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Spacecraft Charging during Ion Beam Emissions in Sunlight

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ABSTRACT

During ion beam emissions from the SCATHA satellite, the potential of the negatively charged satellite body shows a sinusoidal oscillation frequency of once per spin of the satellite. The minimum occurs when the ion beam is sunward. We consider processes that may be responsible for the voltage modulation. Neutralization of ion beam space charge by photoelectrons is examined. The photoelectrons are accelerated by the negative potential of the satellite. Effects of electron impact ionization, excitation of metastable states, and photoionization of xenon neutral atoms in the ion beam are studied in details. Critical ionization velocity interaction is unlikely under the condition considered.

INTRODUCTION

The SCATHA (P78-2) satellite [*Stevens and Vampola*, 1978] is at near geosynchronous altitudes and is cylindrical in shape (about 1m long and 1.6m diameter). It is spin stabilized at approximately one spin per minute with the spin axis normal to sunlight. The spin axis coincides with the cylindrical axis of the satellite.

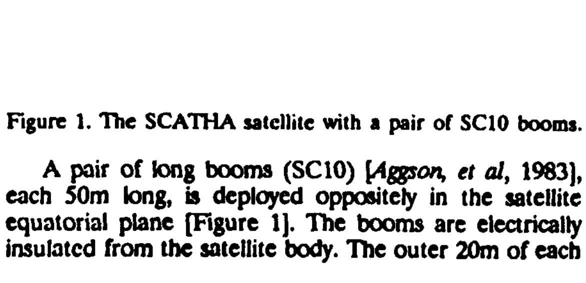

Figure 1. The SCATHA satellite with a pair of SC10 booms.

A pair of long booms (SC10) [*Aggson, et al*, 1983], each 50m long, is deployed oppositely in the satellite equatorial plane [Figure 1]. The booms are electrically insulated from the satellite body. The outer 20m of each boom is a copper beryllium (CuBe) alloy, which has a very high secondary emission coefficient [*Katz et al*, 1977]. The inner segment is coated with Kapton which is insulative. Charging of copper beryllium surfaces is insignificant except in an unusally energetic plasma environment. In sunlight, the copper beryllium surface is charged to a few Volts typically [*Lai, et al*, 1986]. Measurements of the potential difference Φ (SC10 data) between the tip of a boom and the satellite body indicate the approximate satellite potential Φ_{sat} with respect to the ambient plasma.

$$\Phi = \Phi_{CuBe} - \Phi_{sat} \approx - \Phi_{sat} \qquad (1)$$

The approximate equality in Eq(1) is valid if Φ_{sat} is much greater than a few Volts. The SC10 data Φ differs by the satellite potential Φ_{sat} by a sign.

The ion beam (SC4-2) on SCATHA consists of positive xenon ions and neutral xenon atoms. To generate ions, a controlled amount of neutral xenon gas is injected into an ionization chamber in which partial ionization of the gas occurs. An extraction grid, with a controlled negative potential, is located inside the beam nozzle, and extracts ions from the chamber. Electrons cannot leave because they are guarded by the grid. In this manner, an ion beam is formed. The beam is emitted at an angle of about 56 degrees from the spin axis. Since the spin is normal to sunlight, the sun angle subtended by the beam varies sinusoidally as the satellite spins.

Spacecraft charging is due to either natural or artificial causes. Both observation [*Mullen et al*, 1986] and theory [*Laframboise et al*, 1982, 1983; *Lai et al*, 1982, 1983] show that high level natural charging at geosynchronous altitudes occurs when the ambient plasma is energetic. In order to observe the change of spacecraft potential in response to (artificial) ion beam emissions, we choose a quiet day on which the ambient plasma alone is not expected to cause any significant charging.

In the next section, we present the salient features of SC10 data in response to ion beam emissions. In subsequent sections, we will attempt to examine two plausible mechanisms which may explain the features. The mechanisms are (1) neutralization of the ion beam as it traverses a photoelectron potential barrier and (2) ionization of the ion beam neutrals resulting in slow ion return.

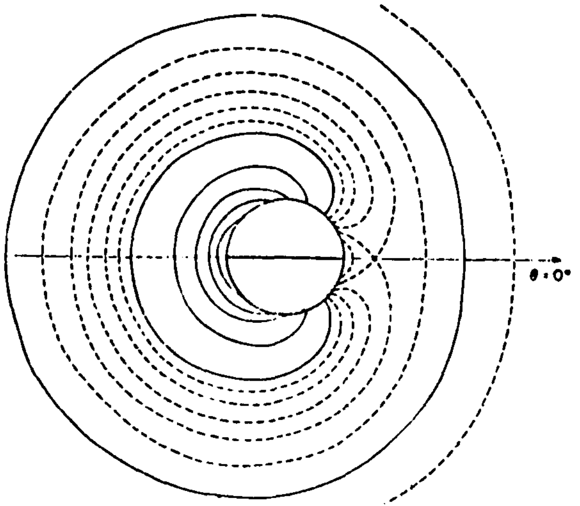

Figure 5. The monopole - dipole potential model [*Besse and Rubin*, 1980].

satellite, the beam propagates through the photoelectron cloud once per spin. When the beam is propagating through the cloud, photoelectrons are dragged along by the beam [Figure 6]; this is a neutralization process in the ion beam. As a result, there are more electrons leaving the spacecraft when the ion beam is sunward. It follows that the magnitude of the beam induced negative spacecraft potential is reduced when the beam is sunward and therefore the potential oscillates with a frequency of once per satellite rotation. This explains the observed features (1), (3) and (4).

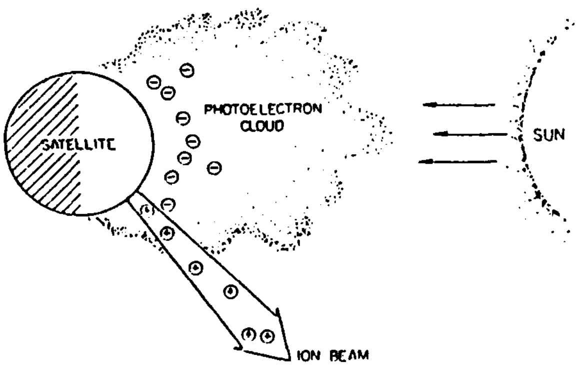

Figure 6. Ion beam passing through a photoelectron cloud on the sunlit side of a satellite.

Details of the beam neutralization process have yet to be worked out. The photoelectrons may be dragged by (a) the space charge of the ion beam or (b) by electrostatic plasma waves. Simple models of ion beam neutralization by space charge have been studied [*Dunn and Ho*, 1963, *Wilhelm*, 1974]. Electrostatic waves due to the two stream instability induced by the beam ions and photoelectrons may lift the latter up and over the barrier in an escalator fashion. We will not discuss details of ion beam neutralization process in this paper.

For an estimate, we take the monopole-dipole model [*Besse and Rubin*, 1980]. Let the spacecraft potential Φ_{dark} on the dark side be -200V and take the potential B of the photoelectron potential barrier as 0.5V. The monopole - dipole model [*Besse and Rubin*, 1980] gives the potential Φ_{sun} of sunlit side of the spacecraft as

$$\Phi_{sun} = \Phi_{dark}[1/3 - 0.8(B/\Phi_{dark})^{1/2}] \qquad (2)$$

which yields Φ_{sun} = - 58.6V. The location R_s of the saddle point of the barrier is given by

$$R_s = 2(\Phi_{dark} - \Phi_{sun})/(\Phi_{dark}+\Phi_{sun}) \qquad (3)$$

which gives R_s=1.0936 in units of satellite radius. For SCATHA, Eq(3) gives 7.49cm as the location of the saddle point from the sunlit surface.

Differences in the properties of various pieces of surface materials on the spacecraft may cause such a high differential charging ($\Phi_{sun} - \Phi_{dark}$=141.4 Volt). For example, when a 6mA electron beam current at 3 keV energy was emitted on Day 114 1979, the potential difference measured between surface samples 2V2 and 1V3 reached 1147 Volts [*Cohen et al*, 1981]. Data of various surface potentials on Day 200 are not known. Evidence of the existence of difference charging with a magnitude of some 150 V between the sunlit and dark sides on this Day is unavailable at this time. Unless evidence to the contrary is found, the potential barrier theory remains a viable candidate for plausible explanation of the spacecraft charging behavior during ion beam emission in sunlight.

RETURNING ION THEORY

The ion beam consists of neutral xenon atoms which wander out from the ionization chamber through the negatively charged grid guarding electrons. The neutrals are at thermal energies. The ratio of neutrals to ions is about 10 to 1 [*Masek*, 1978], but its variations as functions of beam energy and current have not been determined. We will not attempt to assume any specific ratio quantitatively in the following. We stress that the collisional reactions discussed in the following are important, and unavoidable, for all ion beams based on the extraction of ions from partially ionized plasma in chambers.

As the xenon ions and xenon neutrals collide in the beam, charge exchange [*Massey and Burhop*, 1952; *Toburen, et al*, 1968] and ion impact ionization [*Kikiani, et al*, 1975] may occur. At the energy (1 keV) of the SCATHA ion beam on Day200, charge exchange dominates.

$$Xe_{slow} + Xe_{fast}^{+} \rightarrow Xe_{slow}^{+} + Xe_{fast}. \qquad (4)$$

As a result, slow ions are generated and attracted by the negatively charged spacecraft. Thus, the slow ions return to the spacecraft and thereby reduce the level of spacecraft charging. On the sunward side, electron impact ionization [*Stephen and Märk*, 1984] of the neutral xenon (in ground state) occurs:

$$Xe + e^- \rightarrow Xe^+ + 2e^-, \quad (5)$$

which is energetically possible because the photoelectrons are accelerated as they are being repelled by the spacecraft's negative potential (hundreds of Volts negative).

As an alternate pathway, the electrons can excite the xenons to metastable states:

$$Xe + e^- \rightarrow Xe^* + e^-, \quad (6)$$

which are then ionized by electrons or simply by sunlight.

$$Xe^* + e^- \rightarrow Xe^+ + 2e^-, \quad (7)$$
$$Xe^* + h\nu \rightarrow Xe^+ + e^-. \quad (8)$$

Some reaction cross sections concerning xenon are shown in Figure 7. The processes (6 to 8) are energetically possible because the optimal energies for excitation [*Lai et al*, 1988] and ionization [*Ton-That and Flannery*, 1977] of xenon metastable states are near but below 10 eV; while the dominant spectral line (Lyman α) in sunlight has an energy $h\nu = 10.2$ eV [*Hinteregger et al*, 1959].

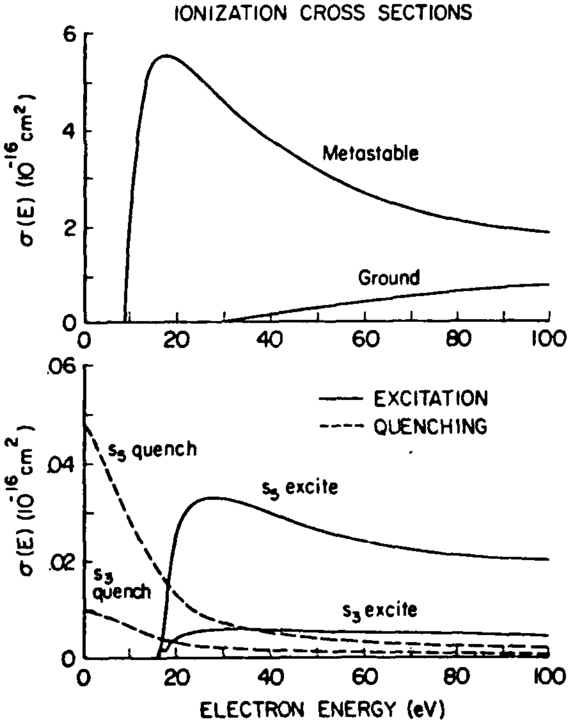

Figure 7. Electron impact excitation and ionization cross sections for xenon [from *Lai et al*, 1988].

As a result of the reactions (4 to 8), slow ions are generated in the ion beam which is partially ionized. Because of the thermal energies of the neutrals, the newly generated ions have kinetic energies much less than 1 eV initially. The ions are attracted by the negatively charged spacecraft (hundreds of eV), thereby reducing the net positive charge flux leaving the spacecraft and, therefore, the charging level of the spacecraft is lowered. Thus, the spacecraft is not expected to charge to the ion beam potential. Since reaction (8) occurs only on the sunlit side, the charging level is expected to be lowest when the beam is in sunward direction. *This is in agreement with observation.*

Furthermore, as the ions are returning to the spacecraft, they are accelerated due to the negative spacecraft potential, and, as they impact the surface, secondary electrons are generated. These secondary electrons join the photoelectrons in the participation of the excitation and ionization processes. These secondary electrons are not due to electron impact; there is no need to consider energy crossing points for the secondary electron emission coefficients because both the incoming ion flux and the outgoing electron flux contribute to the reduction of the level of negative charging of the spacecraft surface. These secondary electrons then join the photoelectrons in the participation of excitation and ionization processes of xenon atoms. Thus, when the ion beam is sunward, the returning ions due to photo-ionization of metastable xenon neutral atoms and the outgoing secondary electrons both tend to reduce the charging level, *in agreement with observation.*

We remark that the three body reaction:

$$Xe^+ + 2Xe \rightarrow Xe_2^+ + Xe \quad (9)$$

followed by

$$Xe_2^+ + e^- \rightarrow 2Xe \quad (10)$$

tends to reduce the returning ion current. For the SCATHA ion beam case, these reactions are expected to be insignificant because of low beam density. However, for dense ion-neutral beams, three body reactions may be important.

CONCLUSION AND DISCUSSION

During ion beam emissions on SCATHA, the SC10 data show modulations at the same frequency as the spacecraft rotation. These data indicate the charging level of the spacecraft ground with respect to the ambient plasma. When the ion beam is sunward, the charging level is minimum. Two plausible mechanisms are discussed, the photoelectron potential barrier theory and returning ion theory. The former theory is possible if significant differential charging occurs; the ion beam drags the photoelectron over the barrier and away. The latter theory stems from the abundance of neutral xenon in the ion beam. Charge exchange, ion impact ionization, metastable state excitation, and photo-ionization of metastable states play interesting roles. The returning ions reduce the spacecraft charging level. Furthermore, the ion induced secondary electrons participate in the ionization and excitation reactions.

We now remark briefly the noisy nature of the data. When there is plasma instability such as a two stream instability between an ion beam and a photoelectron cloud, electrostatic waves appear and they may be noisy. However, when an electron beam is emitted through the photoelectron cloud on SCATHA, no such noise has been observed [*Lai et al*, 1985, 1986] even though a similar argument of two-stream instability may be applied to the electron beam interacting with the photoelectron cloud.

The noise during ion beam emission is present even when in eclipse. This rules out any sunlight interaction as a cause of the noise. Besides, during electron beam emission in sunlight, the noise is absent [*Lai et al*, 1987]. We conclude that the noise must be due to the circuitry of the ion beam.

Finally, critical velocity ionization [*Alfvén*, 1960] under the conditions considered is ruled out. The beam neutral velocity is too slow for critical velocity ionization to occur in the SCATHA ion beam case. Charge exchange between beam ions and beam neutrals is the most likely process responsible for generating returning ions.

APPENDIX

The Frequency Invariance of a Running Average

Suppose we have a function A(t) of the form

$$A(t_i) = \alpha\sin(\omega t_i+\phi) + \beta(t) + c \qquad (A.1)$$

where $\beta(t)$ is a random variable (with a white noise spectrum) and c is a constant, given at a series of *equally* spaced points t_i $(i=0,1,...,N)$. From the function $A(t_i)$, we form the 2n+1 point average $<A>_i$ $(i=m,m+1,...,N\text{-}m)$ defined in the usual way by

$$<A>_i=(\Sigma_{j=-m,m}\alpha\sin(\omega t_i+\phi) + \Sigma_{j=-m,m}\beta(t_i)+\Sigma_{j=-m,m}c) / (2m+1) \qquad (A.2)$$

Assuming that m is large enough, the second term in Eq(A.2) will become negligible, since the average of the random function is zero. $<A>_i$ can then be related to the signal of interest as follows. Defining $\delta=\omega(t_k-t_{k-1})$, we see that $<A>_i$ can be written as

$$\begin{aligned}<A>_i = [&\alpha\sin(-m\delta)\cos(\omega t_i+\phi)\\ &+ \alpha\cos(-m\delta)\sin(\omega t_i+\phi)\\ &+ \alpha\sin(-(m-1)\delta)\cos(\omega t_i+\phi)\\ &+ \alpha\cos(-(m-1)\delta)\sin(\omega t_i+\phi)\\ &+ ...\\ &+ \alpha\sin(\omega t_i+\phi)\\ &+ ...\\ &+ \alpha\sin((m-1)\delta)\cos(\omega t_i+\phi)\\ &+ \alpha\cos((m-1)\delta)\sin(\omega t_i+\phi)\\ &+ \alpha\sin(m\delta)\cos(\omega t_i+\phi)\\ &+ \alpha\cos(m\delta)\sin(\omega t_i+\phi)\\ &+ (2m+1)c] / (2m+1) \qquad (A.3)\end{aligned}$$

Since $\sin(-\theta)= -\sin(\theta)$ and $\cos(-\theta)=\cos(\theta)$, Eq(A.3) can be simplified to

$$<A>_i = (2m+1)^{-1}(1+2\cos\delta+2\cos2\delta+ ... +2\cos m\delta)\sin(\omega t_i+\phi) + c \qquad (A.4)$$

We see that the constant portion of $<A>_i$ is identical to that of $A(t_i)$ and that the sine wave portion (the oscillation amplitude) differs from $A(t_i)$ only by a constant multiplicatyive factor χ given by

$$\chi(m,\delta)=(1+2\cos\delta+2\cos2\delta+ ... +2\cos m\delta)/(2m+1) \qquad (A.5)$$

Furthermore, it is clear that the *frequency* of $<A>_i$ is identical to that of $A(t_i)$, since Eqs(A.1) and (A.4) indicate that $<A>_i$ will have an extremum whenever $A(t_i)$ has an extremum. The amplitude of $<A>_i$ is reduced by a factor χ, which is less than or equal to unity.

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