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POLAR ORBIT ELECTROSTATIC CHARGING OF OBJECTS IN SHUTTLE WAKE*

I. Katz, D. E. Parks, D. L. Cooke, and M. J. Mandell
S-CUBED
La Jolla, California 92038

A. J. Rubin
Air Force Geophysics Laboratory
Hanscom Air Force Base, Massachusetts 01731

A recent survey of DMSP data has uncovered several cases where precipitating auroral electron fluxes are both sufficiently intense and energetic to charge spacecraft materials such as teflon to very large potentials in the absence of ambient ion currents. In this paper we provide analytical bounds which show that these measured environments can cause surface potentials in excess of several hundred volts to develop on objects in the orbiter wake for particular vehicle orientations.

INTRODUCTION

We consider an object in the wake of a spacecraft flying at an altitude of a few hundred kilometers in low polar earth orbit. We suppose that the object is charged to large negative voltages with respect to the ambient plasmas by an intense current, perhaps of order 10^{-8} amps/cm^2, of multi-kilovolt electrons. Our objective is to estimate upper bounds on the ion current attracted by the object, and lower bounds on its electric potential.

We assume that the plasma consists predominantly of O^+ at a concentration of about 10^5/cm^3 and a thermal energy per particle kT ~ 0.1 eV. The speed of the satellite V_0 is 8 x 10^5 cm/sec, corresponding to O^+ flow energy $1/2\ M_O V_0^2$ = 5.12 eV per particle, and a ratio $V_0/\sqrt{2\ kT/M_O}$ = 8. The plasma may also contain H^+, again with kT ~ 0.1 eV, but with a smaller Mach number, $V_0/\sqrt{2\ kT/M_H}$ = 2. In the considerations that follow we assume that the vehicle is in eclipse and that no spacecraft generated plasmas surround the vehicle.

The estimates are based on orbit limited theory collection by a shadowed, ion attracting object in a cold flowing plasma. Initially, thermal effects are not considered; it is anticipated that such neglect is justified for high Mach number flows, especially if the negative potential on the collecting object is very much larger than kT. Supposing that thermal effects are negligible, it is then argued that the theory provides an upper bound on collected ion current, or equivalently, a lower bound on the potential to which the object becomes charged. Because H^+ ion speeds are not very much less than flow velocities, thermal effects on H^+ collection will be further considered later in the paper.

For ionospheric plasmas with negligible hydrogen concentration, energetic electron currents to the wake side object can be neutralized only by attracted O^+ ions. For a one meter object shadowed by a ten meter shuttle,

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we find that the magnitude of the minimum voltage for attracting O^+ ions is about 500 volts. In contrast, space charge limited collection of O^+ ions through a ten meter radius sheath requires about 4 KeV to neutralize a current of 10^{-8} amp/cm^2 of energetic electrons.

The effect of H^+ is to lower the voltage threshold for orbit limited collection to several tens of volts, but H^+ concentrations much larger than 100/cm^3 are required to neutralize energetic electron currents as large as 10^{-8} amps/cm^2 if potentials more negative than 100 volts with respect to the ambient plasma are to be avoided.

THEORY

Consider a sphere of radius a at a potential -V shadowed by a disk of radius R_0 at a distance ℓ from the sphere center. The geometry is axisymmetric, with the symmetry axis defined by the line connecting the centers of the sphere and disk parallel to the plasma flow velocity V_0.

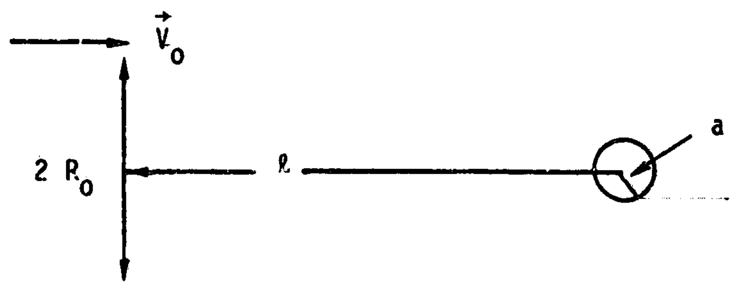

Figure 1. Geometry for ion collection.

To proceed further, we assume that the electrical potential is spherically symmetric about the center of the collecting sphere, and that the potential field is unaffected by the shield. In reality, the configuration of electric potential is much more complex, being strongly shielded by the plasma in the upstream direction and extending over substantial distances into the wake of the shield. Thus, by invoking the assumption of spherical symmetry one overestimates the upstream range of the potential and thereby the collected current.

Given the foregoing assumptions, the maximum ion current drawn by the sphere occurs when the distance between the shield and collector is infinite. Then, in accordance with orbit limited theory, which also overestimates collected currents, the current of ions of a particular species intercepted by the sphere is given by

$$I_i = \pi e N_i V_0 [b_i^2 - R_0^2] \quad (1)$$

where N_i is the density of the species i in the unperturbed plasma and the maximum impact parameter b_i is determined from

$$V_0 b_i = va \qquad \text{conservation of angular momentum} \quad (2)$$

$$\frac{1}{2} M_i V_o^2 = \frac{1}{2} M_i v^2 - eV \qquad \text{conservation of energy} \qquad (3)$$

where M_i is the ion mass, e the electron ion charge, and v the speed of the ion at the collector. Finally the collection current is

$$I_i = \pi e N_i V_o \left[\left(1 + \frac{2 eV}{M_i V_o^2}\right) a^2 - R_o^2 \right] \qquad (4)$$

with a collection threshold at

$$eV = \frac{1}{2} M_i V_o^2 \left[\frac{R_o^2}{a^2} - 1 \right] \qquad (5)$$

For a pure O^+ plasma ($1/2\ M_i V_o^2 \sim 5$ eV) and with $R_o/a \approx 10$, the voltage threshold for the onset of collection occurs at about 500 volts. A current density of 10^{-8} amps/cm^2 corresponds roughly to maximum observed levels of intensity of energetic precipitating electrons ($E > 1$ KeV) (refs. 1-3). For $N_o \sim 10^5$ cm^{-3}, the collected ion current is a sufficiently steep function of voltage that neutralization of the electron current of 10^{-8} amps/cm^2 occurs only slightly above the threshold.

The voltage threshold for hydrogen ion collection is $eV_H \sim 30$ volts for $R_o/a = 10$. Below 300 km altitude the H^+ concentrations are <100 cm^{-3}, and would not contribute substantially to the neutralization of electron energetic electron currents as large as 10^{-8} amps/cm^2. Instead at the 500 volt threshold for O^+ collection, the collected H^+ current is only $I_H \approx 2 \times 10^{-10}$ amps/cm^2 for $N_H^+ = 100$ cm^{-3}, $R_o/a \sim 10$. Thus for $H^+ \sim 100$ cm^{-3} to effectively control the charging by energetic electrons, it is necessary, but perhaps not sufficient, that the charging currents be less than 2×10^{-10} amps/cm^3. Of course, at higher altitudes where the H^+ concentrations are greater, the effect of H^+ in neutralizing charging is correspondingly greater.

The previous considerations, utilizing orbit limited theory with the shield a long distance from the collector, overestimate the collected ion current. We can also estimate the collected current with the shield at a finite distance from the collector. In this case the current is given by

$$I = \pi N eV_o \left[\left(1 + \frac{2 qV}{M V_o^2}\right) a^2 - R_\infty^2 \right] \qquad (6)$$

where R_∞ is the ambient parameter at infinite distance which causes the ion to intersect the outer edge of the shield located at the distance $R_o = (R_o^2 + \ell^2)^{1/2}$ from the center of the collector. To relate R_∞ to the collector potential and geometry, we must know the ion's orbit in the potential field. Suppose for this purpose that the potential is given by

$$\phi = -V_a/r \tag{7}$$

Solving the orbit equations then leads to the relation

$$\frac{R_\infty}{a} = \frac{1}{2}\left\{\frac{R_0}{a} + \left|\left(\frac{R_0}{a}\right)^2 + \frac{4\ eV}{M\ V_0^2}\left(1 - \sqrt{1 - \left(\frac{R_0}{r_0}\right)^2}\ \right)\right|^{1/2}\right\} \tag{8}$$

In Table 1 we compare the voltage thresholds for ion collection for the two extreme cases $\ell = \infty$ ($r_0 = \infty$) and $\ell = 0$ ($r_0 = R_0$), obtained by setting I = 0 in equation (6).

Table 1. Approximate Voltage Thresholds for Ion Collection, R/a = 10, V_T (volts)

	$\ell = \infty$	$\ell = 0$
O^+	507	2000
H^+	31.7	120

Potentials decreasing more rapidly than 1/r for increasing r would lead to increases in the threshold voltage by even more than the factor of four given in Table 1.

We next ask whether thermal effects on H^+ collection will substantially alter our estimates of minimum potential required for current neutralization. For this purpose we neglect shadowing of the collector by the spacecraft and assume orbit limited collection of H^+ ions. The orbit limited collection by a sphere at potential -V in a warm flowing plasma is given by Kanal's expression (ref. 4)

$$I = \pi a^2\ N\ eV_0 \left[\left(1 + \frac{2\ kT}{M\ V_0^2} + \frac{2\ eV}{M\ V_0^2}\right)\ \mathrm{erf}\left(\sqrt{\frac{M}{2\ kT}}\ V_0\right) + \frac{1}{V_0}\sqrt{\frac{2\ kT}{\pi M}}\ \exp\left(-\frac{M\ V_0^2}{2\ kT}\right)\right] \tag{9}$$

For H^+, $M\ V_0^2/2\ kT \sim 3$ and the collected current does not differ substantially from the cold plasma result

$$\frac{I}{\pi a^2} \simeq N_e\ V_0 \left(1 + \frac{2\ eV}{M\ V_0^2}\right) \tag{10}$$

Thus, for $V \sim 500$ volts, $N \sim 100\ cm^{-3}$,

$$I/\pi a^2 \approx 1.3 \times 10^{-9}\ amp/cm^2 \ , \tag{11}$$

and this extreme overestimate of collected H^+ current is still substantially less than the maximum observed charging currents.

So far, we have estimated upper bounds on selected ion current by invoking orbit limited theory. To ascertain how much the estimated bound might exceed actual current collection, let us consider space charge limited collection of O^+ ions by a one meter sphere through a spherically symmetric sheath of ten meter radius, the latter radius representing the radial extent of a wake. The Langmuir-Blodgett theory for space charge limited collection of O^+ by a sphere permits the required voltage to be estimated from (ref. 5)

$$j = 1.37 \times 10^{-8} \frac{V^{3/2}}{(\alpha a)^2} \tag{12}$$

For $j = 10^{-8}\ amp/cm^2$, $a = 100$ cm, and an outer emission radius of 10^3 cm, equation (12) with $\alpha^2 = 30$ gives

$$V \simeq 3.6\ kV \tag{13}$$

DISCUSSION

Simple theoretical considerations have been invoked to estimate upper bounds on the ion current collected by a shadowed object subjected to intense fluxes of energetic electrons. In the course of these estimates, many complicating factors associated with geometry, vehicle potentials, field asymmetries, and charging properties of materials have been ignored. It is appropriate to ask whether any of the effects that have been neglected may substantially alter the magnitude of current drawn by an object located in the wake of an ionospheric spacecraft.

The effect of secondary emission would be to increase the effective current to the object. While secondary emission may be small for primary electron energies ~10 KeV, it may be substantial for softer components of the precipitating electron spectrum, including those reflected from the dense atmosphere.

The effect of a shuttle potential and field asymmetries is difficult to determine. One might argue that a potential on the shuttle increases its effective size and decreases current to a shadowed object; one might also argue that the fields around the shuttle focus more ions into the near wake where the object is located. The theoretical resolution of these questions will require multidimensional calculations of electric fields and ion trajectories in those fields. The required techniques will be embodied in the POLAR code, now under development at S-CUBED.

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