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Worst Case Earth Charging Environment

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The Applications Technology Satellite-6 (ATS-6) geosynchronous satellite charged up to −2200 V in sunlight on day 178, 1974. This event, being the highest known spacecraft charging event in sunlight, is used to estimate a "worst case" geosynchronous plasma environment for predicting the spacecraft potential in eclipse. The advantage of using this sunlight spectrum as opposed to an eclipse case is that the ion and electron fluxes to the detectors are shifted only slightly due to the spacecraft potential. After correcting the available data (energy range of 1ev-81 KeV for ions and 100 eV-81 KeV for electrons) for satellite potential and missing data above 81 KeV, it is found that the plasma can be characterized by a single Maxwellian approximation having an electron density of 1.22 cm^{-3}, electron temperature of 16 KeV, hydrogen ion density of 0.24 cm^{-3}, and hydrogen ion temperature of 29 KeV. In eclipse the spacecraft would have charged up to −28 kV, the highest estimated potential to date in the Earth's plasma environment.

Nomenclature

E,E'	= energy of incident particle, eV
ED	= energy density, eV − cm^{-3}
EF	= energy flux, eV − cm^{-2} − s^{-1} − sr^{-1}
f,f'	= distribution function, s^3/km^6
J_e	= incident electron current, nA − cm^{-2}
J_I	= incident ion current, nA − cm^{-2}
J_{se}	= secondary emission current of electrons due to impinging electrons, nA − cm^{-2}
J_{sI}	= secondary emission current of ions due to impinging ions, nA − cm^{-2}
J_{BSe}	= backscattered electron current due to impinging electrons, nA − cm^{-2}
J_{PH}	= photoelectron current, nA − cm^{-2}
K_p	= geomagnetic activity indice
m	= mass of particle, gm
NF	= energy flux, cm^{-2} − s^{-1} − sr^{-1}
N_e, N_{1H+}, N_{2H+}	= number of electrons and hydrogen ions per unit volume, cm^{-3}; two components are assumed for the ions
q	= electronic charge, e
T_e, T_{1H+}, T_{2H+}	= Maxwellian temperatures of electrons and ions, eV
V	= potential, V

Introduction

As the number of satellites and experiments in space is growing, it is of extreme importance to determine a "worst case" spacecraft charging environment for purposes of design. In particular, spacecraft are known to have charged up to kilovolt levels[1] in the Earth's plasma environment. To date, the highest potentials, −2200 V in sunlight[2] and −19,000 V in eclipse,[3] have been observed with the University of California, San Diego (UCSD) particle experiment on the Applications Technology Satellite-6 (ATS-6) geosynchronous satellite. In this paper, fits to the spectra of the −2200 V sunlight charging event on day 178, 1974 are presented as such a worst case charging environment. The advantage of analyzing this event is that the ambient particle fluxes are shifted only slightly due to the spacecraft potential. As outlined in the following, a single or double Maxwellian distribution function is fit to the data and the resulting moments and plasma characteristics presented. From these characteristics the potential of the spacecraft in eclipse is evaluated to be −28 kV which is well in excess of the observed −19 kV eclipse event.

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Description of the ATS-6 Satellite and the UCSD Auroral Experiments

The satellite employed in this study, the ATS-6, was launched into geosynchronous orbit in May 1974, at 94° W longitude with an orbital inclination of 2.5 deg. One of the purposes of this satellite was to study the charged plama environment and its variations during magnetic storms and other magnetospheric changes. The satellite carried an auroral particles experiment from UCSD (see Mauk and McIlwain[4] for a detailed instrument description) with five electrostatic analyzers placed behind a large (10 m) parabolic Earth-pointed antenna (Fig. 1). One pair of analyzers (one analyzer detecting ions, the other electrons) was located on a head rotating from north to south, the second pair was situated on a head sweeping from east to west through a 220 deg angle. Finally, a single ion analyzer was fixed such that it pointed continuously toward the east. The analyzers are capable of measuring differential energy fluxes over 64 energy levels between 1 eV and 81 KeV. (Note: Due to background contamination from secondaries, backscatter, and photoelectrons, electrons are further limited to energies above 100 eV.) A whole spectrum is scanned in 16 s.

Data and Magnetospheric Conditions

Figure 2 shows the data selected and is taken from Garrett et al.[5] The spectra were taken on day 178 (June 27) at 0419, 1974, which was a period of very high geomagnetic activity (K_p was 6_+). The spacecraft at that moment charged up to −2200 V relative to the ambient plasma and represents the worst charging observed on ATS-6[3] in daylight.

Figure 3 illustrates the spectrogram on day 178, 1974. The spectrogram is a three-dimensional plot in which the *x* axis is time, the *y* axis is energy, and *z* axis is the flux. The spectrogram of Fig. 3 indicates that the satellite went from a mild plasma environment to a very hot plasma environment at 0115 UT. The satellite to space potential indicated by the apparent low energy dropout in the ions varied rapidly between 0225 and 1300 UT and was the highest at 0419 UT with a negative potential of −2200 V. This is reflected by the K_p indices[6] which varied by 5_-, 6_+, 6_0, 4_0, 5_-, 5_0, 6_0, 4_0 during the 24-h period.[7]

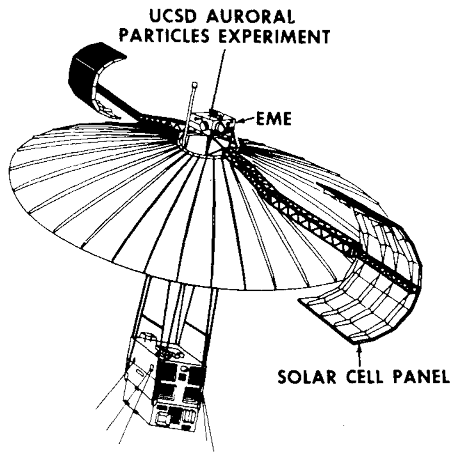

Fig. 1 ATS-6 geosynchronous satellite with the UCSD auroral particle experiment.

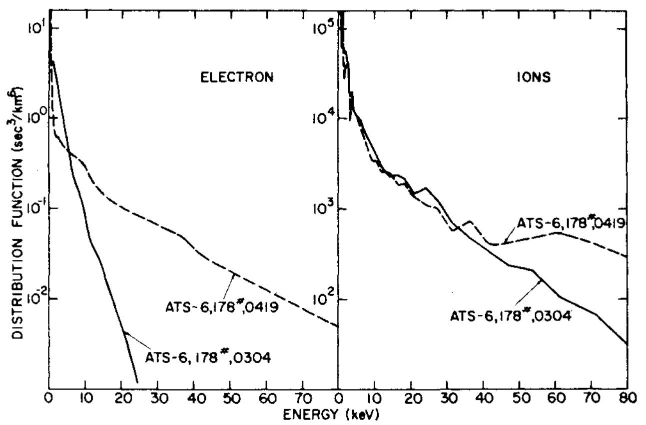

Fig. 2 Distribution functions of electrons and ions observed on day 178, 1974.

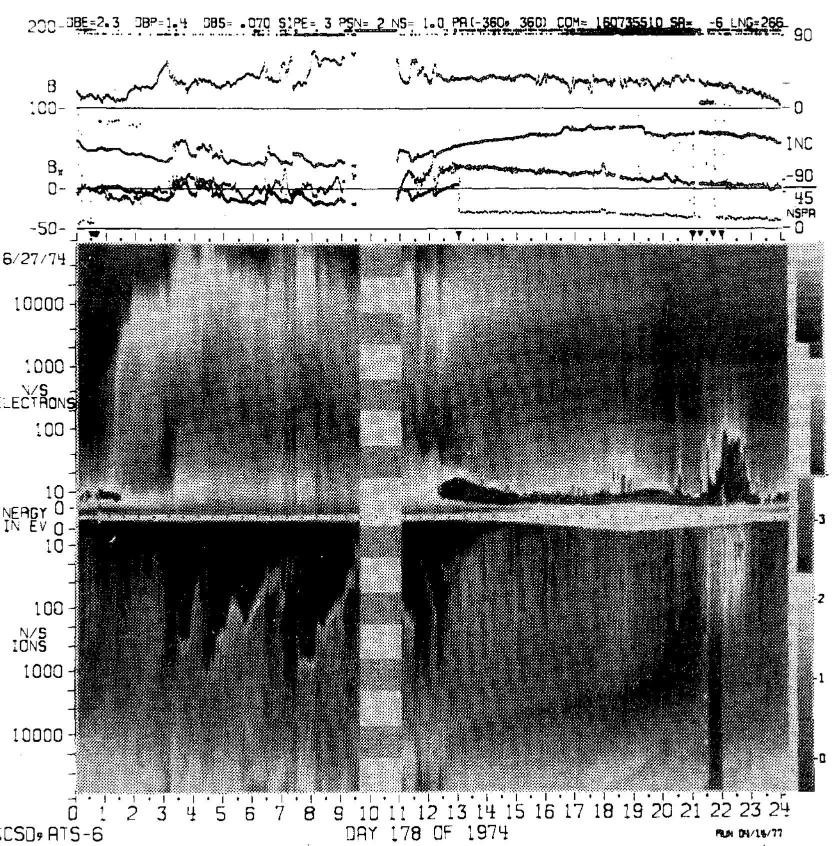

Fig. 3 ATS-6 spectrogram of a day of very high geomagnetic activity (kp 6+).

Data Analysis

The parameter measured by the UCSD particle experiment is the differential energy flux $[\mathrm{d}(EF)/\mathrm{d}E]$ of electrons and ions, which is proportional to the distribution function of a plasma[8]:

$$f = \frac{m^2}{2E^2}\frac{\mathrm{d}(EF)}{\mathrm{d}E} \tag{1}$$

In order to simplify the description of the plasma environment, isotropic Maxwellian-Boltzman functions are fit to the distribution functions of Fig. 2. Whereas the electron distribution function could be well fit by a single Maxwellian (Fig. 4) the ion plasma was simulated more accurately by a double Maxwellian function (hydrogen ions are assumed in our calculations) (Fig. 5)

$$f(\text{electrons}) \simeq N_e \left(\frac{m_e}{2\pi T_e}\right)^{3/2} \exp^{-E/T_e} \tag{2}$$

$$f(\text{ions}) \simeq N_{1H} + \left(\frac{m_{\mathrm{H}+}}{2\pi T_{1\mathrm{H}+}}\right)^{3/2} \exp^{-E/T_{1\mathrm{H}+}} + N_{2\mathrm{H}+}\left(\frac{m_{\mathrm{H}+}}{2\pi T_{2\mathrm{H}+}}\right)^{3/2} \exp^{-E/T_{2\mathrm{H}+}} \tag{3}$$

Such Maxwellian fits are not necessarily the best fits, but from a conceptual and computational point of view they are the easiest to handle.

The values of the double Maxwellian number densities ($N1$, $N2$) and the temperatures ($T1$, $T2$) which characterize the plasma (Table 1) are derived by inverting the first four moments of the distribution function (Table 1).

Number density:

$$N_i = 4\pi \int_0^\infty (V^0) f_i V^2 \mathrm{d}V = (N1 + N2)_i \tag{4}$$

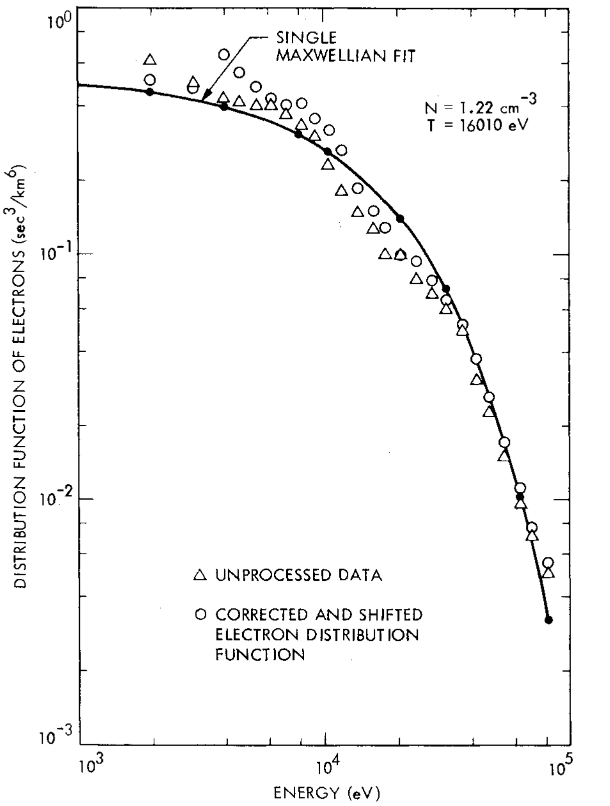

Fig. 4 Single maxwell fit to the corrected and shifted electron distribution function.

Table 1 Raw moments and Maxwellian fits

	Electrons	Ions
Moments of the distribution function		
N, cm^{-3} [a]	0.1034E+01	0.2824E+00
NF, $cm^{-2}-s^{-1}-sr^{-1}$ [b]	0.6574E+09	0.4016E+07
ED, $eV-cm^{-3}$ [c]	0.2237E+05	0.6268E+04
EF, $eV-cm^{-2}-s^{-1}-sr^{-1}$ [d]	0.1915E+14	0.1396E+12
Double Maxwellian number densities and temperatures		
$N1$, cm^{-3} [e]	0.7594E−02	0.6082E−01
$T1$, eV [f]	0.1665E+04	0.1202E+04
$N2$, cm^{-3} [e]	0.1026E+01	0.2216E+00
$T2$, eV [f]	0.1454E+05	0.1854E+05
Single Maxwellian temperatures		
T_{avg}, eV [g]	0.1442E+05	0.1479E+05
T_{rms}, eV [h]	0.1456E+05	0.1738E+05

[a] Number density. [b] Number flux. [c] Energy density. [d] Energy flux [e] Number densities. [f] Maxwell temperature. [g] Average temperature. [h] rms temperature.

Number flux:

$$NF_i = \int_0^\infty (V^1) f_i V^2 \mathrm{d}V = \tfrac{1}{2}\pi \left(\frac{2K}{\pi m_i}\right)^{1/2} (N1T1^{1/2} + N2T2^{1/2})_i \tag{5}$$

Energy density (or pressure):

$$ED_i = 4\pi(\tfrac{1}{2}m_i)\int_0^\infty (V^2) f_i V^2 \mathrm{d}V = \left(\frac{3}{2}\right) K(N1T1 + N2T2)_i \tag{6}$$

Table 2 Raw distribution functions

Energy, eV	$f_e(E)$, [a] s^3/km^6	$f_I(E)$, [b] s^3/km^6
0.100+004	0.100+001	0
0.200+004	0.600+000	0
0.300+004	0.510+000	0.210+005
0.400+004	0.430+000	0.170+005
0.473+004	0.410+000	0.110+005
0.542+004	0.400+000	0.900+004
0.621+004	0.400+000	0.740+004
0.711+004	0.370+000	0.560+004
0.814+004	0.330+000	0.440+004
0.933+004	0.300+000	0.370+004
0.107+005	0.230+000	0.340+004
0.122+005	0.180+000	0.280+004
0.140+005	0.150+000	0.240+004
0.160+005	0.130+000	0.190+004
0.184+005	0.100+000	0.190+004
0.210+005	0.100+000	0.130+004
0.241+005	0.830−001	0.110+004
0.276+005	0.710−001	0.100+004
0.316+005	0.600−001	0.590+003
0.362+005	0.500−001	0.700+003
0.414+005	0.310−001	0.400+003
0.474+005	0.230−001	0.400+003
0.543+005	0.150−001	0.470+003
0.622+005	0.100−001	0.500+003
0.712+005	0.710−002	0.400+003
0.816+005	0.500−002	0.300+003

[a] Distribution function for electrons. [b] Distribution function for ions.

Energy flux:

$$EF_i = \tfrac{1}{2}m_i \int_0^\infty (V^3) f_i V^2 \mathrm{d}V$$

$$= m_i/2\left(\frac{2K}{\pi m_i}\right)^{3/2} (N1T1^{3/2} + N2T2^{3/2})_i \tag{7}$$

The single Maxwellian temperatures are calculated from either T_{avg} or T_{rms} (Table 1)

$$T_{avg} = \frac{2}{3}\frac{ED}{N} \tag{8}$$

$$T_{rms} = \frac{1}{2}\frac{EF}{NF} \tag{9}$$

The plasma also can be described by fitting the data with a least squares fit as described next and illustrated in Fig. 5.

The "raw" data for the distribution functions are read from Fig. 2 and are listed in Table 2. Electron values below 1 KeV have been neglected in this analysis. This does not affect the calculations since the electron fluxes of importance to the charging calculation appear above 2 KeV. The electrons are repelled by the negative potential and lose an energy qV. The ion population, on the other hand, is accelerated by an energy qV toward the detector. The energy of the particles E' at the spacecraft becomes

$$E' = E \mp qV \tag{10}$$

for electrons and ions, respectively.

The distribution function at the spacecraft surface is $f'(E')\mathrm{d}E' = f(E)\mathrm{d}E$ by Liouville's theorem. Employing Eq. (10) and Liouville's theorem, the distribution functions measured at the spacecraft then can be corrected for satellite potential. The "new" shifted distribution functions are presented in Figs. 4 and 5. The "ambient" electron population is shifted toward higher energies and the ion

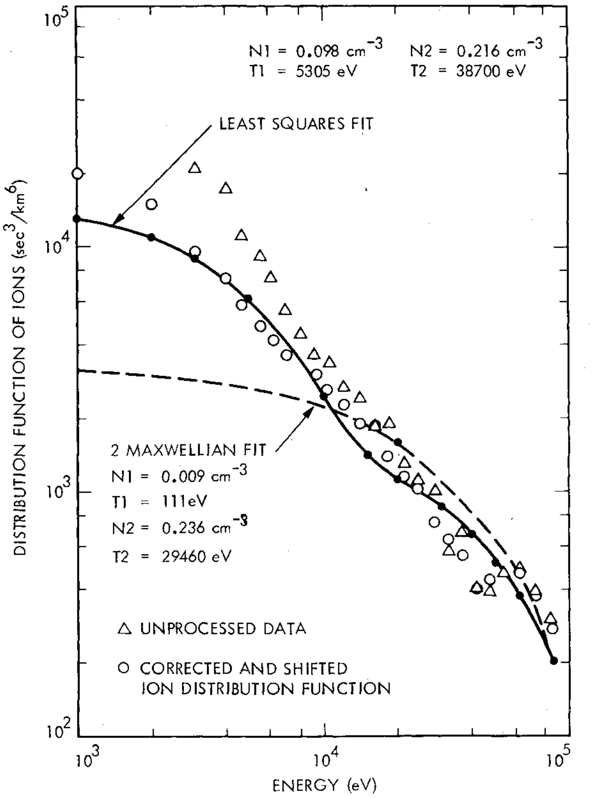

Fig. 5 Curve fits to the corrected and shifted ion distribution function.

Table 3 Moments and Maxwellian fits corrected for satellite potential and missing low energy electrons

	Electrons	Ions
Moments of the distribution function		
N, cm^{-3}	$0.1193E+01$	$0.2068E+00$
NF, cm^{-2} – s^{-1} – sr^{-1}	$0.7602E+09$	$0.3400E+07$
ED, eV – cm^{-3}	$0.2564E+05$	$0.5698E+04$
EF, eV – cm^{-2} – s^{-1} – sr^{-1}	$0.2175E+14$	$0.1308E+12$
Double Maxwellian number densities and temperatures		
$N1$, cm^{-3}	$(0.2576E-03)$	$0.8820E-02$
$T1$, eV	$(0.6464E+05)$	$0.1111E+03$
$N2$, cm^{-3}	$0.1193E+01$	$0.1980E+00$
$T2$, eV	$0.1433E+05$	$0.1920E+05$
Single Maxwellian temperatures		
T_{avg}, eV	$0.1433E+05$	$0.1837E+05$
T_{rms}, eV	$0.1431E+05$	$0.1923E+05$

population toward lower energies. The electron data below 2200 eV have been extrapolated by using an estimated Maxwellian electron temperature T_{avg} and number density. Although this extrapolation slightly underestimates the real values, most of the electron population will be repelled at low energy anyway for negative satellite potentials. Thus, this extrapolation should not effect significantly the charging calculations. The moments, Maxwellian temperatures, and densities obtained using these corrected data are given in Table 3.

Another, more serious, correction to the spectra is for the missing data above 81 KeV. There exist two ways to correct for this.

1) Assume that the electrons and ions are fit by a Maxwellian distribution and compute the plasma parameters by a least squares fit to the data. Table 4 and Fig. 5 show the fit and the plasma parameters for a single and a double Maxwellian approximation. The results are independent of the moments calculated between 0 and 81 KeV.

2) The number density and temperature of the higher energy component can be extrapolated to higher energies using a Maxwellian extrapolation for correcting the moments.[9] The corrected moments and plasma characteristics using this technique are presented in Table 5 and Figs. 4 and 5.

Table 4 Maxwellian fit parameters determined by a least squares fit

	Electrons	Ions
Using a single component for the electron and ion fit		
N, cm^{-3}	$0.1320E+01$	$0.2530E+00$
T, eV	$0.1597E+05$	$0.2137E+05$
Using a double component for the ion fit		
$N1$, cm^{-3}		$0.0980E+00$
$T1$, eV		$0.5305E+04$
$N2$, cm^{-3}		$0.2160E+00$
$T2$, eV		$0.3870E+05$

Table 5 Fully corrected moments and Maxwellian parameters

	Electrons	Ions
Moments of the distribution function		
N, cm^{-3}	$0.1220E+01$	$0.2451E+00$
NF, cm^{-2} – s^{-1} – sr^{-1}	$0.8197E+09$	$0.5041E+07$
ED, eV – cm^{-3}	$0.2931E+05$	$0.1044E+05$
EF, eV – cm^{-2} – s^{-1} – sr^{-1}	$0.2638E+14$	$0.2976E+12$
Double Maxwellian number densities and temperatures		
$N1$, cm^{-3}	$(0.2576E-03)$	$0.8820E-02$
$T1$, eV	$(0.6465E+05)$	$0.1111E+03$
$N2$, cm^{-3}	$0.1220E+01$	$0.2363E+00$
$T2$, eV	$0.1601E+05$	$0.2946E+05$
Single Maxwellian temperatures		
T_{avg}, eV	$0.1600E+05$	$0.2840E+05$
T_{rms}, eV	$0.1609E+05$	$0.2950E+05$

Potential Calculations

Now that the number densities and Maxwell temperatures are known, it is possible to estimate the spacecraft potential by balancing the electric currents.

$$J_e(V) - [J_I(V) + J_{se}(V) + J_{sI}(V) + J_{BSe}(V) + J_{PH}(V)] = 0 \tag{11}$$

Several simple algorithms are available for solving this equation for V given the number density and temperature. The model of Garrett[10] and Tsipouras and Garrett[11] have been utilized. The validity of the assumed fits can be checked by solving Eq. (11) for V in sunlight. When the sun is shining on the spacecraft, the currents, using Table 5, balance to give a potential of -2800 V. This is a confirmation of the validity of the preceding fitting procedures. When the sun does not shine on the spacecraft, the currents balance if $V = -0.2794E+05$ V. This is the most extreme satellite to space potential calculated to date.

Conclusion

Looking at the results of the plasma characteristics, it is evident that $N1$, the number density of electrons, is negligible in its effect on the potential calculations. Therefore, it is recommended that this component be ignored. The lack of charge balance between electrons and hydrogen ions can be explained by assuming oxygen ions are present in the ion population.[12] Due to the characteristics of electrostatic detectors, the effects of using the wrong ion mass is to increase the number density by the ratio of the square root of the wrong mass to the correct mass [i.e., $(16/1)^{1/2} = 4$]. If, for each hydrogen an oxygen is assumed, the number densities of electrons and ions are approximately equal. With the additional assumption that most of the ions and electron plasma are included in the 1-81 KeV energy range of this study, the results should then give a number density of hydrogen ion of 0.24 cm^{-3}, of oxygen ion of 0.96 cm^{-3}, with a 29 KeV Maxwellian temperature remaining unchanged. The electron density and temperature are 1.22 cm^{-3} and 16 KeV, respectively. These values then yield a potential of -28 kV, the most extreme potential ever estimated in Earth orbit.

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