RICE UNIVERSITY

ARGON ION POLLUTION OF THE MAGNETOSPHERE

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A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

MASTER OF SCIENCE

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HOUSTON, TEXAS

JULY, 1982
Acknowledgements

Given the nature of this work, which spans various areas of physics, I sought, and received, the assistance of several people. Among these are Tom Tascione, Dr. R. A. Wolf, Dr. G. H. Voigt, Dr. R. F. Stebbings, and Dr. N. Lane, all of whom I wish to thank. To my thesis advisor, Dr. John Freeman, I extend special thanks for his invaluable advice and aid.

This work was made possible by an NSF graduate fellowship and supported by a Space Foundation Space Industrial Fellowship, which paid for the bulk of my research expenses. I dedicate this thesis to my kid sister, Wilma, and all the other children of this world, to whom space so invitingly beckons.
ABSTRACT

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Ramon E. Lopez

The construction of Solar Power Satellites (SPS) would require the injection of enormous quantities of propellent to transfer cargo from LEO to the construction site at GEO. This propellent, in the form of 2 KeV argon plasma, is expected to considerably modify the space environment since the number of ions injected per SPS ($=10^{32}$) is comparable with the total plasmaspheric content above $\approx 500$ km. In this thesis a model for the dynamics of the ion thruster plasma beam is presented. This model predicts beam travel distances up to a few thousand km, and the transfer of beam momentum to the ionosphere, causing localized heating. Subsequent convection of the argon is investigated using a simple model of the quite-time, and storm-time, magnetosphere. In addition, $\text{Ar}^+$ charge exchange lifetimes are calculated and shown to be too large to significantly reduce the amount of $\text{Ar}^+$ near the plasmapause between magnetospheric storms.
<table>
<thead>
<tr>
<th>Table of Contents</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>I. Argon Thrusters and Quantities of Argon Needed</td>
<td>3</td>
</tr>
<tr>
<td>II. Argon Plasma Beam Dynamics</td>
<td>7</td>
</tr>
<tr>
<td>III. Argon Convection in the Magnetosphere</td>
<td>16</td>
</tr>
<tr>
<td>IV. Charge Exchange of Ar(^+) with Exospheric Hydrogen</td>
<td>24</td>
</tr>
<tr>
<td>V. Conclusions and Future Research Directions</td>
<td>33</td>
</tr>
<tr>
<td>Table I</td>
<td>36</td>
</tr>
<tr>
<td>Table II</td>
<td>36</td>
</tr>
<tr>
<td>Table III</td>
<td>37</td>
</tr>
<tr>
<td>Figure Captions</td>
<td>38</td>
</tr>
<tr>
<td>Figures</td>
<td>39</td>
</tr>
<tr>
<td>References</td>
<td>48</td>
</tr>
</tbody>
</table>
INTRODUCTION

In recent years a large scale energy option, known as the Satellite Power System (SPS), has received increasing attention from the scientific and technical community. The basic concept for SPS is as follows: Large (10 km x 5 km) platforms would be constructed in geostationary earth orbit (GEO) to collect solar energy. This energy would be converted into microwaves and beamed down to Earth, received by a rectifying antenna and fed into the power grid. Since in the foreseeable future, political questions are likely to impede the use of extraterrestrial materials, a major problem (among others) is the transportation system necessary to move the large quantities of men and material up to GEO.

In 1978 Rockwell International (U.S. NASA, 1978) did an extensive system definition study in which a 5 GW (at Earth interface) reference system was developed. The transportation component would mandate the construction of several reusable heavy lift launch vehicles (HLLV) to haul material into low earth orbit (LEO). From LEO the cargo would be shuttled to the construction site at GEO in an equipment orbital transfer vehicle (EOTV). This transportation scheme is illustrated in figure 1.

The EOTV's are envisioned to be solar powered and propelled by argon ion thrusters. Ion thrusters have a number of advantages over chemical rockets. They can operate for long periods of time producing a low, steady
thrust. Since the propellant is accelerated electromagnetically enormous propellant velocities can be developed, therefore much less propellant need be expended to achieve a desired $\Delta v$ as compared to chemical propulsion. In addition argon is very plentiful (\approx 1% of the atmosphere), so it would be cheap in mass quantities. And for an industrial project economy is a strong priority.

In spite of the great efficiency of ion propulsion, due to great mass that must be transported, enormous quantities of energetic argon and the associated (thermal) electrons would be injected into the environment during the construction of SPS. Such a large scale injection of plasma into the magnetosphere is likely to have a considerable impact on earth's magnetospheric morphology and dynamics. This pollution would not only be in the form of ions, but also in the form of energy. For example, the ion beam that leaves the thruster would have an extremely anisotropic velocity distribution, making it unstable and eventually leading to a transfer of energy from the argon plasma to the magnetosphere in general.

Clearly, as large scale industrial projects in space, like SPS, come under increasing consideration, a major question is the overall effect of injecting copious quantities of energetic argon plasma into the region between LEO and GEO. This problem can be subdivided into several areas:

1. Quantities of mass involved and distribution in space.
2. Argon plasma beam dynamics.
3. Large scale convection of argon plasma in the magnetosphere.
4. Loss mechanisms.
5. Argon plasma to magnetosphere - ionosphere energy transfer.
6. Effects of injected argon and energy on magnetosphere system.

As one can see these are very general areas, any of which could be further subdivided into a host of topics. Thus the purpose of this thesis will be to examine most of these topics, some in more detail than others, and to target specific questions for further work.

I. Argon Thrusters and Quantities of Argon Needed

Ion thruster technology is still developing and so the parameters for the thruster in question are uncertain. The Rockwell system definition study described an EOTV propelled by an argon thruster whose grid potential would have a 2 KeV limit, to avoid arcing with the background plasma. Other authors, notably Chiu, et al. (1980), have considered 3.5 KeV thrusters, but for this thesis only the 2 KeV thrusters will be discussed. The thruster described would have an ion beam current of 1904 amps, a radius of =38 cm and a thrust of 69.7 Nt. Eighty such thrusters would be needed for each EOTV, in four groups of 20. Of these 80 thrusters only 64 would be operable at any time, the rest being spares.
Some other Rockwell reference system EOTV parameters are given in table I.

The EOTV, under low thrust, would spiral out to GEO from LEO and back, and we can estimate the amount of argon that would be injected. A continuously circular transfer orbit is assumed to approximate a tightly wound spiral. For a circular orbit Goldstein's "Classical Mechanics" gives that

\[ E = \frac{-mK^2}{2l^2} \quad \text{where} \quad K = mMG \quad \text{and} \quad l = mv \quad \text{(1-1a)} \]

but \( E = \frac{1}{2}mv^2 - K/r \). Setting these equal yields

\[ (1-1b) \quad mv^2 = \frac{K}{r} \quad \text{so} \quad E = \frac{K}{r} + \frac{1}{2} \left( \frac{K}{r} \right) = \frac{-K}{2r}. \quad \text{(1-2a)} \]

If we let \( r = R_\theta R \) then the total energy difference between two circular orbits of radius \( R_0 \) and \( R_1 \) is (using 1-2a)

\[ \Delta E = \frac{MG}{2R_\theta} \left( \frac{m_0}{R_0} - \frac{m_1}{R_1} \right). \quad \text{(1-2b)} \]

If we consider this energy change due to the \( \Delta v \) produced by the thruster, and assume the change in mass between orbits is small (a reasonable assumption for ion propulsion). then the required \( \Delta v \) is

\[ \text{(1-3)} \quad \Delta v = 7.9 \; \text{Kms}^{-1} \left( \frac{1}{1.078} - \frac{1}{R_1} \right)^{\frac{1}{2}}; \quad \text{for} \; R_0 \; \text{at LEO}. \]

The rocket equation is (\( v_p \) is the propellent velocity),

\[ \Delta v = v_p \ln \left( \frac{m_0}{m} \right) \quad \text{(1-4)} \]
and for a 2KeV Ar\(^+\), \(v_p = 98 \text{ Kms}^{-1}\). The thruster, is assumed to ionize only \(\approx 90\%\) of the propellant, the rest escaping as a gas (Carruth and Brady (1980)). Thus the average propellant velocity \((v_{\text{gas}} \ll v_{\text{ion}})\) is

\[(1-5) \quad v_p = (0.9)(v_{\text{ion}}) = 88.2 \text{ Kms}^{-1}\]

Using the numbers given in table I and equations 1-2,3,4 we find that:

- LEO \(\rightarrow\) GEO propellant expended \(505,889\) Kg
- GEO \(\rightarrow\) LEO propellant expended \(64,560\) Kg

Total Propellant Expended \(570,449\) Kg

This value for the total propellant needed is \(\approx 4\%\) higher than the propellant mass quoted in the Rockwell definition study.

To build a 5 GW station of a mass of \(\approx 5 \times 10^7\) Kg, one needs \(\approx 10\) EOTV flights which would inject \(\approx 5.5 \times 10^6\) Kg of 2 KeV Ar\(^+\) into the magnetosphere. If we were to spread this argon out in a triangular torus between LEO and GEO around the earth this would result in an average density of \(4.1 \times 10^4\) cm\(^{-3}\), which is very large compared to an average ambient density of \(\approx 10^2\) cm\(^{-3}\). Considering only the argon injected below \(L = 3\) the average density would be \(\approx 3 \times 10^5\) cm\(^{-3}\), considerably greater than the \(\approx 10^2 - 10^4\) cm\(^{-3}\) found in the plasmasphere.

Since the 10 flights would be spread out over a year, a given L-shell of the plasmasphere will have essentially
five weeks between argon injections to lose the argon via various mechanisms. Thus, if loss processes result in lifetimes considerably less than five weeks then the maximum argon densities will be due to a single EOTV flight; a tenth of those quoted above, i.e. \( \approx 3 \times 10^4 \) at \( L = 3 \). This is still a considerable increase in both the ion population and the thermal electron population. And if the dominant loss mechanism is charge exchange with exospheric hydrogen these \( \text{Ar}^+ \) densities could considerably deplete the neutral hydrogen and substantially increase the thermal proton population.

The thruster produces two distinct plasmas; the beam plasma, and the plasma produced by charge exchange between the beam plasma and the escaping unionized argon. The number of charge-exchange ions produced per second is given by Kaufmann (1976) to be:

\[
\dot{N} = \frac{2\sigma_{\text{CE}} J_B^2 (1-\eta)}{e^2 \nu_{\text{O}} R_B^2} (\text{Ar}\, s^{-1}) \tag{1-6}
\]

where \( \sigma_{\text{CE}} = \text{charge exchange crosssection} = 2 \times 10^{-15} \text{cm}^2 \)

\( J_B = \text{beam current} = 1904 \, \text{A} \)

\( \nu_{\text{O}} = (8KT/ \text{m})^{1/2}; \, KT = 10 \, \text{eV} \)

\( R = \text{beam radius} = 3.8 \, \text{cm} \)

\( \eta = \text{fraction of propellant ionized} \)

Carruth and Brady (1980) state that in experiments with a 900-series, Hughes mercury ion thruster approximately 90\% of the propellant is ionized. The remaining 10\%
escapes through the optics in the form of neutral mercury. Therefore \( n \) is assumed to be \(.9\), in which case \( \dot{N} = 6.05 \times 10^{20} \text{ Ar}^+/s \). This results in a charge exchange current of 96.7 amps (and density of \( \leq n_{\text{Beam}} \)), so about 5% of the beam current is lost due to charge exchange with the neutral argon cloud.

Parks and Katz (1978), and Carruth and Brady (1980) report that laboratory thruster tests show the exchange plasma moves radially outward from the beam. This thermal plasma would be injected into space with essentially the EOTV's orbital velocity. As in the barium release experiments (Scholer 1970), the plasma is expected to expand until \( \beta \approx 1 \) at which point the expansion perpendicular to \( \beta \) is stopped by the field. This thermal argon plasma would be a considerable addition to the thermal heavy ion population of the magnetosphere, especially in the plasmasphere. The remaining unionized argon would be subject to charge exchange and photoionization, the latter of which has an e-folding lifetime given by Siscoe and Mukherjee (1972) to be \( 4.5 \times 10^{-4} \) s\(^{-1}\). The beam ions also are subject to further ionization, however the ionization energy for \( \text{Ar}^+ \) is 27.6 eV so it is likely that the rate for \( \text{Ar}^{++} \) production will be small.

II. Argon Plasma Beam Dynamics

The plasma beam that emerges from the thruster is a dense charge-neutral beam. It is assumed that the beam will continue to travel as a beam until the magnetic field pressure
begins to dominate the beam pressure perpendicular to the field, thus our condition is;

$$\frac{B^2}{2\mu_0} \lesssim P_\perp$$  \hspace{1cm} (2-1)

As this occurs the plasma motion changes from beam motion to individual particle motion. This motion is most easily followed using the guiding center approximation. Then the argon plasma flow, as prescribed by the local electric and magnetic fields, can be determined.

The beam is assumed to be injected roughly perpendicular to B, in the equatorial plane. It is also assumed that in the first phase of the beam's expansion it is shaped like a cone. This has been reported by Haerendel, et al. (1981). As the beam expands the pressure drops until (neglecting the ambient particle pressure relative to the field pressure)

$$nkT \xi \frac{B^2}{2\mu_0}$$  \hspace{1cm} (2-2)

at which point the expansion perpendicular to \( \hat{B} \) and along \( \hat{v}_{\text{Beam}} \times \hat{B} \) is stopped. However, since the magnetic pressure along the field line is small, the beam should start to flatten into a sheet stretched out along the field lines. The beam will continue to travel in this manner until the magnetic energy density begins to dominate over the beam dynamic pressure, at which point the ions begin executing single particle, adiabatic motion.
Chiu, et al., (1980), basing their paradigm on Scholer (1980), argue that the beam would lose momentum by the generation of Alfvén waves (fig. 2). This is intuitively reasonable. As the beam comes out of the thruster it grabs the field lines in front of it, pulling them along thus generating an Alfvén wave. The plasma tethered to these field lines is accelerated, the momentum coming from the beam. Scholer (1970) suggests that the physical mechanism involved is the polarization electric field produced in the plasma cloud. This field accelerates, and polarizes, the ambient, adjacent plasma. The electric field thus propagates down the field line. As this wave reaches the ionosphere it would drive dissipative Pederson currents, heating the ionosphere at a rate $\dot{J} \cdot \dot{E}$.

As a first approximation we can model the argon beam expansion as an expanding Maxwell-Boltzman distribution in the (x-y) plane perpendicular to the beam (z) axis. The beam is assumed to be injected perpendicular to B in the equatorial plane. Since the beam velocity (98 Kms$^{-1}$) is so much higher than the velocity of the EOTV with respect to the field, the beam is assumed to enter the magnetosphere with the ion velocity. It is assumed the plasma is collisionless, that there are no external forces on the beam, that the expansion is in a vacuum and that all internal couloumb forces can be neglected due to the charge-neutrality of the beam. Furthermore we consider only the motion of the ions and assume that the electrons follow along. Because
the ions are so much more massive than the electrons, their dynamics should dominate, the electrons being dragged along.

Liemohn, et al. (1980), assume that for ion thrusters $kT$ is on the order of $10 \text{ eV}$. Since the beam energy is so much larger than the thermal energy we can neglect the thermal expansion along the beam axis. Thus we can write the distribution function at $t = 0$ as

$$f(\mathbf{x}, \mathbf{v}, t=0) = \delta (v_z - v_B) \left( \frac{m}{2\pi kT} \right) n_o \exp \left[ -\frac{m v^2}{2kT} + \frac{\mathbf{x}^2}{2R^2} \right] \quad (2-3)$$

where

$$\mathbf{x} = \mathbf{x} + \mathbf{y}$$

$$\mathbf{v} = \mathbf{v}_x + \mathbf{v}_y$$

$$kT = 10 \text{ eV}$$

$$v_B = 98 \text{ Kms}^{-1}$$

To confine the plasma to the thruster radius, $r_o$, at $t = 0$ let $R = 1/3 r_o$. This means that at $x^2 = r_o^2$ the density has gone down by a factor of $0.011$ and so the bulk of the plasma is localized within the thruster radius $r_o$. Due to particle conservation the number of ions per unit length along the $z$ axis is constant so in normalizing $f$ to the total number of ions emitted, $N$, we can replace integration over $z$ with multiplication by $v_B t$. Thus the normalization condition is:

$$\int f d^3v \, d^2x \, v_B t = N = \frac{I t}{e} \quad (2-5)$$

where $I$ is the ion beam current. The integral is over the
entire x-y plane, even though at \( t = 0 \) we assume that there is no plasma beyond \( r = r_Q \), but since \( f(r=r_Q) = f(r=0)/100 \) the error is small. Normalizing \( f(t=0) \) gives

\[
    n_0 = \frac{9I}{2\pi r^2 v_B}. \tag{2-6}
\]

The time dependence of the distribution function is given by the collisionless Boltzman equation, which in our case reduces to

\[
    \frac{\partial f}{\partial t} + \vec{\nabla} \cdot \vec{v} f = 0. \tag{2-7}
\]

The solution to (2-7) is readily found to be

\[
    f(x',v',t) = \left[ \frac{m}{2\pi kT} \right] n_0 \delta(v_Z-v_B) \exp \left[ -\frac{m v^2}{2kT} + \frac{(x'-vt)^2}{2R^2} \right] \tag{2-8}
\]

and so the density of ions is

\[
    \int f(x',v',t) d^3v = n(x,t) = n_0 \left[ \frac{m/kT}{m/kT + t^2/R^2} \right] \exp \left[ -\frac{x^2}{2R^2} \left( \frac{m/kT}{m/kT + t^2/R^2} \right) \right] \tag{2-9}
\]

which for \( t \gg \frac{10^{-4} s}{t^2} \gg \frac{R^2}{m/kT} \), using (2-6), becomes

\[
    n(r,t) = \frac{n_0 m R^2}{kT t^2} \exp \left[ \frac{-r^2 m}{2t^2 kT} \right] \tag{2-10a}
\]

\[
    = \frac{m}{kT \pi v_B t^2} \exp \left[ \frac{-r^2 m}{2t^2 kT} \right] \tag{2-10b}
\]

The condition for beam capture is \( \rho v^2 = B^2/2u_0 \). If we include the thermal pressure, nkT, and consider magnetic
pressure dominance in the plane perpendicular to \( \vec{B} \), then

\[
\rho v_B^2 \cos^2 \theta + 2n k T = \frac{B^2}{2\mu_o}
\]  \hspace{1cm} (2-11)

which for \( t \gg 10^{-4} \) s, reduces to

\[
\left( \frac{v_B^2 t^2}{\sqrt{r^2 + v_B^2 t^2}} + \frac{1}{200} \right) \left( m \frac{m v_B I_B}{k T} \right) e^{\frac{-r^2}{2t^2 k T}} = \frac{B_o^2}{2\mu_o}
\]  \hspace{1cm} (2-12)

Considering only the dipole field for \( \vec{B} \), and looking along the beam axis to see the farthest extent of the beam \((r=0)\) equation \((2-12)\) reduces to

\[
\frac{m}{k T} \frac{m v_B I_B}{2\pi e t^2} = \frac{B_o^2}{2\mu_o L^6}
\]  \hspace{1cm} (2-13a)

Plugging in the numbers, the time (and distance) the beam travels is:

\[
(2-13b) \quad t = 0.0353 \ L^3 \text{sec} \hspace{1cm} (2-13c) \quad z = 3.46 \ L^3 \text{Km}
\]

where \( L \) is the magnetic shell parameter. At \( L = 4 \) the beam travels for 221.3 Km with a central beam density of 139 cm\(^{-3}\) at transition. Equation \((2-12)\) can also be numerically solved for the transition surface. This results in the beam contours plotted in fig. 3.

As a second approximation to the plasma beam expansion, we can include the loss of momentum due to Alfvén wave generation. Scholer (1970) shows that for a cloud moving perpendicular the velocity is damped like \( e^{-t/\tau} \), where \( \tau \) is the time it takes for the wave front to pass over as
much mass/unit area as is causing the disturbance. Chiu (1980) states that even for a numerical model which takes into account the variation of field strength and ambient density along the field line, the beam velocity behaves like $v_B = v_o e^{-t/\tau}$, with $\tau$ on the order of a few seconds. Following Chiu (1980), let $\tau$ be the mass per unit area of argon along the field lines passing through the beam.

$$\mu = \int ds \rho_{Ar^+}. \quad (2-14)$$

The $\tau$ is the time for the Alfvén wave to cover as much mass/area as $\mu$. Let $\xi = \int n_1 m_1$ along the field lines intersecting the beam, then

$$\tau = \frac{\mu}{2v_A \xi}. \quad (2-15)$$

Our distribution function is now

$$f' = n_o \frac{m}{2\pi kT} \delta(v_z - v_o e^{-t/\tau}) \exp \left[ \frac{-mv^2}{2kT} - \frac{(\dot{x} - \dot{v}t)^2}{2R^2} \right] \quad (2-16)$$

where $n_o'$ is to be evaluated from the normalization. Also $z =$ distance beam has travelled $= \tau v_o (1 - e^{-t/\tau}) \quad (2-17)$

Since $v_B$ is going down it is natural expect the density to go up in the same manner from the continuity equation, thus $n_o' = n_o e^{t/\tau}$. Using (2-17) $f'$ becomes:

$$f'(x, \dot{x}, \dot{v}, t) = n_o \frac{m}{2\pi kT} \frac{\delta(v_z - v_o e^{-t/\tau})}{1 - z/v_o \tau} \exp \left[ \frac{-mv^2}{2kT} - \frac{(\dot{x} - \dot{v}t)^2}{2R^2} \right] \quad (2-18)$$

where $t = t(z) = \tau \ln \frac{1}{1 - z/v_o \tau} \quad (2-19)$
Again we normalize $f$ to $IT/e$, through this time we must integrate over $z$, not multiply by $v_B t$.

$$\int f' d^3x \ d^3v = \frac{IT}{e} \quad (2-20)$$

Integrating (2-20) we find that the constant $n_o$ is just the same as before, and the density $n'(x,t)$, for $t < 10^{-4}$s is,

$$n'(x,t) = \int f' d^3v = \frac{9Ie^t/\tau}{2\pi r_o^2 ev_o t^2} \exp\left[\frac{-x^2}{2t^2} \frac{m}{kT}\right] \quad (2-21)$$

Now the condition for beam capture becomes:

$$\left\{ v_o^2 \cos^2 \theta + \frac{1}{200} \right\} \frac{9Ie^{-t/\tau}}{2\pi r_o^2 ev_o t^2} \exp\left[\frac{-r^2}{2t^2} \frac{m}{kT}\right] = \frac{B^2}{2\mu_o} \quad (2-22)$$

where $\cos \theta = \frac{z}{\sqrt{r^2 + z^2}} = \frac{\tau v_o (1 - e^{-t/\tau})}{\sqrt{r^2 + (\tau v_o (1 - e^{-t/\tau}))^2}} \quad (2-23)$

As one can see (2-23) is a considerably more difficult equation to solve numerically than (2-12). Not only is it a very convoluted equation, with respect to $r$ and $t$, but it also depends on $\tau$, which in turn depends on the Alfvén speed, hence $B$. In addition, since $B$ and the background density vary by orders of magnitude along a field line, the simple expression (2-14) for $\tau$ can give only rough results, but in the plasmasphere, $\tau \approx$ few seconds so the beam travels $\approx 10^3$ Km.

Other models have been proposed by Liemohn, et al. (1980) and in a more qualitative manner, by Curtis and Grebowsky (1980). The latter authors claim that as the
beam moves through the magnetic field it polarizes until $qE_p$ cancels the Lorentz force. A nonpropagating sheath is created which maintains a polarization field that insulates the beam as it passes out of the magnetosphere. Thus the beam deposits only a small fraction of its mass, in the form of the sheath, in the magnetosphere. Unfortunately this conclusion is false. The polarization electric field required to balance the Lorentz force is $E_p = v_B B = (3.05/L^3) \frac{v}{m}$. In beams with widths $> 10^4 m$, this produces potential differences on the order of a KV. Since the field lines threading the beam are roughly equipotentials, the polarization field would be shorted out by field aligned currents, as reported by Haerendel and Sagdeev (1981).

The approach developed by Liemohn, et al., is similar to the one presented here. The condition used for beam capture used is $\rho v^2/2 = .1 B^2/2 \mu_0$, but I elected not to use the factor of .1 and have used a factor of .5 instead. The beam is modeled as an adiabatic expansion perpendicular to the beam axis, and a gaussian density distribution is assumed.

Haerendel and Sagdeev (1981), writing on behalf of the PORCUPINE project experimenters, report an experiment in which a 200 eV Xe$^+$ (charge neutral) beam was injected at $72^\circ$ to $\vec{B}$ in nine events, ranging in altitude from 196 Km to 451 Km. They report three stages in the beam's expansion. The first is the free expansion of the beam until
\( \rho v^2/2 \leq B^2/2\mu_o \). The second is a stage of diffusive expansion during which the polarization of the beam allows for some propagation perpendicular to \( \hat{B} \), but the polarization field is shorted out by field aligned electron currents. These currents are presumed to be the source of the low frequency excitations observed. The third stage is that of individual particle motion.

Thus the PORCUPINE experiment results appear to verify the assumptions made in the beam model as presented above. The polarization phase of the beam, however, will be of varying importance, depending on where the beam is injected. For the thrusters in question the peak \((r=0)\) model transition density for \( L = 3 \) (at which point \( n_t = 876 \text{ cm}^{-3} \)) to \( L = 4 \) is of the order of the ambient plasma density, thus the background is capable of shorting out \( \hat{E}_p \). Therefore for \( 4 \leq L \leq 3 \) field-aligned currents are expected to be more important than for injections at \( L = 4 \) to \( L = 3 \), where the transition between beam and individual motion should take place more rapidly without an extended polarized phase.

III. Argon Convection in the Magnetosphere

Once the argon plasma's transition from beam to individual particle motion is accomplished the subsequent motion is determined by the local electric and magnetic fields. This motion is most easily followed using the guiding center approximation. The two first order drift velocities are the \( \hat{E} \times \hat{B} \) and the gradient-curvature
drift velocities. Thus the general motion of the plasma can be followed by solving the equation,

$$\frac{dx}{dt} = \dot{v}_D = \frac{\dot{B} \times \dot{B}}{B^2} + \mu (1 + \cos^2 \alpha) \frac{\dot{B} \times v|\dot{B}|}{B^2} \quad (3-1)$$

where $\alpha$ is the pitch angle and $\mu$ the magnetic moment.

If we assume injection in the equatorial plane, perpendicular, to $\dot{B}$, then $\alpha = 90^\circ$ and $\cos \alpha = 0$. Since $\dot{E}$ and $\dot{B}$ are functions of $\dot{x}$ (ignoring time dependence), (3-1) must be solved numerically. This is done using a Tektronix 4052 minicomputer.

The coordinate system, illustrated in fig. 4, is as follows: $x$ in the antisunward direction, $y$ along the dawn meridian. For a magnetic field the model of Mead (1964) is used with the magnetopause set at $r = 10R_\oplus$. In the equatorial plane $\dot{B}$ just has a $z$ component:

$$B = B_z = \left(\frac{3.11 \times 10^{-5}}{R^3} + 2.515 \times 10^{-8} - 2.104 \times 10^{-9} R \cos \theta\right) \quad (3-2)$$

where $R$ is in earth radii, $\theta$ is the local time and $B$ is in Webers/m$^2$.

For the electric field there is the corotation component given by

$$E_{cor} = \dot{v} \times \dot{B} = \dot{\Omega} \times \mathbf{r} \times \mathbf{B}_{Dipole} \quad (3-3)$$

Also there is the convection electric field, which is assumed to be a uniform, dawn to dusk, .2 mv/m field. This corresponds to a $\approx 50$ KV crosspolar drop mapped out onto a $40 R_\oplus$ magnetosphere. Thus the total electric field
(in V/m) is:

\[
\mathbf{E}_{\text{tot}} = -r \left( \frac{1.45 \times 10^{-2}}{R^2} \right) - 0.5 \times 10^{-4} 
\]

(3-4)

where \( R \) is in \( R_\oplus \).

The above model for the magnetospheric electromagnetic field has some obvious shortcomings. The greatest of these is the assumption of a uniform convection field. In addition there is an inconsistency in making the approximation made in (3-3), then using it in the equation for \( \mathbf{v}_D \), since the expression for \( \mathbf{B} \) has nondipole components. The proper way to find the corotation field is to calculate \( \mathbf{v} \times \mathbf{B} \) for the field line in question, but due to the limitations of the Tektronix 4052 this was not done. However the above model, even though very rough, is simple and analytic, which lends itself well to the iterative process used in the program. And it should provide a somewhat reasonable approximation to argon plasma convection.

The reference system EOTV has 4 groups of 20 thrusters (16 active/group) with an effective radius of 1.7 m and a post charge exchange beam current (5% beam loss) of 28940.8 amps. The program inputs are as follows: the beam energy, the injection point \((r, \theta)\), the time interval size and the number of time intervals the program is to run. After receiving its inputs the program iteratively calculates the distance the beam travels using equation (2-12). When viewing the equatorial plane from above the north pole the EOTV would spiral outward in the counterclockwise sense.
Thus the beam is assumed to be injected perpendicular to the radial vector at the EOTV position, in the clockwise sense.

Once the beam plasma is captured by the magnetic field the magnetic moment is calculated, then the plasma starts to drift with a velocity given by (3-1), with $\alpha = 90^\circ$. This equation is solved numerically using a second order Runge-Kutta method given below:

\[
\Delta \dot{X}' = \dot{V}(\dot{X}_i) \Delta t \quad \text{(eq. (3-5a, b, c)}
\]
\[
\dot{X}' = \dot{X}_i + \Delta \dot{X}
\]
\[
\dot{X}_{i+1} = \dot{X}_i + (\dot{V}(\dot{X}') + \dot{V}(\dot{X}_i)) \frac{\Delta t}{2} .
\]

The resulting plasma drift path is plotted in the equatorial plane.

Four types of drift paths have been identified: "normal" open and closed drift paths, and "vortex" open and closed drift paths. These paths are illustrated in figure 5. The vortex paths occur when plasma injected beyond $L = 4$ along the dusk meridian. Such injections result in large magnetic moments, and as the plasma is convected close to earth the gradient drift takes over until the plasma drifts away from the earth so that corotation can reassert itself.

To check the accuracy of this method we note that equation (3-1), for $\alpha = 90^\circ$, can be written:

\[
\hat{v}_D = \frac{\hat{B} \times \hat{v} (\phi + \mu B/e)}{B^2} \quad \text{(3-6)}
\]

where $\phi$ is the electrostatic potential. Thus $\hat{v}_D$ always lies
in a plane of constant $\phi + \mu/e B$, which is identified as the total electromagnetic potential, $W$. And so the drift path must always lie in a plane of constant $W$. At each point in the drift path $W$ is calculated, and for an average drift path the variation of $W$ along the path is only a few percent. Therefore the path plotted is reliable, for the given magnetospheric electromagnetic fields.

Using the program described above, 3 different injection regions have been identified. These regions are illustrated in figure 6. Injection in the first region results in trapped plasma on normal drift paths that encircle the earth. This argon acts like a manmade ring current with an energy $< 1$ KeV. Plasma injected into the second region is also trapped, but on vortex drift paths. Plasma injected in these regions will be subject to several loss mechanisms, and this plasma is expected to substantially modify plasmaspheric morphology. The third region results in open drift paths of both normal and vortex varieties, all of which intersect the magnetopause. Plasma injected in this region will drift to the magnetopause, and its subsequent fate will be discussed later.

Periodic magnetospheric storms will modify convection patterns and compress the injection trapping boundary. The outer layers of trapped plasmaspheric argon will be stripped off by the enhanced convection electric field and drift towards the magnetopause. Since storms occur every two or three weeks, plasma in this unstably trapped region will
have a couple of weeks to be removed by loss process, the remaining argon being swept into the general magnetospheric convection by a storm. This argon will add to the long term pollution problem.

One can roughly model, in a simple fashion, the effects of a magnetospheric storm on the trapping boundary. Kivelson (1976), utilizing the work of Freeman (1974) and others, has derived a $K_p$ dependent uniform, dawn to dusk, convection electric field. This model, which is fairly accurate as long as one only considers large scale behavior and $0 \leq K_p \leq 8$, is given to be

$$E_{con} = \frac{.44 \ K_v/R_\oplus}{(1 - 0.097 \ K_p)^2}.$$  \hspace{1cm} (3-7)

Modeling the magnetic compression is easily done utilizing a simple scaling law given by G. H. Voight (personal communication, 1981). If $\hat{B}=(\hat{r})$ is the magnetospheric field with the magnetopause at a radius $r_b$ then the magnetospheric field when the boundary has been compressed to $r'$ is

$$\hat{B}'(\hat{r}) = a^3 \hat{B}(a \hat{r}), \text{ where } a \equiv r_b/r'. \hspace{1cm} (3-8)$$

During the sudden commencement of a storm the magnetopause will often be compressed to $r' = 7 \ R_\oplus$, with the main part of the compression lasting about two hours (Voigt (personal communication, 1982)). After that the magnetopause generally expands out to $r' = 13 \ R_\oplus$ (Freeman (1964)) for a couple of days.
To approximate the storm time magnetosphere equations (3-7) and (3-8) are used in the convection program. The Kp record for days 10-12 of November 1981, as published in JGR (volume 87, March, 1982), is used to simulate an average storm geomagnetic record. The 3-hour Kp block when Kp jumps from 3+ to 6 is assumed to represent the sudden commencement of the storm, at which time α is set to 10/7. After 2 hours α is reset to 10/13 simulating expansion of the magnetosphere. Two days after α is set to 10/13 it is reset to 1. The results are as expected: the injection trapping boundary moves inward (fig. 7).

Plasma that is either injected onto open drift paths, or that becomes detached from the plasmasphere, will drift towards the magnetopause. There the plasma will be accelerated and swept back into the tail (Freeman et al., 1977). According to Freeman (1979) there are two circulation patterns for heavy ions. The first is the transport of plasma over the polar regions and down into the cusps, where it is reflected back out into the plasmamantle. Some of this plasma could precipitate down to create argon induced aurorae. The second is low latitude flow along the inside of the magnetosheath, turning to come up the tail. This convection pattern is illustrated in figure 8.

The argon will therefore contaminate the entire magnetosphere and be accelerated by various mechanisms as it comes back up the tail. Due to the extremely large quantities of argon injected many regions of the magnetosphere
could come to contain substantial quantities of argon relative to the ambient density. For example the storm-time ring current would have a substantial argon component. From figure 5 we can see that plasma injected below $L = 3.5 - 5.5$ is trapped, and since the EOTV has used 80% of its fuel at $L = 4$ (Chiu, et al., 1980), only $\approx 15\%$ of the argon is injected onto open drift paths. This would mean injecting $8.25 \times 10^4$ Kg into the outer magnetosphere per EOTV flight.

Assuming half of this plasma is in the plasmasheet at any one time and that the plasmasheet, for our purposes, is $30 R_E$ wide, $60 R_E$ long and $6 R_E$ high, the resulting density is $0.22 \text{ cm}^{-3}$, roughly the same as the ambient densities of $0.1 - 1/\text{cm}^3$ given by Hill (1974). Although the densities are somewhat comparable the mass of $\text{Ar}^+$ is forty times that of $\text{H}^+$, the dominant ion. Thus mass dependent quantities will be substantially affected. For example, the Alfvén speed would decrease by a factor of $\approx 6$.

This huge increase in mass density could also affect the substorm mechanism. It is reasonable to expect that whatever the critical level of magnetic pressure to trigger a substorm is, the presence of a massive plasmasheet would raise that trigger level. If substorms were to happen 6 times less frequently one would expect them to be 6 times more violent, the energy input being the same. Aurorae many times brighter than normal, with a strong argon component, would be a surreal sight. In addition to being beautiful, such events could disrupt electrical grids in
high latitude areas (Akasofu and Aspnes (1982)) and even increase corrosion in pipelines.

IV. Charge Exchange of Ar\textsuperscript{+} with Exospheric Hydrogen

An important loss process for trapped argon will probably be charge exchange with neutral exospheric hydrogen. To calculate the charge exchange rates a program was written which acts as a subroutine within the framework of the convection program described in Chapter 3. Each injection point is assumed to inject a blob of plasma into the magnetosphere. The argon plasma is convected over varying radial distances along the drift path, so the lifetimes can vary enormously along the path. To get an average lifetime for each time interval the subroutine calculates the remaining fraction of ions and the average e-folding time along the path up to that point.

The probability of charge exchange in a single bounce is:

\[ P = \sigma s_0 d \]  \hspace{1cm} (4-1)

where \( \sigma \) is the crosssection, \( s_0 \) is the path length of a bounce and \( d \) is the neutral density. If the plasma executes \( n \) bounces per time interval, where \( n = s_0/v \), then the amount of argon lost from amount \( N_0 \) at the start of the \( i^{th} \) interval is

\[ N_{\text{Lost}} = N_i (1-P)^n . \]  \hspace{1cm} (4-2)

The remaining number of ions in the \( i^{th} \) interval is then
\[ N_{i+1} = N_i - N_{\text{Lost}} \]

and the fraction of ions lost up to that point is

\[ F_i = N_o \left( 1 - \frac{N_{\text{Lost}}}{N_o} \right). \tag{4-3} \]

If \( t_i \) is the amount of time elapsed to lose a fraction \( F_i \) of the original ions then the average e-folding time is

\[ \bar{\tau} = -t_i / \ln(1 - F_i). \tag{4-4} \]

It is assumed that the argon is executing bounce motion in a dipole field. This results in an inconsistency in that the convection program uses a corrected dipole field (Mead (1964)), while the charge exchange subroutine uses only the dipole component. This was done for the sake of calculational simplicity. In a dipole field the bounce path length is given by

\[ S = 2v \int_{s_m}^{s_m'} \frac{ds}{v|| (s)} = 2 \int_{s_m}^{s_m'} \frac{ds}{[1 - B(s)B_m]^{1/2}} \tag{4-5} \]

in which \( v \) is the velocity (constant over a bounce), \( v|| (s) \) the speed parallel to \( \hat{B} \) as a function of field line position, \( B_m \) the minor field, and \( (s_m, s_m') \) are the conjugate mirror points. For equatorial pitch angles \( 40^\circ < \alpha_o < 90^\circ \) an approximation to (4-5) is given by Roederer (1970) to be

\[ s_o = 4R_\oplus L (1.30 - 0.56 \sin \alpha_o) \tag{4-6} \]

To calculate the number of bounces per time interval it is necessary to calculate the momentum, \( p \), and to calcu-
late $s_0$ from (4-6) $a_0$ is needed. The first adiabatic
invariant gives that

$$
\frac{\delta p}{\delta s} \propto \frac{p^2}{B} \propto \frac{\sin^2 a(s)}{B(s)} \propto \text{constant} \quad (4-7)
$$

The second invariant, $\delta p \parallel ds \equiv J$, can be written using
(4-7), as

$$
J = 2p \int_{s_m^{+}}^{s_m^{-}} \cos a(s) ds = 2p \int_{s_m^{+}}^{s_m^{-}} \left[ 1 - \left( \frac{B(s)}{B_m} \right)^{1/2} \right] ds. \quad (4-8)
$$

Following Roederer (1970) $B(s)$ is expanded as

$$
B(s) = B(0) + \frac{1}{2} a_0 s 
$$

where $a_0 = \frac{d^2 B(s)}{ds^2} \bigg|_{\text{equator}}$ and $B(0) = B_0 = \frac{3.11 \times 10^{-5}}{L^3}$.

Using (4-9) Roederer gives (4-8) to be

$$
J = \frac{2p\pi}{\sqrt{2}} \left( \frac{B_m}{a_0} \right)^{1/2} \left[ 1 - \frac{B_m}{B_0} \right] = \pi \left( \frac{2B_m}{a_0} \right)^{1/2} \cos^2 a_0 \quad (4-10)
$$

where the last step utilized (4-7). To calculate $a_0$ we
have for a dipole field

$$
B(r, \theta) = \frac{K}{r^3} (1 + 3\cos^2 \theta) \quad (4-11)
$$

where $K = 3.11 \times 10^{-5}$, but since for dipole field lines
$r = L \sin^2 \theta$

$$
B(s) = B(\theta(s)) = \frac{K}{L^3 \sin^6 \theta} (1 + 3\cos^2 \theta) \quad (4-12)
$$

$$
\frac{dB}{d\theta} = \frac{dB}{ds} \frac{ds}{d\theta} \quad \text{so} \quad \frac{dB}{ds} = \frac{dB/d\theta}{ds/d\theta} \quad \text{and therefore}
$$
\[ \frac{d^2B}{ds^2} = \frac{d/d\theta (dB/ds)}{ds/d\theta}. \quad (4-13) \]

Since \( dr = 2L \sin \theta \cos \theta d\theta \) and \( ds = \sqrt{dr^2 + r^2 d\theta^2} \)

\[ \frac{ds}{d\theta} = L \sin \theta (1 + 3 \cos^2 \theta)^{1/2}. \quad (4-14) \]

It is found that (4-13), evaluated at the equator \((\theta = 90^\circ)\)

becomes

\[ \left. \frac{d^2B}{ds^2} \right|_{\theta = 90^\circ} = a_o = \frac{9B_o}{(L R_\theta)^2}. \quad (4-15) \]

We also have, using (4-7) and (4-9)

\[ \frac{p_\bot^2}{2m} = \mu B(s) = \mu \left[ B_o + \frac{1}{2} a_o s_m^2 \right]. \quad (4-16) \]

At \( s_m \), \( p_\bot = p \) so

\[ \frac{p^2}{2m} = \mu \left[ B_o + \frac{1}{2} a_o s_m^2 \right] \quad (4-17) \]

Also \( B_m = B_o + \frac{1}{2} a_o s_m^2 \) and \( \cos^2 \alpha(s) = 1 - B(s)/B_m \), so rearranging these we find that at \( s = 0 \)

\[ (B_o + \frac{1}{2} a_o s_m^2) \cos^2 \alpha_o = \frac{1}{2} a_o s_m^2 \quad (4-18) \]

which to second order in \( \cos \alpha_o \) gives

\[ \cos^2 \alpha_o = \frac{1}{2} a_o s_m^2 / B_o. \quad (4-19) \]

Using (4-19) equation (4-17) is solved for \( p \) to yield
$$p = \sqrt{2mB_o} \left( 1 + \cos^2 \alpha_o \right)^{1/2} \quad (4-20)$$

Equation (4-20) coupled with (4-10) give two equations in the two unknowns, $\alpha_o$ and $p$. However, to solve them iteratively (4-10) must be rewritten. Using (4-7), without much trouble, one can derive from (4-10)

$$\alpha_o = \arctan \left( \frac{\sqrt{2p}}{J} \left( \frac{L R_\Phi^2}{9} \right)^{1/2} \cos \alpha_o \right) \quad . \quad (4-21)$$

This has the advantage that the argument of arctan can range from $+\infty$ to $-\infty$. Thus (4-20) and (4-21) can be easily iterated to give $\alpha_o$ and $p$, given $L$ and the initial values of $\mu$ and $J$.

Since it is assumed that the EOTV spirals out to GEO in the equatorial plane, the initial pitch angle would come from the dipole tilt angle. It is found that

$$\alpha_{\text{injection}} = 90^\circ + 11.7^\circ \sin(\phi + 69^\circ - 15G) \quad (4-22)$$

where $\phi$ is the angle, measured from midnight, at the injection point, and $G$ is the Greenwich time (in hours) of injection. The colatitude of injection in magnetic coordinates, $\theta$, is given by

$$\cos \theta = \sin \theta_o \cos(\phi + 69 - 15G). \quad (4-23)$$

Since $B(s^\perp)/\sin^2 \alpha(s^\perp) = B_o/\sin^2 \alpha_o$ it is easy to calculate $\mu$ and $J$ for the first time interval, after which they are held constant.
Next it is necessary to calculate the density of exospheric hydrogen. The model used is that given by Chamberlain (1963). In this model, considering both satellite and ballistic hydrogen, the density is given by

\[ d = d(\lambda_c) \xi(\lambda(r)) \exp\left[\lambda - \lambda_c\right] \quad (4-24) \]

where \(d(\lambda_c)\) is the density at the critical height, \(r_c\), and

\[ \lambda(r) = \frac{mM_G}{kT_c r} . \quad (4-25) \]

It is assumed that \(r_c = 500 \text{ Km}\), therefore \(\lambda_c = 7.033\), \(T_c = 999 \text{ K}\), and \(d(\lambda_c) = 8 \times 10^4 \text{ cm}^{-3}\) (Chamberlain (1978)).

The partition function, \(\xi(\lambda(r))\), is a monotonically decreasing function of \(r\) and is a measure of what fraction of the Maxwell velocity spectrum is unavailable in the velocity integration due to trajectory restraints. This function is given by a numerical table in Chamberlain (1963).

Since the ion has a considerable fraction of its path near the mirror point, the average density along a field line is assumed to be

\[ \bar{d} = \frac{1}{5} (2d(r_{eq}) + 3d(r_m)) \quad (-4-26) \]

where \(r_m\) is the mirror point.

The last piece of information needed is the charge exchange crossection for \(\text{Ar}^+\) on H. Unfortunately, it seems this number has never been measured (D. H. Crandall (personal communication, 1982)). There is, however, a
method of estimating $\sigma(v)$ known as the "Adiabatic Theory" (Rapp and Francis (1962), Hasted (1964)). The method used is to calculate an asymmetric nonresonant process by a two-state approximation, which is based on symmetric resonant charge transfer theory. This analysis is valid for $v < 10^8$ cm/s to $v > 10^5/\mu^{1/2}$ cm/s, where $\mu$ is the reduced mass (in amu) of the pair. Since for a 2 KeV Ar$^+$ $v = 9.8 \times 10^6$ cm/s the velocity is in the proper range.

Rapp and Francis (1962) start out by calculating the probability of charge transfer, as a function of impact parameter and velocity, for the resonant, symmetric case. The result is

$$P(b, v) = \sin^2 \left( \frac{2\pi}{\gamma a_o} \right)^{1/2} \left( \frac{I}{\hbar v} \right) b^{3/2} \left[ 1 + \frac{a_o}{\gamma b} \right] \exp \left[ -\frac{\gamma b}{a_o} \right], \quad (4-27)$$

with $I$ being the ionization potential, $a_o$ the Bohr radius, and $\gamma \equiv (I/13.6\text{eV})^{1/2}$. The crosssection is then

$$\sigma(v) = \int_0^\infty 2\pi P(b, v) b \, db. \quad (4-28)$$

For the nonsymmetric, nonresonant case Rapp and Francis (1962) give that

$$P(b, v) = f P_o(b, v) \text{sech}^2 \left[ \frac{w}{v} \right] \left( a_o \pi b/2\gamma \right)^{1/2} \quad (4-29)$$

where $P_o(b, v)$ is given by (4-27), $w = (\text{ground state energy difference})/\hbar$, and $f$ is a spin statistical factor. In the case of Ar$^+$ ($s = \frac{1}{2}$) plus H ($s = \frac{1}{2}$), we note that only
$[\text{Ar}^+ + \text{H}]$ complexes with $s = 0$ can result in a charge transfer. There are three ways the net spin of $[\text{Ar}^+ + \text{H}]$ can be 1 ($m_s = \pm 1, 0$) and only one way $s$ can be 0 ($m_s = 0$), therefore $f = \frac{1}{4}$.

Equation (4-16), using (4-29), was integrated using a Tektronix mathematics library program (Plot 50). The resulting cross-section is strongly velocity dependent (fig. 9). A table for $\sigma(v)$ was thus prepared and read into the charge exchange program, with linear interpolation between table values.

For each time interval, the charge exchange subroutine iteratively calculates $p$ and $a_0$ to 1% in $a_0$. These numbers are then used to find the mirror point, the bounce path length, etc. Charge exchange lifetimes, averaged over a drift path circulation, are given in Table II. These lifetimes (on the order of months) are very long, since for $v = 100 \text{ Kms}^{-1}$, $\sigma(v)$ is only $3.25 \times 10^{-18} \text{ cm}^2$. Injection points with the lowest lifetimes are either close to the Earth, where the density of H is large, or they are injections that result in vortex drift paths.

Thus charge exchange will not be able to clear out accumulations of plasma in the outer plasmasphere (except for $\text{Ar}^+$ injected along the dusk meridian) before a magnetospheric storm blows the argon sunward. However, the action of both charge exchange (in the inner plasmasphere) and magnetic storms (in the outer plasmasphere) should keep the average accumulation of $\text{Ar}^+$ down to that injected
by a few EOTV flights. Yet this would still result in average Ar\(^+\) densities ranging from \(n_{\text{Ar}^+} \approx \) ambient density at low altitudes, to \(n_{\text{Ar}^+} \approx 10\) times the ambient density in the mid-plasmasphere.

The reliability of the charge exchange subroutine can be checked by comparing the program to previous lifetimes calculated for ring current protons. The convection-charge exchange program is easily modified to simulate ring current protons in the magnetosphere, and calculate \(\tau_{\text{ce}}\). Several authors (Swisher and Frank (1968), Tinsley (1976)) have calculated \(\tau_{\text{ce}}\) for ring current protons. Some of these lifetimes are given along with the ones calculated by the method described, in Table III. One can see the results are in good agreement with Tinsley (1976), but that there is a factor of \(\approx 4-5\) difference with Swisher and Frank (1968). This is due to the different hydrogen models. Tinsley's model is the more reliable one and the densities given in Tinsley (1976) are roughly the same as those given by the model of Chamberlain (1963).

In addition to charge exchange other loss processes will be active, such as the loss cone "drizzle" fueled by coloumb and wave-particle pitch angle scattering. These other mechanisms could be very important in the total loss rate and future work should investigate the subject.
V. Conclusions and Future Research Directions.

The construction of solar power satellites with terrestrial materials would require the injection of $\approx 5.5 \times 10^6$ Kg ($8.3 \times 10^{31}$ ions) of $\text{Ar}^+$ into space between LEO and GEO per SPS. The resulting plasmaspheric densities resulting from such massive injection of ions would be 1 to 10 times the ambient densities. In addition a sizeable fraction of the injected $\text{Ar}^+$ will enter the general convective flow of plasma through the magnetosphere. Depending on $\text{Ar}^+$ loss rates from the magnetosphere, considerable densities of argon in the plasmasheet could build up, significantly altering such fundamental dynamic quantities like the Alfvén speed.

Theoretical modeling of the argon plasma beam indicates that the beam will travel distances $\lesssim 2 \times 10^3$ Km before it is stopped. Two notable features of beam propagation are expected to be Alfvén wave generation by the beam and field aligned currents set flowing by polarization fields in the beam. Both of these effects would result in localized heating of the ionospheric foot of field-lines threading the beam. Thus as the EOTV orbits the earth there should be a "hot spot" in the ionosphere that follows the EOTV as it spirals out to GEO. This model seems to be reliable, as it is in agreement with the experimental observations reported by Haerendel and Sagdeev (1981).

Once the argon plasma makes the transition from beam motion to single particle motion, it drifts, controlled
by the local electromagnetic field. These drift patterns have been calculated and identified using a simple, analytic model of the magnetosphere. Regions of stable trapping have been mapped out using this computer code, and a rough simulation of the storm-time magnetosphere was used to study the effect of storms on the trapping boundary.

Charge exchange loss rates, averaged over a drift path, were calculated. These lifetimes are too long to clear out accumulations between storms or EOTV flights. But at low altitudes and for plasma injected on vortex drift paths, charge exchange is a significant loss mechanism. Because of the not overly rapid rate of charge exchange, the thermal proton population is not expected to substantially increase since the charge exchange rate is less than the total ionization rate for H in the magnetosphere (Siscoe and Mukherjee, 1972).

There are several areas for further study. One of the most important of these is Ar\(^+\) plasma instabilities that transfer energy to the environment. For example, the ion cyclotron resonance is expected to be very strong since the velocity anisotropy of the injected plasma is so great. And since the plasma, once injected, will be around for \(> 2\) weeks there will be plenty of time to transfer energy from the argon to the plasmasphere.

Another major question is the effect on substorms of large quantities of argon ions in the plasmasheet. Also the presence of heavy argon ions is expected to damp the
precipitation of MeV electrons in the radiation belts (Chui, et al. (1980)). In addition more accurate modeling of the magnetosphere is needed, along with calculations of the quantities of momentum lost by the beam and how much the ionosphere is heated by this.

As one can see, there are a multitude of different questions that can arise in regard to this problem. Undoubtedly research in the above mentioned areas will suggest new questions, so there is no lack of room for investigation. Yet these are questions that must be answered before something like the SPS reference system can be constructed. In the meanwhile large ion thruster tests, with extensive observations to study the effects, are now possible with the use of the shuttle. Such experiments would be quite valuable since it is likely that ion thrusters will be an important component in future space propulsion.
Table I: EOTV Characteristics

<table>
<thead>
<tr>
<th>LEO</th>
<th>GEO</th>
<th>LEO trip time</th>
<th>130 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO departure mass</td>
<td>6,667,328 Kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cargo</td>
<td>5,310,568 Kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propellent mass</td>
<td>547,294 Kg</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table II: Ar$^+$ charge exchange lifetimes (drift path averaged)

<table>
<thead>
<tr>
<th>Injection Pt. (R,θ)</th>
<th>Lifetime (days)</th>
<th>Fraction of Ar$^+$ lost over one circulation</th>
<th>Drift path circulation period (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1.3,0)</td>
<td>14.7</td>
<td>7.5 %</td>
<td>27.5</td>
</tr>
<tr>
<td>(1.5,0)</td>
<td>31.8</td>
<td>3.6 %</td>
<td>28.0</td>
</tr>
<tr>
<td>(2,0)</td>
<td>110.5</td>
<td>1.1 %</td>
<td>29.3</td>
</tr>
<tr>
<td>(3,0)</td>
<td>351.9</td>
<td>.39%</td>
<td>33.0</td>
</tr>
<tr>
<td>(3.5,0)</td>
<td>431.9</td>
<td>.35%</td>
<td>36.6</td>
</tr>
<tr>
<td>(3,90)</td>
<td>1170.3</td>
<td>.12%</td>
<td>32.9</td>
</tr>
<tr>
<td>(3,270)</td>
<td>72.9</td>
<td>2.0 %</td>
<td>35.3</td>
</tr>
<tr>
<td>(4.5,225)</td>
<td>26.2</td>
<td>9.4 %</td>
<td>62.5</td>
</tr>
<tr>
<td>*(4.5,240)</td>
<td>1.46</td>
<td>97.4 %</td>
<td>128.0</td>
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<tr>
<td>*(4.5,300)</td>
<td>1.35</td>
<td>97 %</td>
<td>114.0</td>
</tr>
<tr>
<td>(4.5,315)</td>
<td>13.1</td>
<td>20.1 %</td>
<td>70.7</td>
</tr>
<tr>
<td>*(5,270)</td>
<td>3.89</td>
<td>54.5 %</td>
<td>73.5</td>
</tr>
<tr>
<td>*(6,270)</td>
<td>25.5</td>
<td>9.7 %</td>
<td>62.4</td>
</tr>
<tr>
<td>*(5,300)</td>
<td>3.42</td>
<td>61.2 %</td>
<td>77.7</td>
</tr>
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</table>

*These injection points result in vortex drift paths.
Table III: Calculated Ring Current Proton lifetimes compared to Swisher and Frank (1968), and Tinsley (1976)

<table>
<thead>
<tr>
<th>Height $R_E$</th>
<th>Equatorial pitch angle ($\alpha_0$)</th>
<th>Energy (KeV)</th>
<th>(hours) calculated</th>
<th>(hours) Swisher &amp; Frank</th>
<th>(hours) Tinsley</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>45°</td>
<td>30</td>
<td>3.4</td>
<td>---</td>
<td>3.2</td>
</tr>
<tr>
<td>3.5</td>
<td>45°</td>
<td>30</td>
<td>5.5</td>
<td>19$^{a,b}$</td>
<td>5.4</td>
</tr>
<tr>
<td>4</td>
<td>45°</td>
<td>30</td>
<td>8.1</td>
<td>---</td>
<td>8.4</td>
</tr>
<tr>
<td>4.5</td>
<td>45°</td>
<td>30</td>
<td>11</td>
<td>---</td>
<td>12.0</td>
</tr>
<tr>
<td>4.5</td>
<td>61.7°</td>
<td>35</td>
<td>12.7</td>
<td>64$^b$</td>
<td>---</td>
</tr>
<tr>
<td>5</td>
<td>65.2°</td>
<td>35</td>
<td>16.8</td>
<td>91$^b$</td>
<td>---</td>
</tr>
</tbody>
</table>

$^a$Height $= 3.7$ $R_\oplus$

$^b$Energy $= 31 - 49$ KeV
Figure Captions

Figure 1 An illustration of the SPS transportation system.

Figure 2 Thruster plasma plume generated Alfvén wave propagating down to the ionosphere.

Figure 3 The surface at which the magnetic field pressure is twice the plasma beam pressure (thermal plus dynamic). The thruster is assumed to have a post charge exchange beam current of 28940.8 amps.

Figure 4 The coordinate system used in the convection program, including the EOTV.

Figure 5 The four types of argon ion drift paths are plotted in the equatorial plane. Type 1 drift paths are closed "normal" drift paths. Type 2 drift paths are the "vortex" paths, while type 3 and 4 are the open counterparts to type 1 and 2 drift paths.

Figure 6 The injection trapping boundary generated with the argon drift path program. Plasma injected in region 1 is trapped on type 1 drift paths (see figure 5), while plasma injected in region 2 is trapped on type 2 drift paths. Plasma injected in region 3 is convected to the magnetopause on type 3 and 4 paths.

Figure 7 Average injection trapping boundary resulting from the storm-time model. Plasma injected inside boundary remains trapped (on average).

Figure 8 Large scale magnetospheric convection from Freeman (1979).

Figure 9 The charge exchange crosssection vs. velocity as calculated from the equations given by Rapp and Francis (1962).
FIGURE 3

- Each tic is 175 km.
- Each tic is 10 km.
- Each tic is 50 km.
FIGURE 5

THE TICS ARE IN EARTH RADII.
The tics are in Earth radii.
Figure 7

The ticks are in Earth radii.
CROSSECTION (IN UNITS OF 1E-16 cm^2)

FIGURE 9
References


U.S. National Aeronautics and Space Administration, Solar Power Systems Concept Definition Study (exhibit C), SD 78-AP-0115, 1978.