Space Shuttle Orbiter Charging

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This paper considers the charging of the Space Shuttle orbiter by energetic particles of environmental origin and from emission by accelerators. The theoretical results indicate that precipitating electrons quickly induce large voltages. High voltages may also occur when onboard accelerators inject energetic beams into the high-altitude plasma. A significant conclusion from electron beam experiments is that the rocket charged to positive potentials much less than anticipated from the theory of probes in a quiescent plasma. Such theories, however, predict the large negative potentials observed by firing energetic ions.

Nomenclature

B = geomagnetic field strength
d = thickness of tiles on Shuttle
E_ν = $\frac{1}{2}mV_0^2$
e = magnitude of charge on electron
I_ν = total photoelectron current
j_e = one-sided thermal electron current density
j_i = one-sided thermal ion current density
j_p = precipitating hot-electron current density
j_r = ram ion current density
j_ν = photoemission current density
j_p = $j_p(1-s_p)$
j_i = $j_i(1-s_i)$
M = mass of O^+ ion
N = ambient ion density
R_c = effective collection radius for ions
R_0 = radius of spherical spacecraft
S = thickness of precipitating electron current sheet
s_i = total secondary yield from ion impact
s_p = total secondary yield from electron impact
V_0 = Shuttle velocity
$\dot{V}$ = initial rate of voltage buildup across tiles
ϵ_0 = permittivity of vacuum
ϕ = spacecraft potential
λ = Debye length
θ = effective temperature of ram ions for use in Eq. (1)
θ_e = ambient electron temperature
θ_i = ambient ion temperature
θ_p = temperature of precipitating electron

Introduction

THE Space Shuttle orbiter in polar earth orbit sees an environment which differs dramatically from that in equatorial orbit. Near the Arctic circle the orbiter may experience intense fluxes of energetic (~5-10 keV) electrons propagating down along magnetic field lines. Shuman et al.[1] have reported peak electron fluxes at about 800 km of 5.4×10^9 eV $(cm^2\cdot s\cdot sr)^{-1}$ near 0 deg pitch angle in the midst of an inverted-V event where peak energy reached 9.5 keV, corresponding to a hemispheric current of about 50 $\mu A/m^2$. For worst-case scenarios, even larger fluxes should be considered.

The precipitating electrons collide with molecules in the atmosphere to generate the aurora borealis. When they impinge upon the Space Shuttle they may cause potential differences as large as a few thousand volts. In a previous paper, the authors have described the basic mechanism for overall uniform charging of a large object in low polar earth orbit.[2] It was shown that the potentials developed increased rapidly with increasing vehicle dimensions and were extremely sensitive to the ratio of precipitating electron currents to discharging currents, such as those associated with ion collection by the ram effect and secondary electron emission. The question of the potential buildup on electron- and ion-emitting satellites in low earth orbit has been addressed by several authors.[3-6] Parker and Murphy[3] and Beard and Johnson[4,5] consider limits on attainable potentials, the former taking account of the geomagnetic field and the latter neglecting it. Both authors neglect the effects of plasma turbulence which can lead to enhanced electron currents across magnetic field lines. Linson[6] considers a turbulent model in which plasma electrons can reach the electron-attracting satellite after being freely transported across field lines. The present paper is concerned primarily with ion-attracting satellites at large negative potential. The authors are unaware in this case of any evidence of enhanced ion transport resulting from plasma turbulence.

This paper addresses questions about the realizability of large negative voltages by the Space Shuttle orbiter. Review of the theoretical basis of the overall charging clarifies the physical processes which can lead to high voltages on large objects. Moreover, simple considerations indicate that large differential potentials develop rapidly under exposure to currents of energetic particles from the environment. Finally, experimental observations indicate that high negative voltages are easily sustained in low earth orbit.[7]

The combination of intense auroral fluxes, rapid charging time scales and observed high negative potentials creates a convincing argument for the possibility of large differential potentials on the orbiter. The probability that exactly the correct conditions for high-voltage charging occur on a given flight has not been addressed. The final section of this paper summarizes our knowledge and the areas where further experimental and theoretical studies are required in order to develop a more quantitative understanding of electrical charging of large objects in polar orbit.

Review of Mechanisms for Overall Charging

The following analysis taken from Ref. 2 estimates the magnitudes of overall potentials that might develop on objects in low earth orbit (200-400 km) when subjected to high fluxes (~100 $\mu A/m^2$) of hot (5-10 keV) precipitating magnetospheric electrons. Nominal values of the satellite and

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Table 1 Nominal values of parameters which influence electrical charging in low earth orbit

Sphere diameter, cm	1000
Satellite velocity V_0, cm/s	8×10^5
Ambient ion temperature θ_i, eV	0.1
Ambient electron temperature θ_e, eV	0.1
Precipitation (hot) electron temperature θ_p, keV	5-10
Neutral atom density (O), cm^{-3}	10^{10}
Ion density (O^+), cm^{-3}	$10^4 - 10^6$
Ambient Debye length, cm	≤ 1
Thermal electron larmor radius, cm	2
Hot-electron larmor radius, cm	400
Ion larmor radius, cm	300
Current density, A/cm^2	
Thermal electron j_e	$10^{-8} - 10^{-6}$
Thermal ion (O^+) j_i	$5\times10^{11} - 5\times10^{-9}$
Photoelectron j_ν	10^{-9}
Precipitating (hot) electron j_p	2×10^{-8}
Ram ion j_r	$10^{-9} - 10^{-7}$

environmental parameters[8] relevant to the analysis are summarized in Table 1.

The primary focus of this paper is on the possibly large negative potentials that may be produced by the currents of hot electrons incident from the magnetosphere. The geometry, a sphere of radius R_0, adopted for this analysis is highly simplified, but does permit a clear demonstration of the importance of the large dimension of the Shuttle in charging to high potentials. Questions related to the satellite wake and its structure are not considered; the ram ion current density NeV_0 apparent to a comoving observer is considered the only relevant attribute of the satellite motion. Thus, for example, it is anticipated that the $V_0 \times B$ inductive electric fields (≤ 0.4 V/m) are small relative to the electrostatic fields produced by charging. A more precise determination of potential distributions on the Shuttle will require much more elaborate and expensive multidimensional calculations for a complex object subjected to charging currents that are strongly influenced by electric and magnetic fields around the object. Such multidimensional computational techniques exist already for satellites in geosynchronous earth orbit,[9,10] where Debye lengths are much larger than the dimensions of existing satellites, but not for low earth orbit where Debye lengths are typically much less than satellite dimensions. Recent articles by Whipple,[11] Garrett,[12] and Stevens[13] give excellent reviews of the subject of charging of spacecraft in the diverse environments which they encounter.

To proceed further, neglect the magnetic field.[2] The flux of hot electrons to the satellite is stated in terms of an equivalent unidirectional current j_p. Thus, for example, a current of 50 $\mu A/m^2$ isotropic over a hemisphere would correspond to $j_p = 100\ \mu A/m^2$. Since the ram ion energy ($E_0 \cong 5$ eV) is much larger than the ion temperature, the ram ion flux is essentially undirectional. In the absence of electric potential the precipitating electron and ram ion currents to the satellite are denoted by $j_p \pi R_0^2$ and $j_r \pi R_0^2$, respectively. For negative potentials electrons are repelled and the current of anisotropic precipitating electrons at the satellite is approximately $j_p \pi R_0^2 \exp(e\phi/\theta_p)$.[2,14] For all practical purposes in the cases of interest, $-e\phi \gg \theta_e$, and the cold plasma electrons do not cross the sheath region.

Ion current collection by large high-voltage objects in low earth orbit has been studied both theoretically and experimentally.[7,15] Space charge effects dramatically reduce the ion current collected per unit area compared to that predicted by orbit-limited theory. The collection characteristic of a spherical probe with a ratio of radius to Debye length of 10 is shown in Fig. 1. 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.) The

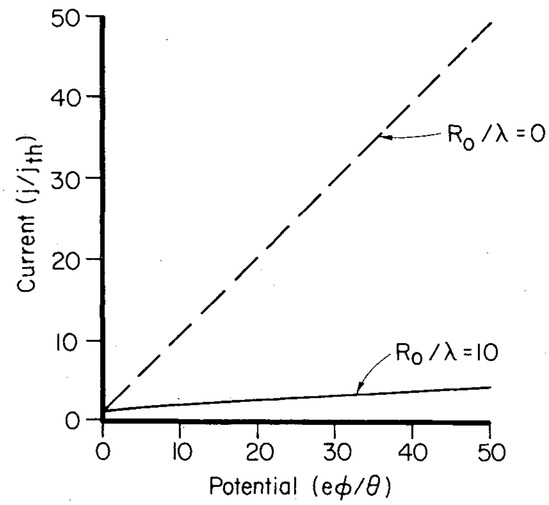

Fig. 1 Collection characteristic for a spherical probe in a small Debye length plasma.

current collected per unit area at large voltages is substantially less than the orbit-limited theory (very large Debye length) would predict. However, the auroral electron fluxes in polar earth orbit are incident currents which may be substantially larger than the ram ion currents. Note from Fig. 1 how dramatically the probe voltage must rise to increase the current collected per unit area. It is this steep characteristic which forms the basis of the following analysis.

The theory of the sheath surrounding a large spherical probe with radius $R_0 \gg \lambda$ at high potential $|e\phi| \gg \theta_e, \theta_i$ in an isotropic plasma is given in Langmuir and Blodgett,[15] Al'pert et al.,[8] and Parker.[16] The effective collection radius R_c for the case of ion attraction can be expressed as

$$\frac{R_c}{R_0} = F\left[\frac{e\phi}{\theta}\left(\frac{\lambda}{R_0}\right)^{4/3}\right] \tag{1}$$

where F is an increasing function of its argument and hence of the probe potential; it is tabulated in Table XXIV of Al'pert et al.[8] Here the effects of a presheath[16] are ignored, since they will not substantially affect collection of ram ions with streaming velocities much greater than thermal velocities.

In order to adapt the Langmuir-Blodgett theory of isotropic collection as an approximation to the case of streaming ions, the temperature θ is related to the kinetic energy E_0 of ions relative to the satellite by choosing the current entering the sheath in the isotropic and streaming cases to be the same,

$$NV_0\pi R_c^2 = \pi R_c^2 N(8\theta/\pi M)^{1/2} \tag{2}$$

giving

$$\theta = \pi M V_0^2/8 = \pi E_0/4 \tag{3}$$

The equivalent Debye length for use in Eq. (1) is

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

For values of $R_c/R_0 \leq 1.05$, the collection radius and potential are related by the plane electrode Child-Langmuir law

$$\frac{R_c}{R_0} = 1 + \frac{2\sqrt{2}}{3}\frac{\lambda}{R_0}\left(\frac{e\phi}{\theta}\right)^{3/4} \tag{5}$$

which approximates Eq. (1) with an accuracy better than 3%.

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

$$\pi R_0^2 j_p(1-s_p)e^{e\phi/\theta_p} = \pi R_c^2 j_r(1+s_i) + I_\nu \tag{6}$$

Corrections for backscatter are assumed incorporated into s_p and s_i. In Eq. (6) it is supposed that ϕ is sufficiently negative to preclude collection of thermal electrons from the ambient plasma. Defining $\bar{j}_p = j_p(1-s_p)$ and $\bar{j}_r = j_r(1+s_i)$ as effective electron and ion current densities corrected for secondary emission, Eq. (6) becomes

$$\kappa = \bar{j}_p / \bar{j}_r = \left[\left(\frac{R_c}{R_0} \right)^2 + \frac{I_\nu}{\bar{j}_r \pi R_0^2} \right] \exp \frac{-e\phi}{\theta_p} \qquad (7)$$

Figure 2 shows the dark ($I_\nu = 0$) 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 $(R_0/\lambda)^{4/3}$ for $|e\phi| \ll \theta_p$, but somewhat more slowly with R_0/λ as $|e\phi|$ increases. Observe that the potential is an extremely sensitive function of κ 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 kV level for effective hot electron to ram ion current density ratios of only about two. This rapid increase of equilibrium voltage with spacecraft size is consistent with the observation of less than 100 V negative potentials on the INJUN 5 satellite by Sagalyn and Burke.[17]

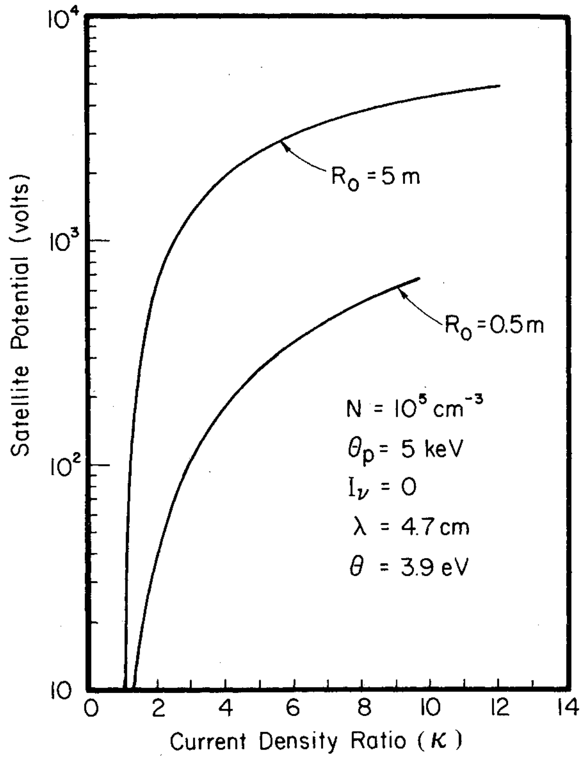

Fig. 2 Satellite potential as function of current density ratio.

Rate of Voltage Buildup

Since the intense auroral currents occur in thin sheets, it is most important to examine the rate of change of surface voltage when exposed to intense fluxes to determine whether significant differential voltages could develop. The shortest exposure times would be those where the orbital velocity was perpendicular to the current sheet. The Shuttle would then cross it in a time $t_{\min} = S/V_0$. For a sheet thickness[18] of 1 km and an orbital velocity of 8 km/s we get a minimum time of $t_{\min} \approx 0.1$ s. To develop differential voltages of the order of a kilovolt in a time less than $t_{\min}$ would require a charging rate of more than 10,000 V/s.

The heat-resistant tiles on the orbiter are much thicker than conventional satellite coatings as well as being extremely good insulators. They are the spacecraft surfaces most susceptible to charging. The initial rate of differential charging across a tile, front to back, is given by

$$\dot{V} = j_p (1-s)(d/\epsilon_0)$$

where a dielectric constant of unity has been assumed. For a tile thickness d of 0.10 m, a secondary yield of 0.5 and an incident current j_p of 200 μA/m^2 the rate of charging is $\dot{v} \approx 10^6$ V/s. This rate is two orders of magnitude larger than the minimum required. Thus even the very brief exposure to currents of high-energy electrons will allow kilovolt levels of differential charging.

These results contrast dramatically with the observations in geosynchronous orbit by the SCATHA satellite. On SCATHA differential charging rates were found to be of the order of 10 V/s.[19] In geosynchronous earth orbit the observed charging currents were typically only 10^{-6} A/m^2 and spacecraft dielectric thicknesses (e.g., 5 mil) are only about 10^{-4} m. Thus the differential charging rates predicted are five orders of magnitude less, closer to 10 V/s, in agreement with observation. It is the combination of thick dielectric covering and intense auroral currents which makes possible rapid differential charging.

Examples of High Negative Voltages in Cold Dense Plasmas

The arguments presented here all depend upon the classical space charge-limited collection of ambient ions. Over a decade ago similar arguments were employed for electron collection and predictions were made that electron beams fired from rockets 100-400 km above the earth would generate large positive potentials. However, the subsequent experiments found positive voltages of less than 100 V. This immediately raises the question, "why then should one believe theoretical predictions of high negative potentials in low earth orbit (LEO)?" To answer this question consider first the ground and space evidence for high negative potentials and the difference between the physical mechanisms involved in ion and electron collection.

The most compelling evidence for the sustainability of high negative potentials in LEO comes from the rocket experiments of Cohen et al.[20] By emitting a low-current beam of ions high negative vehicle potentials were sustained. The maximum potential was greater than 1000 V for an ion current of 400 μA. Hundreds of volts were achieved with as little as 7 μA. This is in stark contrast to most reported rocket experiments which used electron beams, where currents as high as an ampere produced vehicle potentials much less than 1 kV. Since the sheath polarity is negative for a large object in polar orbit being bombarded by auroral electrons, the ion beam emission experiments should be very close simulations and thus one would predict high voltages.

A quantative verification of the space charge limited ion collection model was obtained by comparison with the ground-based experiments of McCoy et al.[21] For their experiments a large high-voltage panel was exposed to a low-temperature, high-density plasma. The ion current collected agreed well with space charge-limited sheath calculations performed by the present authors.[22] There are still unanswered questions relating to the effect of the wake structures, three-dimensional geometry and magnetic field upon the current/voltage characteristics.

The question of why electron collection behaves so differently has not been fully answered. The authors have shown that electron currents in the low-temperature, high-temperature collisionless plasma surrounding ion thrusters behave as though there is a high effective collision frequency for electrons, comparable to the plasma frequency.[23] Investigations by Linson,[6] Bernstein et al.,[24] and Sasaki et al.[25] are also pertinent to understanding the role of anomalous plasma effects in current collection by electron-emitting spacecraft. The "anomalous" collisions heat the plasma and increase the local electron thermal currents. (The same effect has not been seen for ion emission.) The large increase in local electron temperatures increases the electron thermal current so that large potentials are not necessary for large currents. Experiments run on the SCATHA satellite have shown that this enhancement of the collection of electron currents does not apply at geosynchronous altitudes. As reported by Cohen et al.,[7] less than 100 μA of electrons are required to drive the satellite to a potential 3000 V.

Conclusions

Given that the Space Shuttle orbiter encounters intense auroral current, that the space environment around the Shuttle is highly anisotropic, and that the Shuttle body is a dielectric, one can reasonably make the case that substantial differential potentials will develop along the surface. The case is a tentative one, however, since the assumption of a spherical object made in this paper is an extreme simplification and since several important physical phenomena have been neglected. The most important are multidimensional effects, in particular the effect upon charging of nonuniformities in the space environment and of electric and magnetic fields on particle orbits. Magnetic fields probably diminish the collected ion currents and as such would increase any charging. Also not addressed was the question of the time and frequency of occurrence of strong auroral currents impinging upon the Shuttle.

To perform the required three-dimensional calculations, techniques presently available are inadequate. A new computer program to perform such calculations is presently under development. It is being designed to treat the wake structure and sheath effects near objects large compared to the ambient Debye length and potentials large compared to the ambient temperature.

Acknowledgments

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