Chapter eae124
Magnetic Plasma Sails

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1 INTRODUCTION

The kinetic energy requirements for a space vehicle to move around the solar system are enormous. To reach low Earth orbit (LEO), a satellite needs a change in velocity ($\Delta V_o$) of $\sim 8$ km s$^{-1}$ ($\sim 18,000$ miles per hour), and to escape from the Earth, the velocity increment must be $11$ km s$^{-1}$ or $25,000$ miles per hour (Hohmann transfer orbit, http://en.wikipedia.org/wiki/Hohmann_transfer_orbit). To go to Mars on a Hohmann transfer orbit trajectory of 6 months requires a $\Delta V$ just above $16$ km s$^{-1}$ ($36,000$ miles per hour), and to Saturn in 6 years requires a $\Delta V$ of $\sim 26$ km s$^{-1}$ ($58,000$ miles per hour). If you do not mind a long haul, then a $\Delta V$ of $\sim 45,000$ km s$^{-1}$ ($108$ miles per hour) will get you to Alpha Centauri in 60 years.

Plasma propulsion systems offer a tenfold increase in exhaust velocity that can greatly reduce the propellant mass, but at the cost of having to adding considerable mass for the power unit that supplies electricity to the plasma drive. Controlled fusion has the potential for vastly increasing the energy content and exhaust velocities, but these systems are presently too large to be suitable for space exploration. So the question is, "How do we advance space exploration given the above limitations?" The answer is actually simple: Use or extract energy from the environment, in which case you do not have to carry everything with you, and seemingly impossible missions become possible. The trick then is how to extract energy from the space environment.

There are basically two ways to extract energy from the environment. The first is by solar sails using reflection of sunlight for propulsion. It suffices to say that solar photons produce $\sim 9 \times 10^{-26}$ N m$^{-2}$ of pressure. The mechanics of solar sailing is described in another chapter within this series (see Volume 5, Chapter eae292), and it suffices to say that a sufficiently rigid sail area of $\sim 4000$ to $12,000$ m$^2$ would yield a net force of $25$–$75$ mN, depending on the angle of reflection. The main limitation to date for solar sails is in obtaining a sufficiently low density of material to keep the mass fraction of the solar sail low over the large surface areas that are required for useful force production.

The second form of energy is in the form of the high-speed particles that form the solar wind. The solar wind originates from the million-degree solar corona and consists of fully ionized hydrogen (i.e., free protons and electrons) flowing in a continuous stream outward from the sun at speeds between $350$ and $1000$ km s$^{-1}$ (2.2 $\times$ 10$^6$ miles per hour) (McComas et al., 1998). These charged particles can be deflected and guided by a magnetic field (Chen, 1984) to impart momentum on a spacecraft. However, the problem is that a very large
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collecting area is needed because the solar wind dynamic (i.e., effective sail) pressure is nearly three orders of magnitude smaller than the photon pressure.

The initial proposals to harness the energy of the solar wind were through magnetic sails or magsails (Zubrin, 1993). Although different variants have been discussed, the basic concept is to deploy a superconducting magnet with a radius of 100–200 km to attain accelerations on the order of 0.01 m s\(^{-2}\). The use of superconducting electromagnets would essentially eliminate all power requirements except those needed initially for establishing the electromagnet current and to maintain the cryogenic systems for the superconducting electromagnets. The drawback of such a system is that it is massive. With a projected dry mass on the order of a few metric tons, this propulsion system alone would outweigh many of the flagship satellite missions flown to date. In addition, the actual systems to build and deploy such a large magnet in space have not yet been developed.

As discussed in the following, the actual magnetic field that is needed to deflect the solar wind is very low. The fact was emphasized in the alternative system called Mini-Magnetospheric Plasma Propulsion (M2P2) (Winglee et al., 2000). In this system the magnetic field is created by currents supported by the injection of low-energy plasma in a small magnetic system attached to the spacecraft (Figure 1). The advantage over both solar sails and magnetic sails is that there is no deployment of large mechanical objects. Instead, the sail is formed by electromagnetic processes, avoiding issues with mechanical deployment and leading to very large collecting areas to yield nearly 20 times the thrust that could be developed by a standard plasma thruster with the same power and propellant consumption. M2P2 uses the same processes involved in the development of solar flares, coronal mass ejections, and magnetospheres around the planets except at a much smaller scale, hence the word mini. Potential for fast missions out of the solar system or to the planets can be enabled by utilizing ambient energy (i.e., from the solar wind) or from a beamed plasma system. In what follows, the requirements for such a system and the latest developments in the necessary technology to produce effective plasma sails for near-future applications are described.

2 CONCEPT REQUIREMENTS

Coupling to the solar wind is a nontrivial problem. The solar wind at 1 astronomical unit (AU), the mean distance of the Earth from the sun, has a typical density of \(n_{SW} = 6 \text{ protons cm}^{-3}\) and a speed \(V_{SW} \approx 450 \text{ km s}^{-1}\). This combination of particle density and speed yields a dynamic pressure of only 2 nPa. Therefore, a mini-magnetosphere must have a minimum radius of 10 km to produce a thrust of 1 N. For the following we will be conservative and assume that a 20-km radius is needed to take into account efficiencies of \(<100\%\) from the edges of the mini-magnetosphere.

The radius of the mini-magnetosphere is set by pressure balance between the solar wind dynamic pressure and the internal pressure within the mini-magnetosphere, which includes both plasma and magnetic pressures. We will call this distance the standoff distance for the mini-magnetosphere (\(R_{MS}\)). Deflection of a solar wind particle by a magnetic field requires that the magnetic field must be present over at least a gyro-radius; otherwise, the particle does not complete a gyration and therefore experiences little change in its trajectory. This condition is equivalent to requiring that

\[
R_{MS} \geq \frac{V_{SW} m_p}{e B}
\]  

where \(m_p\) and \(e\) are the proton mass and charge, respectively, and \(B\) is the magnetic field strength deflecting the ion. If one assumes a radius of 20 km, then the required magnetic field for deflection of the particle would be only 200 nT. To place this field strength into perspective, the terrestrial magnetic field strength at the equator is \(3.1 \times 10^4\) nT. Therefore, to produce the deflection the magnetic field strength required is only a few percent of the terrestrial magnitude, but this field must extend over tens of kilometers.

For a simple dipole magnet, the falloff of the magnetic field is inversely proportional to the distance cubed; that is, \(R^{-3}\). Thus, even a field as low as 200 nT cannot be supported by a small magnet on the spacecraft because of the large distances involved. However, plasma interactions can lead to the

![Figure 1. Schematic of the creation of mini-magnetosphere around a spacecraft that is then able to deflect charged particle of the solar wind that emanates from the million-degree solar corona.](image-url)
Figure 2. Plasma simulation of the inflation a magnetosphere. The color contours indicate plasma pressure along the vertical and horizontal planes. The arrows show the solar wind velocity in the horizontal plane, whereas the lines show magnetic field lines of the mini-magnetosphere. (a) No plasma injection into the mini-magnetosphere; (b) Interaction region is substantially increased by plasma injection. Reproduced from Winglee et al. (2000) © American Geophysical Union.

generation of currents that result in magnetic field stretching over large distances. This stretching of the magnetic field originates from the frozen-in-theorem (Chen, 1984), which states that for a collision-less plasma the magnetic field is convected or frozen-in to the plasma. Thus, the magnetic field frozen into a freely expanding plasma magnetic field would have the same falloff with distance as the plasma; that is, the magnetic field would fall off as $R^{-2}$. The slower falloff in magnetic field would be supported by induced currents within the plasma. It is this slow falloff in magnetic field that enables the creation of the heliosphere that extends beyond a few 100 AU and magnetospheres around the strongly magnetized planets, including the Earth, Jupiter, and Saturn (Parks, 2004). All of these systems have large-scale current sheets supported by plasma currents that allow the respective magnetospheres to have an area of influence much larger than would be expected from the planet’s magnetic field alone, with Jupiter’s magnetosphere being larger than the Sun itself.

Suppose that this freely expanding plasma now encounters the solar wind, which leads to compression of this system. This compression would slow the falloff even further than the $R^{-2}$ falloff of the freely expanding plasma. This effect is seen in planetary magnetospheres, in which solar wind piles up the magnetic field in the region called the magnetopause, the region of pressure balance between the planetary magnetic pressure and the solar wind pressure (Parks, 2004).

For space propulsion applications, the same configuration can be developed. The requirements are modest and could be met with a magnetic field of a few kgauss on the spacecraft and the injection of low-energy plasma (Winglee et al., 2000).

Because of the injected plasma had comparable energy density comparable to the magnetic pressure falloff in the magnetic field as slow as $R^{-1}$ can be developed when the interaction with the solar wind is taken into account (Winglee et al., 2000).

Since the original proposal of M2P2, the predicted inflation has been numerically modeled by several additional groups (Khazanov et al., 2005; Mengali and Quarta, 2006; Funaki, Ueno and Yamakawa, 2007; Tang, Yao and Wang, 2007). An example of the results is shown in Figure 2. The part of the magnetosphere that faces the solar wind is significantly compressed, while in the tail or downstream of the magnetosphere the field lines are substantially stretched. Without injection of the plasma, the interaction region with the solar wind is very limited (Figure 2a). When plasma is injected on field lines that are preferentially on the side facing the solar wind, the field lines become inflated and the solar wind interaction region is very much larger, as in the Figure 2b. As a result of this enlarged deflection region, the thrust that is generated on the system goes from the $\sim 100 \text{ mN kW}^{-1}$ of regular plasma thrusters to $>1 \text{ N kW}^{-1}$, vastly increasing the capacity for moving payloads around the solar system.

As noted, an important feature here is that the inflation is done by electromagnetic processes with no need for large mechanical structures, as in the case of solar sails. Another difference is that solar sails tend to have fixed surface area. As a result, the amount of thrust decreases (increases) as the spacecraft moves out if (into) the solar system. An inflated mini-magnetosphere is a pressure balance device, so...
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Figure 3. (a) Shows the M2P2 prototype. It consists of an electromagnet encased in a stainless steel jacket to protect it from the ambient plasma. Propellant is fed into the quartz tube, which is wrapped with a radio frequency (RF) helicon antenna. The propellant is ionized by the intense RF fields in the helicon source, and the ensuing plasma flows out of both ends of the quartz tube to inflate the mini-magnetosphere; (b) shows the optical emissions when the system is operated in argon, and the plasma loading of the entire field line.

It increases in size as one moves outward from the sun and decreases as one moves inward, yielding a constant thrust irrespective of position within the solar system.

A picture of the M2P2 prototype is shown in the Figure 3a. The prototype consists of an electromagnet that is encased within a stainless steel jacket. Propellant is injected into the quartz tube that is then ionized by radiofrequency (RF) heating of the plasma. An RF source was chosen so the plasma injection occurred via a mechanically open system and the plasma could flow along the magnetic field line without intercepting any physical barriers. Note that the quartz tube is placed preferentially to the side that would be intercepting the solar wind. This configuration ensures that the plasma is placed on closed magnetic field lines to minimize plasma losses resulting from charged particle flow along the poles of the magnet.

For optimum inflation of the field line, the plasma would flow along the field lines from the core of the magnet. The field strength within the core has sufficient strength at $\sim$1 kG to confine and guide the plasma through the applied magnetic field so it points into the solar wind. At the point along the field line where the field strength drops below a few hundred gauss, the dynamic pressure dominates the magnet pressure, enabling expansion of the field lines in the forward direction; that is,

$$\rho_{\text{Plas}}(x) V_{\text{Plas}}^2 \sim \frac{B^2(x)}{\mu_0}$$  \hspace{1cm} (2)

where $V_{\text{Plas}}$ is the plasma bulk velocity (approximately constant), and $\rho$ and $B$ are the plasma density and magnetic field strengths, respectively, which are both functions of position $x$.

Typical plasma sources yield plasma speeds of $15 \text{ km s}^{-1}$ or more, so the last unknown is the required plasma density. Denoting field strength at the expansion point ($B_{\text{Expansion}}$) then from equation (2) the required number density for the injected plasma is

$$n_{\text{Plas}} = \frac{m_p}{M_{\text{Plas}}} \frac{V_{\text{Plas}}^2}{B_{\text{Expansion}}^2} \mu_0 m_p V_{\text{Plas}}^2$$ \hspace{1cm} (3)

where $m_p$ is the mass of a proton and $M_{\text{Plas}}$ is the atomic number of the propellant. If one assumes that the expansion occurs at a field strength of a few hundred gauss, equation (3) reduces to

$$n_{\text{Plas}} = \frac{m_p}{M_{\text{Plas}}} \times 2 \times 10^{18} \text{m}^{-3}$$ \hspace{1cm} (4)

Although a number of plasma sources exist that can be used to generated the required density (Herman and Gallimore, 2008), most have not been used in the presence of a large-scale magnetic field as needed for M2P2. Another requirement for the plasma source is that it has to be mechanically open so the plasma can flow along the magnetic field lines without intercepting a solid surface. Such a mechanically open system would enable the plasma to follow along the full length of the field lines and not be lost to contact with...
any walls, allowing a long lifetime of the plasma within the mini-magnetosphere.

Although many existing sources can meet the plasma requirement, there are fewer with a mechanically open systems, and even fewer that have been operated in the magnetic field configuration needed for M2P2. Because of these criteria, a helicon source was chosen for the prototype development. Helicons (Miljak and Chen, 1998) use high-intensity RF waves at a frequency between the electron and ion cyclotron frequency to produce the breakdown of the plasma and the heating of the electrons through wave–particle interactions with a driven whistler wave that is driven by the rf once the plasma is created. The heated electrons stream out along the field lines in front of the ions to create an ambipolar electric field that leads to the outward acceleration of the ions.

Figure 3b shows the M2P2 prototype configuration operating in the 400-liter vacuum chamber at the University of Washington (Winglee et al., 2003). The vacuum system is capable of a base pressure of $10^{-7}$ Torr. During normal operation neutral gas is puffed into the source region, where it is ionized by the helicon source, maintaining a high vacuum outside the dipole magnet. Figure 3b shows the prototype in operation using argon. The optical emissions show how the plasma is able to move out along the field line to produce mass loading of the entire field line. The outline of the equatorial Langmuir probe can be seen coming from the left and entering into the plasma column. The optical emissions along with the Langmuir data show that the plasma column retains a very peaked profile, which maps back to the helicon source. Peak densities on the order of $10^{10}$ to $10^{11}$ particles per cubic centimeter are produced at the equator. The most important feature in the data is that there is good confinement of the plasma even at low magnetic fields in the magnetic equator.

Demonstrations of a mini-magnetosphere’s ability to deflect an external plasma source were performed between 2001 and 2003. An example is shown in Figure 4 from tests performed at the University of Washington within a 3-meter-long by 1.5-meter-diameter vacuum chamber. This system used a 1-kW helicon plasma source operating at a frequency of 13 MHz. The M2P2 source was located on the left-hand side of the chamber. In the experiment, xenon, which produces the green optical emissions, was used as the propellant for the M2P2 source. As described, the plasma moves out along the field lines initially, but eventually reaches a region of weaker magnetic field where it pulls the magnetic field outward with the net flow towards the end of the chamber. Note that the path of the plasma is much more extended than if it was following dipole field lines in vacuum.

A high-power helicon plasma source (HPS) (Ziemba et al., 2006), acting as a surrogate for the solar wind, was placed on the right-hand side. This helicon source used a weaker magnetic field at 200 G and a lower frequency of 300 kHz. The lower frequency allowed for the use of solid-state switching that enables the helicon to operate at 10 s of kW. This system was operated in argon, which produces the blue optical emissions. Note that the 1-kW xenon optical emissions penetrate very much deeper into the chamber than the 20-kW surrogate solar wind source; that is, the low-power source is able to deflect the high-power solar wind source, as per the predictions for the M2P2.

The bottom part of Figure 4 shows the measurement of the plasma density from a double Langmuir probe with RF compensation in the middle of the chamber. The magenta line...
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Figure 5. Mars exploration scenario using M2P2. The worst-case scenario of only radial thrust is considered. In this scenario the M2P2 system actually has to travel beyond Mars and then fall back towards the planet, where M2P2 then provides the breaking so the $\Delta V$ is only $\sim 1 \text{ km s}^{-1}$ at arrival at Mars. Similarly, for the return trip to Earth one first sails outward and then falls back inward towards Earth using M2P2 to produce the initial acceleration as well as the breaking. For this worst-case scenario the total mission time is 7 months shorter than the NASA Mars reference mission.

shows the results with all the magnetic fields on, but only the HPS source in operation. A substantial density is seen in the middle of the chamber for this case. With the exact same conditions except with the M2P2 source switched on essentially no plasma from HPS is able to reach the probe. This result confirms the conclusion from the optical emissions that an inflated mini-magnetosphere is very efficient at deflecting more energetic plasma. In this case the system would be deriving the thrust of 20 kW while only expending 1 kW in plasma production. This type of leveraging would make a huge difference in the amount of thrust that can be obtained by a payload intercepting plasma from the solar wind.

3 NAVIGATION

The navigation of the system operating a magnetized plasma sail is similar to that of a solar sail, except that there is potentially more radial acceleration as opposed to azimuthal acceleration. For a mission that would travel out of the solar system, the radial acceleration from the solar wind is an advantage and high speeds could be readily attained after several months of acceleration. An M2P2 system launched now could reach the very rim of the solar system, called the heliopause, before the Voyager spacecraft that was launched in the late 1970s (Winglee et al., 2000). The orbital dynamics for planetary transfers is a little more complicated, but actually adds new flexibility that would not be considered by chemical rocket systems.

One example is the development of a round trip mission to Mars. The NASA reference mission to Mars using chemical rockets is 2.4 years (879 days) long (Ziemba et al., 2006). The corresponding results for an M2P2 system are shown in Figure 5. The orbital calculations assume that payload and power systems are distributed so that 1 N of thrust is derived from the solar wind per kilowatt of onboard power for every 200 kg of spacecraft mass. To create the mini-magnetosphere, a single large source is not necessary, and it may be more efficient to support the mini-magnetosphere by multi-systems, as is illustrated. Multi-systems would lead to shaping the magnetosphere so that there is angled deflection of the solar wind to develop azimuthal acceleration.

For the worst-case scenario it is assumed all the thrust is radial. Going directly to a planet is not an optimum solution, as the $\Delta V$ would be too high for orbit insertion. Thus, if one is sailing from the Earth to Mars for example, the spacecraft has to actually sail beyond Mars’ orbit planet and then fall inward under solar gravity, as shown in Figure 5. As it falls inward, the M2P2 system would again be operated to remove the radial velocity component to arrive at Mars with a $\Delta V$ of $<1 \text{ km s}^{-1}$. Another form of propulsion would be needed to complete orbital insertion. This $\Delta V$ for orbital insertion is very much less than that required for the orbital transfer within the Mars reference mission, so there would be substantial cost savings using this technology.

Similarly for return to Earth from Mars, the spacecraft would first sail outward under the radial force of the solar wind, and then once the M2P2 system is switched off,
it would fall towards Earth under the influence of solar gravity. The ΔV that develops would then be mitigated by again deploying the M2P2 as Earth is approached, so that a ΔV at arrival at Earth would be on the order of 1 km s⁻¹. Again, chemical rockets or another propulsion system would be used to produce the small ΔV to complete the orbital insertion.

Consider the plasma created near the poles of a dipole-like magnetic configuration. One benefit of the higher ΔV orbits is that the round trip mission to Mars goes from 2.4 years for the chemical rocket scenario to only 1.8 years for the M2P2 scenario. M2P2 could also be used for radiation shielding but energy requirements are large (MW). The best use of the power is to travel faster to the destination, as opposed to using chemical rockets for propulsion and needing shielding. The following describes plasma sail applications if high power is available.

4. BEAMED PLASMA SAILING

Although sailing the solar wind offers a reduction in trip time and cost, 1.8 years is still a long mission. Furthermore, the orbital trajectories are complicated by the fact that there is always a radial component to the acceleration vector. New mission scenarios for a variety of applications become available if instead of using the solar wind as the source of energy, the plasma sail is used to deflect a directed plasma beam. The scenario has many parallels with laser light sails (Forward, 1984), but instead of using lasers a higher-power plasma source is used. The advantage of the latter is that significantly less energy is needed to produce plasma with the same amount of momentum flux as a laser beam. The disadvantage of beamed plasma systems is that unlike lasers a high degree of collimation over large distances has yet to be demonstrated. Without this collimation the range over which momentum and energy can be efficiently beamed to the spacecraft is highly limited.

Recent developments in the understanding of magnetic nozzles for plasma thrusters suggest that collimation over large distances is possible and could enable the beamed plasma scenario to become a reality in the near future (Wingler et al., 2007). Magnetic fields are the easiest way to collimate plasmas, but the use of a fixed magnet system in space is not feasible. However, space plasmas can support currents and magnetic fields over large distances, so induced magnetic fields from within the beam plasma can provide a guide magnetic field to keep the beam collimated. Consider plasma created near the poles of a dipole-like magnetic configuration that would be part of a magnetic nozzle system. There are four critical parameters that determine the characteristics of the resultant plasma flow:

1. the ratio of the bulk speed to the ion thermal speed or sonic Mach number (Mₐ);
2. the ratio of the bulk speed to the local Alfvén speed or Alfvénic Mach number (Mₐ);
3. the ratio of the thermal pressure to the magnetic field pressure (βₜ₁); and
4. the ratio of the ion gyro-radius relative to the scale length of the magnets.

If the plasma has a very low β (both thermal and dynamic components), the plasma will flow out along the magnetic field lines without making major magnetic field perturbations. The plasma exactly on the pole will be able to escape to infinity, but the rest of the plasma will tend to be trapped on close field lines and therefore not contribute to any net thrust on the system. As the plasma β is increased, a higher fraction of the plasma will escape as it moves into sufficiently weak fields such that the local β eventually becomes greater than unity. The direction of the plasma is highly dependent on the ratio of the ion gyro-radius to the scale length of the magnet. If this ratio is large, the plasma will have random pitch angles as it escapes, so the plasma plume will have a wide opening angle and the directed thrust will not be optimal.

Instead, suppose that at the source β₁₀₁ ≈ 1 (or Mₐ ≈ 1) and β₁₁ ≪ 1 and the ion gyro-radius is smaller than the scale length of the magnets. In this case, the plasma has sufficient energy density that it can distort the magnetic field. Through the frozen-in theorem these magnetic field perturbations will lead to the pulling out of the magnetic field. An equivalent way to think about the generation of these magnetic field perturbations is that the electrons rotate in a right-hand fashion about the magnetic field, whereas the ions rotate in the left-hand sense. Because of density gradient effects associated with a beam of finite width, the electron and ion currents do not exactly cancel as in homogeneous plasma. Instead there is a net edge current that has an azimuthal component that supports the extension/stretching of the axial magnetic field.

The presence of this axial magnetic field is important because such fields are known to have a stabilizing effect on instabilities (such as the pinch, sausage, and Kelvin–Helmholtz instabilities) that could lead to the disruption of the beam. Because the dynamic pressure is driving the magnetic perturbations, the field lines can be stretched as the plasma moves out, but because β₁₁ < β₁₀ the thermal energy of the plasma is insufficient to cause beam expansion. As the beam propagates into a weaker magnetic field, there is conversion...
of thermal energy (or more exactly, perpendicular temperature) into the directed energy because of the conservation of the first adiabatic, so $\beta_{\text{Dyn}}$ always remains larger than $\beta_{\text{Th}}$.

A critical feature of the system is that with the stretching of the magnetic field, the plasma subsequently injected into the modified field geometry sees a less divergent field. Therefore it will experience stronger collimation than earlier injected plasma. This will be true at all times, leading to the self-collimation of the beam (i.e., the collimation is produced by the magnetic nozzles as well as the induced plasma currents).

The high-power solar wind source of Figure 4 satisfies these criteria for efficient beam collimation and was used to validate the above principles. Figure 6 shows a comparison of laboratory measurements versus predictions from computer simulations. In the absence a magnetic nozzle (left-hand side) the plasma profile is very broad, with an opening angle of nearly $45^\circ$ in both laboratory measurements and computer simulations (Winglee et al., 2007). The magnetic field lines in this case also remain highly divergent. With the addition of a magnetic nozzle (right-hand side) very much stronger collimation of the beam is seen in both the laboratory measurements and computer simulations. The beam divergence is nearly one third of the no-nozzle case, and the measure bulk speed of the plasma along the axis was measured to be about 30% faster. The self-focusing effect is seen in that the magnet field lines are pulled into the plasma beam so that the divergence is much less than the mapping of the field lines in the absence of any plasma injection. The experimental data also showed that the width of the beam profile decreased in time (Winglee et al., 2007).

The longer-term evolution of the system cannot be evaluated in the laboratory because of interactions with the chamber wall. However, the computer simulations as shown in Figure 7 indicate that the self-collimation continues on.
Figure 7. Continuation of the computer simulations of the nozzle configuration in Figure 6 over longer length and time scales. At any fixed position along the beam, the magnetic field is pulled into the beam to create a strong axial magnetic field and the collimation of the beam increases with time; that is, the plasma beam is self-collimating.

large time and length scales well beyond the actual nozzle magnet. On longer times scales the induced plasma currents are sufficient to fully straighten the magnetic field lines -- essentially producing a magnetic field configuration analogous to a long solenoid condition. Within this solenoid configuration these field lines are straight, which would enable beamed plasma propagation with little divergence, as seen in the almost straight the contours of the beam energy density, parallel to the magnetic field lines.

If this self-collimation were to be validated in space, then it opens up the possibility of beam-plasma systems for augmenting spacecraft propulsion. It would be particularly important as it would enable the separation of power and propulsion from the actual payload itself. In the beam plasma scenario, one would require a high-power (MW) beam plasma system in LEO to accelerate payloads. The international space station with a mass of 300,000 kg now has power generation capabilities of 100 kW. Lithium ion battery storage yields $\sim 0.4 \text{ kW h kg}^{-1}$ (or 1.5 MJ kg$^{-1}$). If about half the mass were comprised of batteries, there would be enough energy onboard to give a 10,000-kg payload a $\Delta V$ of about 3 km s$^{-1}$, which is more than enough energy to go from low Earth orbit to a geosynchronous orbit. Once in the higher orbit chemical or electric propulsion on the spacecraft could be used to circularize its orbit. If the orbit is not modified, then it will continue to have its perigee near the space station. In this latter case, another boost can be applied to raise the orbit further and even give the payload sufficient $\Delta V$ to escape Earth.

Two important aspects need to be noted here. First, the amount of mass of the batteries required for the boost is higher than that needed for a chemical rocket to produce the same orbital maneuver to geosynchronous transfer. Cost savings only start to occur if the system is used on multi-spacecraft and/or multiple boosts to raise or lower and orbit on a single spacecraft. Second, in delivering the impulse onto the payload, the space station will experience a back reaction that will modify its orbit. However, difference in the size of the system, the space station will experience a much smaller $\Delta V$ that can be corrected to be the same system used to boost the
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Figure 8. A fast return trip to Mars using M2P2 that intercepts a high-power plasma beam in an analogous fashion as in the experimental setup in Figure 4. By separating the power load from the power system needed to create the plasma beam, the payload can be accelerated to very high speed to enable a return mission within 100 days. In addition to high speed, this system also has the advantage that the infrastructure for creating the beam can be used on a wide range of missions to yield a very cost-effective system.

payload. Because plasma propulsion units are being used, the mass expended is very much less than would be used for chemical rockets.

If the battery/payload mass ratio is increased from 15:1 in the above example to 150:1 (either by increase the mass of the batteries or reducing the mass of the payload), $\Delta V > 20 \text{km s}^{-1}$ are possible. A chemical rocket attaining the same speed launched from the ground would require a fuel-to-payload mass ratio nearly an order of magnitude higher. With this $\Delta V$ a fast trip to Mars in about 50 days is possible. However, breaking at Mars would require a similar system to decelerate the payload and enable orbital insertion. This fast speed is important because the planets at this time are still in close proximity, as shown in Figure 8. A Hohmann transfer orbit to Mars (http://en.wikipedia.org/wiki/Hohmann_transfer_orbit) requires 259 days, by which time Earth and Mars are on the opposite side of the Sun, and a return to Earth is not possible until the planets realign. In the high $\Delta V$ mission scenario the mission can stay at Mars for ~11 days and still have time to make the return to Earth using the same infrastructure that was on the outward leg. In this fashion a fast return trip of ~100 days is possible. An important feature of the beam system is that multiple payloads could be routinely launched to a variety of different locations once the plasma-beaming infrastructure is in place. This architecture could greatly facilitate a broad range of missions throughout the solar system at reduced cost.

5 SUMMARY

Magnetic plasma sails deflecting either the solar wind or plasma beams offer an important way to increase access to space beyond low Earth orbit. The fact that plasma can be both directed by a magnetic field as well as generate currents to modify the magnetic field is an important tool, and its applications are only just beginning. If missions continue to rely on carrying all the propellant and power onboard the spacecraft, then their costs will remain high. Plasma sail technology offers substantial savings and high $\Delta V$ orbits that can enable missions that are not possible with conventional chemical rocket systems.

REFERENCES


Abstract:
Magnetic plasma sails can augment spacecraft propulsion by the deflection of charge particles from an external source, thereby utilizing energy and momentum that is not actually carried on board the spacecraft. The external source could be the solar wind that has speeds of 350–800 km s\(^{-1}\), which is more than an order of magnitude faster than most plasma propulsion system presently being considered. Because of the tenuous nature of the solar wind, a mini-magnetosphere needs to be created by the injection of low energy plasma that expands the magnetic field out to tens of kilometers. This expansion can be achieved by induced plasma currents stemming from the plasma interaction with a base dipole magnet field. An alternative use of plasma sails is the deflection of beamed plasmas. This latter application opens up a host of new applications, including raising or lowering of orbits of spacecraft around the Earth, as well as fast missions to the planets. New developments in magnetic nozzles opens up the possibility of having collimated plasma beams propagate over large distances to achieve efficient beam-plasma applications.

Keywords: plasma sails, magnetospheres, solar wind, orbital dynamics, beamed plasmas, magnetic nozzles
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