REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
22 Jun 2004

2. REPORT TYPE
REPRINT

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Spacecraft Plasma Environment Induced by High Current Beam Emission

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER
5201

5e. TASK NUMBER
RS

5f. WORK UNIT NUMBER
A1

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8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-VS-HA-TR-2004-1041

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Reprinted from proceedings: 41st AIAA Aerospace Scinces Meeting & Exhibit
6-9 January 2003/ Reno, NV

14. ABSTRACT

When the current of an electron or ion beam emitted from a spacecraft exceeds the ambient electron or ion current, there are two effects. (1) The high current beam emission raises the spacecraft potential to high levels, and (2) the spacecraft plasma environment is dominated by the returning electrons or ions at about the spacecraft potential energy. The returning electrons or ions are nearly mono-energetic and can come from the beam itself and/or from the ambient plasma attracted towards the spacecraft. We emphasize that instruments located a short distances outside the spacecraft may be bombarded by the returning beam electrons, or ions, circulating the spacecraft. High level charging of instrument surfaces may cause erroneous measurements, anomalies, or even failures. As cases in point, we discuss two high current beam emission events, vis., (1) the failures of the sC2 instruments on the SCATHA satellite and (2) the supercharging measurements using copper-beryllium booms on the MAIMAK satellite.

15. SUBJECT TERMS
Spacecraft charging
Electron beams
Elecron currents
Space plasmas

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCL	UNCL	UNCL	UNL		Shu T. Lai

19b. TELEPHONE NUMBER *(Include area code)*
(781) 377-2932

AFRL-VS-HA-TR-2005-1041

AIAA-2003-1227

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When the current of an electron or ion beam emitted from a spacecraft exceeds the ambient electron or ion current, there are two effects. (1) The high current beam emission raises the spacecraft potential to high levels, and (2) the spacecraft plasma environment is dominated by the returning electrons or ions at about the spacecraft potential energy. The returning electrons or ions are nearly mono-energetic and can come from the beam itself and/or from the ambient plasma attracted towards the spacecraft. We emphasize that instruments located at short distances outside the spacecraft may be bombarded by the returning beam electrons, or ions, circulating the spacecraft. As a result, the instrument surfaces are bombarded by the nearly mono-energetic beam electrons or ions, circulating the spacecraft. High level charging of instrument surfaces may cause erroneous measurements, anomalies, or even failures. As cases in point, we discuss two high current beam emission events, viz., (1) the failures of the SC2 instruments on the SCATHA satellite and (2) the supercharging measurements using copper-beryllium booms on the MAIMAK satellite.

1. Introduction

The theme of this paper is about the charging of spacecraft emitting a high current electron beam, the return and circulation of the beam electrons, and the impact of the electrons on the instruments located on, or outside, the surface of the spacecraft. As a result, the instruments bombarded can charge. Although the idea applies to both electron and ion beams, we do not discuss ions here because ion chemistry is a complexity that should be addressed separately. We begin with an introduction to spacecraft charging.

Spacecraft charging occurs when there is a net charge of one sign on the spacecraft surface. At geosynchronous altitudes, the space plasma is of low density (about 0.1-1 cm^{-3}) and often reaches high temperature (keV or more). Since electrons are lighter and faster than ions, the electron current intercepted by an object placed in a plasma (in the laboratory or in space) exceeds that of ions.

Intercepting more electrons does not necessarily imply negative voltage charging. For, in the range of about 60-2000 eV of primary electron energy, depending on the surface material, the outgoing electron (secondary and backscattered) flux may exceed that of the primary electrons, i.e. $\delta + \eta > 1$ [Figure 1]. To consider spacecraft charging,

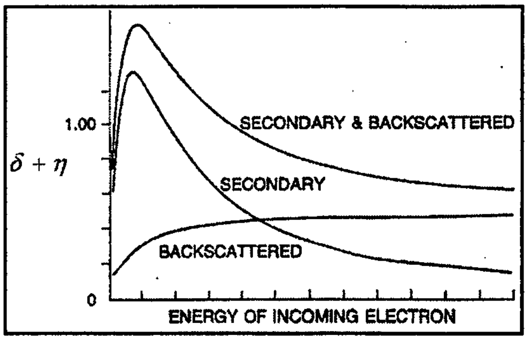

Fig.1 Coefficients of secondary δ and backscattered η electrons from typical surfaces.

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it is necessary to take the secondary and backscattered electrons into account.

2. Current collection with Beam Emission

It is often a good approximation to use the Mott-Langmuir orbit limited formula (eq.1) for describing the current collection of a spacecraft at geosynchronous altitudes.

$$I_e(0)\left(1+\frac{e\phi}{kT_e}\right)^{\alpha} - I_i(0)\exp\left(-\frac{e\phi}{kT_i}\right) = I_b - I_r \quad (1)$$

where $I_e(\phi)$ and $I_i(\phi)$ are the ambient electron and ion current at zero spacecraft potential ϕ, I_b and I_r are the electron-beam and beam-return currents respectively, and e is the magnitude of the electron charge [Figure 2].

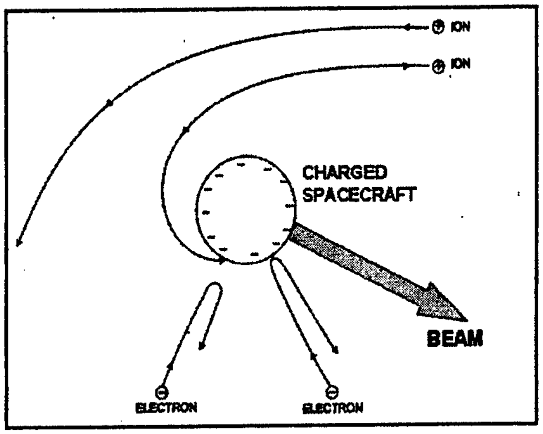

Fig.2 Current collection by a spacecraft with ion beam emission. For electron beam emission, the species and signs are changed accordingly.

3. Beam Return

In eq(1), the net current emitted I_{net} equals I_b - I_r. The exponent α in eq(1) depends on the spacecraft geometry and is unity for a spherical spacecraft. The exponent can be determined by fitting the current-voltage curve for given beam currents [*Lai*, 1994].

When the current I_b of the outgoing electron beam emitted from a spacecraft exceeds that, $I_e(\phi)$, of the incoming ambient electrons, the spacecraft charges to positive potentials. Since a positively charged spacecraft ($\phi > 0$) must repel the ambient ions during electron beam emissions, the ion term, $I_i(0)\exp(-e\phi/kT)$, can be neglected in eq(1) when the beam induced spacecraft potential ϕ is sufficiently high.

$$I_{net} = I_e(0)\left(1+\frac{e\phi}{kT_e}\right)^{\alpha} \quad (2)$$

In eq(2), note that the spacecraft potential ϕ is linearly proportional to the net beam current emitted.

4. Maximum Spacecraft Potential

When the beam current, I_b , increases, the spacecraft potential, ϕ, increases monotonically with I_b (eq.2). When ϕ reaches the beam energy $e\phi_B$, part of the beam returns and I_r becomes finite.

$$I_{net} = I_b - I_r(\phi)\Theta(\phi-\phi_B) \quad (3)$$

where Θ(x) is a step function (Θ=0 for x<0, and 1 for x≥0).

As a good analogy, imagine a person digging the ground. The soil thrown up is analgous to the beam electrons emitted from a spacecraft. The depth of the cavity is analogous to the spacecraft potential. One can only dig as deep as one can throw. If one tries to dig deeper, the soil thrown up must return [Figure 3].

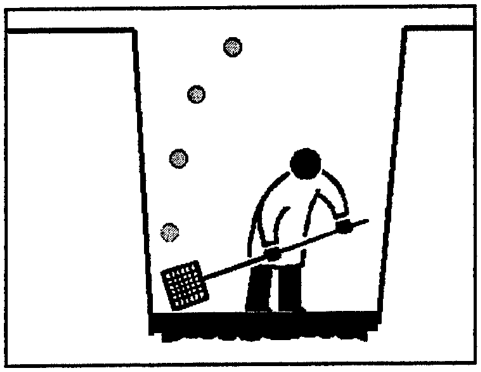

Fig.3 One can only dig as deep as one can throw.

In summary, (1) the spacecraft potential increases linearly with the beam current, (2) when the critical beam current is reached, the spacecraft reaches its maximum potential, (3) the maximum spacecraft potential is simply that of the beam energy, and (4) if an excess beam current is emitted, the net beam current remains constant while the excess beam current returns to the spacecraft.

5. Beam Divergence

Beams of one sign of charge diverges because of space charge repulsion. High current density beams diverge highly.

To appreciate the repulsion, consider, for example, a cylindrical electron beam of current $I = 0.1$A, beam radius $r = 0.1$ cm, and (kinetic) beam energy = 1 keV. The transverse electric field E calculated by using the Gauss law is $E = 0.96$ kV/cm.

$$E = \frac{r\rho}{2\varepsilon_o} = \frac{I}{2\pi r\varepsilon_o \left(2e\phi/m\right)^{1/2}} \qquad (4)$$

where ρ is the charge density, r radius of the beam, I current, ϕ the beam energy, and m the electron mass. Such a high transverse electric field should be noted.

From Gauss, Biot-Savart, and Faraday laws, the equation of motion of an electron on the beam envelope is [*Lai*, 2002]:

$$m\frac{d^2}{dr^2}r(x) = \frac{1}{4\pi\varepsilon_o}\frac{2eI}{r(x)V(x)}\left(1-\frac{V^2(x)}{c^2}\right) \qquad (5)$$

In this coordinate system, x is along the line of cylindrical symmetry of the beam which expands with time t. In eq(5), r(x) is the radius of the beam at distance x from the beam exit point (x=0), I the current, m the electron mass, and V the beam velocity. By beam envelope we mean the trajectory of an outermost beam electron at r=r(0) initially. Eq(5) can be integrated analytically [*Lai*, 2002], if one knows the spacecraft sheath potential profile so that the beam electron velocity V(x) can be formulated.

6. Beam Focusing Assembly

In modern beam emission devices, it is common to feature a focusing assembly which squeezes the beam by applying an electrostatic force transversely at the beam exit point. For example, the beam device on the SCATHA satellite features such an assembly [p.34, *Stevens and Vampola*, 1978]. Such a squeezing force increases the space charge density of the beam and its electrostatic potential. Upon emission, the beam expands at the expense of the space charge potential energy.

7. Environment of Returning Beam Electrons

When a high-current divergent beam is returning to a spacecraft, which has reached its maximum potential, the beam electrons start with nearly zero radial velocity at the commencement of their return [Figure 4]. Their transverse velocities can be large because the transverse kinetic energy of the returning beam is the sum of the potential energy of the beam's original space charge plus that added by the focusing device at the exit point. Depending on the spacecraft potential sheath profile, the radial velocities of the returning beam electrons increase gradually and inversely as function of the electron distance x from the spacecraft surface.

As a consequence of high current beam return, the returning beam electron velocity at every distance x is nearly mono-energetic. There can be an energy spread corresponding to that of the beam emitted.

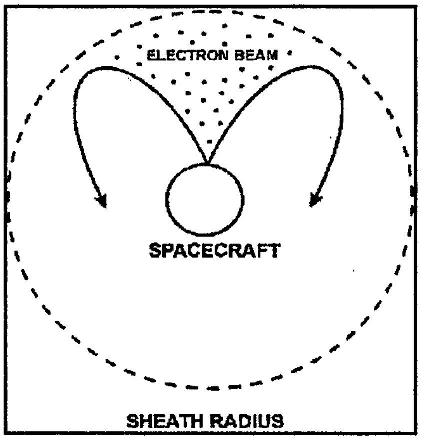

Fig.4 Beam divergence and beam return.

If the beam current emitted greatly exceeds that of the ambient electrons, the returning current can be large accordingly. As a result, the spacecraft environment consists mainly of the returning electrons, which are of high current-density and are nearly mono-energetic.

8. Trapped Orbits

An interesting question for the spacecraft environment during high current beam emission is: "As the returning beam electrons, which are much more abundant than the ambient electrons, are circulating the spacecraft, is there a trapped orbit?" Since the current density in the trapped orbit is high, any instrument located in that orbit would suffer from the impact of high electron current.

The energy E of an electron in a potential ϕ is of the form:

$$E = \tfrac{1}{2} m(u^2 + w^2) + e\phi(r) \tag{6}$$

where u and w are the radial and transveral electron velocity components respectively, and e is the (negative) charge for an electron. In a central force system, the angular momentum J is a constant.

$$J = mwr \tag{7}$$

Therefore,

$$E = \tfrac{1}{2} mu^2 + \left(\frac{J^2}{2mr^2} + e\phi(r) \right) \tag{8}$$

In eq(8), the term in parenthesis is called the effective potential energy $U(\mathrm{r})$. In a trapped orbit located at r, the potential $U(\mathrm{r})$ must be a minimum, requiring the first and second derivatives, $dU(\mathrm{r})/d\mathrm{r}$ and $d^2U(\mathrm{r})/d\mathrm{r}^2$, be zero and positive respectively. For a Coulomb potential, the derivatives yield no solution. Therefore, there is no trapped orbit in a Coulomb potential. However, for a plasma potential $U(\mathrm{r})$ of the Debye form:

$$U(r) = \exp(-r/\lambda)/r \tag{9}$$

there is a solution:

$$J^2 = -emr^3 \left(\frac{1}{\lambda} + \frac{1}{r} \right) \frac{e^{-r/\lambda}}{r} \tag{10}$$

where the Debye length has to satisfy

$$\lambda < r/0.57 \tag{11}$$

approximately.

For example, if the trapped orbit is located at r = 3m, the Debye length λ has to be less than about 6m. The electron density at r has to exceed a critical value accordingly.

As a remark, an instrument located in the paths of the returning and circulating electrons would suffer from electron impact, whether there is a trapped orbit or not. If the instrument intersects a trapped or semi-trapped orbit, the electron current intercepted would be higher.

9. Impact of the Returning Electrons on Instruments

As an application of the spacecraft environment during high beam current emission, we consider instruments installed on or above a spacecraft surface. As the instruments are impacted by the returning electrons, positive or negative charging of the instruments can occur, depending on the primary electron energy upon impact. By using the secondary and backscattered electron coeffcients, one can derive a charging domain map [Figure 5] for such an impact on the instrument surface.

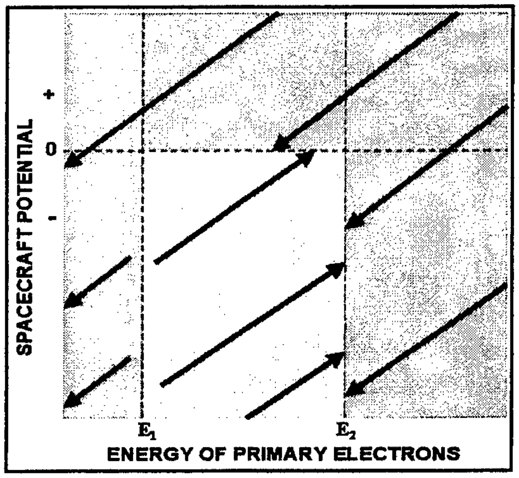

Fig.5 Domain map of charging by the returning beam electrons circulating the spacecraft. The arrows indicate the direction of change of the spacecraft potential for given initial primary electron current and surface potential.

As an illustration, suppose one starts with the impact of electrons of energy E such that $E>E_1$ and $E_2>E$, where E_1 and E_2 are the cross-over points of the outgoing secondary and backscattered electrons [Figure 1]. In addition, one assumes that the initial surface potential is negative. At such an energy, the outgoing electron current is greater than that of the incoming electrons. Therefore, the instrument surface (negative) potential decreases in magnitude, thereby increasing the primary electron energy. Eventually, the instrument surface potential moves to either 0 or a value where the primary electron energy is at the cross-over point E_2 in order to achieve current balance [Fig 5]. It is interesting that under no circumstance would the final primary electron energy settle at E_1. This first cross-over point E_1 corresponds to an unstable current-voltage situation, in analogy to negative Ohm's law.

As another illustration, consider the same initial beam energy but a different surface potential initially. Let the potential be positive so that the secondary electrons, which have a few eV energy only, can not leave. The returning beam electrons come in and accumulate on the surface, reducing the positive surface potential. As a result, the impact energy decreases.

10. Cases in Point

Case 1:

When the electron beam current emitted from the SCATHA satellite increased, the c spacecraft potential increased accordingly [*Lai, et al.*, 1987; *Lai,* 1989]. When the beam current began to exceed about the ambient current, the spacecraft potential became positive [*Lai,* 1994].

When a high current (13mA, 1.5 keV) electron beam was emitted, the intrument SC2 located at about 2m above the spacecraft surface was promptly destroyed even though SC2 was not on the direct path of the outgoing electron beam [*Cohen, et al.*, 1981]. The beam current was so high (13 mA) that the beam electrons came back circulating the spacecraft, entered the instrument SC2, and destroyed the circuit inside.

Case 2:

Both MAIMAK [*Denig, et al.*, 1991] and Gruziya-60-Spurt [*Kochmaryov, et al.*, 1985; *Managadze, et al.*, 1988] experiments used long booms to measure spacecraft potentials with respect to the ambient plasma. As high electron-beam currents were emitted from the spacecraft. the long booms, which were electrically isolated from the spacecrafts, received high currents of returning electrons and became charged negatively [*Lai*, 2002].

$$\text{Objective}: \quad \Delta\phi = \phi_{plasma} - \phi_s \qquad (13)$$

$$\text{Actual}: \quad \Delta\phi = \phi_{boom} - \phi_s \qquad (14)$$

Usually, $\phi_{boom} \approx \phi_{plasma} \approx 0$, so that the measurement $\Delta\phi$ is a good approximation of the magnitude of the spacecraft potential ϕ_s.

On MAIMAK, however, the electron beam was 8 keV in energy and the boom surface material was copper-beryllium which has an $E_2 \approx 3.5$ keV. Suppose the spacecraft charged to its maximum $\phi_s = +8$kV as a result of large-current (hundreds of mA) beam emission, while the boom charged to $\phi_{boom} \approx -4$kV as a result of electron bombardment by the returning beam electrons. The actual difference $\Delta\phi$ would equal to 12 kV (eq.14), a value larger than the actual spacecraft potential ϕ_s which was +8kV only.

Therefore, one should be careful in interpreting this type of measurements [*Lai*, 2002], otherwise it can easily be misinterpreted as supercharging [*Denig, et al.*, 1991; *Kochmaryov, et al.*, 1985; *Managadze, et al.*, 1988].

11. Summary

During high current beam emission from spacecraft, the spacecraft charges to a maximum potential equivalent to the beam energy. To balance the currents, part of the beam current returns to the spacecraft. As a result of energy conversion from the initial beam space charge and that given by the focusing device, the transverse energy of the beam bcomes substantial.

The returning electrons form an artifiical charged environment around the spacecraft. Any instrument placed at the path of the returning electrons would be bombarded by the high current of returning beam electrons circulating the spacecraft. As a result, the instrument may charge, positively or negatively, depending on the impact energy and the surface properties. In worst cases, the instrument bombarded may be destroyed.

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