development of the most suitable plasma source for plasma assisted magnetic sail. Different from the ion engine, which can make plasma effectively in the discharge chamber, the plasma should be generated in an open space in the magnetic field, where the propellant/plasma confinement is almost impossible. This may result in large amount of un-used propellant and a decrease in the propellant utilization efficiency. Under these circumstances, the plasma density as high as 10^{12} cm^{-3} is required, which is a new type of plasma source different from the conventional spacecraft propulsion systems. For the design of the new plasma source, the thermal load on the discharge chamber wall should also be considred because the wall temperature will be too high if a high-density plasma is generated. In this context, a non-contact type plasma source such as microwave and helicon wave is promising. For the first step, 20W class microwave source will be used, followed by the development of the 200W class plasma source for the engineering validation satellite.

5. Summary

In this paper, after briefly reviewing the status of magnetic sail researches, thrust production mechanism of the magnetoplasma sail was studied. A simplified energy balance model showed that the energy required to inflate the dipole magnetic field is small, hence if the energy conversion efficiency from the plasma energy to the magnetic field energy is as high as 20%, thrust to power ratio of 250 mN/kW is possible. The conversion efficiency is still being surveyed using a numerical technique based on resistive MHD equations.

If the above mentioned thrust to power ratio is possible, very short-term deep space missions are possible with a small launcher that will greatly influence conventional time-consuming deep space explorer using swing-by or electric propulsion such as ion thrusters and hall thrusters. Hence the magnetoplasma sail is a very important technology to future deep space mission. However, there are some problems to be resolved before realizing a deep space mission with the magnetoplasma sail. One is the way how to demonstrate the principle of thrust production mechanism; since the magnetoplasma sail has to deal with a large scale interaction between the solar wind and the magnetic field around a spacecraft, demonstration by ground experiment is very difficult. After some scaled-down experiments, we are planning a demonstration experiment in space which will check the overall function of the magnetoplasma sail and its controlling systems. Besides the problems associated with the thrust production mechanism, we have to establish a navigation system to control the direction of a spacecraft in an oscillating solar wind pressure, and to decide what type of plasma source is the best for the magnetoplasma sail. All these problems are now being investigated to establish fastest deep space missions that were never possible within the framework of existing propulsion systems.

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