CHARGING OF A LARGE OBJECT IN LOW POLAR EARTH ORBIT*

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SUMMARY

We have investigated the charging of a large sphere subject to the environment encountered by the shuttle orbiter as it passes through the auroral regions in its low polar earth orbit. The environment consists of a low temperature dense plasma and a relatively intense (200 $\mu A/m^2$) field aligned flux of energetic electrons ($\sim$5 to 10 keV).

The potential on a sphere in eclipse is presented as a function of the ratio κ of the charging rate produced by precipitating electrons to the discharging rate produced by ram ions. We find that a 5 meter conducting sphere charges to potentials of order 1 kilovolt for $\kappa \sim 2$, even though a 0.5 meter sphere charges to less than 100 volts.

It is concluded that the natural charging environment can induce large potentials ($\sim$1 kilovolt) on the shuttle orbiter.

INTRODUCTION

The shuttle orbiter, passing through the ionosphere at altitudes of a few hundred kilometers, develops electrical potentials through accretion of charge from the natural environment. Under normal ambient conditions the particle energies viewed from the satellite range from a few tenths of an electron volt to a few volts. Thus, the magnitude of vehicle potentials are at most a few volts. However, while passing through polar latitudes the vehicle may be subjected to a substantial flux of energetic electrons moving through the auroral zone following their injection in the magnetosphere. This may cause charging to high potentials.

Most experimental studies of spacecraft charging in low earth orbit have concerned small objects ($\sim$1 m) moving through the ionosphere. In the absence of energetic precipitating electrons,

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the magnitude of the observed electric potentials on the INJUN 5 satellite were less than a few volts, in accordance with theoretical expectations (ref. 1). Even during impulsive precipitation events, observed potentials did not exceed -40 volts negative.

More recently, theoretical studies have focused on charging of large objects. Parker has presented a method for computing sheath structures of large spherical bodies with high-voltage surfaces and with photoelectric/secondary emission (ref. 2). McCoy et al. have considered problems associated with the operation of large, high-voltage solar arrays in the ionosphere (ref. 3). Liemohn has considered the electrical charging of the shuttle orbiter in the absence of fluxes of energetic precipitating electrons (ref. 4). Inouye et al. (ref. 4) investigated the charging of a space based radar system having an antenna with a diameter of about 70 meters (ref. 5). Their calculation of electrical potentials in the presence of energetic particles are based on the application of orbit limited theory of Langmuir and Mott-Smith to determine the currents of attracted species (ref. 6).

The investigations of charging presented below are for the regime where body dimensions are large compared to the relevant Debye length. In this regime the currents of attracted species are estimated by adapting the large spherical probe theories of Langmuir and Blodgett (ref. 7) and Al'pert et al. (ref. 8). We examine the charging of a conducting sphere subjected to intense fluxes of energetic electrons. Factors relevant to a more thorough analysis of complex objects with dielectric surfaces are summarized. Conclusions are given in the final section of the paper.

ANALYSIS

The purpose of the following analysis is to estimate the magnitudes of potential that develop on objects in low earth orbit (200 to 400 km) when subjected to high fluxes ($\sim$200 $\mu A/m^2$) of hot (5 to 10 keV) precipitating magnetospheric electrons. Nominal values of the satellite and environmental parameters relevant to the analysis are summarized in Table 1.

We are concerned primarily with the possibly large negative potentials that may be produced by the currents of hot electrons incident from the magnetosphere. Questions related to the satellite wake and its structure are not considered; we consider the ram ion current density $NeV_o \sim 10^{-8}$ amp/cm^2 apparent to a co-moving observer as the only relevant attribute of the satellite motion. Thus, for example, it is anticipated that the $V_o \times B$ inductive electric fields are small relative to the electrostatic fields produced by charging.

To proceed further, let us first neglect the magnetic field. The effects of a magnetic field will be discussed later. The flux of hot electrons to the satellite is assumed unidirectional Since the ram ion energy $(E_o \overset{\sim}{=} 5\ \text{eV})$ is much larger than the ion temperature, the ram ion flux will also be considered unidirectional. In the absence of electric potential the precipitating electron and ram ion currents to the satellite will be $j_p \pi R_o^2$ and $j_r \pi R_o^2$, respectively.

For negative potentials electrons are repelled and the current of precipitating electrons at the satellite is approximately $j_p \pi R_o^2 \exp\{e\phi/\theta_p\}$. This is an accurate approximation if the effective collection radius R_c is not much greater than R_o, that is, if the thickness $R_c - R_o$ of the non-neutral space charge region around the object is less than the satellite radius. For all practical purposes in the cases of interest, $-e\phi >> \theta_e$. Thus the cold plasma electrons do not enter the sheath region.

The effect of space charge upon current collection in low earth orbit by large high voltage objects is well-known, having been studied both theoretically and with laboratory experiments. Space charge effects dramatically reduce the current collected per unit area compared to those predicted by orbit limited theory. The I-V characteristics of a spherical probe with a ratio of radius to Debye length of 10 is shown in figure 1. The current collected per unit area at large voltages is substantially less than the very large Debye length orbit limited theory would predict. However, the auroral electron fluxes in polar earth orbit are incident currents which may be substantially larger than the ram ion currents. We are then interested in the inverse function, that is, the V-I characteristic (figure 2). Note how dramatically the probe voltage must rise to increase the current collected per unit area. It is this steep V-I characteristic which forms the basis of the following analysis.

The theory of the sheath surrounding a large spherical probe with radius $R_o >> \lambda_D$ at high potential $|e\phi| >> \theta_e, \theta_i$ in an isotropic plasma is given in Langmuir and Blodgett (ref. 7) and Al'pert et al. (ref. 8). The effective collection radius R_c for the case of ion attraction can be expressed as

$$\frac{R_c}{R_o} = F\left(\frac{e\phi}{\theta} \left(\frac{\lambda}{R_o}\right)^{4/3} \right) \tag{1}$$

where θ is the temperature of the attracted species and λ the

Debye length. F is an increasing function of its argument and hence of the satellite potential.

In order to adapt the Langmuir-Blodgett theory as an approximation to the case of streaming ions, we relate the temperature θ to the kinetic energy E_o of ions relative to the satellite by requiring that current entering the sheath in the isotropic and streaming cases be the same,

$$NV_o \pi R_c^2 = 4\pi R_c^2 \, N(8\theta/\pi M)^{1/2} \tag{2}$$

giving

$$\theta = \frac{\pi M V_o^2}{8} = \frac{\pi E_o}{4} \tag{3}$$

where M is the ionic mass. The equivalent Debye length is

$$\lambda = 743 \; (N/\theta)^{1/2} \text{ cm} \tag{4}$$

Table 2 gives values of R_c/R_o as a function of $z \equiv (e\phi/\theta)(\lambda/R_o)^{4/3}$. For values of $R_c/R_o \leq 1.05$, the collection radius and potential are related by the plane electrode Child-Langmuir law

$$\frac{R_c}{R} = 1 + \frac{2\sqrt{2}}{3} z^{3/4} \tag{5}$$

with an accuracy better than 3 percent.

The potential on the sphere is determined by balance of currents,

$$\pi R_o^2 \, j_p(1-s_p)e^{e\phi/\theta_p} = \pi R_c^2 \, j_r(1+s_i) + I_\nu \tag{6}$$

where $s_p(s_i)$ is the total secondary yield from electron (ion) impact and I_ν is the total photoemission current.

Defining

$$\bar{j}_p = j_p(1-s_p)$$

$$\bar{j}_r = j_r(1+s_i)$$

as effective electron and ion current densities corrected for secondary emission, equation (6) becomes

$$\kappa = \bar{j}_p/\bar{j}_r = \left(\frac{R_c}{R_o}\right)^2 \exp|e\phi/\theta_p| + \frac{I_\nu}{\bar{j}_r \, \pi R_o^2} \tag{7}$$

Figure 3 shows the dark potential on spheres of 0.5 and 5 m radius as a function of ratio of precipitating electron to ram ion current densities in a plasma with ambient density 10^5 cm^{-3}. For a given current ratio the potential on the sphere scales roughly as the radius. More precisely, the potential scales with radius as $(R_o/\lambda)^{4/3}$ for $|e\phi| << \theta_p$, but somewhat more slowly with R_o/λ as $|e\phi|$ increases. Observe that the potential is an extremely sensitive function of $\bar{j}_p/\bar{j}_r$ for values of this ratio near unity, especially for the larger sphere.

The theory predicts that the 5 m sphere will charge to about the 1 kilovolt level for electron to ram ion current density ratios of only about two. This is to be contrasted with the result predicted by orbit limited ion collection. The approximate dark current balance

$$\frac{j_p}{j_r} \simeq \left(1 + \frac{|e\phi|}{\theta}\right) e^{|e\phi|/\theta_p}$$

for orbit limited collection predicts, for example, that $j_p/j_r \simeq 300$ would be required to sustain a 1 kilovolt potential on the sphere.

DISCUSSION

Several effects have been neglected in determining that hot electrons precipitating from the magnetosphere can charge a large object to kilovolt potentials. We shall now argue that accounting for these effects will not alter the conclusion that such high potentials should be expected for the assumed charging environment.

Consider first the effect of a magnetic field on the ram ions entering the sheath surrounding the satellite. A component of magnetic field perpendicular to the satellite velocity will tend to insulate the surface from the ram ion currents, leading to larger negative potential of the satellite. For cases of interest however, the effect is negligible. A measure of the size of this effect is given by

$$\alpha = \frac{\frac{1}{2} M \omega_{ci}^2 d^2}{|e\phi|} \approx \omega_{ci}^2 \tau^2$$

where M is the ion mass, ω_{ci} its gyrofrequency, d the thickness of the sheath, and τ the flight time of an ion across the sheath. For the cases represented in figure 1, $d \lesssim R$, so that

$$\alpha \lesssim 0.2/|e\phi \text{ (volts)}|$$

which is negligibly small except at very low levels of satellite potential.

The hot electrons responsible for charging the satellite were considered to approach the space charge sheath unidirectionally, as pertains in the limit of strong magnetic fields where the Larmor radius is small compared with the radius of the satellite. More probably, the electrons, because of their pitch angle distribution, would enter the repulsive sheath with a more nearly isotropic distribution of directions. Assuming that the one sided thermal plasma current densities are the same in the unidirectional and isotropic limits, the effective electron current toward one hemisphere of the satellite in the isotropic limit is twice that which pertains in the unidirectional case. In the absence of no other effect associated with the magnetic field, the result would be greater charging.

The charging current given by equation (6) for the case of repelled electrons incident unidirectionally from infinity applies in the limit of zero gyroradius. In the opposite limit of vanishing magnetic fields, again assuming that electrons enter the sheath unidirectionally, fewer electrons reach the satellite because of the deflection by the repulsive electric field. The reduction in current is small however, and the charging current accurately represented by equation (6) provided that the repulsive potential on the satellite satisfies $(e\phi/\theta_p)^2 << 1$. This requirement, which is satisfied in the case of figure 1 for potentials less than about 2 kV, follows from the conservation laws of energy and angular momentum which permit one to express the current to the satellite as

$$I = N_o \; (m/2\pi\Theta_p)^{1/2} \; \pi R_o^2 \int_{\left(\frac{2e\phi}{m}\right)^{1/2}}^{\infty} dv \; v e^{-mv^2/2\Theta_p} \left\{ 1 - \frac{2e\phi}{mv^2} \right\}$$

Essentially, the electron current crossing the sheath is not substantially modified by the magnetic field, a circumstance we expect to pertain is long as

$$(\omega_{ce}\tau)^2 \quad \frac{1}{2}\, m\, \omega_{ce}^2\, d^2/\Theta_p << 1$$

This condition is well satisfied for potentials in figure 3 at the kilovolt level.

In applying the Langmuir-Blodgett probe theory, we have neglected the contribution of electrons to the space charge in the sheath. This is a valid approximation because the velocity of electrons in the sheath is large compared with ion velocities, except perhaps for the contribution of secondary and photoelectrons near the surface. Near the surface, however, the electric fields are dominated by surface charge and little affected by space charge.

Secondary and photoelectrons move through the sheath with smaller energies than the precipitating magnetospheric electrons and are therefore more strongly affected by the magnetic field. The potential developed by the satellite is affected however only if the emitted electrons return to the surface, leading to higher potentials than if the electrons escape.

In all previous considerations, we have supposed that the satellite is a conducting sphere. The shuttle orbiter is actually a geometrically complex object whose surface is coated with dielectric materials, and both ion and electron fluxes are apt to be strongly heterogeneous functions over the satellite's surface. The degree of heterogeneity will be affected by the geometry of the satellite, its motion through the ionosphere, the variation of surface properties, such as secondary yield, and by the magnetic field. Undoubtedly the sheath surrounding the orbiter will have a complicated geometrical structure not easily represented by simple spherical probe models. Multidimensional computer models will be required to determine the strong differential voltages which are expected to develop on the vehicle.

CONCLUSIONS

Ambient currents of hot electrons (5-10 keV) of 200 $\mu A/m^2$ will charge a 5 meter sphere in low polar earth orbit to kilovolt potentials in eclipse. Such potentials are about 1 order of magnitude larger than occur for smaller satellites ($\sim R_o \sim 0.5$ m) in a similar orbit. On this basis, one should expect negative potentials of around 1 kilovolt to develop on the shuttle orbiter. Because of the dielectric coating on the orbiter, and the non-uniform character of the charged particle fluxes expected at the vehicle's surface, differential surface potentials of the order of one kilovolt should also occur.

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TABLE 1. - NOMINAL VALUES OF PARAMETERS WHICH INFLUENCE ELECTRICAL CHARGING IN LOW EARTH ORBIT

Sphere Diameter	1000 cm
Satellite Velocity V_o	8×10^5 cm/sec
Ambient Ion Temperature θ_i	.1 - .5 eV
Ambient Electron Temperature θ_e	.1 - .5 eV
Precipitating (Hot) Electron Temperature θ_p	5 - 10 keV
Neutral Atom Density (0)	10^{10} cm^{-3}
Ion Density (0^+)	$10^4 - 10^6$ cm^{-3}
Ambient Debye Length	≤ 1 cm
Thermal Electron Larmor Radius	2 cm
Hot Electron Larmor Radius	400 cm
Ion Larmor Radius	300 cm
Current Density (amp/cm^2)	
Thermal Electron j_e	10^{-7}
Thermal Ion (0^+) j_i	10^{-10}
Photoelectron j_ν	10^{-9}
Precipitating (Hot) Electron j_p	2×10^{-8}
Ram Ion j_r	10^{-8}

TABLE 2. - EFFECTIVE COLLECTION RADIUS AS FUNCTION OF $z \equiv e\phi/\theta(\lambda/R_o)^{4/3}$

R_c/R_o	z
1.005	.001
1.018	.005
1.030	.010
1.050	.019
1.100	.052
1.150	.094
1.200	.143
1.250	.199
1.300	.264
1.340	.337
1.400	.421
1.450	.510
1.500	.610
1.600	.833
1.700	1.092
1.800	1.384
1.900	1.711
2.000	2.074
2.100	2.479
2.200	2.919
2.300	3.400
2.400	3.920
2.500	4.479
2.600	5.113
2.700	5.752
2.800	6.472
2.900	7.196

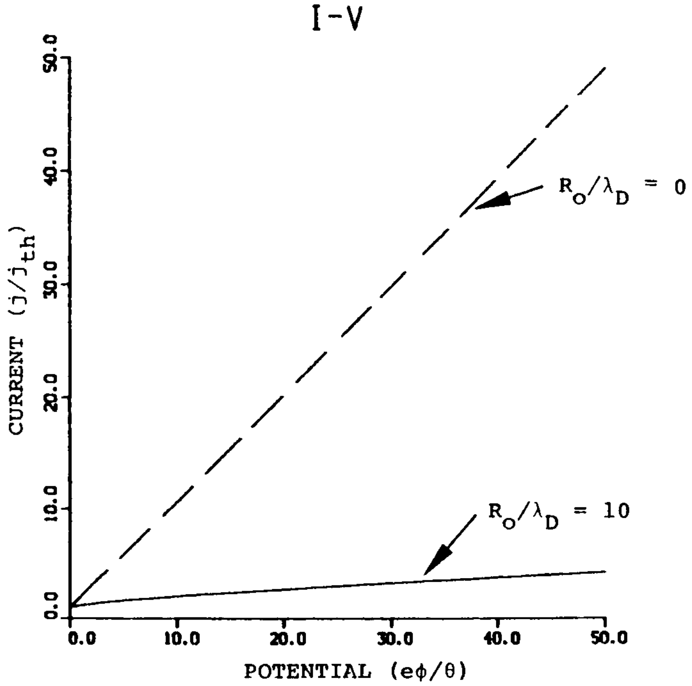

Figure 1. - The I-V characteristic for a spherical probe in a small Debye length plasma. Note how even at large potentials the probe collects just a few times the plasma thermal current. The dashed line is for long Debye length orbit limited collection. It is not applicable to large objects in low earth orbit.

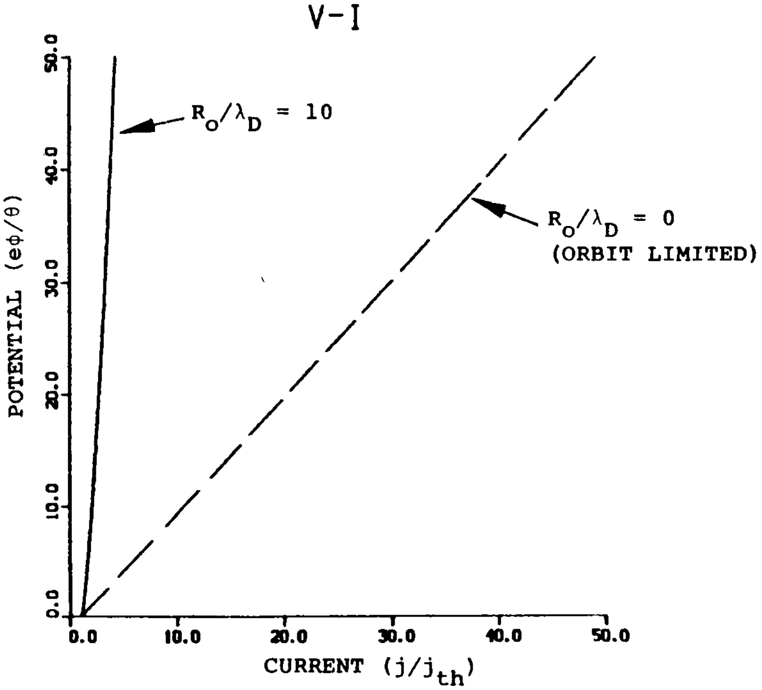

Figure 2. - The V-I characteristic for a spherical probe in a small Debye length plasma. Note how even a small increase in probe current causes a very large change in the potential of the sphere. The dashed line is for long Debye length, orbit limited collection.

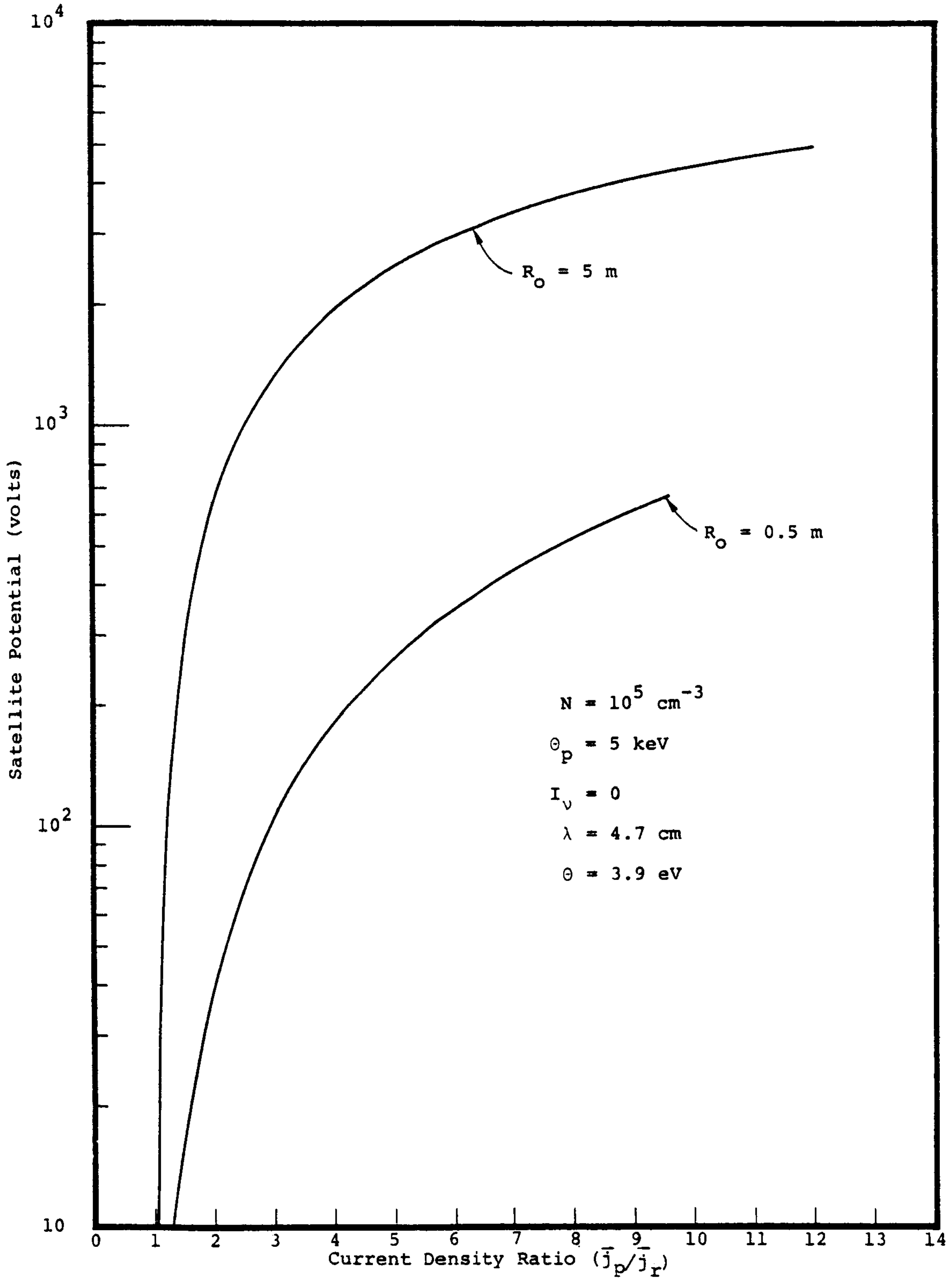

Figure 3. - Satellite potential as function of current density ratio.