J. Plasma Physics (2005), *vol.* 71, *part* 4, *pp.* 495–501. © 2005 Cambridge University Press
doi:10.1017/S0022377804003307 Printed in the United Kingdom

Physical problems of artificial magnetospheric propulsion

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(Received)

Abstract. We discuss here some of the physical problems related to the recently proposed scheme for solar sailing, using an artificial magnetosphere. We will concentrate on the forces acting on the plasma bubble, and their transfer to the spacecraft. Upper and lower limits of the force acting on the bubble are established. The results of test particle dynamics are presented, concerning the interaction of the solar wind with the modified magnetic dipole resulting from the spacecraft coils and the plasma expansion. Propagation of the forces along the magnetic flux tubes, from the bubble magnetopause down to the spacecraft vicinity, is discussed by using a simple MHD theoretical model. Emphasis is made on the distribution of currents flowing in the immediate vicinity of the spacecraft. Finally, results of PIC code simulations of the magnetized plasma expansion are presented and an overall qualitative picture of the physical processes is given, with a discussion of the strategy for obtaining more quantitative estimates of the magnetospheric propulsion efficiency.

1. Introduction

We discuss here some of physical problems related to the mini-magnetosphere plasma propulsion (M2P2) scheme for solar sailing and outer planet exploration. This scheme was recently proposed by Winglee et al. [1], and assumes that a large plasma bubble is formed and expands around the spacecraft, several kilometers in size, and is forced to move due to the solar wind (SW) pressure. The proposed artificial magnetosphere could be created by a helicon plasma source, and confined by the magnetic dipole generated by a coil, also installed in the spacecraft. The plasma particles could stay attached to the spacecraft due to magnetization.

The plasma produced by the plasma source should be dense and warm (n and T of the order of 5×10^{13} cm^3 and 5 eV), so that a discharge of the helicon type, in principle, fulfills these requirements. Most probably, the helicon would produce a weakly ionized, collisional gas with $T_e > T_i$ that is injected into the magnetic field generated by the coil.

The success of the M2P2 idea hinges on the value of the force that acts upon the spacecraft. We also discuss here several aspects that might intervene in its estimate. Upper and lower limits of the force acting on the bubble are established. The results of test particle dynamics are presented, concerning the interaction of the SW with the modified magnetic dipole resulting from the spacecraft coils and the plasma expansion. Propagation of the forces along the magnetic flux tubes, from

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the bubble magnetopause down to the spacecraft vicinity, is discussed by using a simple MHD theoretical model. Emphasis is made on the distribution of currents flowing in the immediate vicinity of the spacecraft. Finally, results of particle-in-cell (PIC) code simulations of the magnetized plasma expansion are presented and an overall qualitative picture of the physical processes is given, with a discussion of the strategy for obtaining more quantitative estimates of the magnetospheric propulsion efficiency.

2. Forces acting on the bubble

While analysing the complex interaction between the SW and the artificial mini-magnetosphere, perhaps the first attempt at estimating the force on the spacecraft comes from the realization that the momentum of the SW particles changes and its conservation requires that it should be picked up by the spacecraft. However, leaving aside the difficulties associated with a realistic calculation of the variation in the SW particle momentum, one cannot conclude that this change is totally absorbed by the spacecraft: the momentum of the artificially injected plasma particles is also modified during the interaction with the SW. An alternative way of addressing the calculation of the force on the spacecraft relies on the consideration of the coil in the spacecraft.

First, we should note that the gravitational attraction of the Sun at 1 AU is of the order of $F_S/\mathrm{kg} = GMm(= 1\ \mathrm{Kg})\ (1\ \mathrm{AU})^{-2} = 5.93\ \mathrm{mN\ Kg^{-1}}$. For a spacecraft prototype of 100 kg this corresponds to $F_S = 0.6$ N. This value gives an estimate of the force necessary for the M2P2 method to work.

Let us now make an upper estimate of the force acting on the plasma bubble. For simplicity, we can define the boundary of the plasma bubble created around the spacecraft as the region where the SW pressure equals the magnetic pressure of the artificial magnetic dipole. We can call it the magnetopause of the artificial magnetosphere. The number of particles hitting the surface of the magnetopause, per unit time and per unit surface, is $N = N_0 v \cos\phi$, where N_0 is the density of SW protons ($\sim$5 $\mathrm{cm^{-2}}$ near the Earth), v is the velocity of the SW ($\sim$400 km $\mathrm{s^{-1}}$), and ϕ is the angle of incidence. If we assume specular reflection of the protons on the magnetopause, they will suffer a change of momentum equal to $2m_p v \cos\phi$, where m_p is the proton mass. So, the pressure of the SW will be $p = 2N_0 m_p v^2 \cos^2\phi$. We can then calculate the force of the SW on the magnetopause, by assuming that this surface is approximately spherical with a radius R. The result is

$$F = \int p\, dS = \pi R^2 N_0 m_p v^2. \tag{1}$$

This expression gives the upper limit of the force acting on the plasma bubble, and this result is illustrated in Fig. 1.

Let us now look at the force acting on the spacecraft itself. The spacecraft creates its own magnetic dipole, which will eventually confine the plasma produced by a helicon source. The expected characteristics of the coil are: number of turns $n_c = 1000$; current in the coil $I_c = 10$ A; and coil radius $a_c = 10$ cm. The resulting value for the magnetic dipolar momentum is $m_c = \pi a_c^2 n_c I_c = 300$ A $\mathrm{m^2}$ and, assuming that the axis Oz coincides with the direction of the magnetic dipolar momentum, we can write $\mathbf{m}_c = m_c \mathbf{e}_z$.

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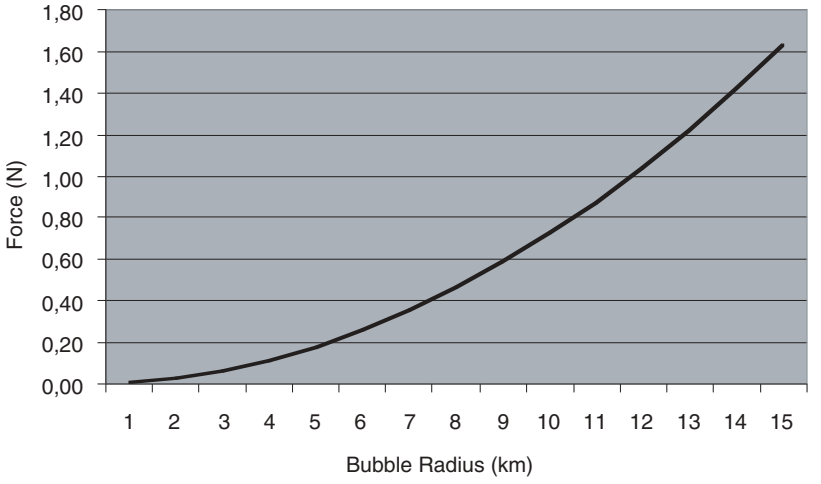


Figure 1. Solar attraction as a function of bubble radius.

The interaction of the SW with the plasma bubble will lead to the formation of induced currents, which will be responsible for the deformation of the magnetic dipolar configuration. The magnetic force acting on the spacecraft will then be due to the magnetic field **B** created by these induced currents:

$$\mathbf{F} = \nabla(\mathbf{m}_c \cdot \mathbf{B}) = m_c \nabla B_z. \tag{2}$$

Or, assuming that the gradient is directed along the axis Ox,

$$\mathbf{F} = m_c \frac{\partial B_z}{\partial x} \mathbf{e}_x. \tag{3}$$

As a simple model for the currents induced in the plasma in the immediate vicinity of the spacecraft, we consider a linear current I aligned with the axis Oy, flowing at a distance x from the spacecraft. The resulting magnetic field at the spacecraft position will be written as $\mathbf{B} = \mu_0 I (2\pi x)^{-1} \mathbf{e}_z$. The resulting magnetic force (in Newtons) acting on the spacecraft will then be determined by

$$F = m_c \left| \frac{dB_z}{dx} \right| = 6 \times \frac{I}{x^2}. \tag{4}$$

This means that, in order to obtain a force similar to the attractive force from the Sun, $F \simeq F_S \simeq 1N$, we need to have a current I such that $I > 10^4 x^{-2}$ A m^{-2}. For a linear current located at a distance $x = 1$ m from the spacecraft, we would need a current larger than ten kilo-Amperes: $I > 10^4 A$. This is an extremely large value of induced currents near the spacecraft, but the actual plasma currents are induced over a large volume inside the magnetic bubble and are not concentrated as assumed in the present model. The interest of the model is that, whatever the actual volume distribution of currents is, it will have to be responsible for the same value of the magnetic field **B**.

Let us now look at the force propagation along field lines. The SW, moving with a velocity $\mathbf{v}_0 = v_0 \mathbf{e}_x$, perturbs the magnetic flux tubes of the magnetic dipole created by the spacecraft coils. This perturbation is described by the MHD equations. These equations relate the velocity of the medium **v** with the pressure p, the current

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density **J** and the magnetic field **B**:

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t}+\mathbf{v}\cdot\nabla\mathbf{v}\right)=-\nabla p+\mathbf{J}\times\mathbf{B} \tag{5}$$

where ρ is the plasma density, and

$$\frac{\partial \mathbf{B}}{\partial t}=\nabla\times(\mathbf{v}\times\mathbf{B}). \tag{6}$$

If we assume a simple geometry such that $\mathbf{v}=(v_x,0,0)$ and $\mathbf{B}=(B_x,0,B_0)$, and use the constancy of the total plasma pressure $p+\mu_0 B_x^2/2=p_0$, we can obtain the propagation equation for the magnetic field perturbation B_x:

$$\frac{\partial^2 B_x}{\partial t^2}=v_{\mathrm{A}}^2\frac{\partial^2 B_x}{\partial z^2} \tag{7}$$

where v_{A} is the Alfvén velocity, $v_{\mathrm{A}}=B_0/\sqrt{\mu_0\rho}$. This shows that the perturbations induced by the SW propagate without significant losses along the magnetic flux tube, with the Alfvén velocity, from the magnetopause down to the spacecraft. Particular solutions for this model were discussed long ago by Scholer [2]. The collisional plasma located in the near vicinity of the spacecraft will eventually introduce some dissipation. However, apart from that, the force is transmitted without attenuation along the magnetic flux tubes.

In order to complete this qualitative discussion let us now use a test particle approach to establish a lower limit for the force produced by the SW over an artificial magnetosphere. We assumed that the magnetic field existing inside the plasma bubble is that of a modified magnetic dipole:

$$\mathbf{B}=\mathbf{b}_0 K r^{-\alpha} \tag{8}$$

where α is the decay factor (the usual magnetic dipole would be $\alpha=3$), K is the magnetic field amplitude that depends of the current and dimensions of the coil installed inside the spacecraft, **b** is a unit vector giving the orientation of the magnetic dipole, and r is the distance of the particle to the spacecraft.

A simple simulation code has been developed to solve the test particle trajectory in such a modified magnetic dipole. This allows us to determine the momentum transfer to the particle due to its collision with the magnetic field as a function of its impact parameter and initial velocity, and thus by momentum conservation, and after averaging over the particle population of the SW, to obtain the force acting on the magnetic dipole. Here we neglect the possible collisions with the particles of the plasma bubble, which means that we can only get a lower limit to the force acting on the dipole.

The area of simulation is a cube of $30\times30\times30$ km^3. A uniform flux of protons from the SW is introduced along the positive Ox direction. The magnetic dipole is oriented along the Oz direction, $\mathbf{b}=\mathbf{e}_z$. Both the magnetic field and particle position-velocity are simulated in three dimensions. Using the Runge–Kutta method, the particles are moved during a step of time, named dt. The velocity of the particles is updated assuming the presence of the magnetic field created by the modified dipole, which is not considered self-consistent.

Several values of the decay factor α (between 3 and 1) were used and the results are shown in Fig. 2. For small values, it is possible to observe a saturation on the force created. This is due to the limited volume of simulation used in our code, and has no physical relevance.

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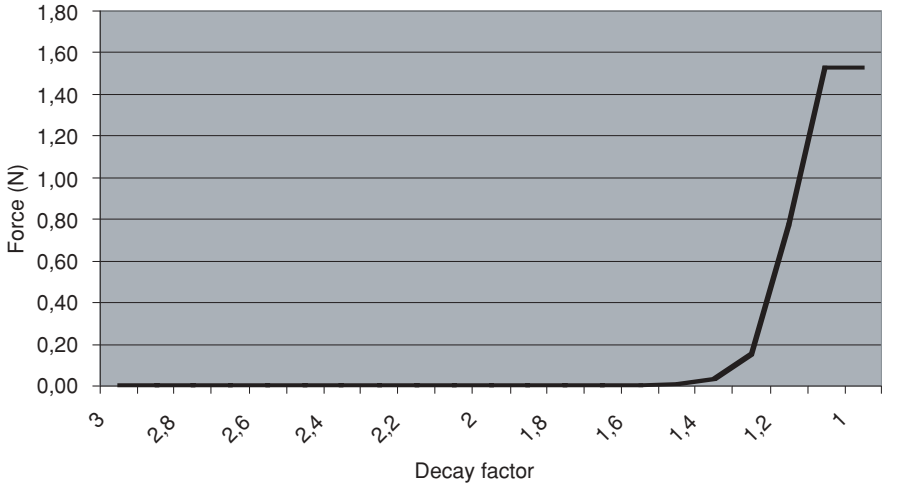


Figure 2. Total force versus magnetic decay factor.

3. Kinetic modeling

Previous studies employed MHD models to validate the assumptions of the magnetic field configuration after the mini-magnetosphere formation. However, as also mentioned in the original paper [1], kinetic effects can play an important role in the dynamics of the plasma-magnetic sail unfolding, in particular, associated with instabilities and wave excitation, that might damp some of the kinetic energy release in the plasma, and can give rise to a foamy sail.

Due to the non-trivial magnetic field configuration arising in a mini-magnetosphere, kinetic simulations are required to understand the plasma sail expansion into a dipole magnetic field configuration. The interaction of the SW with this plasma sail also plays a crucial role in the whole mechanism, and needs to be taken into account. It is clear that an electrostatic PIC simulation cannot model such a system. Only a full electromagnetic PIC code can deal with the currents generated in the plasma that lead to conversion of the plasma kinetic energy into magnetic fields. We have used a modified version of the object-oriented parallel PIC code OSIRIS [3], in order to include cathodes and externally applied fields. The full problem can be split in two different aspects: (i) plasma expansion into a dipole magnetic field configuration; (ii) interaction of the SW with a plasma immersed in a modified magnetic dipole field.

Here we show results of two-dimensional PIC code simulations, performed in two complementary configurations. The first configuration corresponds to a plasma expansion in the polar plane, or the plane Oxy which contains the two poles of the magnetic field. The magnetic field lines here are parallel to the computational plane. The other configuration corresponds to the equatorial plane Oxz, perpendicular to the magnetic field lines. The results of the total magnetic field spacial decay, for these two configurations are shown in Figs 3 and 4. For the initial, intermediate and final times of the runs. We can clearly observe the drag of the magnetic field lines due to the plasma expansion, particularly in the equatorial plane where a decay of $1/r$ is observed.

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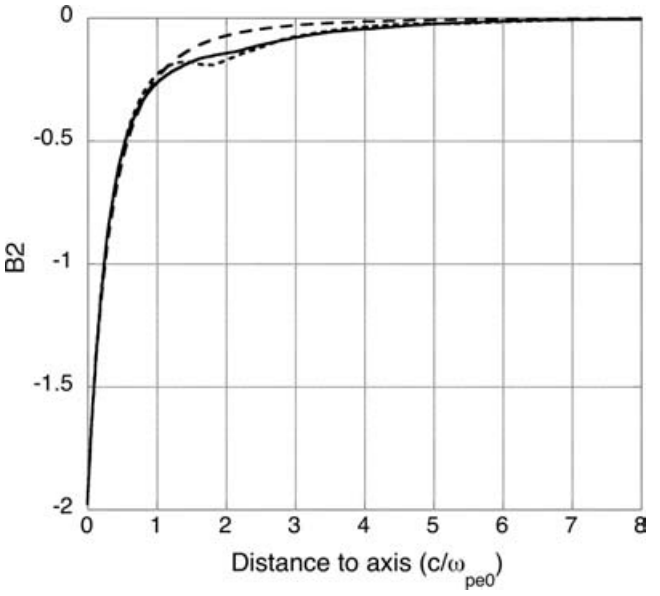


Figure 3. Radial decay of the magnetic field for initial, mid and final times of plasma expansion in the polar plane of the magnetic dipole.

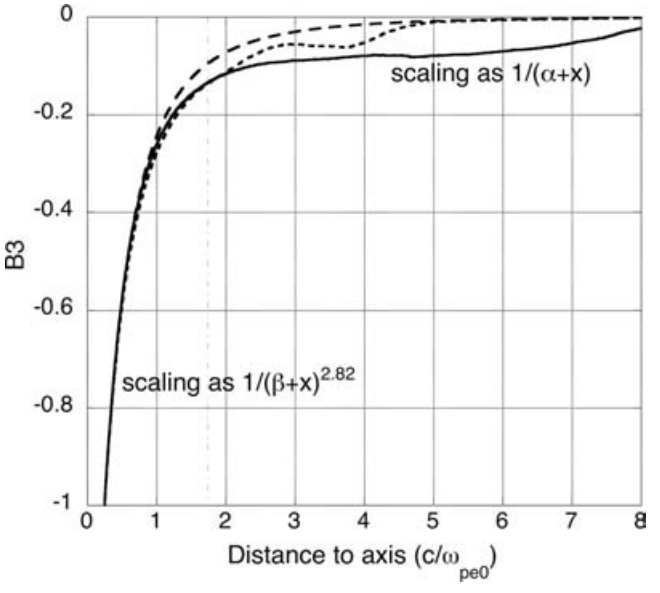


Figure 4. Radial decay of the magnetic field for initial, mid and final times of plasma expansion in the equatorial plane of the magnetic dipole.

4. Conclusions

Several physical problems relevant to the M2P2 propulsion scheme have been discussed. In particular, upper and lower limits of the force acting on the magnetic bubble were established. The upper limit is based on specular reflection at

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the artificial magnetopause, considered as a kind of opaque and totally reflecting barrier. The lower limit was based on the dynamic reflection of SW particles by the modified magnetic dipole field.

We have also briefly mentioned how the perturbed currents, originating near the artificial magnetopause, can propagate down to the vicinity of the spacecraft, with the Alfvén speed and with negligible losses. The resulting magnetic force on the spacecraft is due to large local currents. In order to determine the local current distribution and to establish a convincing value for the magnetic force acting on the spacecraft, we have used PIC code simulations. The first results of these calculations show that the plasma ejected from the spacecraft can indeed drag the magnetic field lines. Expansion of the magnetic field radial decay, from the initial $1/r^3$ down to $1/r$ was observed, thus confirming previous results based on MHD simulations. PIC code simulations of the SW interaction with the magnetized plasma bubble will be presented elsewhere.

A coherent qualitative picture of the process was established. A more quantitative view (of the current distributions) will imply the use of PIC and hybrid code simulations. Another important aspect of M2P2 is related to the plasma formation, which has also been analyzed by us and will be presented in a future publication.

Acknowledgement

This work was financed by the European Space Agency, under the ESTEC Contract no. 16360/02/NL/LvH.

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