

Plasma MagnetoShells (PMS) for Orbit Insertion on Deep-Space Planetary Missions

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Abstract— For deep-space planetary missions, the challenge of orbit insertion at the target planetary body is as critical and potentially as fuel consumptive as launch. The total required velocity change can be on the order of 10s of km/s, resulting in fuel being a large fraction of the spacecraft mass thus limiting valuable payload. Virtually all the planetary bodies in the solar system have an atmosphere of sufficient depth and mass density to provide for rapid vehicle deceleration from aerodrag. Even braking in the Earth's atmosphere would be highly advantageous for a Martian sample return mission. Employing a solid deflector for orbit insertion has been successful in the past, but due to frictional heating, as well as unknown and changing atmospheric conditions, the braking must be distributed over many elliptical orbital passes into the atmosphere to achieve the required braking. The concept to be elucidated in this paper is one possible solution to the limitations of aerobraking with a solid shield. The method entails the deployment of an arrangement of dipolar magnetic field coils that is populated with plasma and sustained in a manner that provides the necessary impediment to atmospheric flow and thereby creates the desired drag. This braking technique is referred to as a Plasma MagnetoShell (PMS). The requisite drag-inducing interactions are between the incoming neutral's directed momentum and the magnetically confined ions in the form of charge exchange and elastic scattering. During the interaction, the neutral's momentum is imparted to the magnetized ion which is then reacted onto the magnetic coils tethered to the spacecraft through field line bending and stretching. It will be shown that there are several unique advantages to PMS braking and aerocapture. Frictional heating is no longer a concern. The aeroshell is now composed of massless magnetic field and plasma. The scale of the magnetic barrier can be as large as needed (~10-100 m) while requiring less than a gram of plasma. While the dipole coil system will be the dominant mass, it is negligible compared to the spacecraft mass. With the ability to control the drag by changing field strength and/or plasma density on a sub-second timescale, the larger drag force and precision trajectory required for aerocapture is now feasible. Since the PMS provides for dynamic control under rapidly changing conditions, it should be suitable for human missions. A laboratory scale PMS was designed, built, and tested in a large vacuum chamber at MSNW. A supersonic flowing neutral jet was aimed a subscale PMS that was mounted on a boom attached to a thrust stand. The tests results validated the concept with the drag force increasing by a factor of 1000X when the PMS was activated. Mission analyses and system designs two missions were also conducted: a Cassini-class Neptune orbiter and a HEOMD-scale Mars orbital insertion. The design included the Plasma MagnetoShell magnet, tether, power processing, and battery mass. The orbital code Copernicus was used to determine optimal trajectories. The results from these studies will also be presented.

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1. INTRODUCTION

For planetary missions one could argue that the challenge of orbit insertion at the target planetary body is as critical and potentially as fuel consumptive as launch. However, orbit insertion can be performed employing several different methods. When one uses the term aerocapture it is in reference to an orbital transfer maneuver in which a spacecraft uses the aerodynamic drag force during what is usually a single pass through a planetary atmosphere to decelerate and achieve orbit insertion. Aerocapture represents a fuel-free method of deceleration which significantly reduces the mass of an interplanetary spacecraft as a substantial fraction of the spacecraft mass is propellant needed for the orbit insertion. Due to the frictional heating encountered during the atmospheric entry, the spacecraft typically is protected by employing a solid deflector or aeroshell to perform the high-dynamic-pressure atmospheric braking. For a rapid mission to Mars, the high entry velocity would require a large braking force to achieve the rapid deceleration upon arrival in order to establish a stable orbit. This demand is even greater for missions to the outer planets or moons. When a low, near-circular orbit around such a body is desired, especially one with a substantial gravitational field, the total required velocity changes can range up to tens of kilometers per second. If this were to be accomplished with chemical propulsion, the rocket equation dictates that a large fraction of the spacecraft mass must be fuel, thereby significantly limiting the useful payload. Virtually all the planetary bodies in the solar system, save Mercury and a few moons, have an atmosphere of sufficient depth and mass

density to provide for rapid vehicle deceleration from aerodrag. Even braking in the Earth's atmosphere would be highly advantageous for a Martian sample return mission. The ability to utilize these atmospheres to slow down and capture spacecraft would dramatically reduce the cost of future missions and enable long term studies of the outer planets and moons that would not be possible with current propulsive braking methodologies. Despite these advantages, aerocapture has yet to be attempted on a planetary mission. The aeroshell must be constructed to withstand the extreme thermal heating due to the high entry velocity of the spacecraft. As such, it can add considerable weight to the spacecraft. Aerocapture has also shown to be high risk as the atmospheric conditions must be precisely known and require manipulation of large, complex, and heavy deflector shells.

Aerobraking is a less demanding aeroassist maneuver that shares similarities but also significant differences with aerocapture. While aerocapture is used for inserting a spacecraft into orbit from a hyperbolic trajectory, aerobraking is used for reducing the apoapsis of a spacecraft that is already in a bound orbit. Implementation of aerobraking by employing a solid deflector or aeroshell as a method for orbit insertion and circularization has been successfully attempted in the past. In order to reduce the effect of frictional heating and dynamic pressure on the typically fragile aeroshell, the braking must be distributed over many orbital passes at a higher altitude in the less dense regions of the atmosphere. It can take several months for the meter-scale aeroshells to execute the many elliptic orbital passes through the atmosphere to achieve the required ΔV reduction. This rather slow method of braking is done not only to reduce frictional heating and dynamic forces, but also to avoid unpredictable dynamic behavior due to turbulence, as well as the unknown local atmospheric composition and temperature. The slow multi-orbit technique provides for sufficient time after each pass to measure the change in velocity and make any necessary corrections for the next pass. Despite these drawbacks, aerobraking and aerocapture have been shown to be mission enabling for deep space orbiters dramatically reducing propulsion requirement for planetary orbital maneuvers. In addition to performing orbit insertion, aerobraking can also be employed for orbit lowering or re-entry with little to no propellant, and thereby yield dramatic cost and mass savings for near earth missions as well as interplanetary manned missions.

Plasma MagnetoShell (PMS) Aerocapture is an innovative approach that has been developed by MSNW with funding support from the NASA Innovative Advanced Concepts (NIAC) program, that would enable low-cost, low-risk aerocapture for a range of Earth and deep space missions. The concept to be described and detailed here is the deployment of a coil set to produce a dipolar magnetic field that is filled with a plasma to provide the necessary impediment to the atmospheric flow and thereby produce the desired drag for braking. It is referred to as a Plasma MagnetoShell (PMS). An array of such "magnetospheric parachutes" at high altitude over Mars is depicted in Fig.1. The advantages of PMS are many. Frictional heating is no longer a concern.

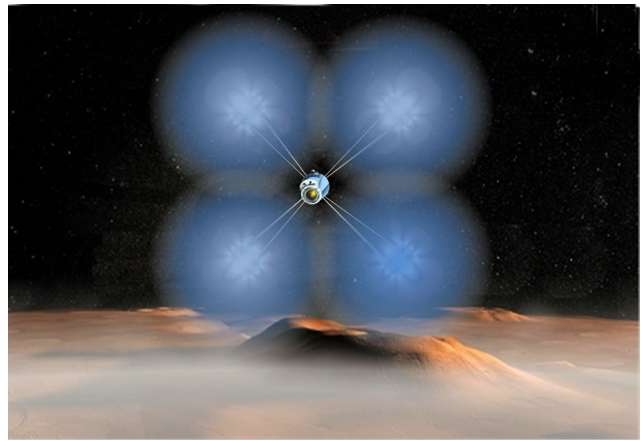


Figure 1. Artist's rendering showing several Plasma MagnetoShells deployed to steer and aerobreak spacecraft in the Martian atmosphere.

With the aeroshell now being composed of essentially massless magnetic field and plasma, the transverse scale of the magnetic barrier can be as large as required (~ 10 m), while needing a plasma mass of less than a gram. While the dipole coil will of course be more massive, it can be orders of magnitude smaller and lighter than an aeroshell. With the ability to rapidly change and control the drag by rapidly changing field strength or plasma density in response to varying atmospheric conditions, risk is much reduced, and a much larger braking force can now be contemplated, possibly all the way to aerocapture. The primary drag-inducing interactions between the magnetically confined plasma ions and the neutral atmospheric particles is that of charge exchange, which has the largest cross section, as well as elastic scattering. During the neutral-ion interaction the neutral momentum is imparted to the magnetized ion which is then reacted onto the magnetic coils harnessed to the spacecraft via field line bending and stretching. A laboratory scale PMS capable of being in LEO has been designed, built, and tested. Results from this testing as well as the several parametric conditions that must be satisfied for the PMS to provide the desired aerobraking on a large spacecraft is presented in Section 5.

2. DESCRIPTION OF THE PLASMA MAGNETOSHELL (PMS) CONCEPT

The concept conceived, analyzed, developed, and experimentally tested in this study is an answer to the limitations of aerobraking with a solid shield. [1] The method involves the deployment of a coil set that would produce a dipole magnetic field filled with a plasma to provide the necessary impediment to the atmospheric flow past the spacecraft and thereby produce the desired drag for braking. The energy dissipation required to slow the spacecraft would be deposited directly into the plasma ions, and then by thermal equilibration to the electrons. The energized electrons then maintain ionization of the neutral particle flow, and thereby sustain the plasma density, and at the same time

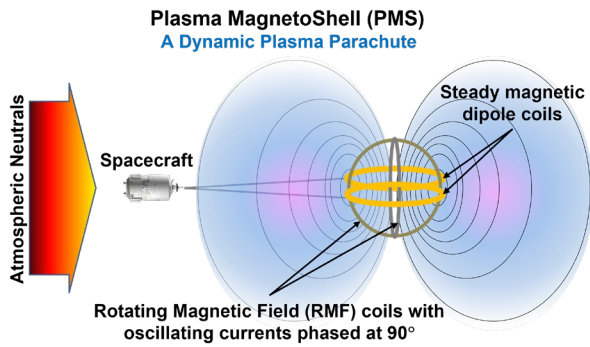


Figure 2. Schematic of the operation of a Plasma MagnetoShell. A Rotating Magnetic Field (RMF) forms a magnetized plasma in a magnetic dipole. This plasma fills the dipole providing for charge exchange with incoming neutral flow. The RMF (similar to an induction motor) induces a large current in a background plasma. This current expands, forming a large, plasma-sustained dipole.

shield the spacecraft itself from frictional heating. In this way the dissipation of spacecraft directed energy shows up as plasma thermal energy which is then eventually carried away at the magnetospheric periphery by particle diffusion and loss in an isotropic manner. The Plasma MagnetoShell (PMS) can extend out to distances far greater than the meter scale of the aeroshell due to the highly extended equilibrium of the magnetic dipole, particularly at high β . Here β refers to the local ratio of plasma to magnetic field energy density. A classic example of this type of dipole expansion is that of Jupiter's magnetic dipole field which is expanded to an equilibrium size larger than the Sun by the high beta plasma contained within its magnetosphere. The expansion can be readily controlled over a wide range by modifying either the strength of the magnetic dipole or the rate of plasma insertion or creation in the dipole field.

Plasma MagnetoShell aerocapture employs a dipole plasma configuration which would initially be populated with plasma of a composition that is similar to the ambient atmospheric gases. This plasma is formed with an electrodeless Rotating Magnetic Field (RMF) plasma source which creates a relatively low electron temperature (10-20 eV) magnetized plasma in the dipole field (see Fig. 2). The charge-exchange interaction between the magnetically confined plasma ions and the incoming neutral atmospheric particles effectively captures incoming particle momentum. After a charge exchange, or for that matter an ion-neutral collision, the magnetized atmospheric ion reacts its newly acquired directional momentum onto the magnet via field line bending and stretching. This action generates large plasma currents which impart a large $\mathbf{j} \times \mathbf{B}$ force on the dipole coils. This force is transmitted to the spacecraft via the tethers and thereby decelerates the spacecraft, acting in effect like a "plasma parachute". The PMS power requirements, even with the scale of the PMS as large as 10s of meters, can be met with onboard solar electric combined with a battery-based power supply. An array of Plasma MagnetoShells as depicted in Fig. 1 can be regulated through the magnitude of the magnetic

dipole allowing precise, dynamic control of the deceleration magnitude and direction for low risk aerocapture and aero-assist inclination change maneuvers.

The Plasma MagnetoShell Process

The development of the PMS concept has as its goal to dramatically improve aerocapture through the use of magnetized plasma to replace the hard-body decelerators. This is to be accomplished by employing what is effectively an atmosphere-breathing plasma propulsion device. Unlike traditional, plasma-based Electric Propulsion (EP), the Plasma MagnetoShell generates a magnetized plasma in a way so as to *not* leave the spacecraft. In fact, it is produced in a magnetic dipole configuration much like a planetary magnetosphere, however in this case with no need for the planet. The dipolar magnetic field is produced by large hooplike conventional electromagnets that are energized from the spacecraft electrical power system. The idea is to confine this spacecraft produced plasma so that it can interact with planetary neutrals as it enters the planet's atmosphere. In the frame of the spacecraft the atmosphere appears as a highly directed, relatively energetic stream ($E_{\text{neut}} \sim 10\text{-}20$ eV) of incoming neutrals that then collide with the ions confined in the spacecraft magnetosphere, and impart its momentum to the ion that is magnetized in the dipolar magnetic field. The energized ions pull and stretch the magnetic field much in the same way the solar wind ions that become ensnared in the Earth's magnetosphere pull and distort the Earth's magnetic field producing the characteristic elongated tail observed on the downwind side. It is due to the fact that this distortion generates electric fields and currents that then react the momentum onto the coil currents through the Lorentz force. This momentum exchange is thus the equivalent of a drag force on the spacecraft during atmospheric entry.

Basic parameter scaling of the Plasma MagnetoShell (PMS) for Aerobraking

The spacecraft deceleration is achieved primarily through charge exchange (CEX) interactions between the magnetized thermal ions in the Plasma MagnetoShell with atmospheric neutrals as this has a larger cross section than elastic collisions in most cases. In the CEX case, the fast and directed neutrals in the atmosphere lose an electron to the ambient ions and are thus converted into ions but now with a large velocity component in the direction of flow. These new ions are now magnetized in the dipole field due to their newly gained charge. Their motion is deflected by the dipole field as it becomes circularized and impart their momentum on the spacecraft through field line bending. In the process, thermal ions are converted into neutrals moving out of the magnetosphere with a random direction reflecting their thermal equilibrium prior to the CEX. A "black box" picture would show thermally cold but highly directed neutrals entering the box on one side and warm neutrals leaving the box in all directions. The box thus experiences a large reactive force acting on it – i.e. the drag force. Since the PMS uses the ambient neutrals as its propellant, it requires virtually no fuel on-board except for startup and possibly sustainment. For the large-scale PMS, the energy and particle confinement

is expected to be very good due to the multi-meter scale of the plasma, even allowing for anomalous losses. The expected particle confinement time would allow the energized ions sufficient time to heat the electrons through electron-ion collisions. These electrons in turn can now ionize incoming ambient neutrals creating even more plasma and even greater interaction with the atmospheric neutrals. This process can bootstrap the PMS to greater size and power than could be provided by onboard electric power resources. The PMS may thus only need startup plasma and reduce the power requirement to that of supplying current to the dipole coils.

It should be noted that the PMS can operate at higher altitude and thus much lower densities than the traditionally conceived aerocapture systems because the MagnetoShell's collection radius is much larger than the spacecraft itself. In

fact, it must be so in order to minimize interference from the spacecraft on neutral particle CEX collection. Actually, operation in the high atmosphere is quite advantageous for several reasons. The frictional heat is deposited into the plasma rather than the spacecraft which helps to sustain the PMS. The structural load on sensitive components like solar panels is kept to safe levels, and avoids risky low-altitude trajectories. The PMS is also a highly dynamic control surface that can be regulated through either the magnitude of the magnetic dipole or the rate of plasma insertion into the dipole field. With the ability to modify the drag rapidly and precisely in varying atmospheric conditions, much larger braking forces can now be contemplated at low risk, enabling very aggressive aerocapture maneuvers. As a result, the PMS resolves the trade-offs between available orbit insertion techniques: it offers the dynamic control and diverse application of modern EP while providing the mission-enabling mass and cost benefits of aerocapture. In addition, the Plasma MagnetoShell can be deployed as a shield against solar radiation and solar flares if need be.

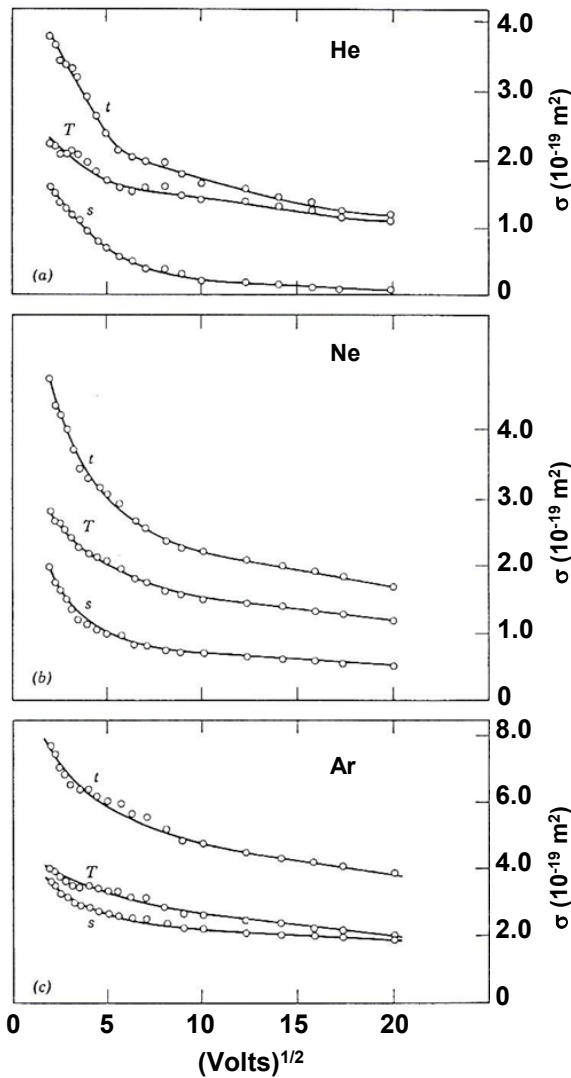


Figure 3. Experimentally determined cross sections (σ), for elastic scattering (s), charge exchange transfer (T), and the sum of the two (t), for Helium, Neon and Argon ions as a function of the square root of the ion energy (eV) in their parent gases. (Figure from Reference [2]).

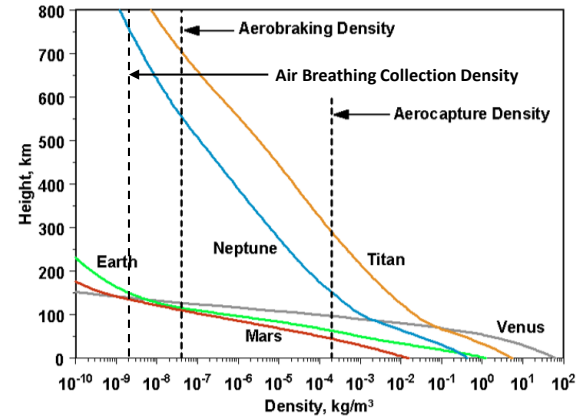


Figure 4. Comparison of density profiles among the planets and Titan

As stated, the primary drag-inducing interaction between the magnetically confined plasma ions of the PMS and the incoming neutral atmospheric particles viewed from the frame of the spacecraft is that of charge exchange, which has the largest cross section, as well as elastic scattering. Fig. 3 shows how these two cross sections vary with particle velocity and mass for three noble gases of varying atomic mass. As can be seen, elastic ion collisions with atmospheric neutrals induce drag as well but in smaller magnitude for the

Planet	Radius (10 ⁶ m)	Orbital Vel. (m/s)	Orbital Per. (hr.)	Alt. where $\rho \sim 4 \times 10^{-8}$ kg/m ³ (km)	Principal Gases (%)
Earth	6.38	7,900	1.4	112	N ₂ [78] O ₂ [21] Ar [1]
Mars	3.4	3,549	1.7	115	CO ₂ [95] N ₂ [3] Ar [1]
Venus	6.05	7,327	1.4	125	CO ₂ [96] N ₂ [3]
Jupiter	71.5	42,078	3.0	350	H ₂ [90] He [10]
Saturn	60.3	25,066	4.2	950	H ₂ [96] He [3]
Uranus	20.6	16,764	2.1	550	H ₂ [83] He [15] CH ₄ [2.5]
Neptune	24.8	16,563	2.6	560	H ₂ [80] He [19] CH ₄ [1]
Titan	2.57	1,865	2.4	710	N ₂ [96] CH ₄ [3.5] H ₂ [0.5]

Figure 5. Candidate planetary and atmospheric data for PMS aerobraking.

lighter atomic masses. From Figs. 4 and 5, it can be seen that for the characteristic mass density of the atmosphere in the region of interest for operation of the PMS ($\rho \sim 4 \times 10^{-8} \text{ kg/m}^3$) the effective incoming neutral velocity ranges from 2 to 40 km/sec. while the molecular mass typically varies in the opposite sense from 30 to 2 amu. The range in directed particle energy is thus roughly 1 to 17 eV with the value at Earth being 9.5 eV. The square root value runs from 1 to around 4, and it is clear from Fig. 3 that PMS plasma densities in the range of 10^{18} m^{-3} or more will assure significant interaction with the neutral flow for a meter scale PMS.

There is additional constraint that relates to the minimum PMS magnetic field. To react the dynamic force onto the magnetic field, the charge exchanged atmospheric ions must stay magnetized long enough to be significantly redirected by the local magnetic field (i.e. the total ion collision frequency must be no greater than the ion cyclotron frequency). Equivalently, the ion-neutral collisional mean free path must be larger than the ion Larmor or “gyro” radius ρ_{Li} . The ion Larmor radius of interest is that of the PMS ions that have interacted with the incoming neutrals through either charge exchange or elastic collisions, and as such will have an effective velocity primarily determined by the directed energy of the original neutral due to the motion of the spacecraft through the relatively motionless neutral gas.

3. ANALYTIC MODEL OF THE PMS PHYSICS

The approximate braking force is found by considering the fraction of planetary neutrals trapped or scattered by the plasma magnetospheric ions. Because kinetic energy is conserved, resonant charge transfer acts as an elastic collision. As can be seen in Fig. 3 at low energies ($< 10 \text{ eV}$), the cross sections are large. The charge exchanged particles are essentially captured in the center of mass (CM) system, after the charge transfer to an effective scattering angle for the ion in the CM system of 180° and a momentum transfer of $2 m_p v_{sc}$ for every collision, where m_p is the mass of the charge exchange particle and v_{sc} is the spacecraft velocity. The drag force on the spacecraft is thus:

$$F_d = 0.5 C_D m_p n_i V_{sc}^2 A_M \quad (1)$$

where A_{pm} is the effective cross-sectional area of the plasma shell, m_g is the mass of the incoming neutral, and v_s is the velocity of the neutral with respect to the spacecraft. There is a minimum scale to assure that a passing neutral experience at least one charge exchange or ion collision inside the PMS. The ion mean free path is given by $\lambda_i = 1/(n_p \sigma_i)$ where σ_i is the total ion-neutral scattering cross section for both elastic and charge transfer collisions. Using Fig. 3 as a rough guide for low energy collisions of medium mass neutrals and ions, the scattering cross section $\sigma_i \sim 5 \times 10^{-19} \text{ m}^2$.

Dipole configuration considerations— β is the ratio of plasma pressure to magnetic pressure and is, in general, an indicator of the energy stored within the PMS in the form of plasma energy. Plasma-filled dipoles can range from a low to high β and a range of magnetic configurations can significantly

affect the plasma β as well as the effective range of the PMS. The pros and cons for the various dipole and antenna configurations examined will now be discussed. It should be noted that all the configurations will function adequately for aerobraking. The choice between the various configuration is primarily related to advantages in implementation simplicity, scalability and drag efficiency.

In the low β case, the plasma does not perturb the magnetic field significantly and the magnetic field radial profiles are the standard vacuum case it was realized that the simple dipole with the typical $1/R^3$ falloff which concentrates virtually all of the magnetic energy near the coils. This possible disadvantage can be more than compensated by using High Temperature Superconducting Coil (HTSC) magnets. The energy and diamagnetic current in the plasma is low and cross-field diffusion is controlled by standard diffusion and lifetime scaling relationships.

In a high β dipole a large diamagnetic plasma current is generated. This plasma current produces a magnetic field which acts to reduce the vacuum magnetic field, which allows for the plasma pressure to expand the radial magnetic field. This produces a larger magnetosphere with a slower radial falloff as well as a decrease in radial plasma diffusion. Realistic equilibria for the magnetic dipole with large diamagnetic currents have been found and analyzed [3]. It was found that plasma pressure profiles $P(\psi)$ that fall off at least as slowly as the adiabatic rate ($\sim \psi^{20/3}$), where ψ is the flux surface coordinate, were stable to both interchange and ballooning instabilities. The modification to the dipole flux function ψ ($\sin(\theta)^2/r$ in vacuum) at high β can be expressed as:

$$\psi = \psi_0 R_0^\alpha \frac{\sin(\theta)}{r^\alpha}, \quad \alpha = \beta_0^{-1/2} \quad (2)$$

where the zero subscript refers to a reference point at the dipole coil center. In the limit of $\beta \rightarrow \infty$ (the plasma pressure is equal to the external field pressure), the dipole field $B(r) \sim B_0 R_0^2/r^2$. With $\beta > 1$, the dipole field drop-off will at best be no slower than $1/r^2$. This can be seen from flux conservation. It is clear that the high β plasma will expand the flux over a much larger region.

Once the expansion is complete, confining the plasma in a large-scale PMS looks to be relatively undemanding. The simplest and most desirable method to achieve the desired density falloff is to simply reduce the particle flow from the source. If the confinement is adequate, or the entrainment of the planetary neutrals through ionization by electrons is sufficient to match losses, source plasma fueling may be completely turned off. If too great a density build-up should occur, it would be suppressed by the nature of the current drive process itself. As the density increases, the driven current increases. This in turn expands the dipole magnetic field, and leads to a further expansion of the PMS. The expansion drops the density, which reduces the current, and a new equilibrium is achieved. The expansion of the dipole is now only limited by the Ohmic power needed to maintain the structure against resistive dissipation. To make a simple

estimation of what this power would be, consider the case of an azimuthally uniform magnetic field where the $1/r^2$ dependence is found in all directions. The Ohmic power, P_Ω , needed to sustain the plasma PMS in this configuration is given by:

$$P_\Omega = \int \eta j_\theta^2 \cdot dVol \quad (3)$$

where j_θ is the azimuthal current density driven by the RMF. Flux conservation demands that $B(r) \sim B_0 R_0^2 / r^2$, so that one has for j_θ :

$$j_\theta = \frac{1}{\mu_0} \frac{dB}{dr} = -\frac{2}{\mu_0} B_0 \frac{R_0^2}{r^3} \quad (4)$$

where B_0 is the magnitude of the magnetic field at the center of the dipole coil. Substituting Eq. (3) into Eq. (4) and integrating one has:

$$P_\Omega = \frac{4\eta}{\mu_0^2} B_0^2 R_0^4 \int_{R_0}^{r \gg R_0} \frac{4\pi}{r^4} dr = \frac{16\pi}{3\mu_0^2} \eta B_0^2 R_0 \quad (5)$$

The high β dipole would require a smaller, lower power magnet to provide the initial magnetic field as the plasma would expand the dipole field significantly.

Generation and sustainment of the PMS—The Rotating Magnetic Field (RMF) technique that was previously mentioned can be employed to generate the high β plasma desired for the PMS. This can also be done with virtually any gas or gas mixtures to match the particular atmosphere of interest. The dipole magnetic field would be generated by a simple electromagnet. While the RMF system has been experimentally demonstrated at high β , it can also be operated in a manner that creates a low β plasma and would still be considered as the best candidate for generating the startup plasma for the PMS. This will be made clearer when alternate multi-dipole configurations are considered. The technique of generating azimuthal electron currents in a plasma by means of rotating magnetic fields was first investigated by Blevin & Thonemann [4], and by several others in the ensuing years [5-7]. The principles of this technique can best be understood as follows. Consider that a transverse rotating magnetic field completely penetrates a plasma inside a steady dipole coil. Provided that the angular frequency ω_{RMF} , of the rotating field lies between the ion and electron cyclotron frequencies calculated with reference to the amplitude of the rotating field, B_ω , i.e., $\omega_{ci} \ll \omega_{RMF} \ll \omega_{ce}$. Provided that the electron collision frequency is much less than the electron cyclotron frequency ($\nu_e \ll \omega_{ce}$), the electrons can be considered as 'tied' to the lines of force of the rotating field B_ω . With the assumption that the electron collisions are relatively infrequent, they will circulate synchronously at the angular frequency ω_{RMF} , whereas the ions (at least over the time of interest) have no net azimuthal motion. The electrons thus form a steady azimuthal current (in fact, the Hall current). In most systems, Hall currents are

inhibited by electric polarization fields. In the situation under discussion, however, charge separation does not occur because of the azimuthal symmetry.

A high β Magnetosphere is generated by employing a pair of polyphase coils that produce the rotating magnetic field transverse to the axis of the stationary magnetic dipole field. The large-scale currents needed for a large-scale PMS are generated by the entrainment of the plasma electrons in a rotating field created by two pair of circular loop antennae (see Fig. 2). With the antennae separated by 90 degrees in azimuth, and with their respective currents separated in phase by 90 degrees, a steady magnetic field rotating in the equatorial plane is produced. These antenna pairs drive the necessary currents in the plasma to inflate and maintain the large-scale high β magnetic structure. More details of the physics of this process can be found elsewhere [8]. The current in the steady dipole is in the opposite direction to that produced in the plasma by the rotating magnetic field. The plasma currents thus act like a diamagnetic current creating a high β plasma dipole equilibrium.

To better understand the way in which the RMF system works consider this mechanical analogy of an induction motor. The RMF field is similar to the field that is produced in a two-pole motor stator winding. Take the case now where the metal rotor is replaced with a plasma rotor. With essentially zero inertial mass, the electrons quickly come into co-rotation with the RMF. The rigid rotation of the electrons is retarded slightly by collisions with the much more massive background ions which, due to their large inertia are unable to respond to the rapidly rotating field and remain relatively motionless much like the atomic nuclei in a wire. In this manner a large azimuthal (θ) current is driven in the plasma. The magnetic field generated by the "rotor" currents couple it inextricably with the stator fields. Like any AC motor, a force applied to the rotor is reacted back on to the stator through these fields without any physical contact between the two. The same momentum transfer occurs with the plasma rotor as well. The eventual "load" on the plasma rotor will be the drag of the neutrals as they are exchanged or scattered off the plasma magnet ions. This directional force is countered by the deflection of the dipole magnetic fields which, through the modification of the magnet currents, is reacted back onto the steady dipole magnetic coil (the stator) tethered to the spacecraft. With no external field to oppose the Lorentz self-force acting on the plasma azimuthal currents, the current ring expands. The only confining force is that of the curvature forces from the steady dipole field created by the RMF driven currents. This force is sufficient to keep the plasma in a high β equilibrium as it expands (the driven current is equivalent to a plasma diamagnetic current in equilibrium). Since the gyroradius of a planetary neutral/ion may be larger than the initially multi-meter size expanding dipole, little distortion of the dipole is expected until the PMS has expanded enough to have significant interaction with the background atmosphere. In addition to expanding the dipole, the driven currents will change the equilibrium field shape significantly from the vacuum field as described by Eq. 2.

Optimized Magnetic Configuration for PMS—While the high β dipolar PMS is sufficient for the task of aerobraking, more optimum arrangements were investigated such as dipole orientation as well as employing additional dipole coils. These additional coils significantly improve the distribution of the magnetic field in a more uniform way while also

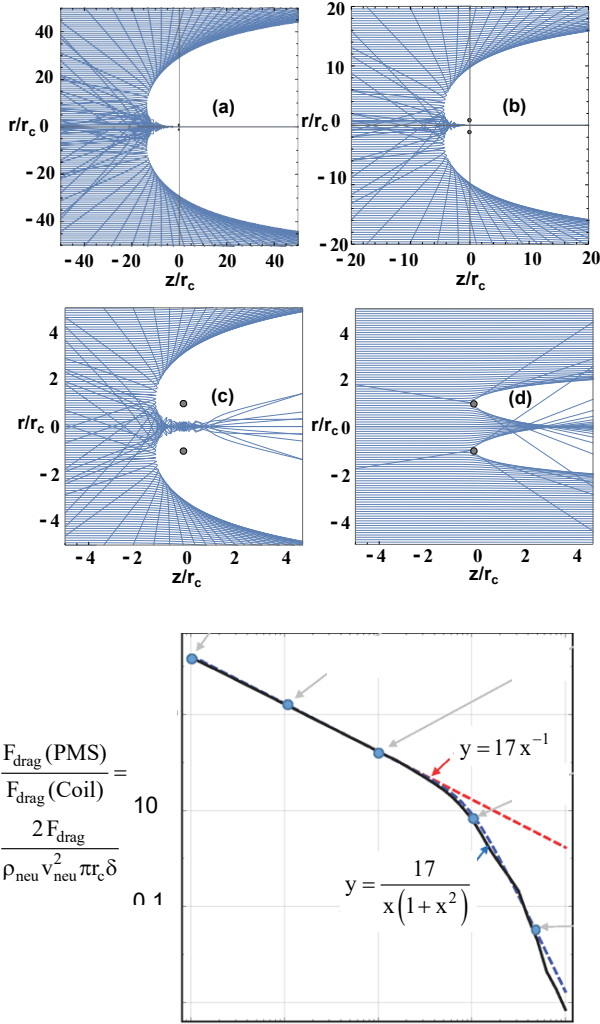


Figure 6. Plot of the drag force on the PMS normalized to that intercepted by the dipole coil area as a function of the ratio of the gyroradius based on the neutral flow energy to that of the coil radius. Smaller figures at the top indicate the trajectory of the particles at different values of this ratio. The coil thickness δ is assumed to equal to $0.1r_c$.

allowing for the concentration of the magnetospheric plasma in a larger but finite region. The PMS must be optimized for a given magnetic field to minimize how large the structure must be employed for the same drag. The simple dipole with the magnetic axis aligned in the direction of flow, while adequate, was found to not be optimal. To analyze this in more detail, a particle-based model was formulated that evaluated the flow-directed charge-exchanged atmospheric ion motion in the field of a dipole coil with the orientation

being aligned with the motion. The result of these calculations can be found in Fig. 6. It can be seen that the drag force can be several thousand times larger than the area intercepted by the dipole coil itself. These values however are only obtained with the largest magnetic dipole fields as the rest of the parameters that characterize the drag magnitude scaling (see the x axis in Fig. 6 lower plot) would be determined by the location and velocity of the spacecraft. The smaller figures inset in the figure indicate what is really going on here. As one turns down the dipole field magnitude, the drag is eventually produced only by trajectories very near the coil itself. This is because the dipole magnetic field vector is primarily aligned with the flow when the dipole axis is orientated in the same direction as the flow. It is however only the transverse magnetic field component to the flow that deflects the highly directed ions. Unlike gravity, the Lorentz force acting on these ions is a non-central force, so that the magnetic field can only deflect the ion, not slow it down.

Clearly, while a transverse (to the flow) orientation of the

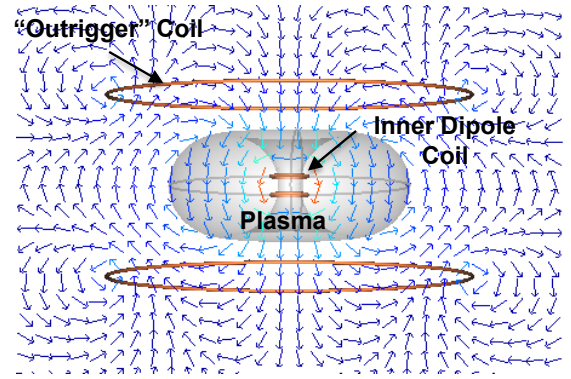


Figure 7. Illustration of the PMS system with additional “outrigger” coils. Magnetic field line vectors reflect plasma toroidal currents driven by RMF.

dipole axis (see Fig. 2) would present to the flow the largest transverse deflecting field for a given magnetic field energy, almost any significant axis tilt significantly reduce the pass-through ions.

It was also found that the addition of two coaxial dipole rings at significantly larger radius from the dipole and antenna set shown in Fig. 2 can considerably enhance the plasma uniformity and density surrounding the inner dipole (see Fig. 7). The field requirement for these additional “outrigger coils” is quite small as the falloff in field for even the high β dipole is still $1/r^2$ so that the confining field from these coils need be no greater than the ambient field at that radius. In addition, the outriggers provide for a rapid means to change the drag force to maintain the proper deceleration in changing atmospheric conditions without attempting to accomplish this through varying the current drive input power and plasma density, which could prove to be slower and possibly more complex than desirable. The dipole plasma generation as well as the outrigger coil control of the high β plasma expansion has been experimentally demonstrated in a large tank test.[8] The small dipole coil with the two antenna loops needed to create the RMF as shown in Fig. 2 was lowered into a

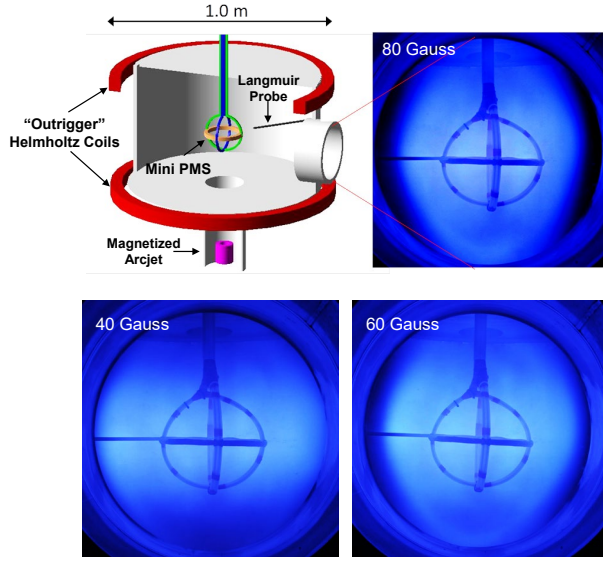


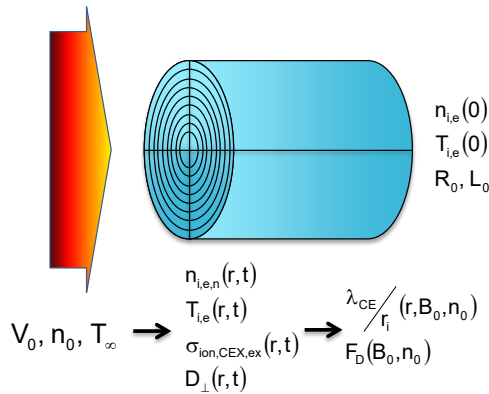
Figure 8. (Top left) schematic of the PMS inside cylindrical vacuum chamber. (Images) Argon plasma created by PMS and confined by outrigger coils at various magnetic field strengths placed external to the vacuum chamber (red coils on schematic).

cylindrical chamber and operated in Argon. A partially ionized Argon gas jet was introduced into the PMS coil set along the cylindrical axis from below which was immediately captured in the plasmoid created by the mini-PMS. The plasma expanded out to radially to the wall of the chamber. Outrigger coils in a Helmholtz configuration were then installed external to the chamber and energized to create the additional dipole field. An axial magnetic field as little as 10 Gauss was all that was needed to limit the plasma expansion to avoid contact the cylindrical vacuum chamber boundary. As this field was increased, it was found that the plasma radial expansion could controlled and decreased with increasing field (see Fig. 8). It should be noted that the blue

light comes only from Argon II as neutral Argon lines are all in the red. From these images it is clear that the PMS plasma is thus fully ionized, well confined and controlled in this configuration.

Plasma MagnetoShell Analytic Model

While the PMS can be made more efficient and controllable by the orientation and the operational mode with outrigger coils, it sufficient to consider the simpler case of the dipole aligned with the flow at low β as in Fig. 6 first as this leads to scaling laws to which the more complex magnetic dipole arrangement will be very similar. The advantage of the multiple dipole configurations is in plasma generation, manipulation, and containment, not so much the scaling with size. The plasma currents do not necessarily have to generate a significant magnetic field and therefore does not affect the scaling of the basic vacuum dipole configuration. A standard dipole magnetic field scaling of $1/r^3$ will thus be used initially, which will also determine a worst-case scenario from an energy efficiency standpoint. The confinement time and radius are still set by the same density and mean free path considerations. In order for a CEX to occur within the PMS the mean free path for a collision must be smaller than the dipole size and as mentioned, places a constraint on the minimum neutral density. To be magnetized, the ion gyroradius must be less than the scale of the dipole in order for the ion to be confined and transfer momentum during a single orbit. If the collisional mean free path is much smaller than the gyroradius, the ions do not stay confined on the time scale of interest. Therefore, as the ion gyroradius is independent of the collisionality, the magnetic field is a free parameter, and a sufficient magnetic field can be determined for any desired gyroradius. The confinement time scale can similarly be described as simply the radial diffusion time of a particle across the radius of the dipole. Finally, for a low β dipole, no energy is required to sustain the plasma except to replace lost particles. However, supplying some energy to sustain the dipole magnetic field is required if one wishes to



Confinement

$$n(r) \sim n(R_0) \left(\frac{R_0}{r} \right)^3$$

$$\lambda_{CE} = \frac{1}{n_0 \sigma_{CE}} \quad r_i = \frac{mU_0}{eB}$$

$$\pi r_i < \lambda_{CE} \leq L_0$$

- Ion gyroradius (r_i) and charge exchange mean free path (λ_{CE}) are less than characteristic length
- Particle must stay confined for a minimum one-half of orbit

Figure 9. Summary of the 2D analytic model and key assumptions.

avoid the complications of HTSC magnets. As will be seen in the system analysis study, it was found that the PMS is well within the limits of traditional copper magnet technology.

In order to determine the equilibrium plasma and gas distribution of a PMS under a specific set of incoming flow characteristics, a 2-D transient model was developed (see Fig. 9). This model uses a cylindrical axisymmetric approximation. This cylindrical approximation has an aspect ratio of 3 and assumes uniform chord properties. This assumption is believed to be accurate for the typical mean free paths of interest in this experiment as only a few collisions will happen along a given cylindrical chord. Assuming a uniform chord property and uniform azimuthal plasma conditions, radial profiles of ion and electron densities and temperatures can be calculated. A uniform incoming neutral flow distribution is assumed with uniform velocity and neutral density, along radial as well as axial cylindrical coordinates. A low-beta dipole scaling is assumed. Previously in this paper, low versus high-beta configurations have been described, but the low-beta energy state is the lowest required plasma energy, as well as the simplest plasma assumption. This low-beta configuration then will have a cubic radial magnetic radial fall off and thus initial plasma density distribution. Two more critical assumptions are made for this low-beta dipolar configuration; the plasma has little effect on the magnetic field, so a fixed magnetic field profile is assumed and finally, collisional cross sections use several empirical models to determine the inter-species interaction of neutrals, ions and electrons. The model also uses the atomic species profile most appropriate for a given planetary atmosphere. For Earth, a Nitrogen atom is assumed. For Mars, an Argon atom, while for Neptune, Hydrogen is assumed. As the mean free path is large, a non-Maxwellian, non-equilibrium plasma condition is assumed in which the plasma ions and electrons do not automatically relax to equilibrium states and equilibrium temperature distributions. The cross sections for charge exchange and ionization can be empirically determined for a given electron temperature [9-11]. The key physics equations for the PMS model are given below. These relate to the various constraints that have been mentioned to determine how large and how efficiently the drag from the PMS can be based on the incoming neutral flow parameters. The various dependencies for the key PMS and atmospheric parameters along with further explanation are given below:

Charge exchange: The plasma densities must be high enough that the PMS is collisional during entry, otherwise neutral particles are unimpeded.

Density profile: The radial plasma density falloff is assumed to have the same spatial scaling as the vacuum dipole magnetic field, i.e. a low, constant β plasma.

$$n(r) \sim n(R_0) \left(\frac{R_0}{r} \right)^3 \quad (6)$$

Collision length: The incoming neutral densities must be low enough so that charge exchange will occur within the PMS of scale L .

$$\lambda_{CE} = \frac{1}{n_{neu} \sigma_{CE}} \leq L \quad (7)$$

Ion Magnetization: The magnetic field and velocity must yield magnetized CEX ions (and source ions) with gyro-orbits less than the size of the PMS.

$$\Omega_i = \frac{eB}{m_i n \sigma_{i-n} v_i} > 1 \quad (8)$$

Ionization: The incoming velocity must be less than the ionization energy for CEX to dominate. Some ionization is acceptable, too much removes almost all electron energy.

$$\frac{E_{cex}}{2m_i} < \frac{m_{neu}}{2} v_{flow}^2 < \frac{E_{ioniz}}{2m_i} \quad (9)$$

Bohm confinement diffusion timescales: Unlike most astrophysical plasmas, this plasma is neutral collision dominated, leading to Bohm diffusion and transport.

$$\tau_n \sim \frac{2\mu_0}{3\eta_i \beta} \ln \left(\frac{r}{R_0} \right) r^2 \quad (10)$$

Thermal equilibrium: Incoming particles result in hot ions, ionization cools electrons, thermal equilibrium controls density and effective radius. The relaxation rate between the ions and electrons is given by:

$$v_{e-i} = \frac{2n_i \sigma_T \ln \Lambda}{\pi^{1/2}} \left(\frac{m_e}{m_i} \right) \left(\frac{k_B T_e}{m_e} \right)^{-3/2} \quad (11)$$

Using the empirical cross section for charge exchange for a given atomic species and electron temperature, the charge exchange reaction rate equation can be calculated for each radial position averaged over a chord length. This calculation then requires the neutral ion and electron densities, neutral velocities, and chord length scale.

$$n_{CEX} = \sigma_{CEX}(T_e) n_n n_e \frac{V_0}{L_0} \Delta t \quad (12)$$

$$n_{ion} = \sigma_{ion}(T_e) n_n n_e \frac{V_0}{L_0} \Delta t \quad (13)$$

$$D_{Bohm} \propto \frac{k_B T_e}{B} \quad (14)$$

$$D_{\perp} \propto \frac{m_i k_B T_e^{1/2}}{B^2} \quad (15)$$

$$v_{s-s} = \frac{2n_s \sigma_T \ln \Lambda}{\pi^{1/2}} \left(\frac{m_e}{m_i} \right) \left(\frac{k_B T_e}{m_e} \right)^{-3/2} \quad (16)$$

It should be noted that charge exchange and elastic collisions do not change the ion and neutral populations (as charge is simply exchanged, not created) but ion temperature and

thermal energy equilibrates to the charge exchange temperature as a function of the charge exchange rate. Ionization is calculated as shown in Eqs. 12 and 13 from the temperature and species dependent cross section densities and mean free path. Ionization rates are used to recalculate ion population, as well as cool electrons. Electron temperature must decrease by the ion energies per ionization event. Plasma diffusion is calculated between layers as plasma diffuses radially outwards from the central core and the external boundary and ends. Two diffusion rates are used; classical (Spitzer) diffusion assumes high plasma conductivity and optimal plasma resistivity in Eq. 15. This is simply diffusion due to the motion of a magnetized plasma particle. Bohm diffusion is applicable for a plasma that is characterized by turbulence and/or field lines that are open to boundaries (e.g. the tethers connecting the PMS to the spacecraft). One could certainly argue that the supersonic streaming of newly CEX ions is a free energy source that could easily drive turbulent transport. Bohm diffusion (see Eq. 14) has been shown to be a good fit to a wide range of experimental data. It is likely to be a factor in the plasma transport in the PMS as Bohm confinement was also inferred from experimental work with the PMS.

However, for low β and low electron temperature plasmas, as would be the case for the PMS, Spitzer diffusivity can be comparable. These two diffusion rates bracket the minimum and maximum diffusion rates respectively and the average value is used to calculate the diffusion times and the equilibrium density. Finally, total equilibrium is calculated using a standard Fokker-Planck equilibrium rate. This rate determines the heating from ion to electron and electron to ion and again is shown in Eq. 16.

The confinement requirements can now be determined. The mean free path for charge exchange is given in Eq. 7 which is the average distance a particle will travel before undergoing a charge exchange collision. Equation 17 expresses the ion gyroradius and is characteristic of the distance an ion will travel in a magnetic field for a single oscillation or gyro-orbit. In order for charge exchange reactions to be dominant, the mean free path for CEX must be less than the size of the magnetic dipole scale L_0 region. Once a newly created charge exchange ion is magnetized, it must stay magnetized long enough to transfer its momentum to the structure. Therefore Eq. 18 expresses the relationships that must be maintained for a CEX collision to transfer momentum to the spacecraft.

$$r_{Li} = \frac{mV_0}{eB} \quad (17)$$

$$\pi r_i < \lambda_{CE} \leq L_0 \quad (18)$$

PMS Analytic Model Results—As the set of equations that characterize the processes in the PMS are time dependent, the time evolution of the PMS does not necessarily guaranty that there will be a stable equilibrium if the feedback from environmental conditions is not well posed. Fortunately, this was not the case here. Several features of the equilibrium are as expected. First, given sufficient time, ion temperature will

equilibrate reflecting the average directed energy of the incoming flow. For typical aerobraking applications, incoming neutrals have directional energies 5 to 30 eV. Electrons equilibrate to a temperature somewhat lower, depending on the specific ionization rate. Ion density will equilibrate to a fixed value based on the incoming neutral

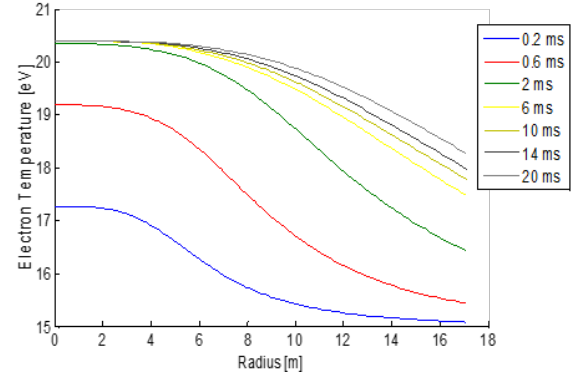


Figure 10. Radial and temporal relaxation of a 20 eV incoming flow. Shown is the case for Venus orbital insertion with a 10 km/s insertion speed.

ionization rate and the diffusion rate. For incoming flow energy that is less than a typical ionization energy (12 to 20 eV) particle density will decay at the diffusion rate. When the density is sustained by limited ionization at flow energies greater than the ionization energy, significant increase in ionization occurs, resulting in an expansion of the PMS until a matching radial equilibrium condition is met in which ionization rate and diffusion rate are equal.

The resulting radial electron temperature profile evolution as a function of time is shown in Fig. 11. Regardless of the initial density or temperature distribution, the radial profile quickly relaxes to a peaked profile, in which external

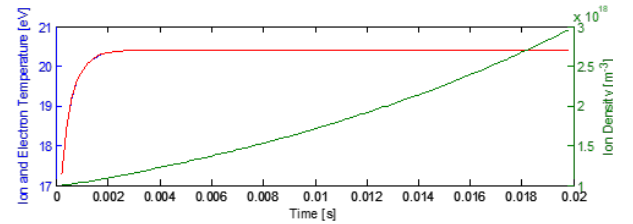


Figure 11. Ion and Electron Equilibration times are ~1 ms, while ion equilibration may take minutes. Shown is Venus with a 10 km/s insertion.

diffusion is supported by the higher density core of the PMS. Temperature also relaxes to a peaked profile quite quickly. Timescales in certain regions are somewhat longer than expected. Thermal equilibrium occurs in a few milliseconds at the core, while the radial profile may take many tens of milliseconds to fully evolve. Density distributions evolve over the time scales of the confinement time, which for these devices and typical operating conditions will be many minutes or longer. Figure 10 illustrates the relevant time scales.

Initial Mission Analysis using Analytic Model Results—Using the empirical atmosphere model and equilibrium conditions of the PMS, the relative diameter, and drag magnitude can now be determined. With a known plasma, neutral density and temperature, confinement can be determined. Two confinement relationships shown in Eqs. 6 and 7 are critical and as well as those of Eqs. 17 and 18. First, the charge exchange mean free path is the effective distance for a charge exchange collision. That distance must be less than the effective radius or chord length of the system. Additionally, the magnetization ion gyroradius must be less than this critical distance and more than the charge exchange mean free path. This is required so that significant momentum can be converted from directed momentum to average equilibrium momentum. From these considerations an effective diameter can be calculated, and using that diameter to obtain a cross-sectional area, a total drag can be determined. For Mars at 120 km, a drag force of 1 kN with an effective radius of 15 m was obtained. In this case, all power and plasma parameters are provided by the incoming flow, and the only spacecraft power required was to maintain the dipolar magnetic field. For Neptune at 1000 km there is an effective drag force of 100 N with a radius of 17 m, and all power, temperature, and plasma energy is sustained by the incoming flow. Clearly significant forces can be generated by this technique to brake in planetary atmospheres.

Numerical PMS Modelling and Simulation—In order to advance the accuracy and predictive capability of the PMS models, it was essential to begin the process of moving the calculations in the direction of 2D and 3D numerical calculations with as much physics included as possible. It turned out that there are no codes that can handle both the neutral and multi-ion species calculations in the regime of interest. There was no atmospheric model with the capability of doing both MHD calculations in the presence of the neutral flow, nor were there any hybrid codes to handle the particle motions that are necessary to capture the full

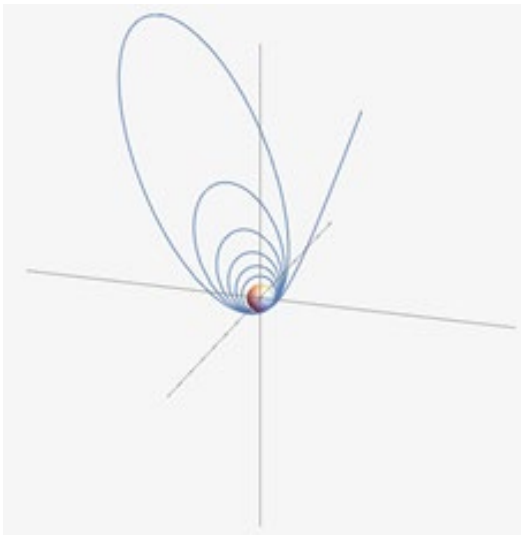


Figure 12. Neptune orbiter aerocapture and aerobraking. PMS Parameters for capture: $B_0 = 326$ G, $R_{\text{eff}} = 7.1$ m

physics. Finally, there are no numerical models that could also include the physical chemistry of the various ion and neutral species involved in the interactions in the PMS system. This meant that only a start in building such a model could be accomplished with the time and monetary resources available. A full model will ultimately be needed before deployment in space, so that starting the process was essential. With continued support it is feasible that such an all-encompassing code can be formulated. With this a proper design and subscale ground testing can be performed to validate the code, and plans for a space-based test could then commence. What was accomplished with the theoretical numerical analysis will now be presented.

PMS Orbital Model Improvements—The initial mission simulations at Mars and Neptune were conducted using the Copernicus orbital software. To make use of this code, static spacecraft parameters based on the output of the analytic model for some prospective orbital environments were used. To improve on this analysis, a code was developed to dynamically compute the PMS parameters along the propagation of the orbit. As a check, the initial Copernicus results were replicated with this more self-consistent model. Copernicus was also used to model the planetary insertion. The position and velocity were extracted, and were used as input to the orbit code as initial conditions for capture. This process was then iterated. The trajectory results are plotted in Fig. 12 for a Neptune orbiter.

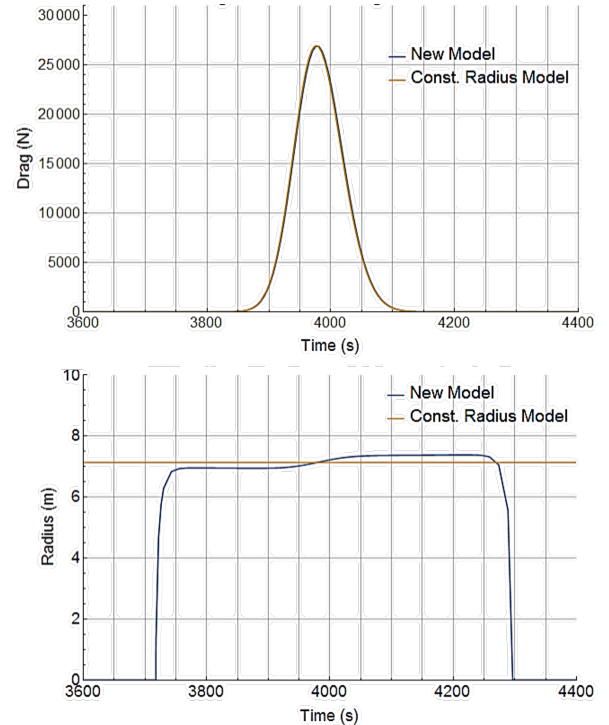


Figure 13. Comparison between static and dynamically computed radius models. $B_0 = 326$ G.

These results agree with the previously simulated two-pass Neptune capture, where the PMS field strength is decreased after the capture pass to ease the braking passes. A comparison between the old model (constant area PMS) and

the new model (dynamically computed area) PMS performance during capture is seen in Fig. 13. It can be seen that the updated model captures the real-time effects of the PMS slowing while passing through a changing atmospheric density. In particular, this result shows only a small window during which the PMS actually captures ions, giving insight into where to deploy the plasma for maximum power efficiency of braking. This is a proof-of-concept code that incorporates PMS physics into an orbit propagator. As more accurate analytic models of PMS are developed; this self-consistent simulator should provide physically reliable results without the limiting approximations imposed by Copernicus. Such simulations will ultimately motivate vacuum chamber testing and the design of a subscale PMS test and mission.

4. PMS MISSION AND ORBIT ANALYSIS

The first spacecraft to utilize upper atmospheric drag in a beneficial manner was HITEN, a Japanese spacecraft in 1991 that shed 1.7 km/s of ΔV from its highly elliptic orbit around Earth. [12] The Magellan Spacecraft was the first mission to use aerobraking on another planet. [13] Magellan used aerobraking maneuvers to lower its apoapsis from about 8500 km to 540 km, in order to conduct gravitational studies of Venus. This maneuver would have required 900 kg of propellant with traditional methods. However, Magellan was able to accomplish this part of its mission with the less than the 100 kg left onboard. In 1997 the Mars Global Surveyor (MGS) also used aerobraking to shed 1200 m/s of Δv to circularize its orbit after initial Mars orbit insertion [14]. For aerobraking, structure loads and thermal issues are the significant factors. For MGS the dynamic pressure was limited to 0.6 N/m² and the Magellan spacecraft experienced maximum dynamic pressure of 0.31 N/m². While small, these forces were non-negligible when applied to their delicate cantilevered solar panels and communication equipment. With a Plasma MagnetoShell virtually all the applied force will be to the PMS system and transferred to the spacecraft through the tethered antenna/coil magnets, which should be readily capable of accommodating much higher dynamic loads. The PMS can be deployed in a manner that would shield the spacecraft and its delicate components from any atmospheric buffeting by deployment ahead of the spacecraft and thereby intercept and divert the atmospheric neutrals. This however would require stiffeners or a boom to transfer the drag load to the spacecraft as the force would now be compressional. A forward positioning of the PMS would likely require several small hydrazine-fueled thrusters to maintain stability of the spacecraft to random off-axis forces.

The other limiting factor is thermal loading. With both previous aerobraking missions, drag was limited due to temperature constraints. For MGS this limit was 65 °C and for Magellan it was 180 °C. With a Plasma MagnetoShell the friction interacts with the plasma around the spacecraft and not the spacecraft itself, eliminating many, if not all, of the thermal considerations. It is important to note that in addition to the thermal, mass, and structural concerns the most

important challenge with conventional aeroshells is the dramatic increase in risk as the braking force increases. The braking forces vary greatly with respect to inclination, time of year, time of day, solar cycle, solar phenomenon and even surface weather. Needless to say, both aerobraking and aerocapture require in-depth knowledge and understanding of the atmosphere, and the ability to rapidly modify drag based on changing conditions making fixed surface aeroshells ill-suited for manned and/or rapid deceleration missions. Clearly, using aerobraking at very remote, poorly understood planetary atmospheres, such as Jupiter or Neptune, would be too risky with current technology. The most widely studied aerobraking case, the MGS, had significant challenges with unanticipated thermal and structural loads. For the Plasma MagnetoShell the drag force on the PMS structure is orders of magnitude larger than that on the spacecraft itself, so the drag force can be increased, or indeed turned-off, as needed at an altitude that would likely not expose the spacecraft to any significant thermal or mechanical stresses.

Aerocapture has never been implemented to date, but there are numerous studies for its application to Mars and other interplanetary missions [15]. These studies have illustrated the many advantages of using aerocapture. First, by reducing the amount of propellant needed at a destination planet, some missions, such as a Neptune Orbiter, become feasible by allowing the spacecraft to fit within the largest available launch vehicles. In addition, aerocapture can allow for faster orbital transfers, reducing trip time and radiation exposures. With faster trip times, higher approach velocities and thus increased delta-V requirements are encountered for capture. The delta-V requirements and mission trajectories for missions to Mars and Jupiter as calculated by Copernicus can be found in Fig. 14. It can be seen that not only does ΔV

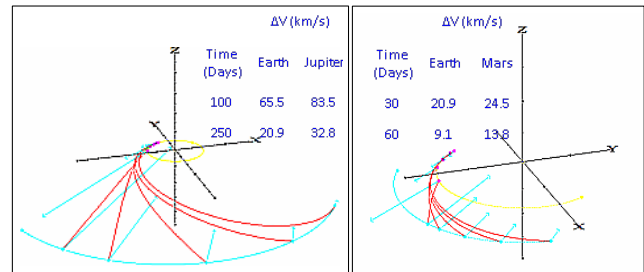


Figure 14. COPERNICUS simulations of impulsive orbital transfer from Earth to Jupiter and Mars. Shown are the ΔV requirements for Transfer and Insertion orbits.

increase with reduced trip time, but that the ΔV required to orbit the target planet is as large, if not even greater than the delta-V required for the transfer orbit. By utilizing a low-mass Plasma MagnetoShell aerocapture, the delta-V requirements for a 1000-day all-propulsion Jupiter mission is the same as a 300 day with Plasma MagnetoShell braking. For Mars, the traditional 120-day trip can be reduced to less than half using conventional propulsion technologies!

In addition to cargo missions, Plasma MagnetoShells would allow beneficial design changes to the crewed aspects of interplanetary mission's architectures. These manned

missions designs do not use aerocapture largely because of the risks enumerated earlier for conventional aeroshells for just aerobraking. Plasma MagnetoShells however allow for dynamic control at any altitude, therefore, they should be safe and reliable for human missions. Plasma MagnetoShells would add additional safety and health benefits as the PMS

Mission	Mars Manned	Venus Sample Return	Neptune Orbiter
Insertion Velocity	5.5 km/s	10.6 km/s	26.7 km/s
Neutral Avg. Mass	43.4 amu	43.4 amu	2.5 amu
Ion Avg. Mass	15.0 amu	14.6 amu	1.6 amu
Directed Energy	7.0 eV	25.5 eV	9.4 eV
Atmos. Density	1E-6 kg/m ³	2.2E-7 kg/m ³	1.5 E-8 kg/m ³
PMS ion density	1.3E19 #/m ³	3E18 #/m ³	3.5E18 #/m ³

Figure 15. Comparison of mission requirements for Aerocapture.

could also be deployed during Mars transit to eliminate the effects of solar flares should they arise. It would have little effect on GCR as shown by numerous previous analyses [12]. Stopping GCR is a formidable challenge, and the most effective solution is simply to reduce exposure. By allowing for high velocity orbit insertion a PMS system would allow for faster transit times between planets thereby reducing exposure. The main mission parameters for three missions of high interest can be found in Fig. 15.

PMS Optimization and Design—A systems level optimization of the Plasma MagnetoShell hardware was undertaken and

$$B_0 = \frac{\mu_0 I N}{2t} \ln \left[\frac{\sqrt{(R_0 + t)^2 + \left(\frac{l_c}{2}\right)^2} + (R_0 + t)}{\sqrt{(R_0 - t)^2 + \left(\frac{l_c}{2}\right)^2} + (R_0 - t)} \right] \approx \frac{\mu_0 I N}{R_0} \quad (19)$$

$$B = B_0 \left(\frac{r}{R_0} \right)^3 \approx \frac{\mu_0 I N}{R_0} \left(\frac{r}{R_0} \right)^3 \quad (20)$$

$$R_{\text{dipole}} \approx \frac{\lambda_i}{\pi} \approx \frac{\sqrt{m_i k_B T_i}}{\pi B} \approx \sqrt{\frac{\pi B_0 R_0^3}{\sqrt{m_i k_B T_i}}} \quad (21)$$

$$P_e = I^2 \left(N^2 \frac{2\pi \rho_c R_0}{t l_c} \right) \quad (22)$$

$$m_c = 4\pi \rho_m R_0 l_c t \quad (23)$$

$$m_B = \alpha_B P_e \Delta t_B \quad (24)$$

$$m_P = \alpha_B P_e \frac{\Delta t_B}{\Delta t_C} \quad (25)$$

$$T_c = \frac{C_p}{m_c} \left(\left(P_e - \sigma(T_c^4) (2\pi r (2t + l)) \right) \right) \Delta t_B \quad (26)$$

completed. Equations (19) through (26) were used to optimize the design of the PMS, and will now be described in more detail. Equation (19) represents the full equation for a finite solenoidal magnetic field solution on axis. This is a strong function of current, I , and coil turns, N , as well as coil radius, R_0 . It is a weaker function of coil length, l_c , and thickness, t . Equation (20) reflects the magnetic dipole falloff for a low β plasma and is a very strong function of the coil radius. The collection radius, R_{dipole} of the PMS as described earlier in the transient and steady analytic plasma model can be approximated as simply the outer limit of the magnetic gyro radius, λ_i which is the largest distance at which a magnetized and trapped charge exchange particle can be contained sufficiently to exchange momentum to the spacecraft. This can be integrated into Eq. (21) and solved simply as a function of the initial magnetic field, B_0 and flow parameters.

At this point, the physical characteristics of a given magnetic coil can be investigated with simple assumptions about materials and dimensions for the dipole coil. The power scaling required to operate this coil is given in Eq. (22). The expression in Eq. (23) reflects the mass of dipole coil in terms of the mean coil density ρ_c . The mass of a battery system needed to deliver the power to the coil is reflected in Eq. (24). Here, the a specific power, α_b for the battery mass is measured in kilograms per kilowatt and for a specific operational time, Δt_b in which the Plasma MagnetoShell is active. The required mass for the power system to recharge that battery is found in Eq. (25), and again under the assumption of a steady specific power, α_b , and for a coast period Δt_c in which the battery is being recharged. Finally, Eq. (26) yields the peak temperature of the coil in terms of the specific heat, C_p , mass of the coil, operation time, as well as the input electrical power and output radiation rates. For these solutions, the operation times were relatively brief and the radiated power turned out to be a minor contributor and could be ignored.

The scaling dependencies for both electrical power and magnet mass are shown for the generation of a $B_0 = 250$ G dipole coil in Fig. 16. Dotted lines show magnet mass for two

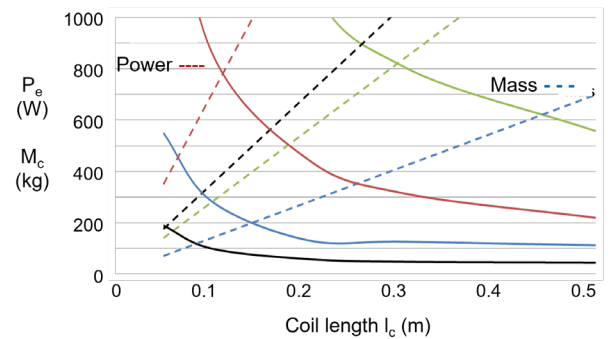


Figure 16. Power and Mass scaling with length for a 250 Gauss coil. Data is for copper and steady heating. Red – 1 m Diam. 0.25 m thick; Black – 0.5 D, 0.1 m t; Green – 1 m D, 0.1 m t; Blue – 0.5 m D, 0.1 m t.

diameters and two thicknesses (widths) while solid lines show power requirement for the 250 Gauss coil. The same analysis was performed for a simple cylindrical rod as an approximation of the tether. The tether mass and power requirements as a function of the coil current and is shown in Fig. 17.

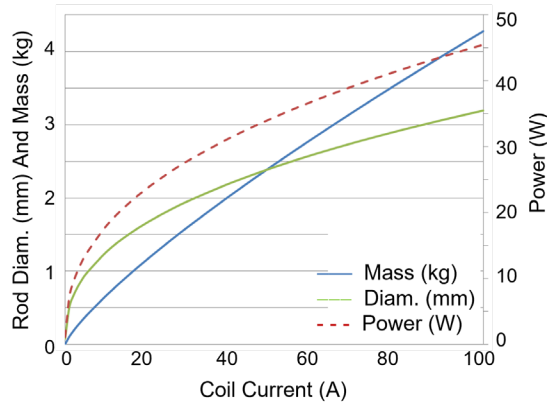


Figure 17 Tether mass, size, and power requirements of a copper tether. Data shown is for copper coil and steady heating.

From these analyses it was not surprising that the mass, energy, and thermal requirements to power the dipole coil, PPU, and tether become paramount. To optimize in this case then requires knowledge of the orbital trajectory, the analysis of which will be described in the following section.

Two missions were fully designed and simulated: a Cassini class Neptune orbiter and a HEOMD scale Mars orbital insertion. The complete system design of both missions including PMS coil, tether, power processing, and battery mass were scaled and specified. The orbital simulation code Copernicus was used to determine optimal trajectory as well as optimize the magneto shell size as a function of minimal altitude. Some conclusions from these two studies can be made. First, PMS dipoles from 2 to 40 meters in radius are feasible with realistic sized power systems and coils. For the mission simulated, forces from a few Newtons through many kilo-Newtons were generated allowing for orbital insertion of spacecraft traveling at greater than 20 km/s. For a Neptune insertion mission, a 1 MT spacecraft was decelerated and placed into orbit around Neptune using a PMS-based aerocapture system with a total mass of 207 kg, including RTG power requirements. This increased the LEO to Neptune dry payload fraction from 32% to 40% and most importantly, allowed for the dynamic capture behavior as a function of the real-time Neptune atmosphere.

For Mars insertion, the primary benefit of the PMS is mass savings. Once demonstrated in space to function as expected, a PMS system could be used for aerocapture on manned missions. A 30 MT aeroshell could then be replaced with a Plasma MagnetoShell system of less than one metric ton. The Martian insertion was accomplished assuming a 60 metric ton payload that fit into a standard faring size. Key parameters for the two missions are summarized in Fig. 18. A more

detailed description of the deployment of a PMS system for aerocapture at Mars will now be presented.

Plasma MagnetoShell Design Parameter	Optimized Configuration for Neptune	Optimized Configuration for Mars
Dipole Coil Average Radius	2 m (Al)	2.5 m (Al)
Total Dipole Coil Mass	81 kg	190 kg
Total Battery and SEP Mass	72 kg	250 kg
Dipole Coil Length	3.5 cm	50 cm
Dipole Coil Width	3.5 cm	1 cm
Effective Aerobraking Radius	9 m	21 m
Total Weight with 30% margin	210 kg	690 kg
Equivalent Aeroshell Weight	885 kg	~20,000 kg

Figure 18. Summary of PMS parameters for a Neptune orbiter and Mars 60 ton spacecraft insertion.

Manned Mars Mission

Using the Plasma MagnetoShell system model developed in the previous section, a 60 MT, large-scale Mars aerocapture mission similar to the NASA Design Reference Architecture DRA 5.0 [16] was modelled. This mission is significantly more ambitious than the Neptune mission in that for aerocapture the PMS must shed the kinetic energy of a 60 t payload. The DRA 5.0 design study has shown that for the lower-risk Martian cargo missions, aerocapture using 20 t aeroshells can reduce the launch mass and cost of the mission significantly. DRA 5.0 currently specifies a minimum of 850 tons in LEO. This mass is packaged into two cargo vehicles and one crewed spacecraft headed to Mars. This design architecture used Nuclear Thermal Propulsion (NTP) for Trans-Mars Injection and aerocapture (for the cargo) for Mars Orbital Insertion (MOI). The 1 t Plasma MagnetoShell would eliminate the need for this massive heat shield, reducing the required mass by 80 t. An additional 46 tons of propellant and 14 t of tankage are saved at MOI due to the lighter payload masses. For the all-propulsion crewed mission, 84 t of propellant and tanks are not needed for MOI with a low-risk Plasma MagnetoShell. In total, a PMS aerocapture has the capability to save 224 t for IMLEO, or on the order of \$2 Billion in launch costs as well as decreased risk. DRA 5.0 also outlines a mission architecture using chemical propulsion instead of NTP. For this architecture the PMS would result in even larger mass savings of 355 t. DRA 5.0 focuses mainly on the launch vehicle, interplanetary transportation and entry, decent and landing (EDL). While it may be feasible for PMS to be used for EDL, it is not the primary goal of this initial investigation. Any benefits with regards to EDL, would be small compared to the mass savings of the MOI.

To provide aerocapture for a manned Mars class mission requires then a significantly larger dipole operating at higher power with only minor increases in available geometric scale compared to Neptune. (see Fig. 18). Due to the sheer number of optimization parameters, a Monte Carlo approach was taken in which a random sampling of possible magnet geometry and operational conditions were simulated by running this calculation for extended periods and down-

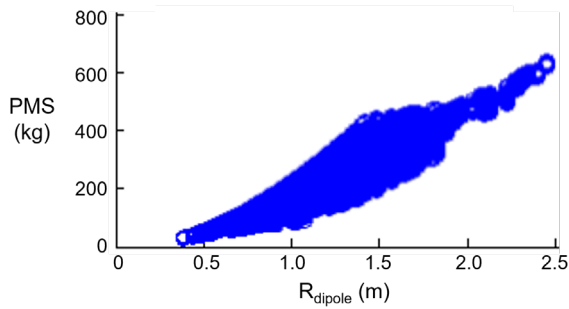


Figure 19. Model solutions for a Mars orbit insertion as a function of dipole coil radius. Shown are all permutations for a wide range of coil sizes (up to 2.5 meters) and power systems. Battery backed and temperature limited.

selecting to the most promising candidates that are still geometrically possible. The optimum magnet design for a desired braking diameter and force could be then determined. The complete set of model solutions for a Mars orbit insertion of a 60 metric ton payload from an earth to orbit insertion is displayed in Fig. 19, where the constraint that the dipole coil fit in a large faring size with no ability to expand or unfold was imposed. Not surprisingly the PMS system mass is increased as the primary dipole radius is varied from 0.4 to 2.5 meters in radius. Clearly the variation in other parameters has a significant effect on the system mass as well. For this mission analysis, this simpler engineering option was chosen and a 2.5-meter diameter magnet was selected as the r^3 drop-off of the dipole is more significant than the nearly linear

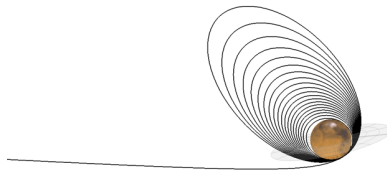
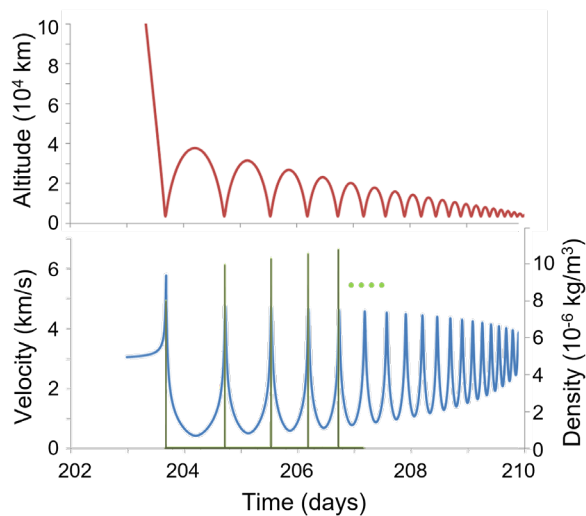


Figure 20. Optimal Mars insertion into Martian atmosphere. (Top) illustration of spacecraft orbits. (Lower graphs). Spacecraft altitude, velocity and Martian atmospheric mass density during orbital periods. Time is from LEO departure.

mass penalty with radius. The more complex dipole with outrigger coils would impact the simple assumption of portability, although these coils could easily be folded and expanded as they need to produce fairly weak fields and would be self-inflating due to the hoop force when energized.

Using this simple 2.5-meter diameter dipole coil with a peak magnetic field of 100 Gauss, a 21-meter dipole can be generated yielding a peak pressure of up to 130 N/m². The solution set for this magnet is shown in Fig. 19 where an optimal 275-kilogram battery system was assumed. The solar power charging system was not included in this mission architecture. The magnet length was limited to 0.5 meters out of structural considerations for the magnet design. Finally, the overall PMS mass was found to be a weak function of the PMS temperature, as in the Neptune mission study. The full magnet design parameters are shown in Fig. 18.

Mars Orbital Modelling—A Copernicus calculation of a Martian aerocapture was also performed. For this calculation a 60 ton spacecraft is inserted via a simple Hohmann transfer. The atmospheric model used came from the standard Mars atmospheric climate database version 5.0. Similar to the Neptune study, an initial large Plasma MagnetoShell is required to perform the initial insertion and capture. In this simulation, a 21-meter diameter PMS is used. An initial capture is performed over the course of five minutes followed by a long coast period of 8 days between aerobraking maneuvers. This allows for recalculation of orbital trajectories and adjusting for the dynamic atmosphere. An 18 orbit aerobraking maneuver is then performed to circularize and lower the Mars orbit. The results for the Martian orbital braking maneuver with a peak braking force of 0.6 g's and dynamic pressure of 130 N/m² are found in Figs. 20 and 21. The calculated ion temperature for this braking maneuver is given in Fig. 21

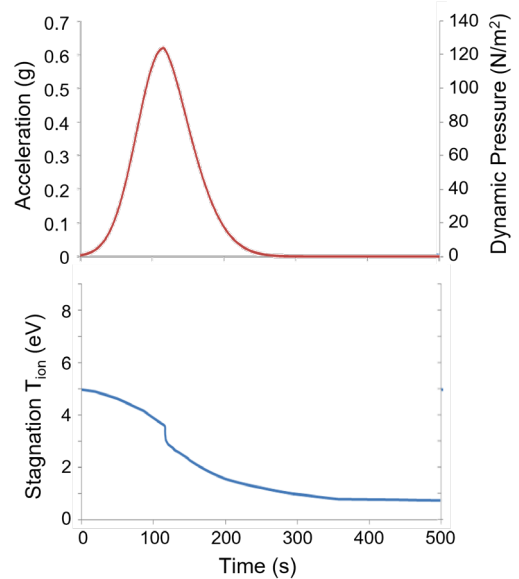


Figure 21. (Top) Close up of the PMS dynamic deceleration and pressure for the initial insertion. (Bottom) Incoming equivalent ion temperature.

5. EXPERIMENTAL TESTING OF THE PLASMA MAGNETOSHELL CONCEPT

Several experimental tests were made of the PMS concept to better understand the relevant physics as well as develop techniques for obtaining the proper plasma density and methods for sustainment. Given the optimal sizes determined in the last section, it was clear that the experimental program would have to be a subscale test. Fortunately, MSNW had a large enough vacuum chamber (9200 liters with 23,000 liters/sec turbo-molecular pumping) to carry out a meaningful subscale test. It was also equipped with a thrust stand and an array of power and diagnostic feedthroughs (see Fig. 22). As was previously discussed (see Fig. 8), a prototype PMS device had been developed and demonstrated a suitable candidate PMS for testing in the large chamber on a thrust stand. The subscale experimental testing presented two challenges. In order to have the CEX/collisional mean free path (mfp) to be on the order of the much smaller PMS, the plasma density must be proportionally higher. As the ionization mfp is typically larger (i.e. smaller cross section – see Fig. 3) this adds an additional challenge. The other is obtaining a suitable neutral flow at the characteristic speeds one would encounter in reentry into a planetary atmosphere. These requirements for a ground test of the PMS system, put certain constraints on the neutral gas injection, the Plasma MagnetoShell, and vacuum facility.

In order to realistically simulate the interaction of an atmospheric flowing gas with a large, magnetized, plasma-filled dipole several design parameters must be met. They are: (1) Neutral gas and plasma densities of the neutral jet and PMS need to be in the collisional regimes of interest, namely neutral particle densities $> 5 \times 10^{18} \text{ m}^{-3}$. (2) Chamber effects must be minimal, i.e. background pressure less than $1 \times 10^{18} \text{ m}^{-3}$. A background density of $1 \times 10^{17} \text{ m}^{-3}$, (1×10^{-5} Torr) was maintained to prevent attenuation of the drag. (3) The neutral jet should be highly directional, i.e., it must be supersonic. (4) The chamber must be sufficiently large so that wall



Figure 22. The 2 m diameter 4 m long MSNW large vacuum chamber with dielectric, asymmetric torsional thrust stand (green G10 garolite).

interaction is minimal. All of these conditions were met for the tests.

There were two major efforts to demonstrate various aspects of the PMS system. The first was to demonstrate the PMS using a plasma/magnetic system of known robustness and efficiency as it was used with success in the Plasma Magnetic Sail experiments [8]. This PMS system was presented earlier (see Fig. 8) and was employed in the second effort which was aimed at demonstrating significant drag enhancement as it would be in space by testing in the large chamber shown in Fig. 22.

Laboratory Demonstration of the PMS—To satisfy the requirements listed above, the required vacuum pumping and chamber size for steady operation would be prohibitive. An Argon gas jet with a particle density of $\sim 10^{19} \text{ m}^{-3}$, and a 1-meter diameter cross section, flowing at 323 m/s would need to deliver gas at a rate of 5,700 sccm. In order to maintain a background pressure of 10^{-5} Torr, this would require a pumping speed of 7×10^6 liters/s! However, a pulsed system can easily satisfy this requirement as long as the time of

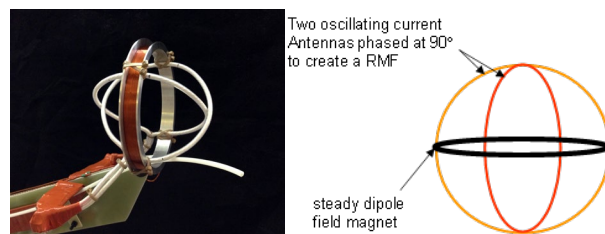


Figure 23. Coil set employed in generating a plasma PMS. The RMF antennas create a magnetic field that rotates about the axis of symmetry of the steady dipole magnet.

interest is less than the fill time from the base pressure ($\sim 1 \times 10^{-7}$ Torr) to 10^{-5} Torr, or approximately 21 msec. for the MSNW large chamber. The MSNW vacuum facility was thus utilized and modified to test the Plasma MagnetoShell with a neutral gas injector in a pulsed manner. The impulse from the Argon flow from the injector can be readily measured on the MSNW torsional thrust stand, which has been shown to be able to resolve approximately 100 $\mu\text{N}\cdot\text{s}$. As was mentioned, the plasma dipole and source were designed and constructed in a manner similar to that used for the plasma magnetic sail experiments and is shown in Fig. 23.

Plasma MagnetoShell Setup—As can be seen in Fig. 23, the dipole field is produced by a 200 turn coil and the rotating magnetic field is produced by two loop antennas perpendicular to the magnetic axis as well as each other. The latter arrangement is to make the generation of the rotating transverse field easier to accomplish as it only requires that the two antennas be produced with oscillating circuits 90 degrees out of phase with each other. These circular loops are single turn as the frequency of the rotating field must lie between the electron and ion gyrofrequency, which for typical magnetic field strengths is in the hundreds of kilohertz range, thus necessitating a much lower inductance in order to

avoid excessive high voltage requirements. To keep the resistance low, the RF antennas were made of low resistance Litz wire encased in a Tef-Zel high temperature insulator. The entire assembly is fed with low-inductance, low-resistance strip line with a silicone high temperature insulation layer. It is mounted on a G-10 boom mount that places the PMS midway between the thrust stand platform and the top of the chamber. This positioning allows the maximum interaction with a 15-degree half angle, expanding neutral jet.

A Power-Processing Unit (PPU) consisting of a pair of IGBT switches, high-efficiency capacitors, all the necessary



Figure 24. PMS installed in chamber. Shown are two in-chamber power supplies (potted), low-inductance stripline, G-10 mount

charging and fiberoptic triggering was made vacuum operable for this experiment. This system, shown in Fig. 24, was operated at 160 kHz and 1.6 kV. The charging power and fiber-optic lines were transmitted through an array of small (low-spring constant) feed cabling on the stand. A gas puff was injected into the center of the PMS by a fast Parker® Series-9 puff valve backed by an Alicat® 500 sccm flow controller. Discharge initiation in the PMS was accomplished by a small dielectric surface flashover discharge to provide a seed electron population. The dielectric thrust stand was used for the PMS testing with the boom used to hold the PMS bolted to it as indicated in Fig. 25. Fig. 23 shows a close-up of the antenna setup, with Fig. 24 shows the external, angled view of the Plasma MagnetoShell thus avoiding the “hole” in the dipole center discussed earlier. A downstream 3-axis linear probe array, a double Langmuir probe with 10 mm² ion collection electrode, 100-turn magnetic field probe, and a Retarding Potential Analyzer (RPA) were all employed to characterize the PMS plasma and partially ionized neutral jet. These diagnostics were mounted on a translation stage and were used to measure the average ion (momentum) and electron (flux) radial profiles of the PMS.

The dielectric torsional thrust stand that was used to measure the drag impulse generated by the Plasma MagnetoShell is an entirely non-magnetic and non-inductive torsional thrust stand that was designed to enable the accurate testing of a pulsed inductive thruster. The G-10 thrust stand employed a

Philtec D63 fiber-optic displacement sensor for isolated, high-accuracy position measurements. The stand is counterbalanced to reduce secondary oscillations and includes a passive eddy-current damping system. Calibration is accomplished at atmosphere with a standard DC, weight calibration system. In vacuum, calibration is accomplished with a standardized, AFRL-calibrated cold gas thruster which is fed a steady Xenon gas flow. By measuring the deflection and comparing with externally validated thrust stand results, the thrust stand spring and deflection constants were calibrated.

Plasma MagnetoShell Operation and Testing—Significant progress was made in testing with this setup with a successful and complete subscale system test. The photograph of the PMS in operation, shown in Fig. 25, was taken while under vacuum through a side window with an elliptical ‘safety’ mirror. In this configuration the arcjet and neutral puff valve were located 1.5 meters from the center of the PMS antenna with the arcjet central axis aligned with the PMS. As the high velocity neutrals impact the PMS mounting and antenna a net impulse is imparted and transmitted down the rigid G-10 support arm, and thus on to the torsional stand. This impulse deflects the stand, which oscillates with a 9.6 second period. Displacement is measured by the optical sensor at the end of the torsional arm.

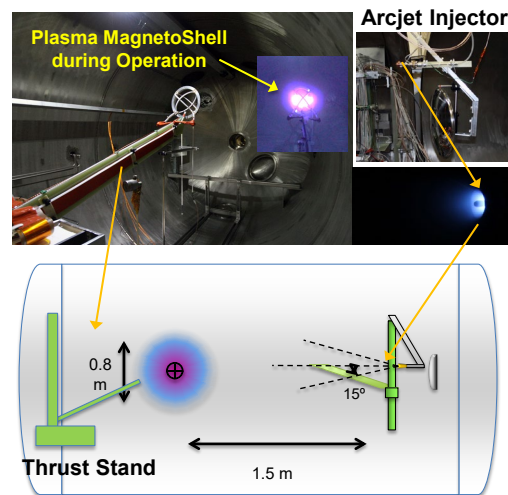


Figure 25. (Top Left) A photo of the PMS mounted on a boom attached to the thrust stand. The inset picture of the PMS was taken during operation **(Top right) A photo of the downstream Arcjet injector and support structure.** The inset picture is that of the arcjet during operation. **(Bottom) Schematic of the relative location of the two devices in the vacuum**

The Plasma MagnetoShell was tested with Argon gas under a variety of operating and gas flow conditions. For this paper a summary of the results will be given. A 3 Joule RMF discharge initiates the PMS plasma entirely out of incoming neutral jet flow from the gas puff which is pulsed on for 30 msec and travels into the PMS region at roughly 350 m/s. As mentioned, the PMS plasma is initiated with a 1 Joule surface flashover discharge. The RMF ringing lasts approximately 40 microseconds with a decaying ring-down. For this case the

gas is entirely sourced from the ambient, flowing neutrals. While this may be an optimal method for operating in the space environment it requires that a significant portion of the neutral gas puff pass through and past the antenna region before a discharge can be formed and maintained. Therefore, a small internal gas feed provided gas injected towards the

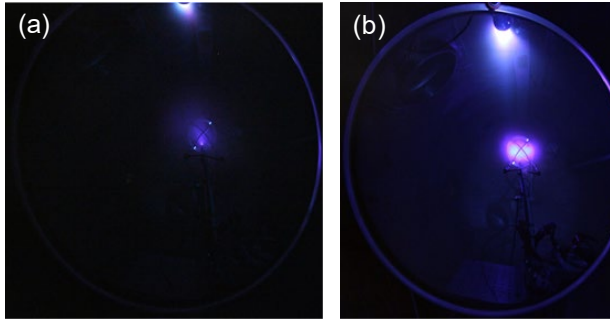


Figure 26. (a) PMS operating with internal gas feed and initiator plasma only while intercepting arcjet gas jet and plasma. Shown is 50 sccm internal feed, 3 Joule RMF, 1 ms arcjet discharge at 1.2 kV and 1 ms delay. **(b) PMS shell operating with internal gas feed and intercepting an accelerated neutral and plasma jet.** Shown is same PMS operation as (a) but with 1 ms arcjet discharge at 1.2 kV following a 20 ms neutral puff.

center of the PMS with a small 6 mm injector located at the magnet edge. Gas is fed to the PMS constantly with a small, 50 sccm flow rate, raising the chamber background pressure from 3×10^{-7} Torr to $\sim 10^{-6}$ Torr. Note, this is only a small fraction ($\sim 10\%$) of the desired PMS density, but was sufficient to provide seed neutral gas at the required position prior to the main arcjet + neutral flow. Adding an internal neutral gas flow also allowed the initial jet puff to be timed so that the PMS RMF was operated during the arrival of the leading edge of the injector neutral gas flow, rather than waiting until sufficient density populated the antenna region.

Figure 26b shows the full, optimized case in which the Plasma MagnetoShell is created with a low density flowing internal argon gas at 50 sccm and on the order of $1 \times 10^{17} \text{ m}^{-3}$ density. The RMF is energized approximately 2 ms after the initiation of the arcjet and when the plasma and neutral entrained jet arrives at the PMS. This timing led to the maximum increase in impulse. Additionally, the neutral jet is puffed 20 ms before the RMF initiation, allowing the neutral front to arrive at the RMF antenna. In this way the gas is swept up by the plasma jet and the higher velocity, partially ionized propellant impinges on the PMS immediately afterward.

By measuring the increase in the deflection of the torsional thrust stand, the impulse could be measured. By comparing the average exposure time of the stand to the various impulses, the approximate average drag could be determined. It should be noted that displacement of the stand from operation of the electromagnetic and gas feed systems was observed to be negligible. The high-velocity, low-ionization-fraction Argon gas jet was produced by a small arcjet which then impinged on the RMF-produced PMS. This Plasma

MagnetoShell demonstrated a dramatic increase in effective drag over the non-ionized, non-magnetized interaction case. By measuring the amplitude, period, and damping rate the impulse applied to the stand can be measured using standard techniques. With that impulse and an approximate discharge time the average thrust can then be determined. Figure 27 provides a summary of thrust results for the key cases of

Operating Condition	Measured Drag	Effective Area	Relative Drag
PMS w Magnetic Bias Arcjet w Neutral Flow	220 mN	2.3 m ²	1150
PMS no Magnetic Bias Arcjet w Neutral Flow	110 mN	1.1 m ²	550
No PMS Arcjet w Neutral Flow and Magnetic Bias	190 μ N	0.02 m ²	1

Figure 27. Summary of Plasma MagnetoShell results, translating impulse into direct equivalent steady thrust measurements.

interest. These numbers have relatively large error bars, in that the estimate of average discharge and impingement length are quite uncertain. However, the three orders of magnitude increase in thrust is not in doubt. The known cross-sectional area of the PMS hardware is 20 cm². By scaling the measured thrust with the known area, an equivalent PMS cross section can be determined. Therefore, the Plasma MagnetoShell measured an equivalent interception diameter of 1.6 m in a 2.2 m diameter chamber. This also approximately agrees with the photographic evidence. In conclusion, while the error in the absolute magnitude of thrust measurement may be quite high, the relative measurement and the large ratio between the bare and PMS cases is indisputable

Experimental Summary—An argon Plasma MagnetoShell was generated and using a supersonic jet, demonstrated active charge exchange, entrainment, and a 1000X increase in drag. The PMS was formed, and a high velocity jet was impinged upon it. The jet impinging on the Plasma MagnetoShell hardware, dipole field, and magnetized plasma field all produced a measurable drag. Shown in Figs 27 and 28 are the conditions that were tested, showing jet timing (duration), arcjet duration, flow rate inside of the Plasma MagnetoShell, dipole magnetic field strength on axis, and RMF plasma generation and injection.

Test Condition	Neutral Jet (ms)	Arcjet (ms)	Internal Flow (sccm)	Dipole Field (Gauss)	RMF (kHz) (kV)
Arcjet	0-30 ms	1-5 ms	0-50	-	-
Neutral Jet	0-30 ms	-	0-50	-	-
PMS	-	-	0-50	0-500	150 1.6
Dipole Field + Neutral Jet	0-30 ms	1 ms	-	0-200	-
PMS + Neutral Jet	10-30 ms	1-2 ms	0-50	0-200	150 1.6

Figure 28. Summary of Plasma MagnetoShell operating and testing conditions

6. DISCUSSION AND FUTURE DIRECTIONS

The Plasma MagnetoShell aerocapture employs a dipole plasma configuration which would initially be populated with plasma of a composition that is similar to the ambient atmospheric gases. This plasma is formed with an electrodeless Rotating Magnetic Field (RMF) plasma source which creates a relatively low electron temperature (5-10 eV) magnetized plasma in the dipole field (see Fig. 2). The charge-exchange interaction between the magnetically confined plasma ions and the incoming neutral atmospheric particles effectively captures incoming particles. After a charge exchange, or for that matter an ion-neutral collision, the magnetized atmospheric ion reacts its newly acquired directional momentum onto the magnet via field line bending and stretching which then decelerates the spacecraft, acting in effect like a “plasma parachute”. The advantages of such a system would be many. Frictional heating would no longer be of concern as the energy dissipation required to slow the spacecraft would be deposited into the plasma ions that then subsequently lost to space through the process of diffusion out of the Plasma MagnetoShell at its periphery. The PMS power requirements, even with the scale of the PMS as large as 10s of meters can be met with onboard solar electric combined with a battery-based power supply. The Plasma MagnetoShell can be regulated through the magnitude of the magnetic dipole fields allowing precise, dynamic control of the deceleration magnitude and direction for low risk aerocapture and aero-assist inclination change maneuvers.

During this study several subscale Plasma MagnetoShell systems were designed built and tested. It was demonstrated that indeed such a system would work well as the observed drag force, which was measured on a thrust stand, due to a supersonic flowing neutral jet, was increased by a factor of 1000X. A wide range of mission studies showed that PMS could enable a Neptune orbiter mission, significantly reduce the cost of a manned Martian mission by \$2B, and provide a low-cost drag system for Earth return missions.

A primary challenge of this and all aerocapture technologies is the testing requirements typically far exceed earth-based capabilities. By utilizing the ISS as a launch or as a package on an Earth-based launch this technology could be demonstrated and at low cost. To that end a more complete system design needs to be performed, and some of the primary technology risks that were not undertaken in this study also will need to be addressed. A detailed examination for a CubeSat demonstration was performed. Unfortunately, it was found to be marginal at best. While a subscale PMS was found to be too underpowered for meaningful test as a CubeSat, further optimization of the magnetic structure and the development of a ground-based simulator provides a path forward. This would consist of a scaling validation with ground-based testing of the optimized PMS magnetic dipole field system (four of which are shown in Fig. 1.). A scaled-up version could then be tested in a large vacuum chamber at a NASA facility.

From the limited MHD analysis of the PMS it is also clear that a more complete and predictive code needs to be developed and include as much of the physics of the PMS as possible, e.g., a fully 3D particle code that can handle multiple ion species, neutrals and can also resolve anomalous transport mechanisms on the relevant space and timescales. This is obviously no small task, but there does exist a plasma particle code that could be modified to perform this task. It was developed for fusion research, but it could be modified to include the type of enhancements needed to describe the physics of a planetary atmosphere in order to accurately capture the PMS behavior and interaction. This unique code could then be employed along with more sophisticated orbit modeling such as the STK Astrogator to accurately predict the magnitude and speed at which the drag can be dynamically changed in various atmospheric and braking scenarios. These code results would of course also need to be experimentally validated in space.

Only after a successful ground-based testing would a space-based demonstration of the PMS would be in order and would bring the TRL to 6 or better. With successful development of the Plasma MagnetoShell, it could immediately be utilized for several applications ranging from nanosatellite technology demonstrators to deep-space flagship science missions providing both, reduced cost and risk. Additionally, as discussed here would be HEOMD Earth and Mars missions, as well as future commercial applications such as reusable cislunar tanker vehicles.

Possibly the most important aspects of the work accomplished so far is this. The physical principles on which the PMS concept was based have been elucidated and demonstrated experimentally. Most importantly, that these results predict that Plasma MagnetoShell Aerocapture could actually be realized. And finally, that it is worthy of future development to make it a reality.

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BIOGRAPHY



***John Slough** received his B.A and PhD in Astrophysics from Columbia University. He has spent over 30 years working in the field of experimental physics. He founded MSNW in 1991, a small business with a long history in the research and development of advanced space propulsion and plasma physics technologies. He was the principal investigator on several large fusion related projects funded by the Dept. of Energy. Experiments performed by Dr. Slough led to advances in the formation and confinement of FRCs as a fusion concept as well as a better understanding of the relevant physics. Recently, he founded a spin-off company, Helion Energy, to develop a commercial fusion reactor which has received both DOE and venture capital funding. Dr. Slough was also on the faculty in the Astronautics and Aeronautics Dept. at the University of Washington for many years.*