

Plasma Magnetoshell for Aerobraking and Aerocapture

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Abstract: The concept explored in this paper is the employment of a greatly expanded magnetic dipole field filled with a high beta plasma to provide the necessary impediment to atmospheric flow past the spacecraft and thereby produce the desired drag for braking. The primary drag-inducing interactions are charge transfer and elastic scattering between the magnetically confined plasma ions and the incoming neutral atmospheric particles. After the interaction, the magnetized ion reacts the directional momentum onto the dipole magnet through field line bending and stretching. The initial dipole magnetic field is generated by a cabled current ring attached appropriately to the spacecraft. The meter scale dipole field is inflated up to 100 m by plasma pressure generated by an RF source. The estimated braking forces would be in the range of 0.01 – 10 N. An estimation of the magnet and plasma power requirements based on both theoretical and empirical confinement studies will be presented

Nomenclature

A_{pms}	=	effective area of the plasma magnetoshell for interaction with planetary atmosphere
B_{RMF}	=	magnitude of rotating magnetic field
B	=	magnitude of steady axial magnetic field
B_0	=	magnitude of dipole field at coil center
β	=	ratio of plasma to magnetic field energy density i.e. $nkT/(B^2/2\mu_0)$
I_{sp}	=	Specific Impulse
δ	=	classical skin depth in a conductor
D_{\perp}	=	particle diffusion coefficient = η/μ_0
ϕ	=	dipole magnetic flux
ψ	=	dipole flux function
F_d	=	drag force on spacecraft
η	=	plasma resistivity
I	=	current in dipole winding
I_c	=	total dipole coil current (=Ni)
λ_{sc}	=	total mean free path for charge exchange and neutral-ion elastic scattering
m_g	=	atomic/molecular mass of planetary gas particle
μ_0	=	magnetic permeability in vacuum
n_g	=	local planetary neutral density for a given gas species
$n_{e,i}$	=	plasma electron, ion density
n_0	=	plasma density near dipole coil
N	=	Number of turns on dipole coil
N_i	=	particle inventory of the plasma magnetoshell
P_{RMF}	=	power delivered into plasma by RMF antenna
r	=	radial distance in cylindrical coordinates

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R_0	=	radius of the Rotating Magnetic Field Antenna and dipole coil
RMF	=	Rotating Magnetic Field
ρ_i	=	ion gyroradius of a charge transfer ion in the plasma magnetoshell
σ_{sc}	=	total ion-neutral cross section
$T_{e,i}$	=	electron, ion temperature in eV
τ_N	=	particle confinement time in the plasma magnetoshell
v_s	=	spacecraft velocity relative to planetary atmosphere

I. Introduction

A rapid mission to Mars requires a large change in vehicle velocity upon arrival 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 be on the order of several kilometers per second. If this is 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 of 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 aero-drag. 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.

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 [1]. 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 . 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 unknown atmospheric composition and temperature. With a limited ability to modify the cross section for drag, 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.

The concept to be considered here is the deployment of a magnetic field filled with a high β plasma to provide the necessary impediment to the atmospheric flow past the spacecraft and thereby produce the desired drag for braking. (Here β refers to the local ratio of plasma to magnetic field energy density). The advantages of such a system are many. Frictional heating would clearly no longer be of concern. In fact, the energy dissipation required to slow the spacecraft would be deposited into the plasma ions helping to maintain the plasma β and at the same time shielding the spacecraft itself from frictional heating. 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 100 meters, and can be sustained by plasma pressure that entails a plasma mass of less than a gram. While the (dipole) magnet will of course be more massive than a gram, it can be orders of magnitude smaller with the plasma magnetoshell due to the highly extended equilibrium of the magnetic dipole at high β [2]. A classic example of this type of dipole expansion is that of the Jovian planet'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 of the dipole field by a high β plasma has been demonstrated in terrestrial laboratory experiments as well. [3] 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 into the dipole field. With the ability to rapidly change and control the drag in varying atmospheric conditions, much larger braking forces can now be contemplated - possibly all the way to aerocapture.

II. Description of the Plasma Magnetoshell Concept

A. Background

The fact that upper atmospheric drag can alter a spacecraft's orbit is not a new concept. Since the beginning of man's interest in space flight, drag has been viewed as a problem, requiring station-keeping maneuvers to maintain a spacecraft's desired orbit. When man broadened his horizons to explore other planets or return to Earth on highly elliptic or hyperbolic trajectories, it was conceived to use these aerodynamic forces to our benefit.

Aerobraking is the use of a planet's atmosphere to cause frictional force, or drag, on a spacecraft to induce a velocity change at periapsis. This results in a decreasing of the apoapsis altitude and total energy of the spacecraft's orbit. Aerocapture is regarded as a much more aggressive form of aerobraking. While aerobraking is used to circularize a highly elliptical orbit over many orbits, aerocapture involves circularizing, usually from a hyperbolic orbit, in just one orbit. Typical aerobraking mission architecture requires an orbital insertion burn to put the spacecraft into its initial highly elliptical orbit. Aerocapture does not require this initial maneuver, so less propellant is needed. However, because aerocapture sheds a large Δv in relatively short amount to time, it puts larger structural and thermal loads onto the spacecraft, therefore requiring significantly more protection.

The first spacecraft to investigate this upper atmospheric drag in a beneficial manner was HITEN, a Japanese spacecraft in 1991 that shed 1.7 m/s of Δv from its highly elliptical orbit around Earth. [4] The Magellan Spacecraft was the first mission to use aerobraking on another planet. [5] Magellan using 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; however Magellan was able to accomplish this part of its mission with the less than 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. [6].

Aerocapture had never been implemented to date, but there are numerous studies to use it for Mars and other interplanetary missions. [7] These studies have shown many advantages to using aerocapture architecture. 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 vehicle. In addition, aerocapture can allow for faster orbital transfers. Faster trip times, means high velocities. All velocity gained must be reduced to zero in order to successfully land on the planet surface. So the faster a spacecraft travels the more propellant it needs to slow down. Recognizing the fact the propellant used at the end of a mission need to be carried and accelerated by previous stages only scales the problem more out of favor. Aerocapture could also enable new missions with increased flexibility by reducing trip times.

Typical aerobraking maneuvers are carried out at a higher altitude where the atmosphere is thinner. This is not only done to reduce frictional heating, but to minimize errors from variation in atmospheric composition, temperatures, and densities. These conditions 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. Aerobraking does have the benefit of allowing mission operators to work with small changes in altitude over many orbits. As was demonstrated with the MGS, small effects and variation in orbit decay can be measured and adjusted for subsequent orbits. An aerocapture requires an autonomous guidance, navigation, and control system capable of adjusting to perturbation in atmospheric and aerodynamic conditions. From the perspective of atmospheric entry, descent, and landing, one of the most foreboding destinations in the solar system is Mars, due in part to its exceedingly thin atmosphere. [8]

Many of the problems associated with aerobraking and aerocapture involve particles directly interacting with the spacecraft itself. The plasma magnetoshell creates a protective envelope around the spacecraft similar magnetopause around the earth. This provided all of the mission advantages of convention aerobraking and aerocapture, but eliminates many of their concerns and limitations.

For aerobraking, structure loads and thermal issues are 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 mostly applied to their delicate cantilevered solar panels and communication equipment. With the plasma magnetoshell all the applied force will be through bending of magnetic field lines and transfer to the spacecraft through the antenna/magnets, which could easily take much higher dynamic loads. 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 would be interacting with the plasma surround the spacecraft and not the spacecraft itself, eliminating many, if not all, of the thermal considerations.

The plasma magnetoshell could also provide faster more controlled aerobraking maneuvers. With thermal and structural considerations greatly eased, the spacecraft can shed more velocity with each orbit. Magellan aerobraking took 70 days while MGS took 17 months. These long missions were not only constrained by the thermal and structure limits mentioned above, but also by the unknown variation in orbital decay rate due to unpredictable upper atmospheric conditions. Magnetoshell can easily react to variation in atmospheric condition by expanding and collapsing the plasma magnet shell. This allows for a more controlled decent though feedback and control. Plus, in worst-case scenario the plasma magnetoshell could be shut off reducing drag to almost zero. While this might be possible with aerodynamic control surfaces, it would not be as easy or as extensively accomplished.

With regards to an aerocapture mission, the plasma magnetoshell would allow for much lighter weight, high altitude system. Aerocapture proposes swooping low into the atmosphere where density is high and therefore force large. This however requires significant heat shields. DRM 5.0 has mission scenarios that use aerocapture require aeroshells that are 20% to 40% of the total lander mass. [9] Because the plasma magnetoshell mitigates thermal issues as stated previously, additional weight can be saved. The plasma magnetoshell also maintains a cross-sectional area that is much larger in area than the physical cross-section of the spacecraft. This would allow for aerocapture maneuvers to be accomplished at lower densities and higher altitudes. This operating regime makes for safer operation in a more stable upper atmospheric environment [10].

B. Basic parameter scaling of the plasma magnetoshell

The primary drag-inducing interaction between the magnetically confined plasma ions 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. After a charge exchange, the now magnetized atmospheric ion reacts its directional momentum (again in the frame of the spacecraft) onto the magnet via field line bending and stretching. Elastic ion collisions with atmospheric neutrals accomplish the same thing as well but with some transport implications.

There are several parametric conditions that must be satisfied for the plasma magnetoshell to provide the desired aerobraking. First, the location in the planetary atmosphere must be at an altitude where the local atmospheric drag on the spacecraft is itself small. For most atmospheres (including our own) this occurs at an ambient neutral number density of $n_g \sim 10^{17} \text{ m}^{-3}$ or less. Secondly, the scale of the plasma magnetoshell at this density must be comparable to the mean free path for charge exchange. This sets the scale of the plasma magnetoshell at 10 m or larger assuming an ambient neutral density of 10^{17} m^{-3} or smaller. The third constraint relates to the minimum plasma magnetoshell magnetic field. To react the dynamic force onto the magnetic field, the charge exchanged atmospheric ions must stay magnetized long enough to be deflected by the local magnetic field (i.e. the charge exchange collision frequency must be less than the ion cyclotron frequency). Equivalently, the mean free path for charge exchange must be larger than the ion gyro-radius ρ_i of the charge-exchanged neutral. At 100 m this requires a local field $B \sim 1.3 \text{ } \mu\text{T}$ for upper atmospheric Oxygen at 0.1 eV (1,160 °K). A more restrictive condition arises from the charge exchanged planetary neutrals. These newly created ions will have an effective temperature determined by the directed energy of the original neutral due to the motion of the spacecraft through the relatively motionless neutral gas. As an example, consider the newly exchanged Oxygen ion for a spacecraft relative velocity of $v_s = 10 \text{ km/sec}$. The effective temperature of the now magnetically trapped ion would be 16 eV. For this Oxygen ion a magnetic field of 16 μT would be required to deflect and confine it within the plasma magnetoshell. It can be seen that a very small magnetic field is required to trap the charge exchange ions. It must also be remembered that the scale of the magnetic structure is 100 m. But even for a 100 m diameter sphere with an average magnetic field of 16 μT , the energy stored in the magnetic field is only $\sim 53 \text{ J}$.

It is therefore believed that these three constraints can be satisfied for the duration required for the plasma magnetoshell aerobraking over a wide range of atmospheres and conditions. The plasma source that was developed for the dipole experiments [3] can be utilized to generate the high β plasma. This can also be done with virtually any gaseous propellant in order to match the particular atmosphere of interest and obtain the maximum charge exchange interaction. The dipole magnetic field would be generated by a simple cabled current ring tethered appropriately to the spacecraft.

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. At low energies ($< 10 \text{ eV}$), the cross sections are large. Because the resonant charge transfer cross section is large, the particles are practically undeflected in the centre of mass (CM) system, leading after the charge transfer to an effective scattering angle for the ion in the CM system of 180° and a momentum transfer of $2 m_g v_s$ for every collision, where m_g is the mass of the charge exchange particle and v_s is the spacecraft velocity. The drag force on the spacecraft can thus be stated as :

$$F_d = 2m_g n_i v_s A_{pms} \quad (1)$$

where A_{pms} is the effective cross sectional area of the plasma magnetospheric shell. There is a minimum scale to assure that a passing neutral suffers at least one charge exchange or ion collision inside the plasma magnetoshell. The ion means free path is given by $\lambda_{sc} = 1/(n_g \sigma_{sc})$ where σ_{sc} it the total ion-neutral scattering cross section for both elastic and charge transfer collisions. For low energy collisions the scattering cross section $\sigma_{sc} \sim 10^{-18} \text{ m}^2$. At a

density of 10^{17} m^{-3} , $\lambda_{sc} = 10 \text{ m}$. Again for our spherical 100 m diameter plasma magnetoshell with the characteristic orbital speed of 10 km/s in an oxygen atmosphere, one has $F_d = 0.42 \text{ N}$.

It is clear from Eq. (1) that a wide range of drag forces can be obtained by varying the orbital altitude (λ_{sc}), the plasma production (n_i), and the scale of the plasma magnetoshell. It will be assumed that the momentum exchange would be maintained in the range of 0.01– 10 N so that little structural reinforcement would be required.

The basic elements of the plasma magnetoshell will be given in the next section C. An estimation of the magnet and plasma power requirements based on both theoretical and empirical confinement studies of the plasma magnetoshell will be presented in section D. It must be emphasized that although there are similarities, this is not the interaction envisioned in concepts for obtaining magnetospheric plasma propulsion from the solar wind [3,11,12]. In these concepts the primary interaction is between an external plasma “wind” and a magnetospheric object. This supersonic plasma exerts a direct compressional effect on the magnetosphere through electromagnetic forces and the interaction is quite complex. While drag could be obtained from the planetary ionosphere by the interaction of the ambient planetary plasma and the plasma magnetoshell, the effect would be significantly smaller as the peak ion density in ionospheres is typically orders of magnitude smaller than the neutral density found at the lower altitudes considered here. In addition, the ionospheres of Mars and other objects of interest are not well understood, and can exhibit large changes in intensity on unpredictable timescales. Since the plasma magnetoshell-atmospheric interface is governed by small-scale, energy conserving particle interactions that do not directly affect the plasma dipole equilibrium, the behaviour becomes much more predictable and controllable.

C. Basic elements of the plasma magnetoshell

As mentioned, the plasma magnetoshell shares a common heritage to the plasma magnetic sail concept [3]. The plasma magnet, unlike the original magnetic sail concept, has the currents necessary for the creation of the large scale dipole magnetic field conducted in a plasma rather than a superconducting coil. In this way the magnet mass is reduced by orders of magnitude for the same thrust power. This is still true for application of the plasma magnet for planetary aerodrag. Here however the plasma not only is necessary for carrying the magnetic currents, but also to provide the target ions for charge exchange and scattering with the atmosphere. A brief description and results from the plasma magnet concept study is useful to understand its role in the plasma magnetoshell concept.

The plasma magnet consists of a pair of polyphase coils that produce a rotating magnetic field (RMF) that drives the necessary currents in the plasma to inflate and maintain the large-scale magnetic structure. Details of the physics of this process can be found elsewhere [3] (see Fig. 1).

The plasma magnet is deployed by the Lorentz self-force on the plasma currents, expanding outward in a disk-like shape until an equilibrium with the steady dipole field produced by a much smaller wire loop. The current in the steady dipole is in the opposite direction to that produced in the plasma by the rotating

Two oscillating current Antennas phased at 90° to create a RMF

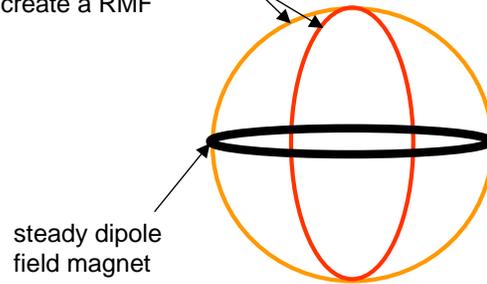


Figure 1. Coil set employed in generating a plasma magnet. The RMF antennas create a magnetic field that rotates about the axis of symmetry of the steady dipole magnet.

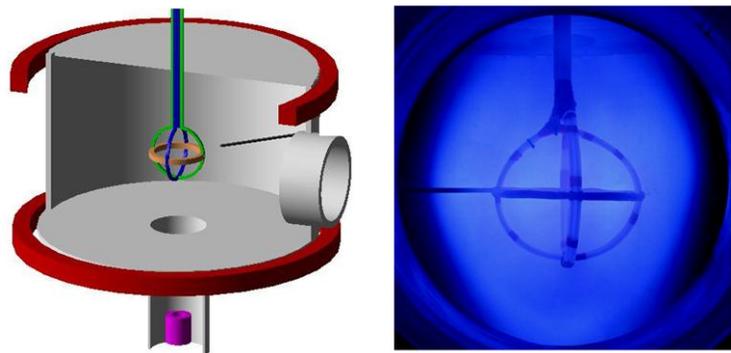


Figure 2. (Left) Schematic of plasma magnet experimental test chamber. (Right) Picture of Argon plasma magnet. Plasma magnet is compressed by an 8 mT axial magnetic field generated by a pair of Helmholtz coils placed external to the vacuum chamber (red coils on schematic).

magnetic field. The plasma currents thus act like a diamagnetic current creating a high beta plasma dipole equilibrium.

A small prototype plasma magnet was built and tested [3]. These experiments demonstrated the ability to drive sufficient current in the plasma magnet to have the resultant dipole field push out well beyond the 10 km scale. In addition it was demonstrated that a large force imparted on the plasma magnet was reacted back on the RMF antennas with no plasma detachment. A schematic of the chamber and pictures of the Argon plasma magnet are shown in Fig. 2. To keep the scale of the plasma magnet to the meter diameter of the chamber an external axial magnetic field was employed in these experiments. The magnetic field pressure was over six orders of magnitude larger than required for the plasma magnetoshell which will allow the same plasma magnet to expand to the kilometer scale desired for the plasma magnetoshell. The process of expansion is indicated in Fig. 3. The physics and scaling will now be considered.

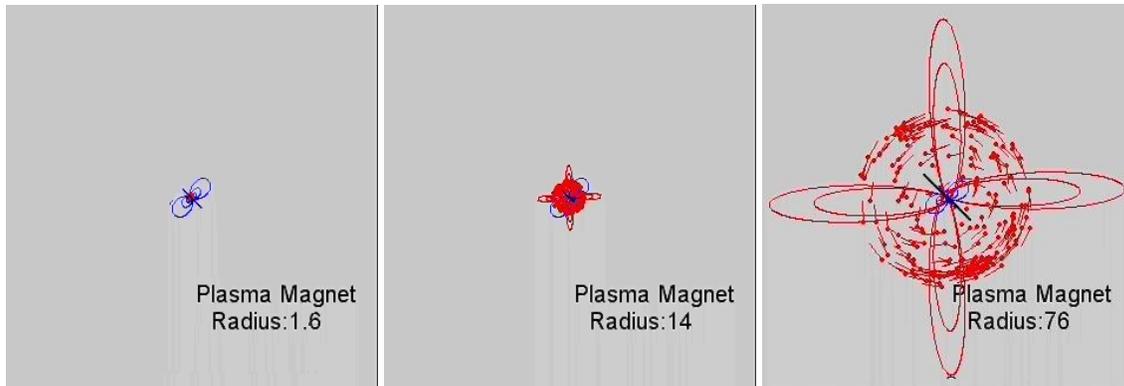


Figure 3. Illustration of the plasma magnet inflation. *The rotating dipole field (blue field lines) is seen in the first frame as the dominant field at small scale. As more plasma is created, the steady dipole field (red field lines) arises from the synchronous azimuthal flow of electrons (red dots). The rotating field is convected outward with the expanding current ring (second frame). The expansion continues with the dominant field now being the steady dipole field forming the magnetospheric object that ultimately comes into a dynamic balance with the stretched dipole field from the steady dipole coil at radius of 50 m or more.*

D. Physics and scaling of the plasma magnetoshell

The plasma magnet generates the large scale currents needed for a large-scale plasma magnetoshell by the entrainment of the plasma electrons in a rotating field created by two pair of loop antennae (see Fig. 1). With the loops 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. In analogy to the induction motor, this is the same as the field that is produced in a two pole stator winding. Normally a “squirrel cage” rotor would be inserted inside these coils and the currents induced in the rotor by the rotating field, together with the stator magnetic field, produce the torque that causes the rotor to come into synchronous rotation with the field. Consider the case now where the metal rotor is replaced with a plasma rotor. With nearly zero 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. 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 planetary 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) attached 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 will be

much larger than the initially meter size expanding dipole, little distortion of the dipole is expected until the plasma magnet has expanded large 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. Realistic equilibria for the magnetic dipole with large diamagnetic currents have been found and analyzed [2]. It was found that plasma pressure profiles $P(\psi)$ that fall off at least as slow as the adiabatic rate ($\sim \psi^{20/3}$), where ψ is the flux surface coordinate, were stable to both interchange and ballooning instabilities¹². This is significant in that a well-confined plasma is important for maintaining a low plasma resistance as an anomalous plasma resistivity increases the amount of power that must be delivered to drive the same current.

The modification to the dipole flux function $\psi (= \sin(\theta)^2/r$ 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 surface near the RMF antenna. As the current is increased, the flux function is considerably modified from the vacuum case as can be seen in Fig. 4. The flux surfaces become more disk-like as the plasma expands. This is primarily due to the lower magnetic field of the dipole near the equatorial plane. As the plasma current (pressure) is raised, the dipole field is distorted into a shape that enhances the curvature force at the point of lowest field pressure (i.e. the equatorial region). In the limit of $\beta \rightarrow \infty$ (the plasma pressure 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 and deploy the flux over a much larger region (with equatorial area A_{pms}).

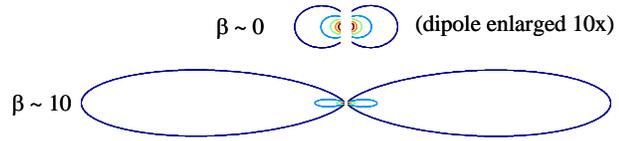


Figure 4. High β dipole equilibrium. Flux lines in R-Z plane for analytic equilibrium solution for a point dipole configuration at high β .

The initial dipole flux $\phi_0 = B_0 A_0$ must equal BA at any point later. One has then that $B \propto 1/A \sim 1/r^2$. In order to have an average magnetic field of 16 μT at a radius of 50 m one would require a flux $\phi \sim 0.13$ Wb. From Faraday's law this flux can be stated in terms of the coil inductance L_c with N turns each carrying a current i :

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$$N\phi = L_c i \Rightarrow \phi = \frac{L_c}{N^2} I \cong 4 \times 10^{-6} R_0 I. \quad (3)$$

where R_0 is the coil radius, $I (= Ni)$ is the total loop current and the approximation for a short coil (length/diameter ~ 0.1) was employed for L_c . Assuming a coil radius of 2 m, a total loop current $I = 15.7$ kA-turns is required. For an aluminum coil the Ohmic losses would be roughly 500 W. With more power available to operate the coil the coil can be made smaller and operate at higher field.

The plasma is initially created and ohmically heated by the driven RMF currents. Ohmic electron heating should only help to lower the plasma resistance reducing the power required to sustain a large plasma magnetoshell. The RMF current is driven in an inherently steady manner, which allows for the expansion and sustainment of the configuration. With the electrons magnetized to the RMF, the RMF is convected along with the dipole field as it expands, but the RMF will fall off as $1/r^2$ since there is no more rotating flux than that produced by the antennas. This will limit the current drive to the inner dipole area which is where all the current must flow anyway to support the high plasma beta ($\beta \sim 1$). The power requirements for the RMF system will be much smaller as the RMF field energy is over an order of magnitude smaller than the magnetic field energy created by the RMF driven plasma currents.

The confinement of the plasma in the plasma magnet dipole field can be expressed as:

$$\tau_N = \frac{\int \mathbf{n} \cdot d\text{vol}}{4\pi r^2 D_\perp \frac{dn}{dr}} = \frac{2\mu_0}{3\eta_\perp \beta} \ln\left(\frac{r}{R}\right) r^2 \quad (4)$$

where it has been assumed that the plasma density decreases as $1/r^3$. With this assumption, the total plasma inventory N can be calculated with $N_i \sim 4\pi R_0^3 n_0 \ln(r/R_0)$. One assumes a plasma temperature of $T_e = T_i = 16$ eV. This is consistent with past experiments with RMF as well as the “heating” that will occur due to the capture through charge transfer of the planetary neutrals. The plasma resistivity η will thus be $\sim 1.6 \times 10^{-5}$. For an RMF antenna with $R = R_0 = 2$ m there will be sufficient current (i.e. a particle density $n_{i0} \sim 10^{17} \text{ m}^{-3}$) to expand to $r = 50$ m [3]. From Eq. (4) one has $\tau_N = 422$ s which is roughly comparable to the time spent during drag at apogee. The total plasma mass required to refill the plasma magnetoshell for each pass is $m_g \cdot N_i = 4.0$ mg for Oxygen. Clearly refueling should not be a major concern for any working gas. The actual confinement of the plasma in the plasma magnetoshell in the presence of a background atmosphere is a quantity that, most likely, will be determined empirically. It should be noted that neither charge transfer nor elastic collisions of like species should influence the ion transport.

In any case, once the expansion is complete, confining the plasma in a large scale plasma magnetoshell 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 good enough, or the entrainment of the planetary neutrals through ionization by the plasma magnetoshell electrons is sufficient to match losses, the 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 plasma magnetoshell. 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 from 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 RMF power, P_{RMF} , needed to sustain the plasma magnetoshell in this configuration is given by:

$$P_{\text{RMF}} = \int \eta j_0^2 \cdot d\text{Vol} \quad (5)$$

where j_0 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_0 :

$$j_0 = \frac{1}{\mu_0} \frac{dB}{dr} = \frac{-2B_0}{\mu_0} \frac{R_0^2}{r^3} \quad (6)$$

where B_0 is the magnitude of the magnetic field at the center of the dipole coil. Substituting Eq. (5) into Eq. (6) and integrating one has:

$$P_{\text{RMF}} = \frac{4\eta}{\mu_0^2} B_0^2 R_0^4 \int_{R_0}^{r \gg R_0} \frac{4\pi}{r^4} dr = \frac{16\pi\eta}{3\mu_0^2} B_0^2 R_0 \quad (7)$$

For the coil parameters stated above to achieve the requisite flux ($R_0 = 2$ m, $I_c = 15.7$ kA) one has $B_0 = 5$ mT. For the plasma parameters stated above for the plasma confinement, one has $P_{\text{RMF}} = 6.3$ kW. The RMF power required drops rapidly with the coil/antenna size ($P_{\text{RMF}} \sim R_0^{-3}$) as well as from atmospheric heating which has been neglected here though it is likely to be the dominant effect in maintaining the plasma magnetoshell from decay.

III. Conclusion and Discussion

Aerobraking with a plasma magnetoshell represents a unique approach to aerobraking and aerocapture. The deployment of a magnetic field filled with a high β plasma provides the necessary impediment to the atmospheric flow past the spacecraft and thereby produces the desired drag for braking. The advantages of such a system are many. Frictional heating would clearly no longer be of concern. The energy dissipation required to slow the spacecraft is effectively deposited into the plasma ions through charge exchange and elastic scattering off the planetary background gas. This lowers the need for plasma heating to maintain the high plasma β essential for maintaining a large dipolar magnetic configuration, the transverse scale of which can be as large as 100 meters but contain no more than a few milligrams of plasma. The plasma confinement at this scale is sufficient to last for the

time spent in the higher density regions where significant drag can be obtained. The plasma magnetoshell also acts to shield the spacecraft from frictional heating.

The drag force scales strongly with the plasma magnetoshell size and plasma density. The power consumption scales inversely with the size of the dipole coil radius, so that it is paramount to obtain the plasma expansion with minimal dissipation. Ultimately the only way to know how well the concept will work is to construct such a device at smaller scale and test in as large a vacuum system as possible. A scaling study with a dipole coil of 0.2 meters expanding to 2 meters with exposure to the appropriate high velocity neutral density flow would be a first step. A possible source would be an array of arcjets or a large MPD-type device similar to the that used in the plasma magnet studies [3]. Success here with the observance of a favorable scaling would then justify a full scale test in LEO.

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