Performance Scaling and Mission Applications of Drag-Modulated Plasma Aerocapture

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Plasma aerocapture is an orbit insertion maneuver using the drag of an atmosphere on a magnetized plasma, or “magnetoshell,” to transfer a spacecraft from a hyperbolic to elliptic trajectory around a planet. Stored energy and electromagnetic forces entrain and deflect flow to produce drag. A global model of the interaction between hypersonic flow and a dipole plasma is developed and the exchange of mass, energy, and momentum is analyzed. The strength of the interaction is found to depend heavily on the spacecraft velocity. A critical-ionization-like effect is observed that implies a minimum threshold velocity in order for the magnetoshell to utilize the flow for plasma sustainment and drag. The implications of this threshold velocity for mission applications at Venus, Mars, Saturn, and Neptune are discussed with some limiting approximations. Performance scaling indicates the viability of plasma aerocapture at Saturn and Neptune, and by inference, Jupiter and Uranus. At Mars and Titan, the low orbit insertion velocities pose challenges to using magnetoshells due to the threshold physics observed. The flight envelope at Venus appears to support use of a magnetoshell, but further development of the plasma model to simulate molecular species must be done before feasibility can be assessed.

I. Introduction

Aerocapture is an orbit insertion maneuver that uses drag of a planetary atmosphere on a spacecraft to slow it from a hyperbolic trajectory to a closed elliptic orbit. Hall et al. have shown that aerocapture can offer significant cost reduction and increase in delivered mass to all eight solar system destinations with tangible atmospheres. They also identify the maneuver as an enabling technology for missions of interest at Jupiter, Saturn, and Neptune. Several relatively mature aerocapture technologies are being developed, such as the Hypersonic Inflatable Aerodynamic Decelerator (HIAD), the Adaptive Deployable Placement Technology (ADEPT), and ballutes, yet none has ever been used on a mission because of the associated risks. These aeroshell devices rely on structures to deflect atmospheric flow and are therefore susceptible to the high heat and dynamic pressure inherent to reentry conditions. Atmospheric entry at the gas and ice giants occurs at velocities in excess of 20 km/s; a recent study showed these extreme environments require advancements in thermal protection technology to implement aerocapture at Uranus and Neptune, while Jupiter and Saturn are not feasible destinations for aeroshells in the near term.

Plasma aerocapture is an alternative approach that proposes to generate drag through interaction of the atmosphere with a magnetized plasma. Instead of a rigid aeroshell, it uses a “magnetoshell” consisting of a magnetic field that confines the plasma (Fig. 1). The device may be either fixed to the spacecraft or towed behind it in a parachute-like configuration. Drag is produced when an atmospheric neutral becomes an ion through charge exchange (CX) or electron-impact ionization. The new ion imparts momentum on the spacecraft when it is either magnetically deflected or confined in the plasma. Though each individual particle produces a minuscule force, the production of new ions from the flow is so widespread that significant macroscopic drag can occur.

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There are numerous proposed advantages to plasma aerocapture over aeroshells. The magnetic field introduces the ability to continuously modulate the drag force.\textsuperscript{8,9} Continuously-variable drag modulation is shown to result in significant improvements to post-maneuver orbit targeting over unmodulated aerocapture or even one- and two-stage drag skirt jettison systems.\textsuperscript{10} Another advantage is that the plasma interaction with the flow reaches far beyond the physical extent of the magnet, so the effective drag surface can be much larger than mechanically-limited aeroshells.\textsuperscript{7,9} This enables aerocapture at higher altitudes where heat and structural loads on the spacecraft are reduced. The atmospheric flow and energy contribute overwhelmingly to sustaining the plasma discharge, making this an in-situ resource utilization (ISRU) technology. The magnetized plasma can then act as a sort of thermal protection since it absorbs and utilizes the flow heat.

Although there are clear advantages to plasma aerocapture over other approaches, its physics and performance are still not well characterized. Ground testing this large-scale device in a low density, high velocity flow that simulates atmospheric entry is not possible in existing wind tunnels. Therefore, novel experimental techniques and simulation approaches must be developed to assess the feasibility of this technology. A prior analytic model\textsuperscript{9} indicated good system performance for DRA5 cargo delivery at Mars\textsuperscript{11} and a Neptune orbiter.\textsuperscript{12} However, performance prediction relied on a phenomenological model based on single-particle processes rather than the global, coupled interaction of plasma and flow. Also, drag was modeled by approximating a solid body, though more recent work has shown the plasma allows some flow to pass through it,\textsuperscript{8} highlighting the need for a higher fidelity drag model.

In this paper, we develop an analytic model of the hypersonic flow/plasma interaction and use it to investigate the performance characteristics of magnetoshells and their applicability to deep space missions. This model uses a control volume to analyze the global exchange of mass, energy, and momentum between the magnetoshell and an atmosphere during aerocapture. A brief derivation of this model is presented in Section II. In Section III, we run simulations across a broad range of inputs describing spacecraft and atmospheric parameters and use the results to derive scaling laws for drag, plasma behavior, and other performance metrics. Section IV analyzes these results and the unique physics of the flow interaction in the context of various interplanetary missions to assess the viability of plasma aerocapture. A brief summary and discussion is provided in Section V.
II. Global Plasma Model

The model is built from conservation equations that describe the exchange of mass and energy among the plasma and flow. The equations are normalized and averaged over a control volume which eases computational load and therefore enables a broad parameter study from which we can identify physical scaling laws. Ions, electrons, and secondary neutrals (those resulting from charge exchange with the stream) are tracked directly using a three-fluid model. The control volume is derived from an analysis of ion trajectories in the dipole field and the model equations are integrated over this volume to track total populations and energies.

A more detailed derivation of this model was previously described.\(^8\) Here we present an abbreviated derivation, including some changes to the specific form of some terms.

A. Three-Fluid Model

The prevailing physics of the plasma/flow interaction must be determined in order to develop the global model equations. Because this is a control volume analysis, we start from basic conservation equations which allow us to account for all possible internal sources/sinks as well as flows across the boundary surface. The fluid model treats ions (subscript \(i\)), electrons (\(e\)), and secondary neutrals (\(2n\)) separately. Conservation of mass and energy for each species \(\alpha\) is described by

\[
\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha u_\alpha) = \sum \frac{\partial n_\alpha}{\partial t} \tag{1}
\]

\[
\frac{\partial \varepsilon_\alpha}{\partial t} + \nabla \cdot (\varepsilon_\alpha u_\alpha) = \sum \frac{\partial \varepsilon_\alpha}{\partial t} \tag{2}
\]

where \(n_\alpha\) is the number density, \(\varepsilon_\alpha\) is the energy density, \(u_\alpha\) is the fluid velocity, and \(\frac{\partial}{\partial t}\) is the partial derivative with respect to time. Stream neutrals (\(sn\)) are not included in the fluid model. However, their energy is kinetic only (i.e. does not depend on the tracked species) and their density \(n_{sn}\) can be computed from the tracked species populations. We assume quasineutrality and singly-charged ions so that \(n_i = n_e\), reducing the system to two continuity equations and three energy equations. In the regimes of interest for magnetoshells, the plasma is low-beta, so the density profile strongly follows the magnetic field,

\[
n_i = n_{i,0} \hat{B}\tag{3}
\]

where \(n_{i,0}\) represents the density at the center of the magnet and \(\hat{B}\) is the magnetic field profile normalized to unity at the magnet center.

B. Control Volume

The conservation equations of the three-fluid model apply to a closed volume which must be defined. The control volume (CV) representing the dipole plasma describes the spatial extent to which post-charge-exchange ions are trapped by the magnetic field. In other words, the CV is enclosed by a boundary inside which an ion with initial velocity \(u_\infty\) is confined. Previous analysis of ion trajectories\(^8\) revealed a toroidal volume defined by a constant surface of magnetic flux,

\[
\psi^* = \sqrt{2} \rho_L \tag{4}
\]

where \(\psi^*\) is the magnetic flux value along the boundary contour and

\[
\rho_L = \frac{m_i u_\infty}{qB_0 r_c} \tag{5}
\]

is the ion Larmor radius normalized by magnet coil radius \(r_c\) for ion mass \(m_i\), stream velocity \(u_\infty\), center-field strength \(B_0\), and elementary charge \(q\). Figure 2 shows the azimuthal cross-section of the toroidal CV boundary surface, \(S^*\). The cross-sectional area of this toroid as seen by the flow (moving along positive \(\hat{z}\)) is \(\hat{A}\). The volume of the toroid is \(\hat{V}\).
C. Normalization

The model described in Section II.A will be simulated for a wide range of flow and plasma conditions. Therefore, it is desirable to normalize the model so that physical scaling laws can be readily identified using dimensionless parameters. Length $x$ is normalized by coil radius, $\hat{x} = x/r_c$. Time $t$ is normalized by the transit time of a stream particle traveling with velocity $u_\infty$ across the coil, $\tau = tu_\infty/r_c$. Species number density $n_\alpha$ is normalized by the stream density, $\hat{n}_\alpha = n_\alpha/n_\infty$. Fluid velocity $u_\alpha$ is normalized by the stream velocity, $\hat{u}_\alpha = u_\alpha/u_\infty$. Species energy density $\varepsilon_\alpha$ is normalized by the stream energy density, $\hat{\varepsilon}_\alpha = \varepsilon_\alpha/\varepsilon_\infty$, where $\varepsilon_\infty = \frac{1}{2}m_sn_\infty u_\infty^2$ assumes the thermal energy of the stream is negligible. Species temperature $T_\alpha$ is normalized by stream effective temperature, $\hat{T}_\alpha = T_\alpha/T_\infty$, where $T_\infty = \frac{2}{3}\varepsilon_\infty/n_\infty$. Magnetic field $B$ is normalized by the center-coil field strength, $\hat{B} = B/B_0$.

D. Global Model Equations

We may now adapt the three-fluid model of Section A to describe the magnetoshell. We do this by normalizing all terms and integrating them over the control volume. After this process, the total population of a species is defined as

$$\hat{N}_\alpha = \int_{\hat{V}} \hat{n}_\alpha \, d\hat{V}$$

From our low-beta plasma assumption, $\hat{n}_\alpha = \hat{n}_{\alpha,0}\hat{B}$. Thus the center-coil density can be defined as $\hat{n}_{\alpha,0} = \hat{N}_\alpha/I_B$, where

$$I_B = \int_{\hat{V}} \hat{B} \, d\hat{V}$$

Similarly, the total energy in the CV is defined as

$$\hat{E}_\alpha = \int_{\hat{V}} \hat{\varepsilon}_\alpha \, d\hat{V} = \frac{2/3}{\gamma - 1} \hat{N}_\alpha \hat{T}_\alpha$$

based on Meier’s\textsuperscript{13} definition of $\hat{\varepsilon}_\alpha$.

This system consists of five nonlinear ordinary differential equations that solve for the five unknowns $\hat{N}_i$, $\hat{N}_{2n}$, $\hat{T}_i$, $\hat{T}_e$, and $\hat{T}_{2n}$. The equations are ion/electron continuity, secondary neutral continuity, ion energy, electron energy, and secondary neutral energy. Note that the following equations have been modified slightly from the previous work.\textsuperscript{8}
ION/ELECTRON CONTINUITY EQUATION  The following contributions are included in the continuity equation for ions and electrons, listed in alphabetical order of the subscripts used to describe them:

- **diff**: ion/electron diffusion
- **inj**: plasma injection from the spacecraft
- **iz,2n**: ionization of secondary neutrals
- **iz,sn**: ionization of stream neutrals

Note that charge exchange makes no net contribution to the ion population since it simultaneously produces and removes an ion. The full form of the ion/electron continuity equation is

$$\frac{d\hat{N}_i}{dT} = -\left( \hat{D}_B \hat{T}_e + \hat{D}_c (\hat{T}_e + \hat{T}_i) \right) \hat{N}_i \frac{I_{diff}}{I_B} + \hat{N}_{inj} + \zeta_{iz,2n} \hat{N}_e \hat{N}_{2n} \frac{I_{B^2}}{(I_B)^2} + \zeta_{iz,sn} \hat{N}_e \hat{I}_{sn} \left( I_B \right)^2 \tag{9}$$

where \( \hat{D}_B \) and \( \hat{D}_c \) are normalized forms of the Bohm and electron-collisional diffusion coefficients, \( \hat{N}_{inj} \) is the rate of plasma injection from the spacecraft, \( \zeta_{reac} \) is a dimensionless reaction rate, and the various \( I \) are volume and surface integrals arising from the derivation. All these terms are defined in the Appendix.

SECONDARY NEUTRAL CONTINUITY EQUATION  The following contributions are included in the continuity equation for secondary neutrals, listed in alphabetical order of the subscripts used to describe them:

- **cx,sn**: charge exchange between stream neutrals and ions
- **diff**: neutral diffusion
- **iz,2n**: ionization of secondary neutrals

Charge exchange contributes to the secondary neutral population when an ion loses its charge to a stream neutral. The full form of the secondary neutral continuity equation is

$$\frac{d\hat{N}_{2n}}{dT} = \zeta_{cx,sn} \hat{N}_i \frac{I_{sn}}{I_B} - \hat{D}_{2n} \sqrt{T_{2n}} \hat{N}_{2n} \frac{I_{B^2}}{(I_B)^2} - \zeta_{iz,2n} \hat{N}_e \hat{N}_{2n} \left( I_B \right)^2 \tag{10}$$

where \( \hat{D}_{2n} \) is a nondimensional form of the secondary neutral diffusion coefficient, defined in the Appendix.

ION ENERGY EQUATION  The following sources and sinks are included in the equation of state for ions, listed in alphabetical order of the subscripts used to describe them:

- **cx,2n**: charge exchange between secondary neutrals and ions
- **cx,sn**: charge exchange between stream neutrals and ions
- **diff**: ion diffusion
- **inj**: plasma injection from the spacecraft
- **iz,2n**: ionization of secondary neutrals
- **iz,sn**: ionization of stream neutrals
- **th,ie**: thermalization between ions and electrons
Thermalization is modeled according to Braginskii’s transport equations. The full form of the ion energy equation is

\[ \frac{2/3}{\gamma - 1} \left( \frac{d\hat{N}_i}{d\tau} \hat{T}_i + \hat{N}_i \frac{d\hat{T}_i}{d\tau} \right) = \frac{3}{2} \frac{Z_{\text{cx,2n}}}{I_B^2} (\hat{Q}_{\text{e,2n}} - \hat{Q}_{\text{2n,i}}) \hat{N}_i \hat{N}_2n \frac{I_B^2}{(I_B)^2} + \frac{M_{i/sn}}{I_B} \left( \hat{\zeta}_{\text{cx,sn}} - \hat{Z}_{\text{cx,sn}} \hat{Q}_{\text{sn,i}} \right) \hat{N}_i \hat{I}_sn \frac{I_B}{I_B} \]

\[ + \frac{2M_{e/i}}{\tau_e} \hat{N}_e (\hat{T}_e - \hat{T}_i) - \frac{2/3}{\gamma - 1} \left( \hat{D}_B \hat{T}_e + \hat{D}_e (\hat{T}_e + \hat{T}_i) \right) \hat{N}_i \hat{T}_i \frac{I_B^2}{(I_B)^2} + \frac{\hat{P}_{i,inj} + \hat{\zeta}_{\text{iz,2n}} \hat{N}_e \hat{N}_2n \hat{T}_2n \frac{I_B^2}{(I_B)^2}}{\hat{I}_sn} \]

\[ + \frac{M_{i/sn} \hat{\zeta}_{\text{iz,sn}} \hat{N}_e}{I_B} \frac{I_B}{I_B} \]

where \( Z_{\text{react}} \) is a dimensionless rate parameter, \( M_{\alpha/\beta} \) is the ratio of two species masses, \( \tau_e \) is Braginskii’s electron collision time, \( \hat{P}_{i,inj} \) is the rate of plasma energy injected from the spacecraft, and \( \hat{Q}_{\alpha,\beta} \) is a normalized form of the heat transfer term given by Meier. All are defined in the Appendix.

**Electron Energy Equation** The following contributions are included in the equation of state for electrons, listed in alphabetical order of the subscripts used to describe them:

- **diff**: electron diffusion
- **inj**: spacecraft plasma injection
- **iz,2n**: ionization of secondary neutrals
- **iz,sn**: ionization of stream neutrals
- **th,ie**: thermalization between ions and electrons

Thermalization is modeled as in the ion energy equation. Ionizations of secondary and stream neutrals are derived from Meier and Shumlak. The full form of the electron energy equation is

\[ \frac{2/3}{\gamma - 1} \left( \frac{d\hat{N}_e}{d\tau} \hat{T}_e + \hat{N}_e \frac{d\hat{T}_e}{d\tau} \right) = - \frac{2/3}{\gamma - 1} \left( \hat{D}_B \hat{T}_e + \hat{D}_e (\hat{T}_e + \hat{T}_i) \right) \hat{N}_e \hat{T}_i \frac{I_B^2}{(I_B)^2} + \frac{M_{e/2n} \hat{T}_{2n} - \frac{2}{3} \hat{\phi}_{\text{iz,2n}}}{I_B} \]

\[ + \left( M_{e/sn} - \frac{2}{3} \hat{\phi}_{\text{iz,sn}} \right) \hat{\zeta}_{\text{iz,sn}} \hat{N}_e \frac{I_B^2}{(I_B)^2} + \frac{2M_{e/i}}{\tau_e} \hat{\phi}_{\text{iz,sn}} \hat{T}_i + \hat{P}_{e,inj} \]

where \( \hat{\phi}_{\text{iz,\alpha}} \) is the ionization cost, defined in the Appendix.

**Secondary Neutral Energy Equation** The following contributions are included in the equation of state for secondary neutrals, listed in alphabetical order of the subscripts used to describe them:

- **cx,2n**: charge exchange between secondary neutrals and ions
- **cx,sn**: charge exchange between stream neutrals and ions
- **diff**: diffusion of secondary neutrals
- **iz,2n**: ionization of secondary neutrals
The charge exchange and ionization terms are derived from Meier and Shumlak. The full form of the secondary neutral energy equation is

\[
\frac{2/3}{\gamma - 1} \left( \frac{dN_{2n}}{dt} + \dot{N}_{2n} \right) = \frac{3}{2} \left( Q_{2n, i} - Q_{i, 2n} \right) \dot{N}_{2n} \frac{I_B^2}{(I)^2} + M_{sn} Z_{cx, sn} \dot{Q}_{sn, i} \dot{N}_{i} \frac{I_{sn}}{I_B} \]

\[
- \frac{2/3}{\gamma - 1} D_{2n} T_{2n}^{3/2} \dot{N}_{2n} I_{\text{diff}} - \zeta_{ix, 2n} \dot{N}_{ix} \dot{N}_{ix} \left( \frac{I_B^2}{(I)^2} \right) \]

(13)

See the Appendix for definition of terms.

III. Magnetoshell Performance Scaling

The plasma/flow interaction is simulated by solving Eqs. (9)–(13) and evolving them until they reach steady state. The time-resolved numerical solutions of \( \dot{N}_i, \dot{N}_{2n}, T_i, T_e, \) and \( \dot{T}_{2n} \) are obtained which can be manipulated to reveal underlying trends in the physics of the interaction. The derivation of the model does not depend on species, however it is implicit that the plasma and stream species are the same, as more than five conservation equations would be required to track any additional particles or reaction products. Furthermore, like species exhibit resonant charge exchange which greatly enhances the plasma/flow interaction.

For this section we limit our analysis to argon because it only has Ar and Ar\(^+\) as reaction products, there is a wealth of available empirical reaction data, and its mass (40 amu) is similar to atmospheric species of interest for plasma aerocapture, such as CO\(_2\) (44 amu) or N\(_2\) (28 amu). Table 1 summarizes the data used to implement the model with Argon.

<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma = 5/3 )</td>
<td>Assumed</td>
</tr>
<tr>
<td>( \sigma_{Q_m} = 1.57 \times 10^{-18} \text{ m}^2 )</td>
<td>Phelps(^{15} )</td>
</tr>
<tr>
<td>( R_{cx} = f(T_i, u_\infty) )</td>
<td>Phelps,(^{15} ) Meier(^{13} )</td>
</tr>
<tr>
<td>( \sigma_{gk} = 5 \times 10^{-19} \text{ m}^2 )</td>
<td>Lieberman(^{16} ) (via Smirnov(^{17} ))</td>
</tr>
<tr>
<td>( \nu_{ei} = f(T_e, n_i) )</td>
<td>Goldston(^{18} )</td>
</tr>
<tr>
<td>( \nu_{en} = f(T_e, n_{2n}) )</td>
<td>Itikawa(^{19} ) and Harstad(^{20} )</td>
</tr>
<tr>
<td>( R_{iz} = f(T_e) )</td>
<td>Lieberman(^{16} )</td>
</tr>
<tr>
<td>( \phi_{iz} = f(T_e) )</td>
<td>Lieberman(^{16} )</td>
</tr>
<tr>
<td>( T_{i, inj} &lt; T_{r, inj} = 10 \text{ eV} )</td>
<td>Assumed</td>
</tr>
</tbody>
</table>

A. Plasma Behavior

After initializing the simulation, the plasma quickly evolves to steady state. Figure 3 shows spatially how the flow and plasma densities reach equilibrium for a single simulation with conditions of \( n_\infty = 10^{17} \text{ m}^{-3} \), \( u_\infty = 12 \text{ km/s}, B_0 = 0.5 \text{ T}, r_\infty = 1 \text{ m}, \) and \( \dot{m}_{\text{inj}} = 0.5 \text{ mg/s} \) (these conditions will hereafter be referred to as the nominal conditions). At the nominal conditions, \( \tau = 1.2 \times 10^4 \) is one second. The plasma density \( \dot{n}_i = \dot{n}_{i, 0} B \) is computed from the relation \( \dot{n}_{i, 0} = \dot{N}_i / I_B \). The stream density profile \( \dot{n}_{sn} \) is computed by integrating 1D continuity with stream ionization and CX reactions along chords in \( \tilde{z} \),

\[
\dot{n}_{sn} = \exp \left[ -\zeta_{\text{tot}} \int_{-\infty}^{\tilde{z}} \tilde{B} d\tilde{z} \right] \]

(14)

where \( \zeta_{\text{tot}} \) is defined in the Appendix and represents the total rate of conversion from stream to plasma through CX and ionization. By \( \tau = 5 \times 10^3 \), there is a some conversion of stream neutrals to plasma.
Figure 3. Spatial distribution of the plasma and stream densities as the system evolves to steady state. Simulations conditions are $n_\infty = 10^{17} \text{ m}^{-3}, u_\infty = 12 \text{ km/s}, B_0 = 0.5 \text{ T}, r_c = 1 \text{ m},$ and $\dot{m}_{\text{inj}} = 0.5 \text{ mg/s}.$

Most of the flow is unimpeded and only a column near the magnet has lost a small fraction of neutrals. The plasma population increases, concentrated around the magnet where $\vec{B}$ is strongest, and the stream is impeded mostly in the vicinity of the coil at $\tau = 10^4$. By this time no flow is able to penetrate past the central plasma region, but the far-field is still unaffected. The plasma continues to absorb flow particles and reaches steady state by $\tau = 1.8 \times 10^4$. It is now orders of magnitude denser than the flow and neutrals are converted to ions even far outside the control volume. The magnetoshell produces a fairly large wake as most neutrals are unable to pass through unimpeded.

The nature of the equilibrium reached by the plasma depends on the flow velocity. We observe in Figure 4 that there are three distinct physical regimes of plasma/flow interaction characterized by large jumps in $\zeta_{\text{tot}} / A \equiv \Gamma$. These data are derived from the steady-state outputs of several simulations with different input conditions. $\Gamma$ is akin to a flux density describing the rate at which the plasma ionizes and captures the stream. In other words, it represents the strength of the coupling between flow and plasma, making it a useful single measure of magnetoshell operation. At low velocities, the only energy deposited into the plasma comes from injected power, as the kinetic energy of flow neutrals is too low to add any energy to the ion population. As the velocity increases, the magnetoshell reaches a sharp transition to the “CX regime” in which charge exchange becomes a significant power source for the plasma. The energetic flow is converted to ions, effectively heating the ion population. Nearly all this energy goes into the electrons through Coulomb collisions, heating them enough to ionize the secondary neutrals produced by CX. In this sense, charge exchange acts as the primary source of plasma sustainment by supplying neutrals for ionization and the energy to ionize them. This is part of a critical ionization feedback loop; stream CX adds energy to the electrons which enhances their ionization of secondary neutrals, which increases the plasma density, which in turn increases the rate of charge exchange. At even higher velocities, we observe a more classical form of the critical ionization effect (CIV regime). The same feedback mechanism drives plasma sustainment but the ion energy is supplied by direct ionization of the flow rather than CX. This results in a higher flow utilization ($\Gamma$) than the CX regime because the energy and particle losses associated with secondary neutrals diffusion are reduced.

Figure 4 is highly relevant to plasma aerocapture mission design since $u_\infty$ is equivalent to the spacecraft velocity. The injection regime is impractical for magnetoshell operation; the drag forces involved would entail unreasonable system requirements on the onboard plasma injector propellant and power. Thus, the CX regime transition defines the minimum entry speed for a magnetoshell to be used in an aerocapture maneuver. This will be discussed further in Section IV. For now, we stress that plasma aerocapture must utilize the CX and CIV regimes of magnetoshell operation. This conclusion imposes a limit not seen in previous, phenomenological modeling. Although this earlier work examined mission applications, these new revelations from our self-consistent model fundamentally change the plasma aerocapture design space. We...
will now investigate the effect of these physics on the drag-producing mechanism of magnetoshells to better inform such mission design.

B. Magnetoshell Drag

Figure 3 highlights an important characteristic of magnetoshells that distinguishes them from aeroshells: they can affect the flow far from the physical structure of the device. We can see the defined control volume does not strictly block the flow, so it is difficult to describe drag in terms of a cross-sectional area. However, we also see some atmosphere is ionized out to a diameter of over 20 m for the 2 m-diameter magnet depicted in Figure 3. Ions will be deflected by the magnetic field even at these large distances which transfers momentum to the spacecraft. Ions trapped in the CV similarly slow the spacecraft.

We represent magnetoshell drag as the rate of momentum transfer from flow undergoing CX and ionization to the magnet, normalized by the characteristic drag of a magnet-sized aeroshell under the same flow conditions:

$$
\dot{F}_D = \int \frac{1}{2} m_{sn} n_{sn} \Delta u_z u_\infty^2 \pi r_c^2
$$

where $\dot{n}_{sn}$ is the volumetric rate of ion production from the flow and $\Delta u_z$ is the axial deceleration of an ion by the magnetic field (e.g., an ion trapped inside the CV or deflected by 90° has $\Delta u_z = u_\infty$; an ion that is reflected 180° has $\Delta u_z = 2u_\infty$). By definition, $\dot{F}_D$ is equivalent to the drag coefficient $C_D$ of an aeroshell with area $\pi r_c^2$. Figure 5 demonstrates how the magnetic field produces a drag force by showing the “force density” represented by the integrand of Eq. 15. The drag resulting from magnetic deflection and trapping is produced primarily in front of the magnet, with relatively little occurring inside the control volume. Figure 5 also highlights the intuitive scaling we expect: drag increases as the plasma gets denser ($\zeta_{tot}$); it also increases with magnetic field strength and magnet size ($p_L$).

After normalization and applying the plasma assumptions detailed in Section II we may compute the drag given by Eq. 15. Figure 6 shows how the drag force depends on magnetic field strength for a variety of simulations. This supports our earlier assertion that plasma aerocapture maneuvers must utilize the enhanced physical regimes; the transition to CX regime manifests as a large jump in drag. Before the CX regime, the flow interaction is weak ($C_D A \leq \pi r_c^2$). Operating in the CX regime yields significant improvement in the momentum transferred from flow to magnet.

Figure 6 reveals another important characteristic of magnetoshells. Since magnetic field strength is controlled by an electrical current, continuously-variable drag modulation is possible. Drag modulation aerocapture efficacy is highly dependent on the range of spacecraft $\beta$ where

$$
\beta = \frac{m}{C_D A}
$$

Figure 4. The flow utilization, $\hat{\Gamma} \equiv \zeta_{tot}/\hat{A}$, reveals three distinct physical regimes depending on velocity. The fixed conditions are $n_\infty = 10^{17}$ m$^{-3}$, $B_0 = 0.5$ T, $r_c = 1$ m, and $\dot{m}_{inj} = 0.5$ mg/s.
for spacecraft mass $m$ and cross-sectional area $A$. Lower $\beta$ and a larger $\beta$ range are both shown to improve post-aerocapture orbit targeting accuracy. While currently proposed drag modulation systems aim to vary $A$ mechanically, plasma aerocapture magnetically modulates its effective $C_D (= \hat{F}_D)$ to produce a wide range of $\beta$. Figure 6 shows the spread of effective $C_D A$ for an Argon simulation at nominal conditions. While this drag modulation capability is promising in theory, generating a magnetic field of $10^3$–$10^4$ Gauss with a 2 m-diameter coil requires a heavy magnet. We must therefore examine whether such a system can be reasonably flown.
IV. Deep Space Mission Applications

Our global model has yielded important new results regarding the flight regime for plasma aerocapture. Specifically, the mode transition observed in flow utilization has a major impact on whether magnetoshells will generate significant drag. Using the velocity and density thresholds dictated by these physics, we conduct a preliminary analysis of plasma aerocapture feasibility for several possible destinations. The global plasma model is so far only built to simulate atomic, like species, whereas atmospheres of interest are composed of mainly CO$ _2$ (Mars, Venus), N$_2$ (Titan, Earth), or H$_2$ (Jupiter, Saturn, Uranus, Neptune). Therefore we make some simplifying approximations until more detailed plasma chemistry is incorporated in the model. The following discussion is not a comprehensive systems analysis but rather it is intended to provide a first-order estimate of the types of missions that may benefit from plasma aerocapture over aeroshells.

For all the planets discussed, we use the same baseline magnetoshell design. The design parameters are listed in Table 2. The system described assumes a magnetoshell is tethered to the spacecraft and contains the copper electromagnet, a battery bank to operate the magnet up to 1,000 seconds (longer than a typical aerocapture atmospheric flight time), and power processing electronics (PPU). The batteries store energy on board that will be rapidly discharged to drive the magnetic field, as solar arrays must be stowed during atmospheric flight and RTGs cannot supply the short-duration high power requirement. We assume the PPU specific mass is 6 kg/kW based on electric propulsion mass models. The magnet mass is estimated from the copper required to generate NI amp-turns (where $B_0 = \mu_0 NI/2r_c$) with a discharge current on par with that achieved by a Tesla electric car battery bank (which is comprised of NCR18650 Li-ion batteries, regularly used in spacecraft applications). We assume a mass growth factor of 1.5. Propellant mass is less than a gram and the hardware to inject an RF plasma in the magnetic field is negligibly light compared to the magnet.

The final estimated mass for this magnetoshell is 1,623 kg. Systems analyses for other aerocapture spacecraft estimate the mass fraction of the aeroshell between 25–50% of the total spacecraft mass. Thus, a magnetoshell of this design is suitable for a Cassini- or Juno-size orbiter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_c$</td>
<td>1 m</td>
</tr>
<tr>
<td>$B_0$</td>
<td>0.25 T</td>
</tr>
<tr>
<td>$\dot{m}_{inj}$</td>
<td>0.5 mg/s</td>
</tr>
<tr>
<td>Max current</td>
<td>1.2 kA</td>
</tr>
<tr>
<td>Magnet power</td>
<td>9.4 kW</td>
</tr>
<tr>
<td>Magnet mass</td>
<td>1,000 kg</td>
</tr>
<tr>
<td>Battery mass</td>
<td>26 kg</td>
</tr>
<tr>
<td>PPU mass</td>
<td>56 kg</td>
</tr>
<tr>
<td>Mass growth</td>
<td>1.5</td>
</tr>
<tr>
<td>Total mass estimate</td>
<td>1,623 kg</td>
</tr>
</tbody>
</table>

A. Saturn and Neptune

The atmospheres of Neptune and Saturn consist primarily of molecular hydrogen. The plasma model presented here is developed only for atomic species, so further work incorporating more complex plasma chemistry is required for a faithful simulation in these atmospheres. Still, we adapt our model to simulate atomic hydrogen and assume that H$_2$ is dissociated upon interaction with the plasma. We neglect the energy loss associated with dissociation, but we also neglect gains from direct ionization and CX of H$_2$, so this approximation is suitable for a first-order analysis of a hydrogen magnetoshell. Simulations are run for a broad range of flow velocities and densities and we extract the minimum threshold velocity required to activate the CX regime of the magnetoshell at each density. We then correlate the H density to the altitude at each planet. The atmospheric density profiles are given by Justus for Saturn and Neptune. The H ionization reaction rate is given by Voronov, the effective ionization loss is fit by Little to data from Dugan, and the H-H$^+$ charge exchange cross section is tabulated by Barnett.
Figure 7 shows the results of this analysis at Saturn. The reference mission for Saturn is defined by Hall et al.\textsuperscript{1} in terms of the entry and final velocities required for successful aerocapture; the "mission ∆v" represents this range. The green region represents the range of velocities and altitudes at which the magnetoshell CX regime is active (and therefore drag is generated). In other words, the magnetoshell will operate in the CX or CIV regime everywhere to the right of the blue curve. It has a characteristic flattened "C" shape: at high altitude, the flow is too tenuous to supply the sustainment energy required; at too low an altitude, the atmospheric density is so high that neutrals extinguish any possible dense plasma. The overlap of magnetoshell operation and mission velocity requirements indicates that there is a feasible flight envelope for plasma aerocapture at Saturn. In other words, the atmospheric flight requirements of a Saturn mission are compatible with the effective operation of magnetoshells, making this a good candidate mission for plasma aerocapture.

The same analysis at Neptune is shown in Figure 8. The magnetoshell requirement of high velocity flow makes this flight envelope more restricted, since mission velocities for Neptune are lower than at Saturn. We included a reference trajectory for the Neptune ellipsed-style aeroshell mission design of Lockwood.\textsuperscript{25} (The atmosphere model is derived from the same study, which utilizes Neptune-GRAM.) This highlights one of the main benefits of plasma aerocapture: maneuvers can occur at higher altitudes where dynamic pressure and heating are reduced. This is a promising result since aerocapture at Neptune has been determined not possible without advancements in thermal protection (TPS).\textsuperscript{6} Plasma aerocapture may eliminate the need for breakthrough TPS technologies by leveraging the high velocity entry to sustain the magnetoshell and operating at lower densities.

Although the flight envelopes are promising for Neptune and Saturn, they are not useful if the magnetoshell cannot produce the drag required to slow the spacecraft at those altitudes. Figure 9 shows the drag force and effective $C_D A$ for the magnetoshell design presented here ($B_0 = 0.25$ T, $r_c = 1$ m, $\dot{m}_{\text{inj}} = 0.5$ mg/s). The three densities shown correspond to altitudes between 400\textendash700 km at Neptune and 650\textendash800 km at Saturn, both falling within the flight envelopes of Figures 7 and 8. We observe extremely high drag, exceeding 100 kN at lower altitudes, suggesting the flight envelopes will provide more than enough opportunity to achieve the required decelerations. (For example, to attain the Neptune mission $\Delta v = 6$ km/s on a 5,000 kg spacecraft, the magnetoshell must average around 50 kN of drag for the maneuver duration.) The effective $C_D A$ is also extraordinarily high which holds promise for the success of plasma drag modulation at accurate orbit targeting. This is especially helpful at the outer planets where knowledge of the atmosphere is uncertain and robust drag control can mitigate this risk.
Figure 8. Minimum spacecraft velocity required for magnetoshell to operate in CX regime in Neptune’s atmosphere. Gray curves are estimated dynamic pressure, $\rho v^2/2$. The green region shows the range where the magnetoshell generates drag, and the mission velocity range 23-29 km/s is the reference mission given by Hall et al. The shaded overlap of these regions is the available flight envelope for a plasma aerocapture maneuver. The reference aeroshell trajectory is simulated by Masciarelli and highlights how much higher altitude the plasma aerocapture maneuver can be.

Figure 9. Drag and effective $C_D A$ are extraordinarily high in a hydrogen atmosphere. The density range $10^{18}$–$10^{20}$ m$^{-3}$ corresponds to altitudes of 400–700 km at Neptune and 650–800 km at Saturn. The fixed conditions are $B_0 = 0.25$ T, $r_c = 1$ m, and $\dot{m}_{\text{inj}} = 0.5$ mg/s for hydrogen plasma model.

B. Venus and Mars

Venus and Mars have atmospheres of primarily CO$_2$. Again, the plasma model is not equipped to simulate molecular species, and CO$_2$ can dissociate and ionize into a large variety of species that must be tracked separately. We use our Argon model as a low-fidelity approximation for this analysis as its molar mass is very similar. This should prove to be an overestimate of the performance of plasma aerocapture at Venus and Mars for two reasons. First is that molecular species in general have higher threshold ionization velocities than atomic species because there are more energy loss mechanisms. Second is that lighter species (like those resulting from CO$_2$ dissociation) will drive the threshold velocity higher, as observed in the difference between the Ar and H models presented in this paper. Therefore these results should be taken as best-case. Atmospheric density for both Venus and Mars is given by Justus.

Figure 10 shows the flight envelope at Venus. The maneuver $\Delta v$ is from the “V2” mission referenced by Hall et al. There is a good correspondence between magnetoshell operation and the velocity requirement of the mission. However, the final spacecraft velocity (8.4 km/s) barely exceeds the threshold velocity of magnetoshell operation. Since this model overestimates performance, it is possible that the flight envelope is much more limited than what is observed in Figure 10 or that it does not intersect the Venus mission velocity at all. Further work is required to develop a plasma model describing a CO$_2$ atmosphere before we...
Figure 10. Minimum spacecraft velocity required for magnetoshell to operate in CX regime in Venus’ atmosphere. Gray curves are estimated dynamic pressure, $\rho v^2/2$. The green region shows the range where the magnetoshell generates drag, and the mission velocity range 8.4-11.7 km/s is the reference mission “V2” given by Hall et al.\textsuperscript{1} The shaded overlap of these regions is the available flight envelope for a plasma aerocapture maneuver.

can make a definitive assessment of plasma aerocapture at Venus.

The low planetary mass of Mars causes the orbit insertion and aerocapture velocities to be very low. This means that the velocity threshold physics we have observed may make plasma aerocapture challenging at this destination. Figure 11 demonstrates this by showing that the magnetoshell operating regime requires higher velocities than those experienced during aerocapture at Mars. In all simulations with both Ar and H, no threshold velocity was observed as low as the 4.7 km/s required of the reference “M2” mission from Hall et al.\textsuperscript{1} Recent analysis\textsuperscript{6} has determined that modern aeroshell technologies are already mature enough for aerocapture at Mars. That combined with the physical improbability of magnetoshells working in the Martian atmosphere indicate that plasma aerocapture is likely not a replacement for aeroshells on Mars missions. However, it may fit into broader system architectures. For instance, a magnetoshell could be used to enable faster trip times for human missions which will have higher entry velocities, or they may be used in the upper Martian atmosphere for drag modulation precision steering. Further analysis is required to assess the role of magnetoshells in such architectures.

V. Conclusion

We have developed a self-consistent model analyzing the global interaction between a magnetoshell and a hypersonic atmospheric flow during aerocapture. We find the physics of this interaction are dynamic, depending heavily on the flow velocity and magnetic field strength. In particular, the magnetoshell exhibits critical-ionization-like phenomena whereby it rapidly increases its consumption of flow once a threshold velocity is reached. This is a new result that was not apparent in previous modeling. The implication for plasma aerocapture is that a maneuver must at all times remain above this critical velocity for the magnetoshell to generate the large drag required of aerocapture maneuvers. We apply this principle to determine the flight envelope (altitude and velocity) in which a magnetoshell will operate at Saturn, Neptune, Venus, and Mars. Plasma aerocapture is promising at Saturn and Neptune because the high velocity entries are an asset when considering the unique physics of this technology. Further, the high altitude of these two flight envelopes suggests a much lower heat load on the spacecraft, potentially reducing the stringent TPS requirements on these giant-planet missions. Analyzing the flight envelope at Venus and Mars requires us to make very simplifying assumptions. Even with these approximations giving us a best-case scenario, plasma aerocapture at Mars poses significant challenges due to the low mission velocities involved. There are indications that Venus is a viable destination for plasma aerocapture, but further development of our model is required to simulate the advanced plasma chemistry in a CO\textsubscript{2} atmosphere.
We have so far excluded Earth, Jupiter, Titan, and Uranus from our discussion of mission applications. Earth, similar to Venus, requires velocities that border on the edge of magnetoshell viability (8–10.3 km/s for the Hall\(^1\) reference mission). We have not adapted our model for nitrogen so it is difficult to make an assessment based on current results, but Earth should not be ruled out. Jupiter requires much higher spacecraft velocities (40~60 km/s) than other destinations, which is advantageous for the dynamics of the plasma/atmosphere interaction. Titan, on the other hand, has extremely low velocities (1.5-5.9 km/s) associated with capture into its small gravity well. Even with further development of the plasma model to simulate nitrogen atmospheres, we expect to find the threshold velocity of magnetoshell operation makes plasma aerocapture a difficult technology to employ there. Uranus may be treated nearly the same as Neptune due to their similar mass and atmospheric composition,\(^6\) so it is a viable candidate as well. Plasma aerocapture is a promising technology for missions demanding high entry velocities and drag modulation. In general, this makes it suitable for gas and ice giants where the gravity well is large and knowledge of the atmosphere is uncertain. A comprehensive systems analysis of an ice/gas giant orbiter leveraging plasma aerocapture is warranted to assess mission feasibility.
Appendix

The following terms result from the derivation of the dimensionless plasma model equations. See Section D for their application. α and b are generic species subscripts. “Reac” denotes a specific reaction type, such as cx,sn or iz,2n. σ_qm is the momentum transfer cross section. σ_gk is the gas-kinetic cross section. ν_eα is the electron-α collision frequency. \( \hat{\nabla} \) is the del operator in normalized coordinates. T_α,inj is the energy of injected ions or electrons. t_e is the electron collision time. R_reac is the reaction rate coefficient. φ_iz is the effective ionization energy including losses due to excitation and scattering.

\[
\begin{align*}
\hat{D}_{2n} &= \left(2r_c u_\infty n_\infty (\hat{N}_i \sigma_qm + \hat{N}_{2n} \sigma_gk)\right)^{-1} \left(\frac{\pi T_\infty}{m_{2n}}\right)^{1/2} \\
\hat{D}_B &= \frac{T_\infty}{16eB_0 r_c u_\infty} \\
\hat{D}_c &= \frac{m_e T_\infty (\nu_{ei} + \nu_{en})}{e^2 B_0^2 r_c u_\infty} \\
I_B &= \int_V \hat{B} \hat{d}\hat{V} \\
I_{B2} &= \int_V \hat{B}^2 \hat{d}\hat{V} \\
I_{\text{diff}} &= \iint_S \frac{\hat{\nabla} \hat{B}}{\hat{B}} \hat{d}\hat{S} \\
I_{\text{sn}} &= \int_V \hat{B} \exp \left[-\zeta_{\text{tot}} \int_{-\infty}^{\hat{z}} \hat{B} d\hat{z} \right] d\hat{V} \\
M_{\alpha,b} &= \frac{m_\alpha}{m_b} \\
\hat{N}_{\text{inj}} &= \frac{\hat{\dot{m}}_{\text{inj}}}{m_i u_\infty r_c^2} \\
\hat{P}_{\alpha,inj} &= \frac{5}{2} \frac{\hat{\dot{m}}_{\text{inj}}}{\hat{\dot{m}}_{\text{inj}}} \frac{T_{\alpha,inj}}{m_i u_\infty r_c^2} \\
\hat{Q}_{\alpha,b} &= \hat{v}_{T,\beta} \sqrt{\frac{4}{\pi}} \hat{v}_{T,\alpha} + \frac{64}{9\pi} \hat{v}_{T,\beta} + \hat{v}_{\alpha,b}^2 \\
\tau_e &= t_e u_\infty / r_c \\
\hat{v}_{T,\alpha} &= \frac{\sqrt{2T_\alpha/m_\alpha}}{u_\infty} \\
\hat{v}_{\alpha,b} &= \frac{u_\alpha - u_b}{u_\infty} \\
Z_{\text{reac}} &= n_\infty r_c \sigma_{\text{reac}} \\
\zeta_{\text{reac}} &= \frac{R_{\text{reac}} n_\infty}{u_\infty / r_c} \\
\zeta_{\text{tot}} &= \left(\frac{R_{\text{cx,sn}} + R_{\text{iz,sn}}}{u_\infty / r_c}\right) n_\infty \hat{u}_{e,0} \\
\hat{\phi}_{iz} &= \frac{\phi_{iz}}{T_\infty}
\end{align*}
\]

Acknowledgments

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References


