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SHEATH IONIZATION MODEL OF BEAM EMISSIONS FROM LARGE SPACECRAFT

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An analytical model of the charging of a spacecraft emitting electron and ion beams has been applied to the case of large spacecraft. In this model, ionization occurs in the sheath due to the return current. Charge neutralization of spherical space charge flow is examined by solving analytical equations numerically. Parametric studies of potential of large spacecraft are performed. As in the case of small spacecraft, the ions created in the sheath by the returning current play a large role in determining spacecraft potential.

INTRODUCTION

The potential difference created between spacecraft ground and the ambient plasma during the ejection of a beam of electrons from a sounding rocket payload in the ionosphere (ref. 1) has been found to be much less than had originally been theoretically predicted (ref. 2). To determine the reasons for this limited potential difference, large-vacuum-chamber tests were conducted in which electron and ion currents were ejected from a payload into a simulated ionosphere.

As a plausible explanation to the observed current voltage behavior, sheath ionization models (refs. 3,4) for small spacecraft have been studied. When an electron beam is emitted from a spacecraft, ambient electrons are attracted by the charged spacecraft (ref. 5). They collide with the neutral atmospheric molecules in their paths and may be energetic enough to ionize the neutrals to form new electrons and ions (ref. 6). These newly created charges alter the space charge current arriving at the spacecraft and shift the potential to a lower value. The beam electrons are assumed to be energetic enough to leave the spacecraft completely and to play a negligible role in the ionization. This mechanism is capable of explaining the nonmonotonic current-voltage behavior observed.

In this paper, we apply the sheath ionization model to large spacecraft in the ionosphere. In particular, it is important to find out whether the nonmonotonic current-voltage behavior during electron beam emissions would still be present for large spacecraft. Details of the method are given and followed by a discussion of results.

SYMBOLS

e	electron charge
E	electric field
I_b	beam current
m_e	mass of electron
m_i	mass of ion
n_e	density of ambient electrons
n^+	density of ionization ions
n^-	density of ionization electrons
P	probability of ionization
R	radius of spacecraft
r	radial position measured from center of spacecraft
r'	radial position used as integration variable
r_o	radius of sheath measured from center of spacecraft
v_e	velocity of an electron in sheath
v_{th}	thermal velocity of ambient electron
v_s	sweep velocity
ϵ_o	permittivity of space
λ	mean free path of electron neutral collision
ρ	space charge density
ϕ	electric potential

MATHEMATICAL FORMULATION

The method of approach used is to study an analytical "plasma probe" model (refs. 3,4,7,8), with space charge flow of electrons accelerating through the sheath surrounding a spherical "probe," which represents a spacecraft in an ionizable plasma environment. Magnetic field effect is ignored in this model.

The beam is assumed to be energetic enough to leave the spacecraft completely and is not stopped by its own space charge at all. As the beam electrons leave, the spacecraft becomes charged oppositely. A polarization region (sheath) is formed in the vicinity of the spacecraft. In our model, ions are assumed to be depleted due to charge repulsion inside the sheath (fig. 1).

The depletion radius r_o will be defined by the balance of the outgoing beam current with the incoming ambient current. For a beam current I_b, the depletion radius r_o is determined by

$$I_b = 4\pi r_o^2 n_e e v_{th} \tag{1}$$

where v_{th} is the thermal velocity and n_e is the number density of ambient electrons. Some typical values of sheath radius as calculated by means of equation (1) are shown in figure 2.

The potential ϕ at any point inside the sheath is governed by Poisson's equation:

$$\nabla^2\phi = -\frac{\rho}{\epsilon_0} \qquad (2)$$

where ρ is the space charge density and ϵ_0 is the permittivity of empty space.

Spherical Symmetric System

To simplify the geometry, we assume spherical symmetry in the spacecraft and sheath system. Equation (2) becomes simply a radial equation:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\phi(r)}{\partial r}\right) = -\frac{\rho(r)}{\epsilon_0} \qquad (3)$$

where the gradient of the potential ϕ gives the electric field E:

$$\frac{\partial\phi(r)}{\partial r} = -E(r) \qquad (4)$$

Taking into account the electron and ion pairs created as a result of ionization, the charge density ρ at any point r in the sheath is given by the sum of charge densities (fig. 3):

$$\rho(r) = e\,[n^+(r) - n^-(r) - n_e(r)] \qquad (5)$$

where n_e is the return current (primary) electron density and n^+ and $n-$ are the ionization ion and electron densities, respectively, due to return current electron collisions with neutrals.

The ionization electron density $n^-(r)$ is due to all ionizations that occur outward of r, and the density $n^+(r)$ of ions at r is due to all ionizations that occur inward of r. Thus

$$n^-(r) = \frac{1}{r^2}\int_r^{r_0} \frac{\left[\frac{dn}{dt}\right]_{r'} r'^2\,dr'}{[2e|\phi(r) - \phi(r')|/m_e]^{1/2}} \qquad (6)$$

and

$$n^+(r) = \frac{1}{r^2}\int_R^{r} \frac{\left[\frac{dn}{dt}\right]_{r'} r'^2\,dr'}{[2e|\phi(r) - \phi(r')|/m_i]^{1/2}} \qquad (7)$$

where

$$\left[\frac{dn}{dt}\right]_{r'} = \lambda^{-1}\rho[v_e(r')]n_e(r')v_e(r') \tag{8}$$

Numerical Method

To solve the system of equations (3) to (8), one divides the space of the sheath into N concentric shells and sets up N equations for the N unknowns Φ_i (fig. 4). In view of the complexity of the ionization terms in equations (6) and (7), it is impossible to solve these equations exactly. Instead, one seeks the approximate solutions that minimize a function F, the mean square of f_i, constructed from the radial Poisson equation (eq. (3)) for the i^{th} cell, where $i = 1, \ldots, N$.

$$f_i(E_1,\ldots,E_N) = (r^2E)_{i+1} - (r^2E)_i - \frac{1}{\varepsilon_0}\left[r^2\rho(E_1,\ldots,E_N)\right]_i \Delta r \tag{9}$$

where the electric field E (eq. (4)) is constructed in a finite difference scheme:

$$\Phi_i - \Phi_{i+1} = \frac{\Delta r(E_i + 2E_{i+1} + E_{i+2})}{4} \tag{10}$$

The numerical method used to solve equations (8) to (10) is the standard Newton-Raphson method of iteration:

$$E_i^{(j+1)} = E_i^{(j)} - \frac{f_i\left[E_1^{(j)},\ldots,E_N^{(j)}\right]}{\partial f_i\left[E_1^{(j)},\ldots,E_N^{(j)}\right]/\partial E_i} \tag{11}$$

A set of trial solutions is used to start in the Newton-Raphson iteration process, and a convergent set of solutions is sought for each set of input parameters such as beam current, ambient electron density, ambient electron temperature, mean free path, and spacecraft radius.

RESULTS AND DISCUSSION

Figure 5 shows the computed results of spacecraft potential as a function of electron beam current for various electron densities, electron temperatures, and mean free paths. The nonmonotonic behavior of potential current curves shows up. At low currents, the potential increases with beam current. When the current increases further, ionization occurs inside the sheath. The potential then turns around as the current of the electron beam increases.

The ion and electron charges created by ionization alter the behavior of the space charge flow, originally governed by the single charged Poisson equation. The potential turns to a lower value and stays approximately constant as current further increases.

At this stage, the potential profile as a function of radial distance shows locally flat gradient. This is due to ions created inside the sheath not being able to move out quickly because of their heavy masses. If a local ion charge buildup forms a potential hump, ion motion would be two ways, and the theory would then break down.

To overcome this difficulty, a sweep velocity v_s is added to the ions. Equation (7) becomes

$$n^+(r) = \frac{1}{r^2} \int_R^r \frac{\left[\frac{dn}{dt}\right]_{r'} r'^2 \, dr'}{\left[2e|\phi(r) - \phi(r')|/m_i + v_s^2\right]^{1/2}} \tag{12}$$

It is argued that the motion of a spacecraft relative to its plasma environment can provide such a sweep velocity v_s (eq. (12)). The value of v_s is of the order of spacecraft velocity and is an arbitrary input to the computation. However, at a higher current, a potential hump again shows up, and the computation fails to converge. The technique breaks down. It is conjectured that two-way space charge flows should be accommodated when a potential hump appears.

For increasing spacecraft radii, the nonmonotonic current-voltage behavior still persists (fig. 6). However, increased spacecraft radius lowers the maximum spacecraft potential induced by beam emission. Also, the amplitude of the difference between the maximum potential and the minimum (beyond the turnaround) diminishes. Figure 7 shows a plot of the envelope of maximum and minimum potentials for various spacecraft radii.

For a given beam current I_b (eq. (1)), the sheath surface area remains constant and is unaffected by the increase in spacecraft radius. The sheath thickness (defined as the sheath radius minus the spacecraft radius), however, diminishes. As a result, a lower spacecraft potential is sufficient to attract ambient electrons, through the sheath, for the compensation of electron beam current leaving the spacecraft.

Beyond the turnaround point in a current-potential curve, the minimum potential is limited by the minimum energy required to ionize a neutral molecule in the atmosphere. Since such a minimum energy is generally of the order of 20 eV (ref. 6), the minimum potential in a current-potential curve is expected to approach about 20 eV asymptotically, depending on the model of ionization used. For the same reason, if the maximum potential induced by beam emissions is below about 20 eV, no nonmonotonic behavior is expected.

Figure 7 shows the calculated envelopes of the maximum and minimum (beyond turnaround) potentials for various spacecraft radii in a given ambient environment. The amount of ionization becomes very small as the sheath potential approaches the minimum ionization potential. The amplitude of the potential drop beyond the turnaround also approaches the value of minimum ionization energy.

There is another critical beam current, which manifests itself for large spacecraft, but not for small ones. This current is determined by equating the sheath radius to the spacecraft radius. If the sheath radius is too small, the spacecraft will receive enough ambient electrons to compensate beam emissions without being charged up. The potential of the spacecraft is that of natural charging, in this case. Beyond this critical current, the beam emission is able to swing the spacecraft to an opposite potential and hence control the charging of the spacecraft. This phenomenon shows up in the calculations (fig. 6).

In the model studied, as the radius of a spacecraft increases, three regimes of physical behavior can be identified. Figure 8 shows these regimes clearly. The potential-versus-spacecraft-radius curve is relatively flat in the small-radius regime. This is the regime in which saturated ionization occurs (i.e., this is the regime beyond the minimum potential in a current-voltage curve). The second regime is characterized by the presence of the potential maximum, which is the main feature of nonmonotonic behavior. The third regime occurs when the spacecraft is so large that its radius exceeds the sheath radius (measured from the spacecraft center) for a given current. The beam loses its control of the spacecraft potential and natural charging dominates.

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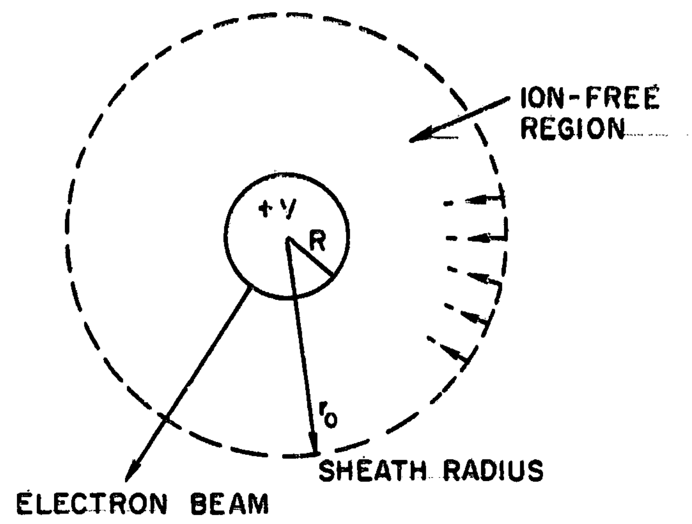

Figure 1. - Sheath formation during beam emission.

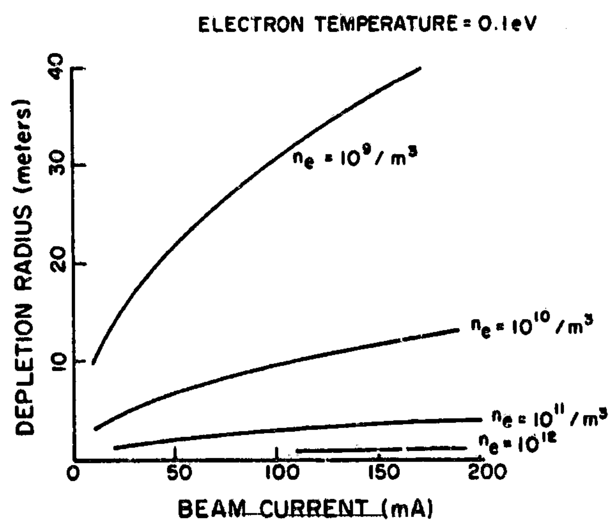

Figure 2. - Parametric dependence of sheath size.

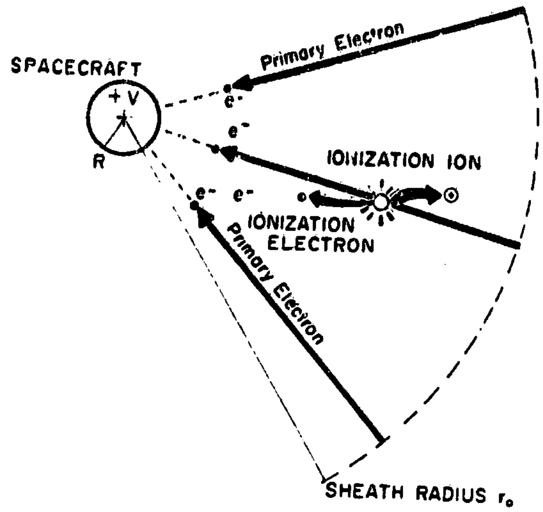

Figure 3. - Ionization pair - creation in sheath.

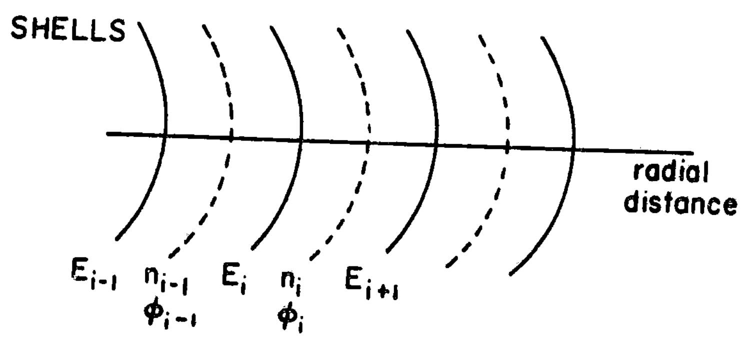

Figure 4. - Decomposition of sheath into shells.

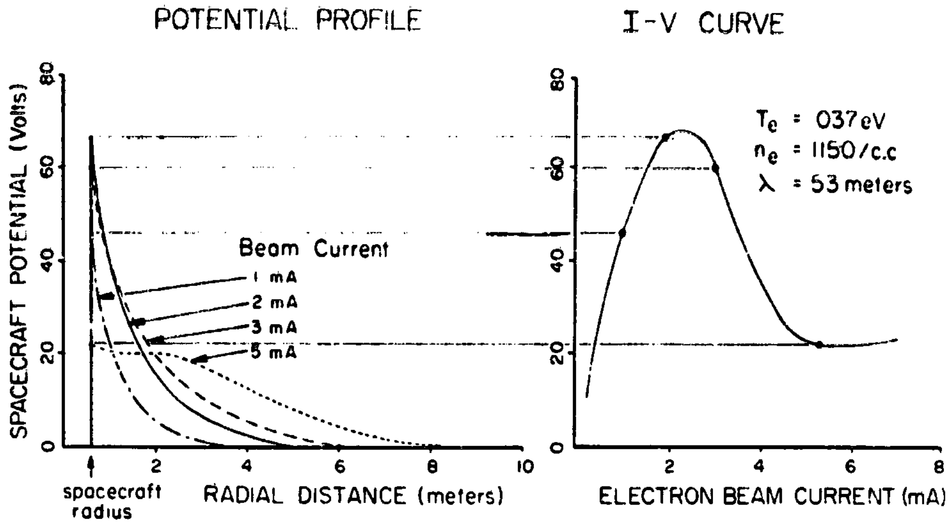

Figure 5. - Relation between potential profile and I-V behavior.

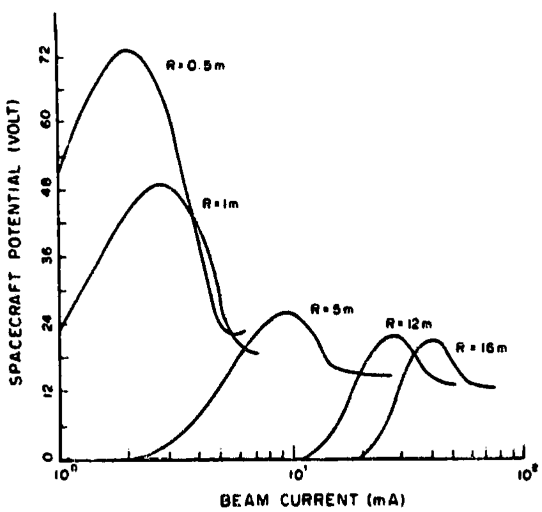

Figure 6. - Persistence of nonmonotonic I-V behavior. Parametric conditions are as in fig. 7.

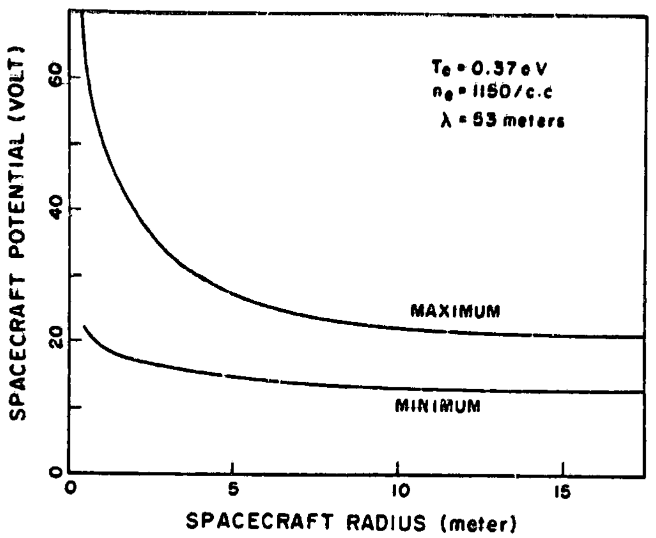

Figure 7. - Envelope of potential extrema in fig. 6.

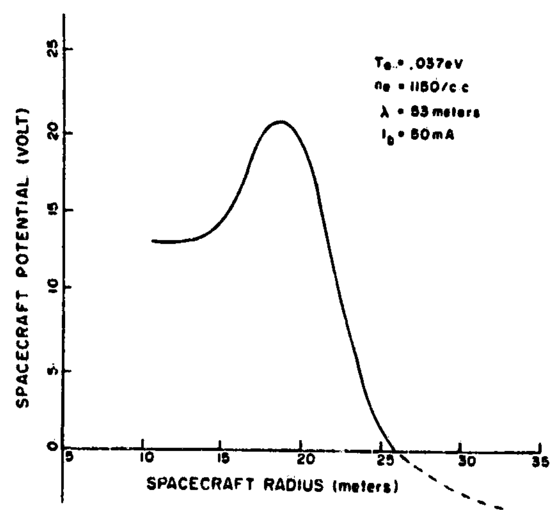

Figure 8. - Nonmonotonic behavior of spacecraft potential as a function of spacecraft radius, for a given electron beam current.