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An Overview of Electron and Ion Beam Effects in Charging and Discharging of Spacecraft

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AN OVERVIEW OF ELECTRON AND ION BEAM EFFECTS IN CHARGING AND DISCHARGING OF SPACECRAFT

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Abstract - **The electron and ion beam effects on the charging and discharging of the SCATHA satellite are presented.**

I. INTRODUCTION

Charging of spacecraft in the space radiation environment may be hazardous to the health of on-board electronics [1-3]. It may affect telemetry, navigation, operation, and even the survivability of spacecraft, and degrade scientific measurements [1-3]. Spacecraft charging may be due to natural or artificial causes. Natural charging is due to the interaction between a spacecraft and its space radiation environment. Artificial charging is due to beam emissions, for example. In the geosynchronous environment (Fig.1), a spacecraft is often charged negatively during eclipse [4,5]. SCATHA data show that the average electron density is 1.09 /c.c. and the average temperature is 2.49 keV [6]. The odd shape of the plasmasphere (Fig.1) is a result of its corotation with the earth. Inside the plasmasphere, the electron density is dense (10 to 1000 /c.c.) and the average temperature is below 30 eV. There is a transition region outside the boundary of the plasmasphere with a steep gradient in plasma density. Depending on the level of magnetic activity, the boundary of the plasmasphere may change. The plasmasphere can extend to geosynchronous orbit. Data obtained on SCATHA show that high level natural charging occurs when the electron temperature is high [7,8]. Following the occurence of multiple substorms, negative charging may reach as high as several kV due to the sharp increase in high energy electron flux [7,8]

To study spacecraft charging and the mitigation of it, the SCATHA (P78-2) satellite (Figure 2) was launched into near geosynchronous orbit in 1979 [9,10] The satellite spins at about 1 rpm with its axis perpendicular to sunlight [9,10]. A pair of booms, electrically isolated from the satellite body, is used to measure satellite potential with respect to the ambient plasma [10-12]. Electron and ion beam experiments [13-20] have been conducted on SCATHA with interesting results.

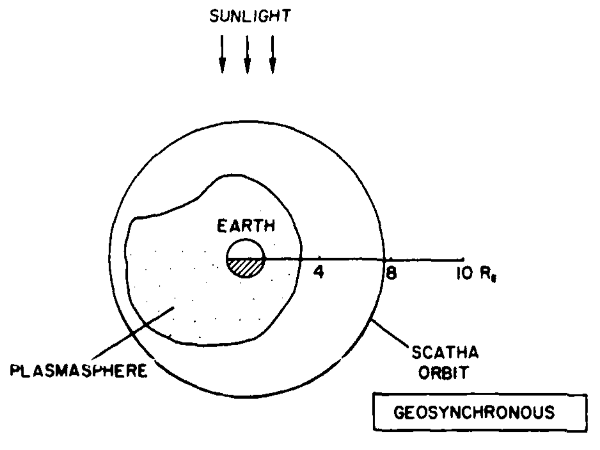

Figure 1. Spacecraft charging environment at geosynchronous altitudes.

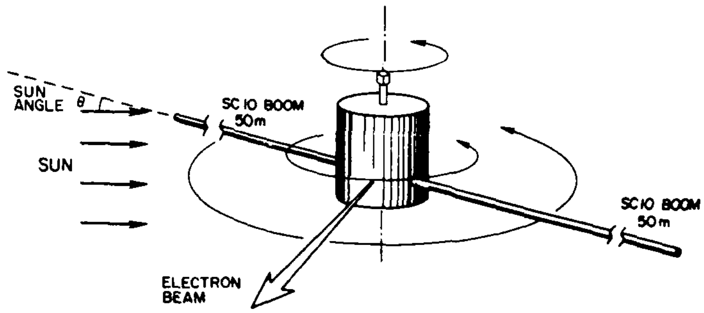

Figure 2. Schematic diagram of the SCATHA satellite with beam emission (from [18]).

II. ELECTRON BEAM EFFECTS: SPACECRAFT CHARGING

Experiment data taken on the SCATHA satellite showed that electron beam emission can charge the satellite to positive potentials [14,17,18]. Typically, in quiet times, a high energy electron beam of .01mA can charge SCATHA to nearly 10 V. Depending on beam energy and ambient conditions, higher currents often charge SCATHA to higher potentials (Figure 3).

The highest electron beam current emitted from SCATHA is 13 mA. The event was on Day 89, 1979. The spacecraft potential reached 4 kV in a quiet period. Differential charging between some surface materials reached more than 1 kV. (For example, surface potential

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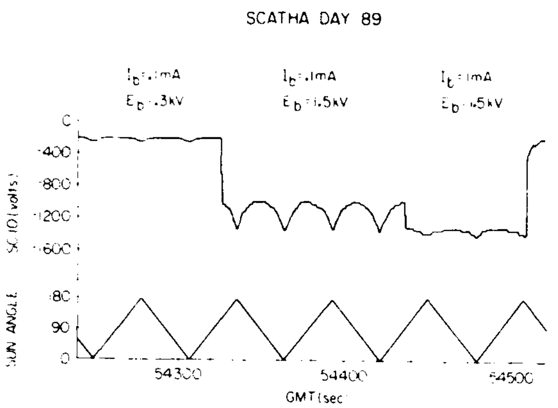

Figure 3. SCATHA potential in response to electron beam emissions in sunlight (from [18]).

monitor measurements on SCATHA show that the differential charging between the aluminized kapton sample 2V2 and the spacecraft ground reached 1.189 kV [14].) As a consequence, two parts of a valuable instrument, SC2, on SCATHA were promptly knocked out permanently [14]. This event serves as a strong demonstration on the danger of high level spacecraft charging, especially differential charging.

The exact charging level depends on the beam energy and the balance of currents. When a spacecraft is charged to near beam energy, the beam spreads due to space charge repulsion and partial beam return occurs [17,18]. When the beam energy is high relative to the spacecraft potential, space charge effect is negligible and the beam leaves completely. Inside the plasmasphere [17], the charging level is generally lower because of higher densities of low energy ambient electrons.

A. Multi-Body Interaction.

A remarkable effect observed on SCATHA is that photoelectrons from nearby booms tend to return to the spacecraft body during electron beam emissions [18]. This is a case of "multi-body interactions" in space plasma during beam emissions (Figure 4). The booms, which are electrically isolated from the spacecraft body, are partially engulfed in the plasma "sheath" of the highly charged spacecraft body. The total photoelectron current I_{ph} going towards the spacecraft body depends on the potential Φ of the spacecraft with respect to the space plasma, the distance r of the photoelectrons from the spacecraft surface, the boom surface area, and the sun angle h of the boom. In a simple model [18], the total photoelectron current I_{ph} is given by

$$I_{ph}(\theta,\Phi)=2D\,|\sin\theta|\int dr\; J(r,\Phi) \qquad (1)$$

where

$$J(r,\Phi) = f[\Phi(r)]\; j_{ph}(\theta) \qquad (2)$$

where D is the diameter of the boom, and the factor 2 accounts for two booms, f is the fraction of photoelectron current going towards the spacecraft body, and j_{ph} the photoelectron current density generated. When SCATHA rotates in sunlight, I_{ph} varies sinusoidally. As a result, the photoelectrons cause modulation (Figure 3) in spacecraft potential which is determined by current balance. The theory [18] explains the variation of modulation amplitude as a function of the sun angle, beam current, and beam energy. This effect may have important implications for future large-scaled space structures where large photoelectron currents from large neighboring surfaces may be significant during electron beam emissions.

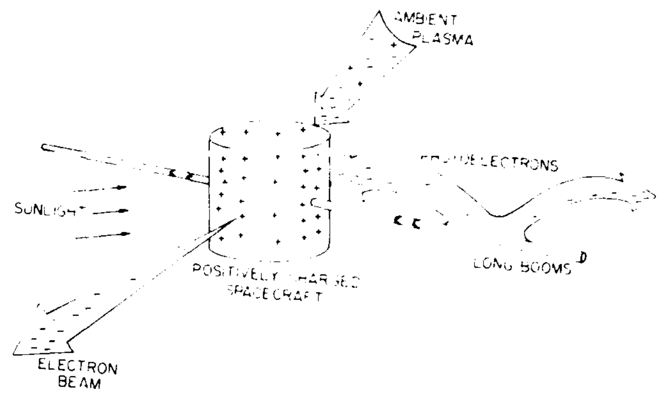

Figure 4. A "multi-body" interaction : photoelectron currents from isolated booms tend to go towards the spacecraft body during electron beam emissions.

III. ELECTRON BEAM EFFECTS: SPACECRAFT DISCHARGING

Electron beam emission can discharge a negatively charged spacecraft partially or completely in quiet days and in storms [13,14,17]. The level of discharging depends on the beam current and energy, and the ambient condition.

The use of low energy electron beam emissions (for example, from heated filaments) on SCATHA shows that it is inefficient for discharging. Potential barriers [21,22] due to differential charging of surfaces or space charge effects in the beam may reflect low energy electrons and hence reduce the net outgoing electron current.

Discharging the conductive ground of a spacecraft by means of electron beam emission may induce differential charging. Initially, the potentials between the ground and the dielectric surfaces follow each other but only for a transient period. Then differential charging gradually emerges because of capacitance effects. The level and time scale depends on the capacitances, beam current, and ambient conditions. Thus, discharging a spacecraft by means of electron beam emissions may bring on differential charging, an adverse situation.

IV. ION BEAM EFFECTS: SPACECRAFT CHARGING

A. Non-monotonic Behavior

On SCATHA, ion beam emissions have produced several interesting results in spacecraft charging and discharging. The ion beam operating at 1 to 2 keV can charge the spacecraft to 0.1 to 0.3 kV typically [13] depending on the beam energy, beam current and ambient conditions. SCATHA data (Figure 5) taken on in a quiet period show that when the ion beam current increases, the magnitude of spacecraft charging reaches a maximum and then decreases, a non-monotonic behavior [23,24].

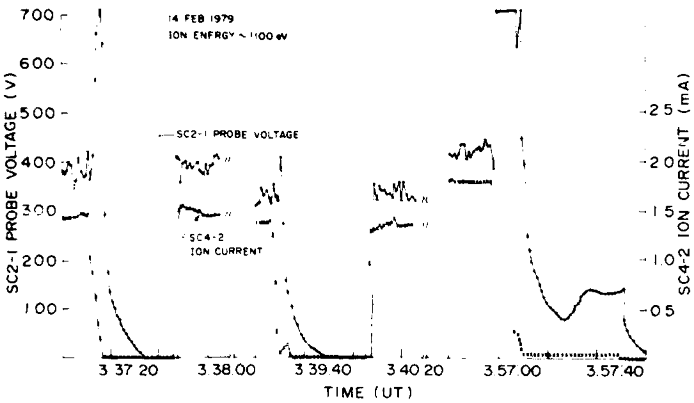

Figure 5. SCATHA potential (SC2-1 measurement) in response to high energy (keV) ion beam (SC4-2) emissions in eclipse on Day 45, 1979 (from [10]).

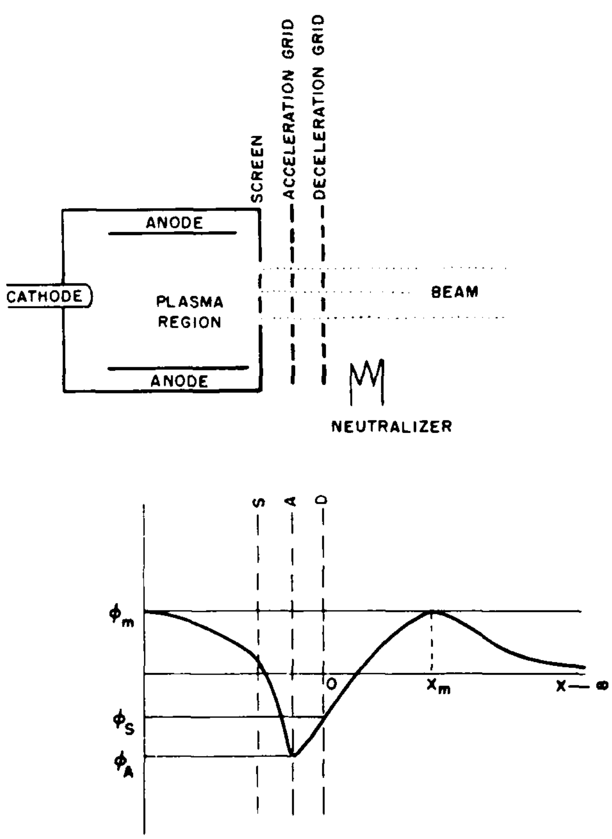

Figure 6. SCATHA ion beam design (Upper). Space charge potential along the ion beam (Lower).

B. Space Charge Effect

A plausible explanation of the non-monotonic behavior resorts to space charge effect in the ion beam; at high currents, a virtual anode is formed near the exit point of the beam [23,24] (Figure 6). The virtual anode reflects part of the beam. Such a behavior is similar to that observed in diodes [25,26]. For the SCATHA ion beam, the location of the virtual anode was estimated to be about 1 to 2 cm from the exit point [23].

C. Charge Exchange

A physical process which is of potential importance is ion beam charge exchange [20]. In this paper, no attempt is made to relate the effect discussed in this section with that in Sec.VI *A*. The principle of most ion beam sources is based on the extraction of ions from a discharge chamber in which ionization occurs. The electrons can be effectively guarded by negatively charged grids; the neutrals can wander out without being affected by the grids. The ion beam emitted from SCATHA is not a pure ion beam, but a xenon ion beam mixed with thermal xenon neutrals, the fraction of ions to neutrals being about 1 to 6 % [27]. Both ion-neutral impact ionization (eq.3) [28] and charge exchange (eq.4) [27] can ionize the thermal neutrals.

$$Xe_{slow} + Xe^{+}_{fast} \rightarrow Xe^{+}_{slow} + Xe^{+}_{fast} + e^{-} \quad (3)$$

$$Xe_{slow} + Xe^{+}_{fast} \rightarrow Xe^{+}_{slow} + Xe_{fast} \quad (4)$$

where Xe_{slow} and Xe_{fast} denote thermal xenon atoms (energy less than 1 eV) and beam xenon atoms (~keV) respectively. For the SCATHA ion beam, charge exchange dominates. As a result, thermal ions are generated. The thermal ions are slow and attracted towards the spacecraft while the electrons are being repelled by the negative

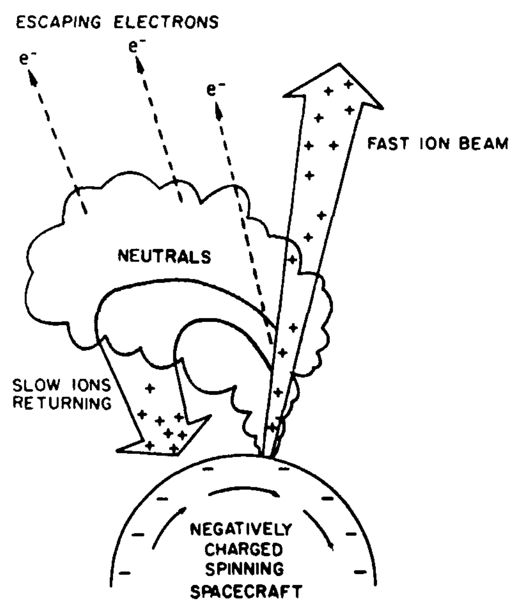

Figure 7. Ionization of (slow) neutrals in a (fast) ion beam.

spacecraft potential (Figure 7). The space charge due to the returning thermal ions slows down the outgoing beam ions, thus enhancing charge exchange and therefore further space charge build up. Theoretical modeling has to take into account neutral cloud expansion, ion beam divergence, and the fraction of neutrals to ions emitted as a function of ion beam current and energy.

V. ION BEAM EFFECTS: SPACECRAFT DISCHARGING

A. Ion Beam Return

A surprising finding from the SCATHA data is that emission of a low energy ion beam can discharge a negatively charged spacecraft - how paradoxical ! Intuitively, one might expect that ion emission at any energy would charge the spacecraft more negatively. In Figure 8, the ion beam current is emitted in pulses, and the spacecraft potential is given by SC-9. Before the turn on of the ion beam, the spacecraft is negatively charged to the kilovolt level [15]. During this period, the spacecraft is in eclipse. The ion beam current ranges from about 5 to 20 μA and the beam energy 50 eV. Instead of charging the spacecraft to higher negative potentials with the ion beam emission, it is found that the spacecraft is partially discharged (Figure 8).

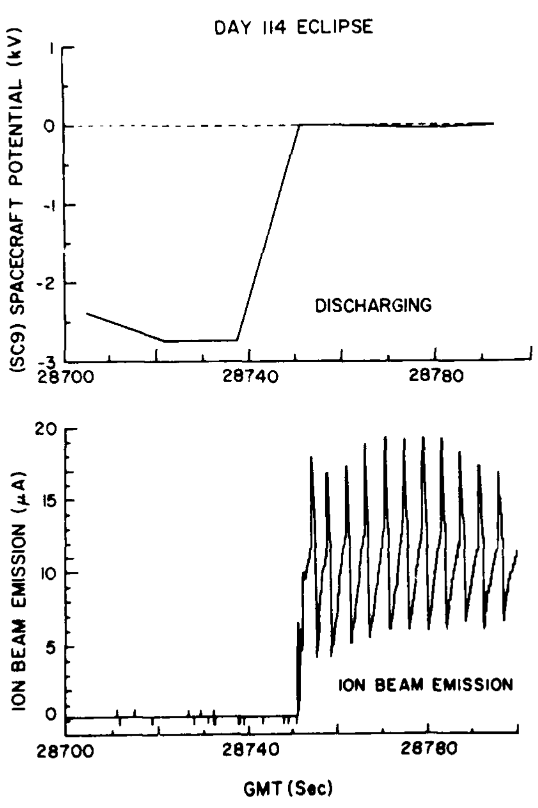

Figure 8. SCATHA potential (SC9-1 measurement) in response to low energy (50 eV) ion beam emission in eclipse on Day 114, 1979 (from [15]).

We suggest a theory as follows: the low energy beam ions can not leave because of the Coulomb attraction of the negatively charged spacecraft. In addition, ions generated by charge exchange also contribute to the returning ion current I_r:

$$I_r = I_b + I_x \tag{5}$$

where I_b is the returning ion beam current and I_x the charge exchange generated ion current. The ion current I_i generated from ion impact ionization is less important at the energies (keV) of the SCATHA ion beam and is neglected on the RHS of eq(5). As the low energy ions ($I_b + I_x$) return and impact on the spacecraft surface, not only do they neutralize the surface charge but also they generate secondary electrons which leave and carry away some negative charge (Figure 9). Including the outgoing secondary electron current I_s, the quantity I_p of positive charge input per unit time on the spacecraft surface is

$$I_p = I_b + I_x + I_s. \tag{6}$$

In addition, the outgoing secondary electrons may contribute to further ionization because they are being accelerated outwards by the negative spacecraft potential.

We remark that there is no need to consider the energy cross-over points E_1 and E_2 for the secondary electrons in eq(6), because the secondary electrons are due to ion impact. Unlike the case of secondary electrons due to electron impact, there is no competition between the incoming primary current and the outgoing secondary current in the present case. Both the incoming ion current I_x and the outgoing I_s contribute to positive charge build up on the surface.

An advantage of using low energy returning ions is that they may be able to automatically "home in" on the "hot spots" of the surfaces on the spacecraft. Thus, it is better to use low energy ion emission to discharge a negatively charged spacecraft than to use electron beams.

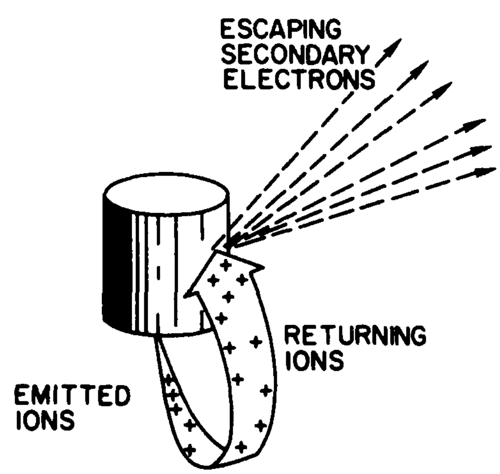

Figure 9. Generation of secondary electrons by returning ions attracted by a negatively charged spacecraft.

B. Plasma Beam

Finally, the emission of a mixed beam of low energy ions and electrons discharges a negatively charged spacecraft more efficiently than either electron or ion beam emissions alone [13]. This phenomenon has been observed not only on SCATHA but also on the ATS-6 satellite [31]. Previous explanation attributes this to the dilution of space charge [13]. We suggest, again, a returning ion theory. The electron beam leaves because of spacecraft repulsion and the electrons carry away negative charge; the low energy ions return because of spacecraft attraction, thereby neutralizing the spacecraft's negative charge. The ions are attracted by the spacecraft. They return and impact on the surface generating secondary electrons which leave and carry away more negative charge (Figure 10). Thus, the use of low energy plasma beams is more efficient in discharging a negatively charged spacecraft than using high energy electron or low energy ion beams alone.

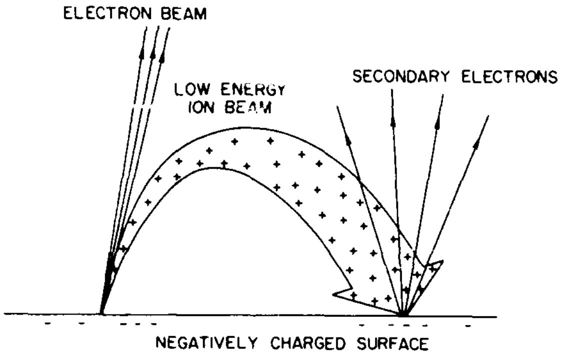

Figure 10. Emission of electrons and low energy ions from a negatively charged spacecraft. The returning low energy ions generate secondary electrons which escape.

VI. CONCLUSION

Five points on the charging and discharging of the SCATHA satellite by means of electron and ion beam emissions in the geosynchronous environment have been discussed. (1) During electron beam emissions in sunlight, photoelectrons from nearby surfaces isolated from the satellite body tend to return to the body, thus affecting the potential of the body. This is a 'multi-body' interaction, which deserves the attention of the community of spacecraft scientists and engineers. It may have important implication for future large-scaled space structures emitting electron beams in sunlight. (2) Attempts to discharge a spacecraft by means of electron beam emission may result in a worse situation - differential charging between dielectric surfaces and spacecraft ground. (3) At low ion beam currents, the level of spacecraft charging increases as the current increases. Beyond a critical current, the level decreases with a 'non-monotonic' current-voltage behavior. (4) Abundant neutrals are present in the ion beam. Low energy ions generated by charge exchange return to the spacecraft and reduce the charging level. Most ion beam designs are based on extraction of ions from discharge chambers from which neutrals can wander out. Charge exchange in ion beams seems inevitable, unless ion beam engineers can come up with better design principles. It may have useful applications and deserves further studies. In this paper we have treated the monotonic behavior and the charge exchange effect separately. (5) Discharging by means of low energy plasma beam emission is more efficient than using an electron or ion beam alone. This conclusion is important for spacecraft engineers designing automatic discharge systems for future spacecraft. Finally, we remark that material properties such as secondary electron emission coefficients due to ion as well as electron impacts are also important for spacecraft designs. The trajectories of the low energy ions traveling towards various charged surfaces are not trivial even for simple surface geometries (c.f. [32]) and have to be computed carefully by the 'automatic spacecraft discharge systems' design engineers in the future.

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