Laboratory Testing of the Mini-Magnetospheric Plasma Propulsion (M2P2) Prototype

R. M. Winglee[1], T. Ziemba[2], J. Slough[2], P. Euripides[1] and D. Gallagher[3]

[1]*Geophysics Program, Box 351650, University of Washington, Seattle WA 98195-1650*
ph: 1-206-685-8160, e-mail: winglee@geophys.wasington.edu
[2]*Aeronautics and Astronautics, Box 352400, University of Washington, Seattle WA 98195-2400*
[3]*NASA Marshall Space Flight Center, Space Science Laboratory, Huntsville AL 35812*

Abstract. Mini-Magnetospheric Plasma Propulsion (M2P2) seeks the creation of a magnetic wall or bubble (i.e. a magnetosphere) attached to a spacecraft that will intercept the solar wind and thereby provide high-speed propulsion with little expenditure of propellant. Results from a laboratory prototype that demonstrate the basic formation and expansion of a mini-magnetosphere are presented. The prototype uses a helicon source embedded asymmetrically in a dipole-like magnetic field. Breakdown of the plasma can be produced at neutral pressures of between about 0.25 to 1 mTorr to produce plasma densities of the order of 10^{11} - 10^{12} cm^{-3} with a temperature of a few eV. The plasma pressure is sufficient to cause the outward expansion or inflation of the mini-magnetosphere. The motion of both open and closed field lines within the vacuum chamber is demonstrated through the optical emissions from the helicon plasma. Inflation of the magnetosphere to several feet away from the magnetic coil and the equatorial confinement of the plasma are demonstrated. In space, inflation to about 15 – 20 km would be expected for the same configuration, which would potentially lead to the acceleration a 70 – 140 kg payload to speeds of about 50 – 80 km/s over a 3-month acceleration period. At this speed, missions to the heliopause and beyond can be achieved in under 10 yrs.

INTRODUCTION

While the solar wind provides an abundant source of high speed (> 300 km s^{-1}) particles that could be used propel a spacecraft to high speed, the problem has always been to efficiently couple to this plasma wind. Coupling to the solar wind is in principle easy in that it only requires a magnetic field. However, the practical application is made difficult by the tenuous nature of the solar wind, which has densities typically of about 6-8 particles per cm^{-3} at 1 AU. Thus, in order to collect an appreciable amount of force the interaction region needs to have a radius greater than about 10 km for a small scientific spacecraft, and nearly 100 km for observatory class spacecraft. The original concept to tap into the solar wind was called “magsail” (e.g., Zubrin,1993) required the deployment of a superconducting magnet in space with a radius 100-200 km. The drawback of such a system is that it is fairly massive (of the order of a few metric tons) and the physical construction and cost of such a system presently limit its potential usage from technical and/or economical viewpoints.

Mini-Magnetospheric Plasma Propulsion (M2P2) (Winglee et al., 2000a,b) is analogous to solar and magnetic sails in that it seeks to harness ambient energy in the solar wind to provide thrust to the spacecraft. It is unique though in that it seeks to create a mini-magnetosphere or magnetic bubble around the spacecraft through electromagnetic processes (as opposed to mechanical structures). It uses the fact that when a collisionless plasma is created in a magnetic field, that magnetic field is frozen into the plasma and as such as the plasma expands outward it can carry the mechanical field with it. Thus, the technical and material problems that have beset existing sail proposals are removed from the problem. Because the deployment is electromagnetic large-scale cross-sections (15 - 20 km for a prototype version) for solar wind interactions can be achieved with low weight (< 50 kg for the device) and low power (< 3 kW) requirements to produce thrust of a few newtons. The M2P2 system acts similar to a balloon in that it will expand as the solar wind dynamic pressure decreases with distance from the sun. As such it will provide a

CP552, Space Technology and Applications International Forum-2001, edited by M. S. El-Genk

constant force surface (as opposed to a mechanical structure that provides a constant area surface) and thereby provide almost constant acceleration to the spacecraft as it moves out into the solar system.

In order to achieve the desired expansion of the mini-magnetosphere, the onboard device has to be able to produce a plasma with a density of ~ 10^{11} cm^{-3} at a temperature of a few eV in magnetic fields greater than about a few hundred gauss. The conditions on the plasma density and energy are set by the requirement that the corresponding plasma pressure exceeds the magnetic field pressure. The field strength is set such that when its is stretched out to 15-20 km, it will be of the order of the 50 nT that is required to deflect the solar wind ions. This paper describes developments of a laboratory prototype and initial results demonstrating that the above plasma conditions and plasma inflation can be achieved with existing technology are presented.

OPTIMIZATION OF ANTENNA AND MAGNETIC CONFIGURATION

The original design for the M2P2 was based on laboratory helicons, which can produce plasma densities of the order of 10^{12} - 10^{14} cm^{-3} in field strengths of few hundred to 1200 G (Miljak and Chen, 1998; Gilland et al., 1998). These devices typically use 600 W to 1 kW RF power to produce argon ions and electrons with temperatures of about 4 eV for devices with diameters ~ 5 cm (Conway et al., 1998). These plasma conditions are equivalent to about 40 mN of force utilizing about 7.5 $x10^{-6}$ kg/s or about 0.6 kg/day, and are almost identical to that required by the M2P2 to produce a mini-magnetosphere of 15-20 km in the solar wind at 1 AU (Winglee et al., 2000). For a typical solar wind density of 6 cm^{-3} and a speed of 500 km s^{-1}, the solar wind dynamic pressure is about 2 nPa so the total amount of force that would be intercepted by the mini-magnetosphere would be about 1.5 to 3 N.

Figure 1 shows the original design of the M2P2 prototype. The plasma is produced by the rf heating of the propellant gas which is fed through a central copper tube into a inner quartz tube which is open at both ends. The rf heating is facilitated by a helicon (Type III Nagoya) antenna (5 cm diameter) which is wrapped around the inner quartz tube. In order to isolate the antenna from the plasma an outer quartz tube is inserted over the antenna and the region between the two quartz tubes is sealed off.

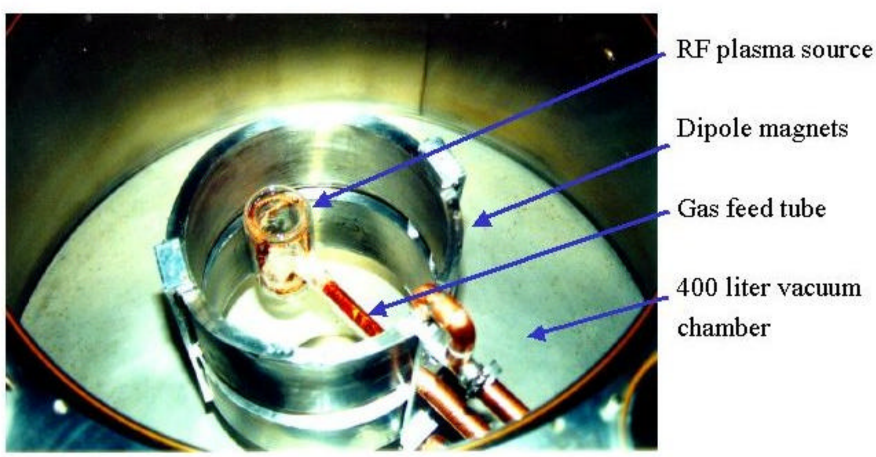

FIGURE 1. The M2P2 prototype in a small (1m) vacuum chamber at the University of Washington.

The magnetic coils (20 cm diameter) which are encased in stainless steel jackets to shield then from degradation from plasma interactions are then placed around the helicon inside the chamber (1 m diameter) so that the plasma, when it is created, is embedded on closed magnetic field lines, i.e. the plasma can flow along the field lines and will re-circulate through the helicon antenna with out striking chamber or magnet walls. This configuration differs markedly from its laboratory helicons when the system is magnetically open with the bulk of the plasma flowing straight to chamber walls or objects. As such the M2P2 configuration has the advantageous features of minimizing plasma losses while maximizing plasma heating.

Plasma production in the absence of a magnetic was first tested. Such plasma production is shown in Figure 2 (left hand side) when the chamber was back filled to a pressure of 40 mTorr of Helium. In the absence on any magnetic field the plasma is seen to have very little structure and rapidly expands in all directions at the ends of the quartz tubing. In addition the plasma production is not very efficient being produced capacitively (i.e. by the presence of large electric fields from the antenna). If is for this reason that some breakdown can be seen along the length of the feed tube to the antenna.

However, this ionization process is inefficient. It requires a minimum pressure of about 30-40 mTorr which corresponds to a density of ~ 10^{15} cm^{-3}. This high density of neutrals causes the rapid loss of energy of the plasma and results in the optical emissions to be restricted to the near vicinity of the antenna. This level of neutral density required for capacitive breakdown is typical of such configurations.

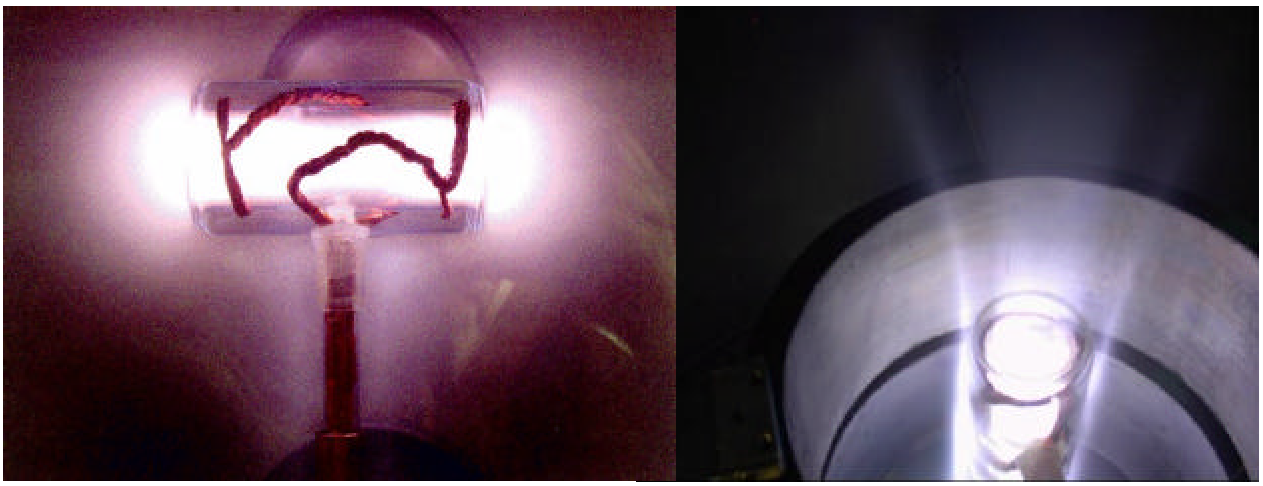

FIGURE 2. The production of plasma with no magnetic field (left hand side) and at 350 G magnetic field (right hand side).

When the magnetic field is applied, the plasma is produced by inductive processes involving electromagnetic whistler (or helicon) waves. It allows more efficient coupling of energy from the antenna into the plasma. An example of this breakdown in argon at 15 mTorr with 350 G magnetic field is shown on the right hand side of Figure 2. In addition to improving the efficiency, the plasma is also seen to stream along magnetic field lines indicating that the plasma can be produced and localized to the magnetic field as desired for the successful operation of the M2P2.

However, the plasma emissions in Figure 2 also show a weakness in adapting the laboratory helicon directly to the M2P2 configuration. In laboratory helicons both the magnet and antenna are outside the chamber. When both components are in the chamber we can see that there is strong plasma production on the outside of the antenna as well as on the inside of the quartz tubes. In addition, the plasma emission is seen touching both the inside and outside of the quartz tube. This means that a significant amount of plasma energy is being lost to interactions with the quartz tubing.

A MORE EFFICIENT ANTENNA DESIGN

The original premise of the quartz tubing was that it should produce insulation between the magnet and the antenna from the plasma. The plasma emissions of Figure 2 show that even though some of it is produced on the outside of the quartz tubing all the plasma is strongly confined so that much of the plasma is in fact unable to reach the magnet itself. Furthermore, plasma losses would probably be reduced if the quartz where actually not there. In other words the quartz tubing, which is a key component in laboratory helicons, isn't actually needed for the M2P2 prototype. Thus, the next step in the development of the prototype was to replace the quartz-encased antenna with a bare wire antenna. This step allows a major simplification to the design of our prototype while at the same time allowing orders of magnitude increase in its efficiency.

This improved efficiency is demonstrated in Figure 3. The minimum neutral required for breakdown is reduced to about 0.25 mTorr which is smaller by more than an order of magnitude than that required for the initial prototype and its laboratory equivalents. The low pressure causes the optical emissions to appear diffuse but close inspection shows that the plasma is still well collimated. This collimation is more clearly seen in the right hand side where the neutral pressure is increased to 1 mTorr. This pressure is nearly still nearly an order of magnitude lower than in which the original prototype with the quartz tubing could operate.
In addition, the plasma is produced in a much more uniform column and it remains curved by the presence of the magnetic field as in the original design. The artificial structures produced by the quartz tubing are now eliminated. The plasma densities produced by this configuration are estimated to be in the range of 10^{12} - 10^{13} cm^{-3}, which is higher than the minimum required for the successful operation of the M2P2. The field strengths are also in the desired range of a few hundred gauss. This plasma is produced at about 400 W electrical into the antenna, which is also at the level originally estimated in Winglee et al. (2000b).

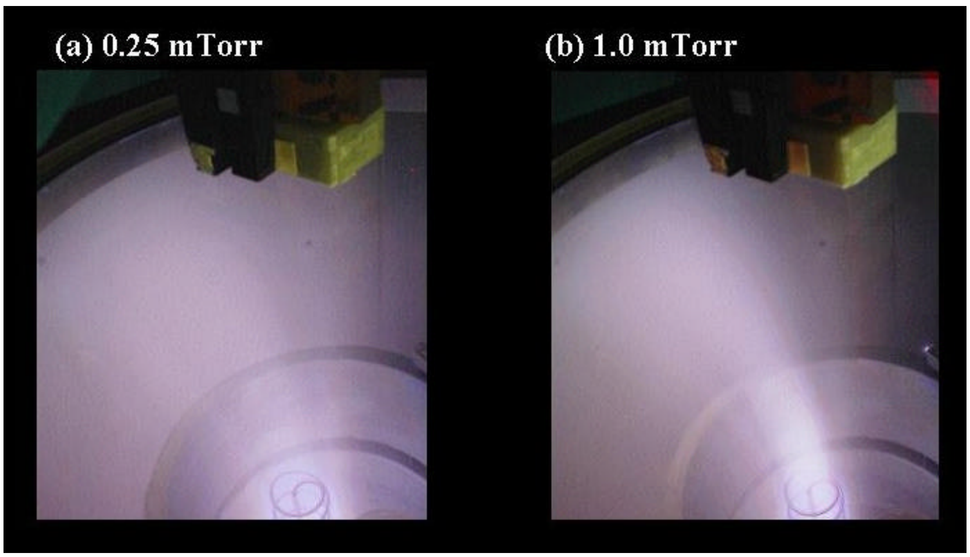

FIGURE 3. Plasma production in argon using a bare wire antenna for a field strength of 350 Gauss. Left hand side shows the emissions near the minimum neutral pressure required for breakdown to occur.

EVIDENCE FOR THE MOTION OF MAGNETIC FIELD LINES

The other objective of the prototype is to demonstrate that the dipole field can be inflated or dragged outwards by the plasma. An example of this motion is shown in Figure 4. The chamber has an average pressure of 2 mTorr of argon and the magnetic field strength is 500 G. Three consecutive frames from a digital camera taking frames every 250 msec are shown. The most striking feature is that the light emission is actually increasing over the period shown. This result is surprising since the transit time of the ions to the wall of the chamber is less than a msec. The brightening of the emission is solely due to the increasing build up of hot plasma along the field line, and the fact that it occurs of nearly a second indicates that much of the plasma has a chance to recirculate through the center of the antenna due to the closed magnetic field configuration and this facilitates the build up of the plasma and the associated optical emissions.

The second important feature shown in Figure 4 is the position of the plasma, which can be referenced relative to the large rectangle on the top of the chamber that holds fiber optics for light diagnostics. In the first frame the plasma emission reaches a peak that intercepts the fiber optics box. In the next frame, the ridge of peak emission is just below the right hand edge, and in the last frame the ridge is well below the right hand side. At the same time, there is no evidence of a change in the structure of the emissions near the antenna, i.e. the same field lines are being loaded by plasma but as the plasma pressure increases the field lines move to maintain pressure balance. It is this type of motion driven by plasma pressure that is at the heart of the inflation of the mini-magnetosphere.

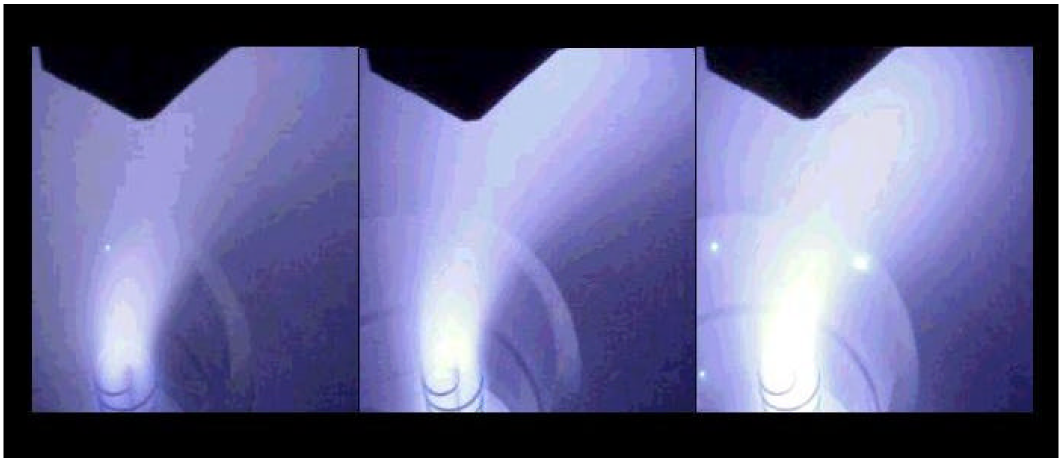

FIGURE 4. Time evolution of the plasma production and motion of the magnetic field lines during a 800 msec shot in 500 G magnetic field and 2 mTorr of argon with the frames being separated by 250 msec.

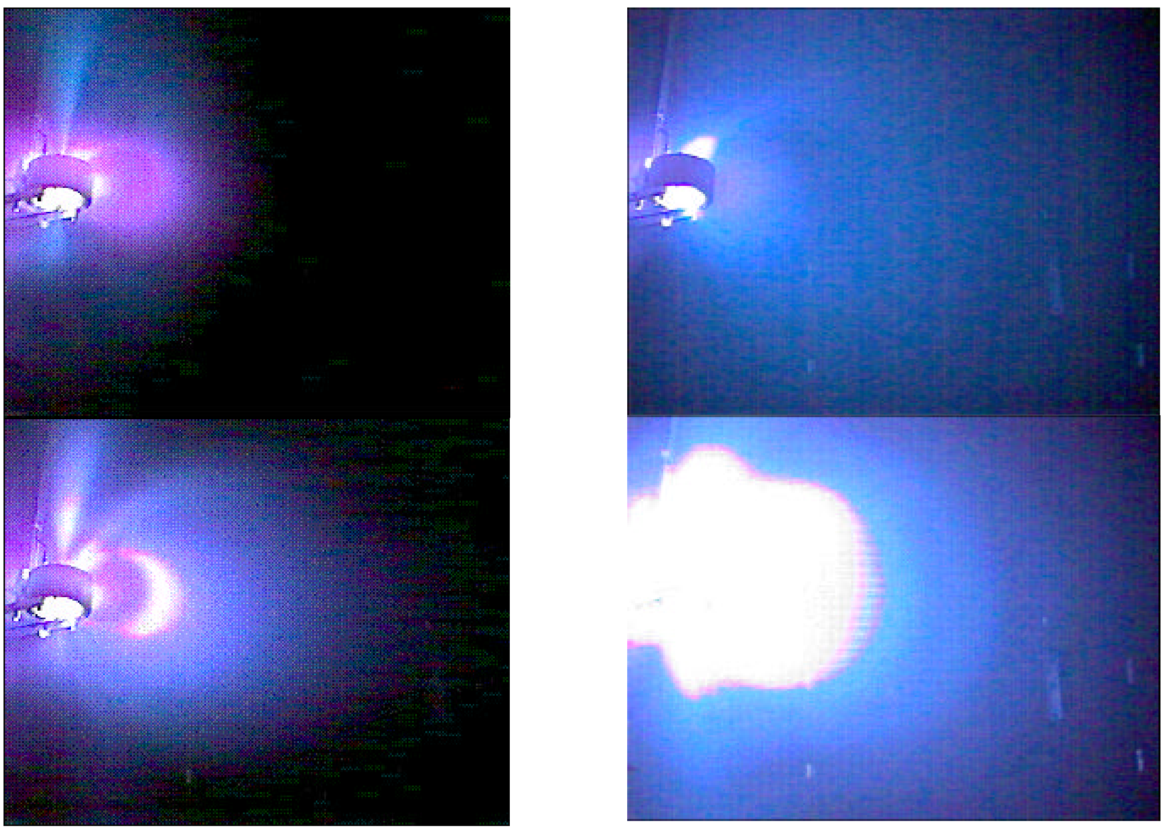

FIGURE 5. Inflation of the mini-magnetosphere in the large vacuum chamber at MSFC.

The plasma production in Figure 4 is primarily on open field lines, i.e. field lines that intercept the chamber walls. In order to remove the influence of walls, tests were undertaken in a large (32’ by 20’) vacuum chamber at NASA Marshall Space Flight Center in Test Area 300 using the same magnet and antenna as in Figure 4. Results for a high-density (0.5 mTorr) shot are presented on the left hand side of Figure 5. The field of view is 64 inches with the diameter radius of 8 inches. The field strength of the magnet is such that it reaches the terrestrial value within 36 inches. These images clearly show the presence of closed field lines out to several magnet radii and the presence of equatorial confinement of the plasma.

The presence of neutrals at large distances tends to suppress the optical emissions in the distant field of view. If the helicon is fed less density (0.1 mTorr) as in the top right hand side of Figure 5, fairly uniform emission is seen across the full field of view. The view from below (not shown) indicates that the plasma is confined in width which would suggest that even at large distances the plasma holds its profile from the initial dipole field, but the magnetic field to have an influence at these large distances from the magnet would have to imply stretched closed field lines. Further evidence for stretching or inflation of the field lines is seen when the camera exposure is increased by 50% as in the bottom right hand side of Figure 5. The frames prior to this overexposed shot look similar to that of the lower left hand with plasma streaming out the poles. When the two intense polar sources meet the brightest emissions expand from a similar profile on the left lower panel to the much-enhanced region in the right lower panel.

CONCLUSIONS

In order to explore the outer solar system and nearby interstellar space spacecraft will have to travel at speeds in excess of 50 km/s. The power requirements needed to obtain such high speeds are much higher than can be presently supported by solar electric propulsion. The system, which we call Mini-Magnetospheric Plasma Propulsion (M2P2), seeks to inflate a large magnetic bubble around the spacecraft to deflect and thereby pickup the momentum from the solar wind particles which are traveling at speeds of 350 to 800 km/s. A prototype for the device, consisting of a helicon plasma source inserted asymmetrically in a moderately strong magnetic field has been constructed and tested in laboratory vacuum chambers. The results show that the inflation of the dipole magnetic field by the injection of plasma can indeed occur as suggested in the original computer simulations of Winglee et al. (2000b). Motion of both closed and open field lines in large (small) vacuum chamber tests is seen from changes in the optical emissions from the plasma as well as the equatorial confinement of some of the plasma. Thus, at this time the process of inflating a mini-magnetosphere has been demonstrated. Work is continuing to try and demonstrate the additional pickup of momentum from the interaction of the mini-magnetosphere with an external solar wind.

ACKNOWLEDGMENTS

This work was supported by a grant from NASA’s Institute for Advance Concepts 07600-032, NSF Grant ATM-9731951 and by NASA grant NAG5-8089 to the Univ. of Washington. The simulations were supported by the Cray T-90 at the San Diego Supercomputing Center which is supported by NSF. The authors are greatly indebted to the technical crew in Test Area 300 for their assistance, enthusiasm and support during the large tank tests.

REFERENCES

Conway, G. D., A. J. Perry, and R. W. Boswell, Evolution of Ion and Electron Energy Distributions in Pulsed Helicon Plasma Discharges, *Plasma Sources, Sci. and Tech.,* **7**, 337, 1998.

Gilland, J., R. Breun, and N. Hershkowitz, Neutral Pumping in a Helicon Discharge, *Plasma Sources, Sci. and Tech.,* **7**, 416, 1998.

Miljak, D. G., and F. F. Chen, Density Limit in Helicon Discharges, *Plasma Sources, Sci. and Tech.,* **7**, 537, 1998.

Winglee, R. M., J. Slough, T. Ziemba, and A. Goodson, Mini-Magnetospheric Plasma Propulsion: High Speed Propulsion Sailing the Solar Wind, *Space Technology and Applications International Forum-2000*, edited by M. S. El-Genk, American Institute of Physics CP504, l-56396-9, p. 962, 2000a.

Winglee, R. M., J. Slough, T. Ziemba, and A. Goodson, Mini-Magnetospheric Plasma Propulsion: Tapping the Energy of the Solar Wind for Spacecraft Propulsion, *J. Geophys. Res., 105, 20,833*, 2000b.

Zubrin, R. M., The Use of Magnetic Sails to Escape from Low Earth Orbit, *J. British Interplanetary Society, 46*, 3, 1993.