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Fate of Argon-Ion Injection in the Magnetosphere

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Large-scale operation of argon-ion engines in space may give rise to global-scale modifications of the magnetosphere. This paper considers ion-injectant effects of solar-powered orbit transfer operations of large payloads ($\sim 10^7$ kg) similar to that of the projected Satellite Power System. It is likely that the ion beam would interact and deposit its energy and mass in the magnetosphere. Magnetospheric heating may change the compositional distribution of thermal ions, thus causing enhancement of relativistic Van Allen radiation belt electrons. Effects of magnetospheric response to the ion engine beam will be discussed in this paper.

Introduction

THE transportation of large payloads, such as that of the proposed satellite power system, from low Earth orbit to higher space orbit (e.g., geosynchronous orbit) by ion engines implies substantial modification of the magnetospheric environment. This is because the mass of exhaust plasma approaches or exceeds that of the local natural magnetospheric plasma. This paper examines the basic physical scenarios of magnetospheric modification by the artificially injected plasma. The emphasis will be placed on identifying the physical mechanisms of the modifications rather than on a specific enumeration of space-based and Earth-based systems which may be affected by these modifications.

The subject of magnetospheric modification by a massive plasma cloud is obviously very complicated and, to a major extent, unsolved. An attempt to trace the dynamical history of the artificial plasma is too difficult a task here, although it would eventually have to be faced. The efforts here will be limited to the initial phases of the problem for which the question of the long-term fate of the artificially injected material is ignored.

Argon-Ion Emission Models

The current technology of ion engines is still evolving.[1,2] Therefore, the parameters of argon-ion engine operations in space must largely be regarded as uncertain at present, although it is by now fairly firm that the most economical and environmentally safe propellant is argon. According to the reference system report of the satellite power system concept development and evaluation program,[3] argon-ion engines of specific impulse (13,000 s) are projected to perform major propulsion and stationkeeping duties for cargo orbit transfer vehicles (COTV) as well as for the spacecraft at geosynchronous orbit. Some projected characteristics of the ion-engine operation are listed in Table 1.

From Table 1, it is seen that the ion-beam exhaust is a very dense but fairly cool plasma whose streaming kinetic energy (3.5 keV) far exceeds the thermal energy. Furthermore, in order to propel the COTV to geosynchronous orbit, the argon plasma beam will be directed perpendicular to the geomagnetic field at the equatorial plane in the azimuthal direction (Fig. 1). Plasma beams propagating perpendicular to the geomagnetic field entail very interesting dynamical interactions with the magnetosphere-ionosphere system.

For consideration of emission parameters, Fig. 2 shows[4] the relationship between payload mass and argon-propellant mass needed to transport the payload from low Earth orbit (350-km altitude) to synchronous altitude with an accompanying orbital plane change of 28.5 deg. Obviously, the amount of propellant required for a given payload depends on the ion-beam streaming speed. For a satellite power system payload of $\sim 10^7$ kg, it will be necessary to expend $\sim 10^6$ kg of argon propellants. This is $\sim 10^{31}$ Ar^+ ions, roughly comparable to the total content of the natural plasmasphere and ionosphere above 500 km. The exhaust deposition rate in terms of the fraction of mission lifetime, which is nominally 130 days, is shown as a function of geocentric radius R on Fig. 3. Thus, 80% of the total propellant content is released in the plasmasphere, $R \leq 4R_E$. The number of Ar^+ ions released at a given geocentric distance (within a flux shell of twice the argon gyroradius thickness) for a payload mass of 10^7 kg is shown in Fig. 4. For comparison, the number of ambient electrons lying within the same flux shell at the given distance R is also shown. The energy content released into a given shell dominates the ambient energy content, however, since the kinetic energy of the streaming Ar^+ is considerably greater than the ambient thermal energy.

The fate of the injected Ar^+ ions depends largely on the plasma dynamics of the Ar^+ ion cloud interacting with the ambient magnetosphere. Some features of this dynamical interaction will be addressed in the next section.

Beam-Magnetosphere and Beam-Ionosphere Interactions

The physics of a plasma beam propagating transverse to a homogeneous magnetic field is very simple. If the beam is sufficiently dense so that polarization currents can maintain the charge-separation electric field necessary to satisfy $\bar{E}+(1/c)\bar{v}\times\bar{B}=0$ ($\bar{v}$ is the beam velocity), the beam will propagate across the magnetic field. An alternative view of the effects of the polarization electric field $\bar{E}$ seen by a comoving observer above is that, in the coordinate system of the stationary magnetic field outside the cloud, the plasma cloud, under the force of $\bar{E}$, appears to be drifting with a velocity $\bar{v}=c(\bar{E}\times\bar{B})/B^2$. But $\bar{v}$ is also the drift velocity of magnetic-field lines in the cloud induced by the electric field $\bar{E}$; hence, the field lines in the cloud are said to be "frozen" into the plasma, drifting with velocity $\bar{v}$ relative to the field lines outside the cloud. For this condition to apply, the beam density n_A must satisfy

$$4\pi n_A m_A c^2/B^2 \gg 1 \tag{1}$$

where m_A is the argon-ion mass.[5] Numerically, Eq. (1) yields $(500-30{,}000)\ n_A(\mathrm{cm}^{-3} \gg 1$ for $2\leq L\leq 4$, which would seem to be well satisfied for the beam parameters of Table 1. If so, the beam simply moves out of the magnetosphere to be dissipated in space.[5]

Unfortunately, such a simple situation does not hold in the Earth's ionospheric and magnetospheric environment. Plasmas in the magnetosphere, and especially in the

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Table 1 Ion-engine characteristics

Specific impulse (s)	13,000
Ar^+ kinetic energy (keV/Ar^+)	3.5
Ar^+ streaming speed (km/s)	130
Current density (A/cm^2)	2.5×10^{-2}
Temperature (K)	~1000
Beam density (cm^{-3})	$\sim1.5\times10^{10}$
Beam diameter at exit (cm)	100
Beam spread at exit (deg)	~10 deg
Number of engines required for SPS/COTV	~300

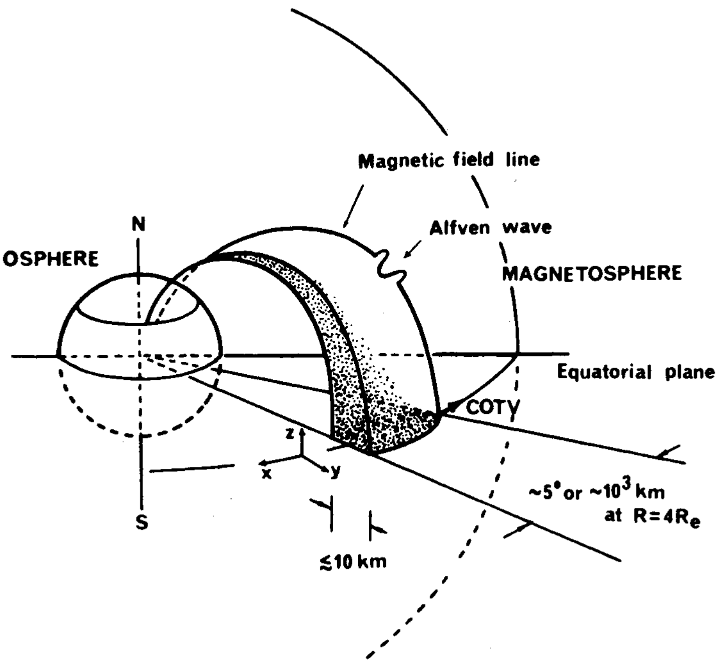

Fig. 1 COTV argon-ion emission scenario at L-4.

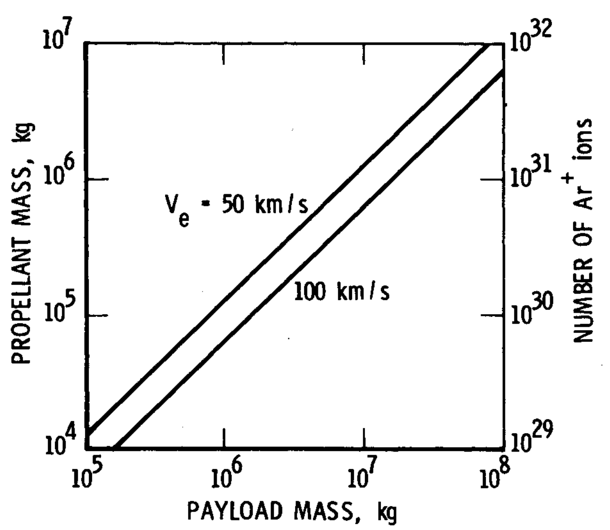

Fig. 2 Argon-propellant mass necessary for transport between 350 km and synchronous altitude.

ionosphere, act to short out the charge-separation electric field $\vec{E}$ and stop the beam in a distance of the order of 1000 km. As a consequence, the simplest effects of magnetosphere-ionosphere coupling would predict dissipation of the beam energy in a rather localized region and may well deposit (by Joule heating) a substantial amount ($\sim10^{14}$ ergs/s) of energy in a relatively small area of the ionosphere connected by magnetic-field lines to the argon beam (Fig. 1), long before the majority of Ar^+ ions are physically present in the ionosphere.

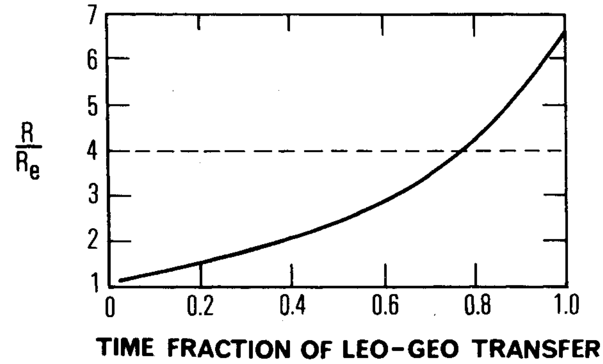

Fig. 3 Fraction of mission lifetime spent at various geocentric distances.

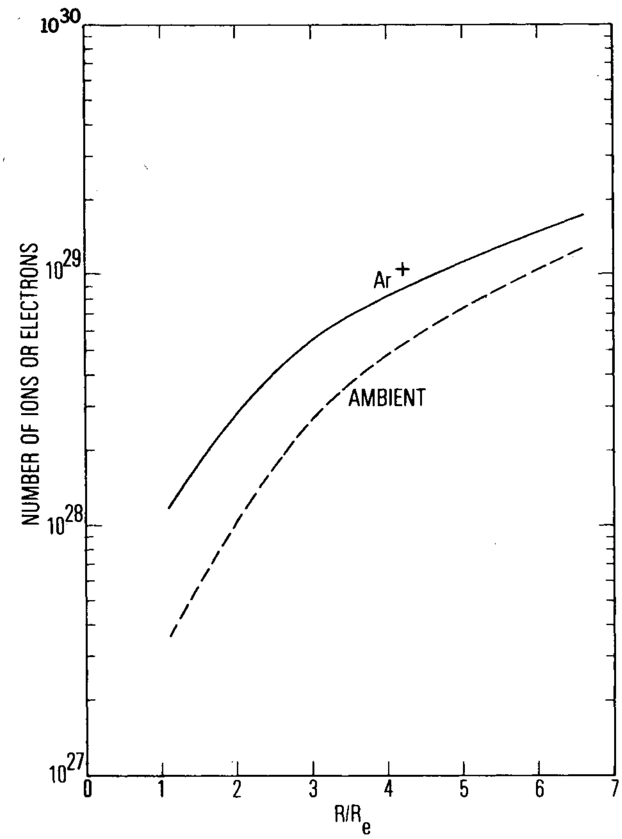

Fig. 4 Ratio of Ar^+ ions released to ambient electrons in a dipole field shell two argon gyroradii thick.

The basic physics of the largest-scaled magnetospheric response to a plasma beam is well known and was worked out by Scholer[6] and Pilipp[7] in connection with the HEOS-I release of an ionized barium cloud.[8] This high-altitude release had, as will the argon engines, a high initial β ($=8\pi P_\perp/B^2$ where $P_\perp$ is the pressure perpendicular to the field lines of the injected plasma). The beam expands rapidly, in a direction perpendicular to $\vec{v}$ and to $\vec{B}$, to the point where $\beta\leq1$. Of course, the beam also spreads without constraint (except for mirroring forces) along $\vec{B}$.

One could calculate the final beam spread Δy in the y direction (or $\vec{v}\times\vec{B}$ direction; see Fig. 1) using zero-Larmor-radius magnetohydrodynamics; that is, by equating $P_\perp$ (including thermal pressure $n_A kT$ plus dynamic pressure $\frac{1}{2}n_A m_A v^2\tan^2\theta$) to the asymptotic plasmaspheric pressure, which is essentially $B^2/8\pi$. Assuming $\Delta z\geq\Delta y$, one finds that Δy is less than $\sim$ 1 km for $L<4$, much smaller than the argon-Larmor-radius R_A. In effect, this calculation of the confinement of gyration centers shows that Δy is of the order of the argon-Larmor-radius (40-80 km at $L=4$), because the gyration centers are confined to a Δy much smaller than the

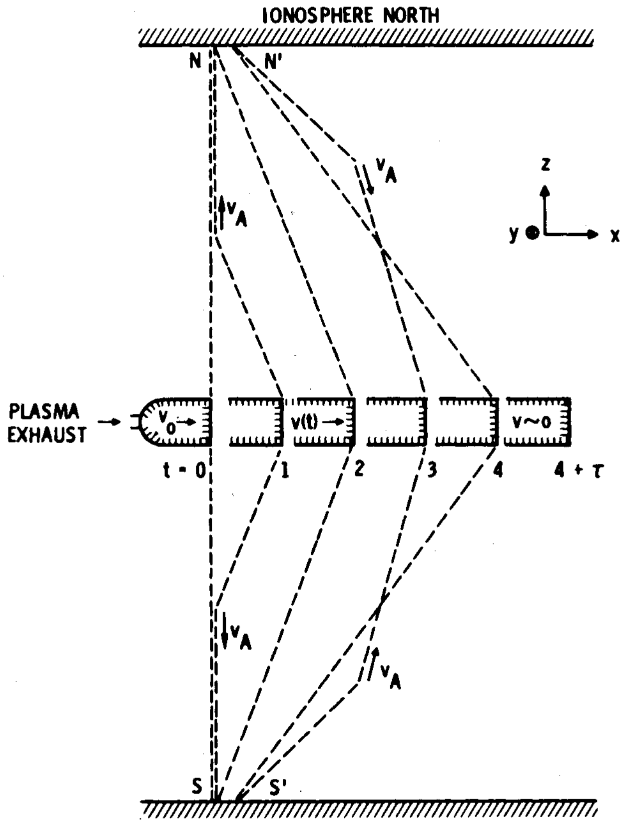

Fig. 5 Beam-magnetosphere and beam-ionosphere interactions.

argon-Larmor-radius, at least for the first ten or so Larmor radii downstream from the nozzle. Past this, the ~10-deg angular divergence of the beam could produce substantially larger Δy as long as Eq. (1) continues to hold.

In first approximation then, a beam of $\Delta y \approx R_A$ propagates across the Earth's field as shown in Fig. 5. In this figure, the dotted lines show schematically the Earth's magnetic-field lines at various times. The condition $\vec{E} + (1/c)\vec{v} \times \vec{B} = 0$ means that these lines are frozen into the plasma beam at the equator. Their distortion is an Alfven wave ($t = 1$, in Fig. 5). At $t = 2$, the wave reaches the ionosphere, where the foot of the field line slips, because of the ionosphere's finite conductivity; the wave then reflects back to the beam ($t = 3, 4$).

The field lines act somewhat like rubber bands, tending to retard the cloud. The physical mechanism is that the polarization charges responsible for $\vec{E}$ move along the field lines at the Alfven speed v_A, accelerating magnetospheric plasma and transferring momentum out of the beam. Ultimately, the Alfven wave reaches the ionosphere and drives dissipative Pedersen currents. (In the absence of dissipation, the argon beam would oscillate like a mass on a rubber-band field line.)

Letting M_A be the mass density of the argon beam integrated along field lines passing through the beam, we obtain

$$M_A = \int \mathrm{d}z n_A m_A \tag{2}$$

When this mass density is equal to the mass per unit area incorporated by the Alfven wave, namely $2v_A \tau n_0 m_p$, the beam is essentially stopped. Here τ is the time it takes the Alfven wave to travel a distance $v_A \tau$, and $n_0 m_p$ is the magnetospheric mass density per unit volume.

In a numerical-model calculation based on the physical ideas discussed above but with realistic magnetospheric and ionospheric magnetic fields and plasma densities (which vary drastically in space), it is demonstrated that the beam velocity behaves like $v \simeq v_0 \exp(-t/\tau)$ with $\tau \simeq 10$ s. Thus the beam can only travel a distance of $v_0 \tau \simeq 10^3$ km downstream before the major part of its momentum is soaked up by the magnetosphere and ionosphere.

The ionosphere "feels" the beam after a time $\approx l/v_A \approx$ tens of seconds (l is the length of the field line). The electric field E_I imposed on the ionosphere differs from the $(1/c)\vec{v} \times \vec{B}$ field, mapped to the ionosphere, for two reasons: First, the electric field diminishes along the field line by a factor of order $\exp(-l/v_A \tau)$; second, the electric field is partly reflected at the ionosphere (to make the upgoing Alfven wave at $t = 3, 4$ in Fig. 5). Scholer gives the relation

$$E_I = [2/(1+\chi)] E_{\text{out}} \tag{3}$$

$$\chi = 4\pi \Sigma_p v_A c^2 \tag{4}$$

where E_{out} is the field just outside the ionosphere, E_I the field in the ionosphere, and Σ_p the ionospheric Pedersen conductivity.

Numerical-model calculations indicate that the rate of beam-energy dissipation in the ionosphere is roughly a few ergs/cm^2/s occurring over an area of 10^3-10^4 km^2 in the ionosphere. These numbers are very much similar to energy dissipation by the aurora, except that the beam energy will be dissipated at middle and low latitudes.

Although the above scenario of magnetospheric response to the heavy-ion plasma beam is qualitatively in agreement with experiments in the far magnetosphere,[8] the quantitative aspects need to be verified by conducting active beam-plasma experiments in space. The physical basis for the Alfven shock interaction was first discussed in connection with Echo I satellite drag.[9] Preliminary evidence of Alfven shock generation connected with large artificial plasma injection in the ionosphere have been reported.[10,11] It has been claimed[5] that Alfven shocks would not be generated for beam speeds of ~300 km/s because such beams are "trans-Alfvenic." However, the above experiments[10,11] in the ionosphere and model calculations[12] indicate Alfven speeds greater than ~1000 km/s. In any case, the reference solar-power satellite-system plasma-beam speed shown in Table 1 (130 km/s) is definitely sub-Alfvenic. Therefore, Alfven-wave generation is an unavoidable consequence.[10,11]

The above discussion of beam-magnetosphere interaction concentrates on the largest-scaled interaction through generation of Alfven waves. On a smaller spatial scale, the beam interacts with the local magnetosphere through generation of plasma turbulence. The details of this interaction are very complex and current scientific understanding of beam-plasma turbulent processes is at best rudimentary.[12,13] However, the physical expectation that the plasma turbulent energy must be drawn from the beam streaming energy is unavoidable; hence, it must be concluded that plasma-turbulence processes increase, rather than decrease, the efficiency of the beam-stopping processes. The above Alfven-wave consideration is thus the slowest or minimal beam-stopping mechanism; yet, it is sufficient to stop the beam inside the magnetosphere. Should a turbulent sheath be formed locally, the anomalous resistivity associated with the turbulent sheath, formed perhaps by the observed ion cyclotron waves,[10,11] would act like the ionospheric resistivity to dissipate and short out the polarization electric field essential for beam propagation perpendicular to the magnetic field.[13] Thus, contrary to some claims,[5] the present preliminary observational evidence[10,11,13] points to plasma-turbulence effects to further decrease the beam-stopping time.

Intermediate Term Interactions of Argon Ions

Granted that the argon beam is dissipated in the magnetosphere, it begins to act like a man-made ring current of ≤ 1 keV ions, with a residual pitch-angle anisotropy left over from the initial injection nearly perpendicular to $\vec{B}$. (Just what energy and anisotropy are left after the beam-plasma interactions described in this section is not known at present;

they need to be evaluated in order to give a more precise picture of their influences on systems operations, such as increase in airglow and changes in radiation-belt dosage levels.) This ring current acts much like a natural one, subject to charge exchange, Coulomb scattering, and wave-particle interactions. A major difference is that the argon ring current is mostly inside the plasmasphere, while the natural ring current penetrates perhaps one Earth radius inside the plasmasphere with the rest outside. Nonetheless, there could be substantial overlap between the ring currents, especially during storm times when the plasmasphere is eroded and the natural ring current is driven in by convection electric fields. The argon ring current can make a substantial contribution to the plasmaspheric pressure and hence to the currents that flow there (both across and along $\vec{B}$). This will significantly stiffen the plasmasphere to deformations associated with enhanced storm-time convection electric fields and diminish the strength of electrostatic radial diffusion. The result will be (other things being unchanged) a buildup of ring-current particles and inhibition of inward transport of higher-energy particles.

Long-range Coulomb collisions with ambient electrons degrade the kinetic energy into ambient thermal energy causing substantial changes in pitch angle because these Coulomb collisions are primarily forward scatterings. For the energetic Ar^+ ions to be physically lost from the magnetosphere, they will have to suffer charge-exchange collisions which would allow the neutral argon atom to escape the plasmasphere. Figure 6 shows the comparison of charge-exchange lifetimes of Ar^+ ions in the plasmasphere ($L \geq 2$) with the thermalization lifetime due to Coulomb collisions. Note that the energies of Ar^+ ions shown in this figure are substantially lower than 3.5 keV because the effects of these collisions are deemed to be important substantially after the major part of beam-streaming energy is deposited in the magnetosphere. Also, note that the charge-exchange lifetimes ($\sim$100 h) are comparable to the average duration between magnetospheric storms which typically defines the lifetimes of the natural magnetospheric plasma. Thus, one expects that the injected Ar^+ plasma will substantially modify the magnetosphere with a time constant roughly equal to several days, until a new magnetospheric storm sweeps out the accumulation if the storm mechanism remains effective under the modified circumstances.

The energy input in the magnetosphere and ionosphere, by Joule dissipation of beam electric fields (previous section) and by Coulomb collisions with ambient electrons, will eventually evolve into the final form: thermal energy of the modified magnetosphere. In the average sense, this heating would raise the ionospheric-plasmaspheric temperature to a few electron volts. What is the primary consequence of ionospheric-plasmaspheric heating to a few electron volts? It is argued that this will lead to a modification of plasmaspheric composition. This argument is based on a steady-state model of the density and composition distribution of the plasmasphere[14]; thus it needs qualification and refinement based on further applied research. However, since the results are physically sound, the first-order estimates are sufficiently significant for present purposes.

Results of simple model calculations show that the addition of the argon ions will not upset the normal distribution of the plasmaspheric hydrogen and oxygen. However, as shown by the right-hand panel in Fig. 7, the addition of heat by the argon-ion interaction with the ambient medium or by Joule heating can drastically alter the plasmasphere. At high altitudes, hydrogen can be replaced by the heavier constituents (oxygen or a combination of oxygen and argon). These results are easily understood, because the increased heating drives O^+ and H^+ ions up the field line but the supply of ionospheric O^+ ions is orders of magnitude higher than H^+ ions, thus increasing the proportion of O^+ ions in the higher-altitude region. This situation is further accentuated by the gravitational sinking of Ar^+ ions relative to the accompanying electron, driving up more O^+ ions to maintain charge neutrality. It must be recognized also that the

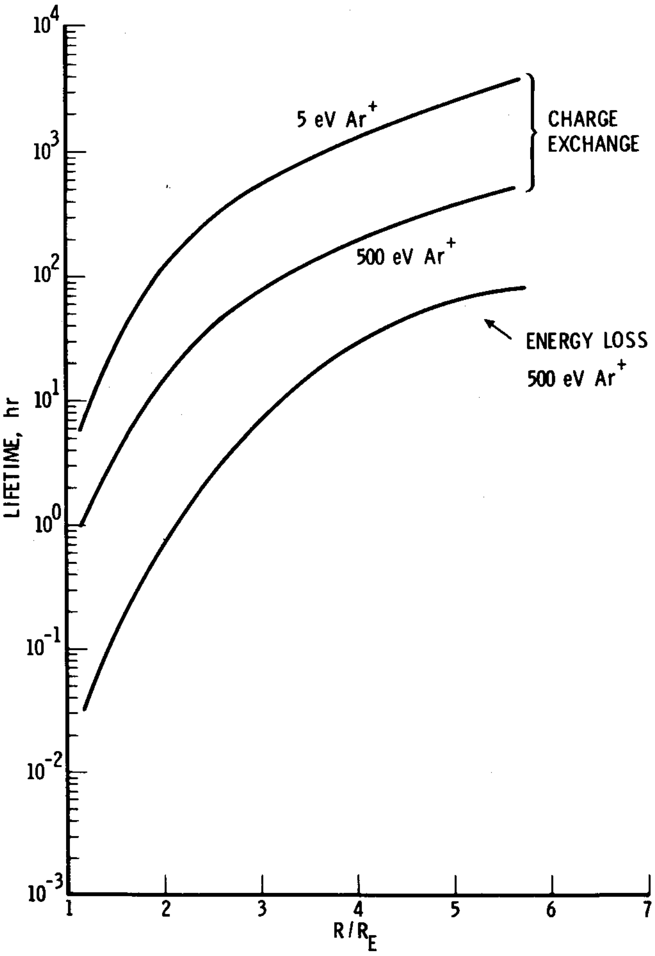

Fig. 6 Charge exchange and Coulomb lifetimes of Ar^+ ions in the equatorial plane.

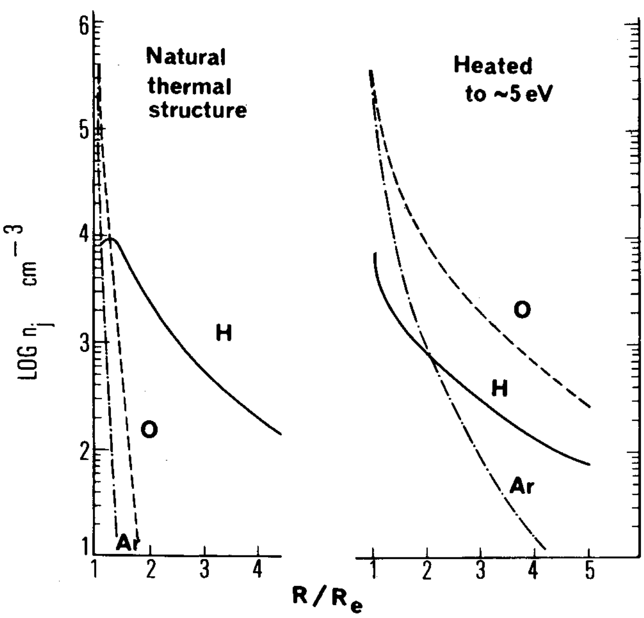

Fig. 7 The composition of the plasmasphere under natural thermal conditions (left panel) and under heated circumstances (right panel).

assumed boundary conditions are simplifications of the actual situation, which is very far from steady state. The argon ions will be introduced onto different L shells at different times. Plasma-convection processes and radial diffusion can modify the spatial distribution of the argon which, because of the nature of its source, is already quite different from that of a normal plasmasphere constituent. In addition, interhemispheric flows, which may affect the plasmasphere as a

Table 2 Satellite power system magnetospheric effects

Effect	Cause	Mechanism	System/Activities Impacted
1) Dosage enhancement of trapped relativistic electrons	O^+ and Ar^+ ions in magnetosphere due to exhaust and plasma sphere heating	Thermal heavy ions suppress ring current ion cyclotron turbulence which keeps electron dosage in balance in natural state	Space equipment; modification of human space activity
2) Artificial ionospheric current	Ionospheric electric field induced by argon beam	Beam-induced Alfven shocks propagate into ionosphere	Powerline tripping; pipeline corrosion
3) Modified auroral response to solar activity	Neutrals and heavy ions in large quantities	Rapid charge-exchange loss of ring-current particles	May reduce magnetic storm interference with Earth- and space-based systems
4) Artificial airglow	3.5-keV argon ions	Direct impact on atmosphere from LEO	Interference with optical Earth sensors
5) Plasma-density disturbance on small spatial scale	Plasma injection	Plasma instabilities	Signal scintillation for space-based communication

whole, were not included in the model. Work on including these effects is currently underway.

Large concentrations of heavy ions in the plasmasphere can cause major perturbations in the dynamics of the radiation-belt relativistic electrons.[4]

Conclusions and Magnetospheric Effects

This paper assesses the initial phases of the magnetosphere modification scenario of ion-engine exhaust from the projected cargo orbit transfer vehicles of the satellite power system. Aside from summarizing the emission scenarios of the various options, several important aspects of the initial fate of the ion-engine exhaust plasma, using presently available information, have been dealt with.

The question of the propagation of the ion-engine exhaust plasma beam across the geomagnetic field was examined. The plasma beam moves across the geomagnetic field and causes a disturbance of the magnetospheric plasma in the form of an Alfven wave. The inertia of the natural magnetospheric plasma, driven by the Alfven-wave disturbance, represents a braking force on the motion of the beam. This reaction force is able to stop the ion beam in a distance of ~ 1000 km, according to scaling of a number of studies conducted for release of barium in the ionosphere and magnetosphere.[8,10,11] The generation of an Alfven-wave disturbance by the plasma beam further implies that an electric field of magnitude comparable to the auroral electric field but associated with the Alfven wave is applied to the ionosphere at the footprint of the magnetic flux tube of the plasma beam (Fig. 1). The Joule dissipation (heating) in the ionosphere by this electric field is comparable to that in the auroral region during a magnetic storm.

The density and composition changes of the plasmasphere were roughly modeled under the assumption that the entire ion-engine exhaust will be stopped inside the magnetosphere. It is found that the mere addition of Ar^+ ions to the plasmasphere does not drastically change the composition of the plasmasphere, but the input of heat associated with the Ar^+ plasma exhaust will have a tendency to change the plasmaspheric composition by allowing ionospheric O^+ ions to be forced up into the far plasmasphere where the radiation belts are located.

The dynamical evolution of the injected argon-ion energy, roughly outlined above, determines the fate of these ions; but it also implies a number of magnetospheric effects upon space systems and upon human activities on the ground. For details of these, the reader is referred to Ref. 4. Table 2 is a summary of satellite power system magnetosphere effects.

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