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CHARGING OF DMSP/F6 SPACECRAFT IN AURORA ON 10 JANUARY 1983

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Two independent instruments on the spacecraft showed charging to a moderate (14 volts) negative potential. The electron spectrometer showed a flux of 2 X 10^9 electrons ($cm^{-2} sec^{-1} ster^{-1}$) peaked at 9.5 keV. This was marginally sufficient to overcome the flux of cold ambient ions. Charging calculations are presented showing where simplications are justified and where serious uncertainties exist. More serious charging is predicted for the Shuttle in polar orbit.

INTRODUCTION

Spacecraft charging has been widely observed in geosynchronous orbit on the ATS-5 and ATS-6 pair and on the SCATHA spacecraft (ref 1 & 2). An adequate theory for explaining the observations exist. Neither the data or theory can be exported to low polar orbit and its drastically different environment. This paper gives evidence of charging on the DMSP F6 spacecraft (see ref 3 for instrumentation). A simple model is set up explaining the observations.

BRIEF THEORY OF SPACECRAFT IN THE AURORA

The cold ambient electrons can charge a spacecraft to a few volts negative at most. More severe charging occurs in the earth's shadow when the energetic (over a kilovolt) precipitating electron current exceeds the ram ion current. Charging continues until an increase in ram ion current and/or a decrease in precipitating electron current produces a zero net current.

In the absence of plasma shielding, the ram ion current increases rapidly with increasingly negative potentials. This typically limits charging to tens of volts negative. In the presence of intense plasma shielding (electrostatic or magnetic) the ram ion current does not respond to negative potentials. Charging then proceeds to much higher negative potentials until a slowly decreasing precipitating electron current brings about a current balance. Calculations indicate possible potentials of several kilovolts. Below some size plasma shielding is negligible and above some size it dominates. There exists no commonly accepted way of calculating these sizes.

A knowledge of the relative velocities and densities of the various particles is essential to the understanding of auroral charging. Typical values arranged in order of increasing velocity are:

Ambient oxygen ion: $v = 1.5 \times 10^5$ cm/sec; $N = 1 \times 10^4$ cm^{-3}

Spacecraft: $v = 8 \times 10^5$ cm/sec

Ambient electron: $v = 3 \times 10^7$ cm/sec; $N = 1 \times 10^4$ cm^{-3}

Precipitating electrons: $v_{\perp} = 6 \times 10^9$cm/sec; $N = 1$ cm^{-3}

Also essential is a knowledge of the various time scales involved. Typical values arranged in order of increasing time are:

Charging response: 0.01 Seconds

Aurora, fine structure: 0.1 Seconds

Instrument response: 1 Seconds

Aurora, coarse structure: 10 Seconds

The value for charging response applies to the main frame. Thin dielectric coatings may charge differentially with very much longer response times. The aurora time scale is in the spacecraft's frame of reference and is due primarily to spatial variations in the aurora.

DETECTION OF SPACECRAFT CHARGING

Charging was detected by an ion spectrometer sensing acceleration of the ram ions to 30 volts or more and by a probe sensing the deceleration of ambient electrons. Charging to negative potentials less than 30 volts was detected by the probe alone.

The accelerated ions appeared as an intense narrow band never occupying more than one energy channel. This is as predicted by theory. However, the spectrum was not void below the intense band as predicted by theory and observed on geosynchronous spacecraft.

THE CHARGING EPISODE

The probe indicated charging starting at 74701 seconds UT and ending at 74737 UT, with a very brief drop out at 74705. The start, drop out, and end of charging accompanied large abrupt changes in electron flux, particularly in the 4.4 keV channel. The ion spectrometer indicated charging to potentials of 30 to 65 volts negative for a portion of this period, namely from 74721 UT to 74731 UT. The evidence that charging to these levels actually occurred appears to be conclusive.

PRECIPITATING ELECTRON SPECTRA

Five representative time intervals, each lasting from three to five seconds, were chosen for study. Within each time period the spectra remained relatively constant. The electron spectra were averaged over each interval. The average spacecraft potential was determined by probe and ion spectrometer data. When the charging was insufficient to show up on the ion spectrometer but showed strongly on the probe, a value of 10 volts was assigned. The five spectra are shown in figure 1. The starting times from A to E were respectively: 74697, 74708, 74712, 74722, and 74729. Durations were respectively 4, 3, 5, 4 and 3 seconds. Average fluxes and potentials are given in the figure. The fluxes include only five channels from 3.0 to 13.9 kilovolts for reasons to be discussed later.

The figure shows both broad spectra and narrow "inverted V" spectra. The actual shape of the "inverted V" spectrum is unresolved, it could be much narrower and more intense than shown. The electron spectrometer is not designed for accurate flux measurements when the spectrum is very narrow, therefore, the flux indicated in the figure for the "inverted V" may be in error.

We authors postulate an accelerating electric field that is sometimes high above the spacecraft and sometimes close above the spacecraft. In the former case, but not in the latter, there should be strong collisional broadening of both the energy and the pitch angle distribution.

CHARGING CALCULATIONS

Five first order approximations will be made. They are:

1) A spherical spacecraft with a conducting and hence equipotential surface.

2) Zero ambient electron temperature. The energy of these particles in either the plasma frame of reference or in the spacecraft frame of reference was much smaller than the measured potentials.

3) Infinite precipitation electron temperature. The energy of these particles was very large compared to the measured potentials.

4) Precipitating electron flux equal to that measured in the 3 to 14 keV energy range. Fluxes at higher energies were very low. Fluxes at lower energies were small and were largely offset by secondary electrons. Secondaries were not included in the calculations. The flux is treated as isotropic within some field aligned solid angle and zero elsewhere.

5) Ambient ion temperature equal to the drift energy of an ion in the spacecraft frame of reference. This energy is large compared to the thermal energy. Probe theory assumes that the total particle energy (kinetic plus potential) is independent of position. This assumption is valid in and only in the spacecraft frame of reference. The ambient ions are predominantly singly ionized atomic oxygen.

The first four approximations simplify calculation of the electron current to the negatively charged spacecraft. The "zero temperature" ambient electrons are repelled and do not reach the spacecraft. The "infinite temperature" precipitating electron current is independent of the spacecraft potential. Secondary electrons are adequately allowed for by discarding the low end of the spectrum and need not appear explicitly in the calculations. With these considerations, the electron current to the spacecraft becomes

$$I_e = -e\ J\ S\ (\pi R^2) \tag{1}$$

where I_e = electron current
e = elemental charge
J = precipitating electron flux per steradian in 3 to 14 keV channels
S = solid angle of precipitating electrons
R = spacecraft radius
(πR^2) = spacecraft electron collision cross section.

The first and fifth approximations simplify calculation of the ion current to the spacecraft. Spherical probe theory gives the ion current in the long Debye length limit as:

$$I_i = e\ v\ N\ \left[(\pi R^2)\left(1 + \frac{-eV}{T}\right)\right] \equiv evNA;\ -eV \geq 0 \tag{2}$$

where I_i = ion current
v = ion drift velocity
N = ion density $\approx 1 \times 10^4\ \mathrm{cm}^{-3}$
V = spacecraft potential
T = temperature associated with ion drift velocity $\approx$ 5ev
A = spacecraft ion collision cross section.

When the Debye length is not long compared to the probe radius, a sheath containing a net positive charge forms around the probe. The charge in the sheath shields ambient ions outside the sheath from the probe's electric field, thereby reducing the number attracted to the probe. The shielding effect may be incorporated in equation (2) by multiplying the potential by a shielding factor K less than unity. This factor is a function of potential and generally does not appear explicitly in probe theories. It may also be a function of the ion angular distribution (in this case almost mono-directional in the spacecraft frame of reference).

At equilibrium potential the absolute values of electron and ion currents are equal. This leads to the equilibrium equation

$$JS = v \cdot N \cdot \left(1 + k\,\frac{-eV}{T}\right);\ eV \leq 0,\ k \leq 1 \tag{3}$$

where k = shielding factor.

The unknowns in this equation are the electron solid angle S and the ion shielding factor k. These unknowns were evaluated from the data in figure (1) and from other measurements. The solid angle is determined from equation (3) using the threshold flux required for charging. The data consistently yields a narrower solid angle for inverted "V" spectra than for broad spectra. The shielding factor was determined by the electron flux associated with a potential of -44 volts. This flux was approximately four times greater than the threshold flux. The results of the evaluations were

$S \approx \pi$, inverted "V" spectra
$S \approx 2\pi$, broad spectra
$k \approx 1/2$.

These results should be regarded with caution. The data is not conclusive due in part to an environment whose rate of change is fast compared to the sampling rate of the instruments - probably fast compared to any practical sampling rate.

The value given above for the shielding factor is substantially less than unity. If true, this has serious implications. It means that the DMSP spacecraft are already of a size where space charge in the sheath acts to increase the magnitude of charging potentials and that any larger spacecraft such as the Shuttle, will charge to higher potentials, other factors being equal.

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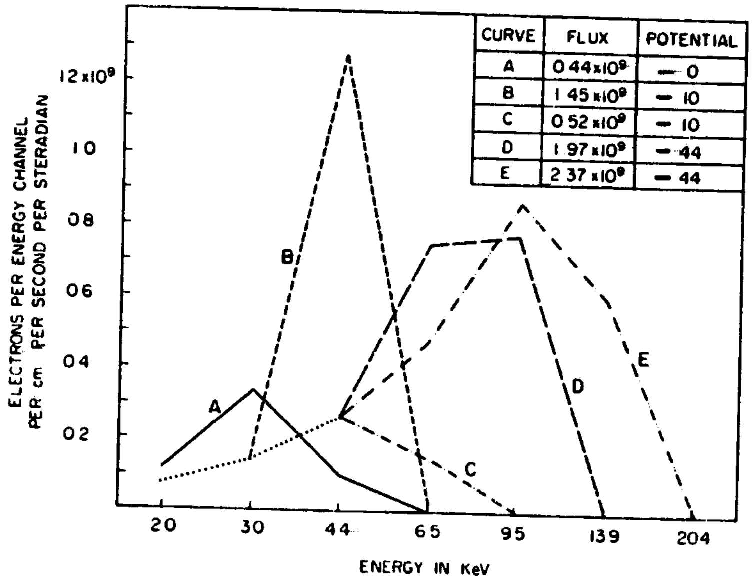

Figure 1. - Five precipitating electron spectra. (The flux associated with each spectra is listed in the upper right corner along with the corresponding spacecraft potential.)