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Magnetospheric Propulsion (eMPii)

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Authors:
P. K. Toivanen, P. Janhunen, H. E. J. Koskinen*
Finnish Meteorological Institute, Space Research Unit, Helsinki
*also at: University of Helsinki, Department of Physical Sciences

Introduction

Magnetospheric propulsion is a propulsion concept that applies the dynamic pressure of the solar wind to spacecraft thrust. It has been proposed as a revolutionary propulsion concept that could provide spacecraft with unprecedented speeds of 50 to 80 km s^{-1} or 10 AU yr^{-1} for low power requirements. The concept is similar to that of the solar sail that harnesses the solar radiation pressure. While the solar sail is a mechanical reflecting foil absorbing the momentum of the solar radiation, the magnetospheric propulsion utilizes a magnetic bubble generated around the spacecraft by an electrical current coil attached to the spacecraft. In this study theoretical and technical aspects of two magnetospheric propulsion concepts, Plasma-Free Magnetospheric Propulsion (PFMP) and Mini-Magnetospheric Plasma Propulsion (M2P2) have been studied.

The magnetic field forms a magnetic bubble, or an artificial magnetosphere, around the spacecraft. The sail, in this case, is a magnetic structure or current layer termed magnetopause that shields the artificial magnetosphere from the solar wind and diverts the solar wind flow around the magnetic bubble (Figure 1). As the dynamic pressure of the solar wind is typically 5000 times weaker than the radiation pressure, the effective area of the magnetopause has to be significantly larger than the area of a solar sail for an equal thrust level. In spite of this fact, the magnetospheric propulsion is appealing, since the artificial magnetosphere is not a mechanical structure.

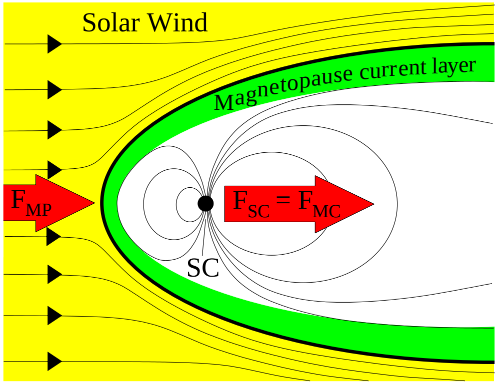

Figure 1: Schematics of magnetospheric propulsion with vacuum magnetic bubble: a magnetopause (thick solid line) works as a sail to divert the solar wind flow (yellow) and to generate a force (F_{MP}) exerted on the magnetopause of the artificial magnetosphere (green + white). The force on the spacecraft (F_{SC}) equals to the Lorentz force (F_{MC}) caused by the magnetopause currents.

The artificial magnetosphere can either be a vacuum magnetic bubble [*Zubrin*, 1993] (Figure 1; PFMP, Plasma-Free Magnetospheric Propulsion) or a magnetic bubble filled with plasma [*Winglee et al.*, 2000] (Figure 2; M2P2, Mini-Magnetospheric Plasma Propulsion). A crucial difference between these two systems is the radial profile (r^{-p}) of the magnetic field. In vacuum, the magnetic field falls off as the third power ($p = 3$) of the distance from the spacecraft suggesting a substantially large magnetic moment for the current coil. In fact, a superconducting coil with a radius of about 30 km and current of about 50 kA is required to reach the proposed cruising speed. Such dimensions imply a massive current coil which makes the propulsion less effective. *Winglee et al.* [2000] proposed that the size of the current coil at the spacecraft can be reduced by inflating the artificial magnetosphere by injecting plasma to a vacuum magnetic field. The injected plasma can then support electric currents that contribute to the magnetic field profile resulting in a decay power smaller than that of the vacuum field ($1 < p < 3$).

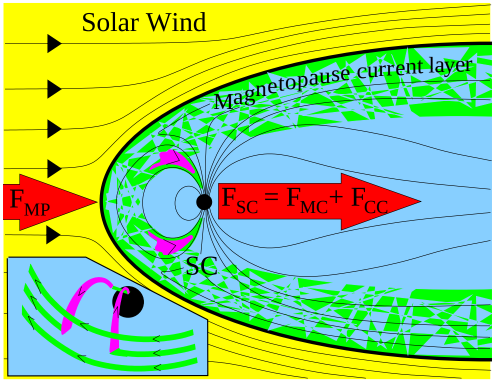

Figure 2: Schematics of magnetospheric propulsion with plasma-filled magnetic bubble inflated by plasma injection from the spacecraft. Shown are the magnetopause (thick solid line), solar wind flow (yellow), and forces ($F_{\rm MP}$) and ($F_{\rm SC}$) affecting on the magnetopause and spacecraft, respectively. The force on the spacecraft ($F_{\rm SC}$) equals to the Lorentz force caused by the magnetopause currents ($F_{\rm MC}$) and internal currents such as the magnetopause closure currents ($F_{\rm CC}$). The spatial distribution of the closure currents is depicted with magenta on the upstream side of the magnetosphere and in the insert. In addition, any escaping injected plasma extracts the solar wind momentum and decreaces the force on the spacecraft.

Theory

Since the artificial magnetosphere is not a mechanical structure, it is central to understand how the force exerted on the magnetopause is transferred to the spacecraft: The current coil attached to the spacecraft feels the Lorentz force caused by the current systems of the artificial magnetosphere generated by the solar wind.

The most obvious current structure forms at the magnetopause. It can be shown that a scaling law for the ratio between the force transferred by the magnetopause currents to the spacecraft ($F_{\rm MC}$) and that exerted on the magnetopause by the solar wind ($F_{\rm MP}$) can be given as

$$\frac{F_{\rm MC}}{F_{\rm MP}} \propto \left(\frac{2\mu_o P_d}{B_{\rm L}^2}\right)^{\frac{3}{2p}-\frac{1}{2}} \tag{1}$$

in terms of the solar wind dynamical pressure (P_d), the magnetic pressure at the spacecraft ($B_{\rm L}^2/(2\mu_o)$), and the magnetic field decay power (p). For a vacuum field ($p = 3$), the ratio (1) scales to unity, and the magnetopause force is fully transferred to the spacecraft, since the spacecraft is the only sink for the absorbed solar wind momentum. However, in the case of a plasma-filled magnetosphere ($p < 3$) the ratio (1) scales to less than unity. In fact, for an effective enough inflation, p must be close to 1. In this case, the ratio (1) is of the order of 10^{-9}, and the force ($F_{\rm MP}$) is, in practice, not transferred to the spacecraft by the magnetopause currents.

In the M2P2 magnetosphere, the injected plasma supports current systems that may also affect on the force transfer. In order to estimate this effect, let us postulate that the magnetopause current partially closes near the spacecraft. A scaling law similar to (1) can then be written for the ratio between the force caused by the closure currents ($F_{\rm CC}$) and the magnetopause force,

$$\frac{F_{\rm CC}}{F_{\rm MP}} \propto \alpha \left(\frac{2\mu_o P_d}{B_{\rm L}^2}\right)^{\frac{1}{2p}-\frac{1}{2}} \left(\frac{L}{s}\right)^2 . \qquad (2)$$

Here, α is the fraction of the magnetopause current closed near the spacecraft ($0 < \alpha < 1$), and s is the distance of the current closure from the spacecraft. For $p = 1$, the ratio scales to α, if the currents were closed at the spacecraft ($s = L$). A current closure perpendicular to the large magnetic field magnitudes at such a distance requires both large plasma pressure gradients over the scale lenght of the closure region and a plasma density of $\sim 10^{19}$ m^{-3} at the spacecraft. As ratio (2) decreases as the inverse square fo s, $F_{\rm CC}$ is significant only if the current closes very near the spacecraft.

The injected plasma as an additional sink for the solar wind momentum plays also a role in the momentum transfer of the M2P2 system. Any injected plasma escaping from M2P2 extracts solar wind momentum through acceleration by the solar wind electric field. Although there are no quantitative studies on such plasma escape, it may be a central factor to the efficiency of the M2P2 system. It can be expected that the solar wind and magnetospheric plasmas are mixed in the magnetopause boundary layer. An approximate thickness of the M2P2 magnetopause current layer, 10 – 20 km, can be determined as a deepest penetration of the solar wind protons into the M2P2 magnetic radial profile (r^{-1}). Such a thick boundary layer implies that a large amount of the injected plasma is exposed to the solar wind flow and the associated electric field.

Technological requirements

Both concepts, PFMP and M2P2 are technologically challenging in deployment of the artificial magnetosphere around the spacecraft. The technological issues of PFMP are related to the cooling and large spatial scales of the superconducting coil. In the case of M2P2, the challenges are the inflation of the artificial magnetosphere and the resulting high plasma densities near the spacecraft.

Cooling of the superconducting coil can either be passive or active. Passive cooling in space can be realized by coating the superconducting wire with semi-transparent material that reflects the solar radiation, but passes through the black body radiation from the superconductor. With the best usable materials, the coil can be cooled down to 170 K at 1 AU. Such a temperature is too high for presently available superconducting wires, and passive cooling can only be used at distances of Jupiter or Saturn and beyond. As the solar wind pressure decreases radially, operation inside 1 AU is desirable for adequate propulsive effects implying that an additional active cooling system has to be used. A convenient and technically feasible way to accomplish active cooling is to use a hollow wire with liquid nitrogen flowing inside. However, active cooling of the 200-km coil is technically challenging, increases the total mass of the spacecraft, and reduces the efficiency of the PFMP concept. Finally, packaging and deployment of the 200-km coil in space is non-trivial. Note, however, that the magnetic tension of the coil maintains the spherical shape of the coil.

The plasma source of M2P2 has to produce plasma at high β, at high efficiency, and at multikilowatt power level. Such a source exists and is based on a Rotating Magnetic Field (RMF) [*Slough and Miller,* 2000]. The induced plasma currents driven by RMF ionizes and heats the plasma. The RMF source is an inductively coupled source like the helicon and has no power, plasma density or temperature limitations. The high-density plasma and associated heat flux near the spacecraft set a challenge to spacecraft insulation: the heat flux cannot be reduced by using cooler plasma due to recombination, and the insulation cannot be provided by the magnetic field because the plasma is collisional (collisions fill the loss cone and plasma leaks to the spacecraft surface).

Conclusions

Magnetospheric propulsion has been proposed as a revolutionary propulsion concept that could provide spacecraft to travel out of the solar system as a 10-year mission. The thrust is expected to be attained by harnessing the solar wind dynamical pressure by coupling the spacecraft to the solar wind through an artificial magnetosphere working as a sail in the solar wind. The artificial magnetosphere can be generated around the spacecraft either by utilizing a large-scale super conducting vacuum magnetic field (Plasma-Free Magnetospheric Propulsion; PFMP) or by injecting plasma into a magnetic field supported by solenoid coils on the spacecraft (Mini-Magnetospheric Plasma Propulsion; M2P2).

Theoretically, the PFMP concept is sound and can be applied to spacecraft thrust.

However, the critical temperatures of presently available superconducting wires can only be obtained by passive cooling beyond Jupiter or Saturn. In the near future, it is possible that new superconducting materials will be developed, but presently active cooling has to be applied to maintain the superconductivity at radial distances closer than 1 AU.

On the other hand, the M2P2 assumes a significantly smaller electric coil at the spacecraft, and the artificial magnetosphere with a scale size and force on the magnetopause similar to the PFMP system has been proposed to be achieved by plasma inflation. However, this force is not fully transferred to the spacecraft by the magnetopause currents, and the force transfer to have any propulsive interest, would have to take place via currents flowing close to the spacecraft. Presently, it is debatable wheather such currents can be both fed as field-aligned currents close enough to the spacecraft and closed perpendicular to the large magnetic field near the spacecraft. During the present study no evidence for such currents was identified. In addition, any future computer simulation, laboratory testing, or space investigation has to also address the role of the escaping injected plasma in the solar wind momentum transfer.

References

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