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Parasitic Current Losses Due to Solar-Electric Propulsion Generated Plasmas

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Solar-electric propulsion is a leading candidate for many upcoming space missions. Under many circumstances plasma produced by charge-exchange reactions within the ion beam dominates the ambient environment near the spacecraft. The calculations presented here contain a predictive hydrodynamic model for the charge-exchange plasma expansion and a fully three-dimensional model for the structure of the plasma sheath around the solar array wing. Results of calculations for several configurations and voltage levels indicate that with kilovolt biases power losses of $\sim 10\%$ or more are likely, even with only one engine in operation, and that ameliorative measures should focus on the inboard portion of the solar arrays.

Nomenclature

$\vec{E}$ = electric field
m = ion mass
n = local plasma density
n_A = ambient plasma density
q = ion charge
r = radial coordinate
r_{min} = minimum radius of computational space for charge-exchange ion expansion
$\vec{V}$ = ion velocity
Z = axial coordinate
α = angle from the thruster beam direction; (as subscript) Cartesian component
Δr = radial mesh spacing
Δz = axial mesh spacing
θ = electron temperature, eV
ρ = ion density
ϕ = electric potential

Introduction

SOLAR-electric propulsion is a leading candidate for lifting large structures from shuttle orbit to geostationary altitude. Previous studies[1,2] demonstrated that plasma produced by charge-exchange reactions within the ion beam may dominate the ambient environment near the spacecraft. Currents flowing through this plasma between the engine neutralizers and the solar arrays are a drain on the power systems. If the losses become too large, they may have a substantial mission impact.

Simple calculations have been performed to estimate parasitic currents flowing through the charge-exchange plasma.[1,2] While the potential seriousness of the interaction was identified, the ad hoc nature of the previous work made clear the need for a more accurate treatment of the expansion of the charge-exchange plasma and the resultant solar array power losses. The calculations presented here are an improvement over previous work in that they contain a predictive model for the charge-exchange plasma expansion and a fully three-dimensional model for the structure of the plasma sheath around the solar array wing.

The generation mechanism of the charge-exchange plasma is clearly understood.[3] However, until recently there were no predictive models of the expansion dynamics of these slow-moving ions; it was necessary to assume the spatial density of charge-exchange ions to assess their interaction with solar arrays. This work, as well as that of Robinson, Kaufman, and Winder,[4] describe the ions as streaming under the electric field created by barometric law behavior of the plasma electrons. The model described here treats the ions numerically as a cold fluid, while Ref. 4 calculates representative ion trajectories by particle pushing. Both calculations are presently done assuming axial symmetry.

The collection of ions and electrons by solar arrays has been the subject of much recent interest. Experiments have been performed on large array-like objects in the vacuum tank at the NASA Johnson Spaceflight Center.[5] A three-dimensional computer code which simulates plasma interactions in low Earth orbit (LEO) was developed by the authors and was shown to provide qualitative and quantitative agreement with experiment.[6] This program, NASCAP/LEO, in a somewhat modified form is used in this study to describe the charge-exchange plasma/solar array interactions.

In this paper a new model is presented for the expansion of the charge-exchange plasma from an ion thruster. This predicted charge-exchange plasma is then used as the environment surrounding solar arrays in the LEO plasma interaction model. Thus, improved estimates of power losses for a variety of solar array configurations are obtained.

Theory

This study considers a single 30 cm diameter mercury thruster producing 2 A of beam current and 25 mA of charge-exchange current.[3] The charge-exchange ions are emitted radially, with energies of 5-10 eV, within a downstream distance equal to 1 diam of the beam. This gives a density of $\sim 2.5 \times 10^{14}$ m^{-3} at the beam edge, which exceeds the LEO plasma density of 10^{10}-10^{12} m^{-3}. Thus the charge-exchange plasma dominates the ambient to a distance of several meters from the thruster in LEO, and over the entire spacecraft for substantially more tenuous environments.

The conditions in this plasma are long collision lengths ($\sim 10^3$ m) and short Debye lengths ($\sim 10^{-3}$ m). The assumption that the electron gas adjusts itself to maintain isothermal, quasineutral conditions implies a barometric law

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potential,

$$\phi = \theta \ln (n/n_A) \tag{1}$$

where θ is the electron temperature (eV), n the local plasma density, and n_A the ambient plasma density. The barometric law is not an essential feature of the model. In the future we expect to remove the isothermal restriction and utilize fluid-like equations to describe the electrons.[7] The barometric law potential causes expansion of the ion cloud as it emerges from the beam edge. Far downstream the electrostatic forces become small, so that the ion density takes the form $f(\alpha)/r^2$, where α is the polar angle relative to the beam and r the distance from the engine.

The ion gas is modeled hydrodynamically, i.e., the ion density and velocity are assumed to be well-defined functions of position and the ion thermal motion is taken to be unimportant. This representation is chosen for ease of generalization; particle-pushing techniques would require extensive computer time for three-dimensional applications. The motion then satisfies the equations of continuity of mass and momentum

$$\frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot (\rho \vec{V}) \tag{2}$$

$$\frac{\partial}{\partial t}(\rho \vec{V}) = -\vec{\nabla} \cdot (\vec{V} \rho \vec{V}) + \frac{\rho q \vec{E}}{m} \tag{3}$$

where $\vec{E}$ is the electric field. The challenge is to develop numerical methods capable of finding the steady-state solution to Eqs. (1-3) in the R-Z (cylindrical) geometry appropriate to the problem.

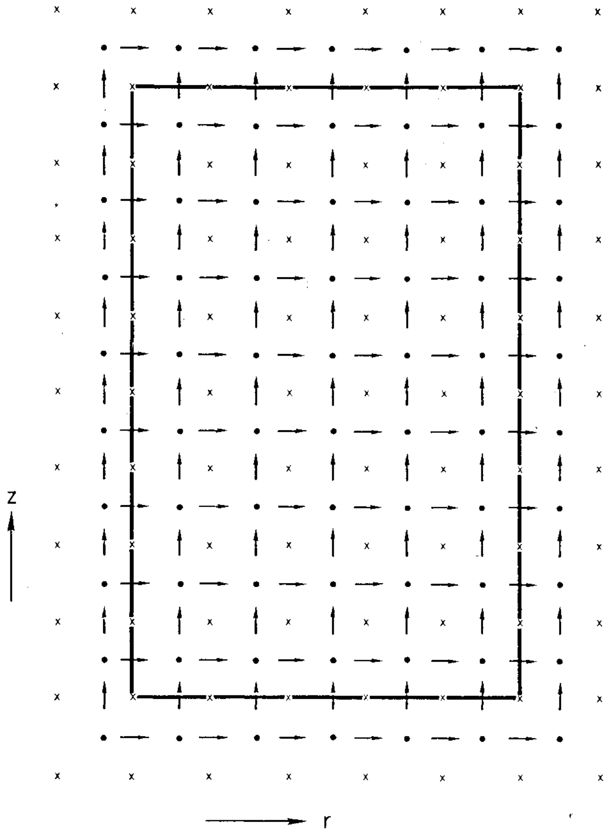

Fig. 1 Computational space, showing points for definition of velocity (×), density (●), and mass flux (→).

Numerical Methods

The numerical implementation of this theory separates into two parts: the steady-state solution of Eqs. (2) and (3) for the charge-exchange plasma density, and the collection of current from this short Debye length plasma by high-voltage surfaces. Methods for the latter have been described previously.[6] A brief description of the hydrodynamic method used to calculate the charge-exchange plasma expansion is included here for completeness. Further details are available elsewhere.[8,9]

Hydrodynamic equations such as (2) and (3) do not lend themselves to global, implicit solutions for their steady state, so that they must be explicitly time-stepped to equilibrium. The computational space (Fig. 1) is a staggered mesh consisting of density definition points at the centroids of mass element volumes and velocity definition points contained within momentum element volumes. The algorithm consists of updating the densities and velocities in accordance with the mass and momentum fluxes across the boundary surfaces of the appropriate volumes. A key element is that mass flux (density × velocity) is calculated in an "upwind" sense, i.e., using the density upstream of the surface with only a geometric correction rather than an interpolated value. The formulas used[8,9] are accurate to first order in Δt and second order in Δr, Δz.

For the calculations described below, the charge-exchange ion fluid enters the mesh radially across a cylinder about the positive z axis. It is accelerated by its own self-consistent electric field

$$\vec{E} = -\vec{\nabla}(\theta \ln \rho)$$

which is updated at each time step. The problem is run until there is no further variation of velocities in time. This empirical steady state is generally achieved in a few times the time it takes a fluid particle to traverse the mesh.

Results

The above model has been applied to calculate the expansion of an ion charge-exchange plume with initial conditions similar to a case measured by Poeschel et al.[3] The initial conditions were:

Emission energy (radial) = 10 eV
Initial radius $r_{\min} = 0.15$ m
Current density

$$q\rho(r_{\min}, z)\, v_r(r_{\min}, z) = \begin{cases} 0, & z<0 \\ 0.123 \exp(-z/0.22), & z>0 \end{cases}$$

(total current = 25 mA)

Electron temperature $\theta = 1$ eV
Mass (Hg ion) $= 3.34 \times 10^{-25}$ kg
Ambient density $n_A = 10^{12}$ m^{-3}

It follows that

$v_r(r_{\min}, z) = 3095$ m/s
$\rho(r_{\min}, 0) = 2.48 \times 10^{14}$ m^{-3}
$\phi_{\max} = \theta \ln[\rho(r_i^{(v)}, 0)/n_A] = 5.5$ V

The calculation was done in three phases:

1) $0.15\ \text{m} < r < 1.15\ \text{m}$; $\Delta r = 0.05$ m
   $-1.0\ \text{m} < z < 1.0\ \text{m}$; $\Delta z = 0.10$ m
2) $1.0\ \text{m} < r < 5.0\ \text{m}$; $\Delta r = 0.2$ m
   $-2.0\ \text{m} < z < 2.0\ \text{m}$; $\Delta z = 0.2$ m
3) $2.0\ \text{m} < r < 12\ \text{m}$; $\Delta r = 0.5$ m
   $-4.0\ \text{m} < z < 4\ \text{m}$; $\Delta z = 0.4$ m

Initial conditions for the second and third phases were obtained by interpolating data from the previous phase and

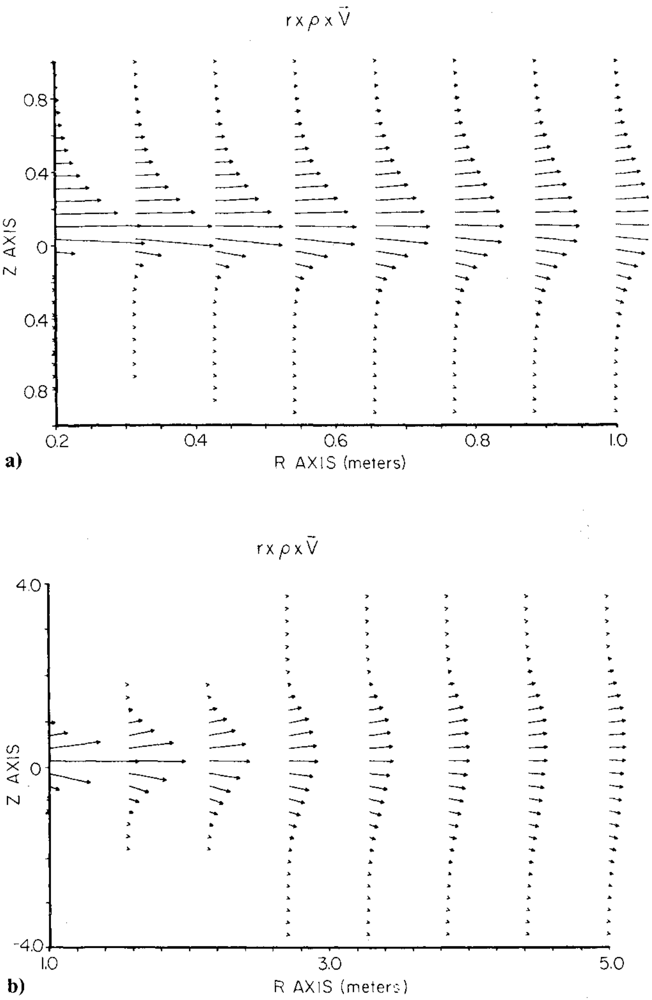

Fig. 2 Cylindrically scaled current density plots for ion plume flow: a) near the beam and b) in the "spherical expansion" region.

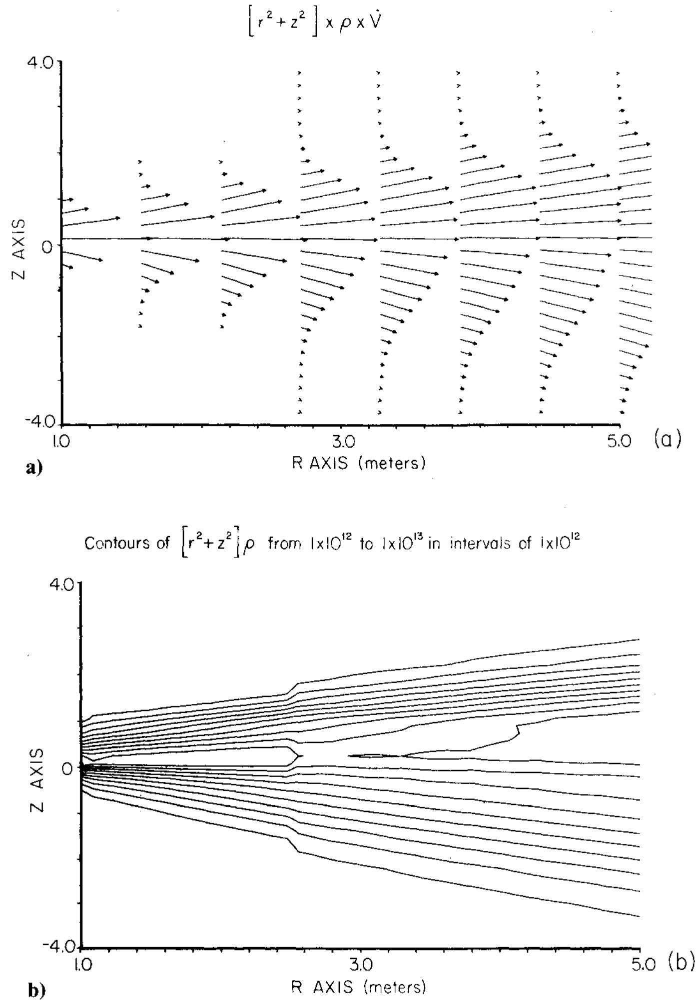

Fig. 3 Spherically scaled plots of: a) current density and b) particle density contours.

renormalizing to retain the correct total current. At each phase, the calculation was carried out until steady-state densities and velocities were reached.

The results are shown in Figs. 2 and 3. It is seen that the initially asymmetric expansion (Fig. 2) becomes roughly symmetric by a radius of ~ 1 m from the beam. This is seen in Fig. 3a in which spherical (r^2+z^2) scaling maintains constant arrow length, and in Fig. 3b which indicates radial contours of equal (r^2+z^2) times the density. The density (m^{-3}) beyond 1 m from the engine is reasonably approximated by

$$\rho \approx 10^{13}(\sin\alpha)^{12}/(r^2+z^2)$$

where α is the angle from the beam direction. A closer inspection of Fig. 3b indicates that the plume extends further upstream than downstream. This is attributable to "pressure blowoff" at the upstream plume edge near the engine where the density gradient is high.

Experimental data on charge-exchange plasma expansion have been presented by Kaufman[10] and Carruth and Brady.[11] The latter measurements were taken on a 30 cm thruster comparable to that modeled here. Measurements taken at $r=0.66$ m indicated a direction of velocity in good agreement with the fifth column of Fig. 2a. The measured upstream densities are also in excellent agreement with the present work. Figure 4 shows the measured upstream densities scaled by $(\sin\alpha)^{12}/(r^2+z^2)$. The agreement is nearly perfect except at such low densities that facility ions dominate the measurement. Carruth and Brady did not measure the downstream density. However, Kaufman's measurements,

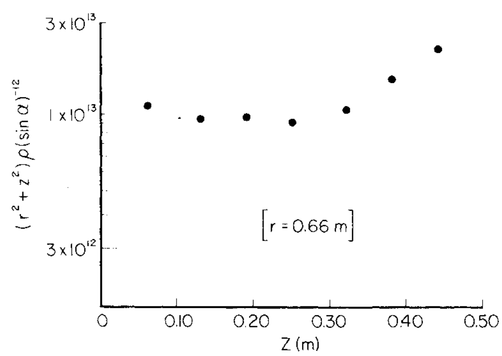

Fig. 4 Upstream densities measured by Carruth and Brady[11] at $r=0.66$ m, scaled by the expression suggested in this work.

taken with smaller thrusters, indicate plasma density increasing monotonically toward the beam direction rather than forming a pancake. This is probably attributable to the departure of the electrostatic potential from barometric law within the beam.[7,9] This effect, more pronounced for smaller thrusters, would tend to accelerate ions downstream, and indicates the inadequacy of the purely radial initial conditions used here. Work on a more fully self-consistent model is in progress.

The plasma parameters determined from the above model are used as input to a fully three-dimensional computer program designed to predict current collection by high

Table 1 Power losses for 8 × 30 m solar array for one thruster and various configurations

Configuration	Voltage, V Inboard	Center	Outboard	Current Inboard	(one side), Center	A Outboard	Power loss (per wing), kW
a,d	1000	2000	3000	1.4	0.6	0.6	4.4
b,d	2000	2000	2000	4.7	0.6	0.5	12.0
b,d	1000	2000	3000	3.7	0.6	0.5	6.4
a,c	1000	2000	3000	1.1	0.3	0.4	5.9
a,c	100	1000	2000	0.8	0.3	0.4	2.3
a,d	200	200	200	1.4	0.3	0.2	0.38
a,d	400	400	400	1.5	0.3	0.3	0.85

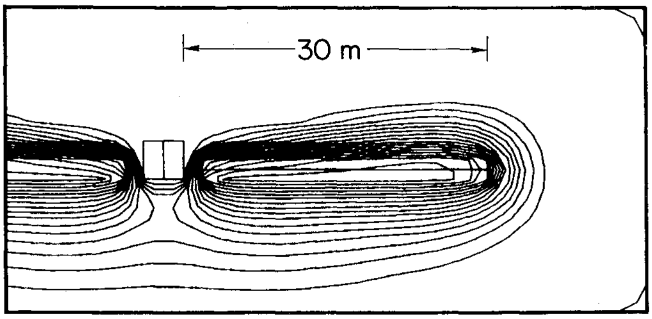

Fig. 5 Potential contours about a 2 kV solar array in the presence of the charge-exchange plume (the contour differences are 100 V).

voltages in low-temperature, short Debye length plasmas.[6,12] This model uses an analytic, nonlinear space charge formulation, correct in both Debye screening and thin sheath limits, to determine the electrostatic potential and the boundary of the plasma sheath. The model allows the plasma temperature and density to vary in space. The plasma density was taken to be the sum of the ambient and charge-exchange densities. Figure 5 gives a sample of electrostatic potential contours near a solar array wing, illustrating the symmetry caused by the charge-exchange plasma being predominantly on one side of the wing. The potential is shielded more strongly above the wing (where the charge-exchange plasma is densest) than below. By tracking electrons inward from the sheath boundary, good parasitic current estimates are obtained. Iterating on the two stages of the calculation allows nonlocal effects to be included. Additionally, a high-resolution capability is available to compute the current distribution over a complex pattern of solar cells.

Table 1 gives sample results for an 8 × 30 m, 25 kW solar array for several orientations and configurations. In these calculations, the spacecraft body was held at plasma ground and the solar array was divided into three equal sections, each of which was positively biased. Parasitic currents to both sides of each 10 m section of the wing were separately monitored. Several trends are apparent: 1) the inboard section of the wing draws most of the current, even though it is at a low voltage, because of the r^{-2} expansion of the charge-exchange plasma; 2) the current to the outboard section is similar to the center section current, due to the large end effect in the tenuous plasma; and 3) when the beam is in the plane of the panel, an increased loss is caused by the array's intersecting the charge-exchange pancake. It is apparent from these results that with kilovolt biases power losses of $\sim 10\%$ or more are likely, even with only one engine in operation, and that ameliorative measures should focus on the inboard portion of the solar arrays.

Discussion

As large, high-powered solar-electric propulsion vehicles come closer to reality, it becomes more important to place realistic bounds on the plasma/array interactions. Previous studies[1,2] have assumed simple models of the charge-exchange expansion. The expansion model is so important in estimating power losses that the author's previous work[2] parameterized the results in terms of an undetermined expansion angle. The calculations presented here are a vast improvement, inasmuch as the expansion of the charge-exchange plasma is determined on a reasonable theoretical basis and the plasma collection is fully three-dimensional.

However, certain other aspects of the model presented here are just as primitive as in the earlier studies. In particular, the isothermal barometric law description of the electrons, the lack of self-consistency between expansion and sheath models, and the absence of any turbulent heating mechanism during electron collection place severe restrictions on the accuracy of these results. For mission analysis, there also remains unanswered the question of charge-exchange plasma generation and expansion in a multiple thruster configuration. These are some of the technical questions which must be addressed to provide an accurate assessment of parasitic current losses due to ion propulsion generated plasmas.

Acknowledgments

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