A Survey of Spacecraft Charging Events on the DMSP Spacecraft in LEO

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Abstract. The DMSP satellites orbit the Earth at ~840 km and carry various instruments for sensing the space environment. They provide the ideal platform from which to investigate spacecraft charging in low-earth orbit (LEO). We have searched 12 years of DMSP satellite data, 1989 - 2001, for events in which the spacecraft frame charged to more than 100 V negative. We found 1253 events, all associated with an intense energetic electron precipitation event (an auroral arc) within a region of very low plasma density in the auroral zone. The occurrence frequency of events was highly correlated with solar activity with the preponderance of events occurring near solar minimum; indeed, no events were found during the peak the last solar cycle in 1989 - 1990. There was a strong hemispherical asymmetry with almost 80% of the events occurring in the southern hemisphere due to the seasonal relationship of the spacecraft orbital plane and the Earth's spin axis. There was a strong seasonal dependence with all of the events centered around winter solstice and none occurring at summer solstice due to solar illumination. During solar minimum, the plasma density was three orders of magnitude or more less than the density at solar maximum. During solstice, the density was up to three orders of magnitude less in the winter hemisphere than in the summer hemisphere. The currents associated with precipitating electrons in an auroral arcs are usually much smaller that the currents from the in situ plasma. However, the plasma density can be low enough at DMSP altitudes that the currents from precipitating electrons dominate, driving the spacecraft potential negative. We have shown that these conditions exist a significant fraction of the time, particularly in the southern hemisphere at winter solstice, such that high-level charging events occur almost daily on the DMSP spacecraft.

1. Introduction

Spacecraft charging has been the cause of a number of significant anomalies on high altitude spacecraft, which leading to a number of investigations entirely devoted to the study of spacecraft charging in high-earth orbit. However, little effort has been devoted to the study of high-level charging in low-earth orbit due to the rarity of its occurrence. For satellites in low-earth orbit, such as the DMSP spacecraft (~840 km), the plasma density is usually high and the main contributors to the currents to the spacecraft are the thermal electrons and ions that constitute the ionosphere. When the plasma density is very low, however, the contribution to the currents to the spacecraft from other sources such as precipitating electrons in the auroral zone can become very important. In fact, the spacecraft can charge to high negative voltages during times when the plasma density is very low and the flux of energetic electrons is very high. *Gussenhoven et al.* [1985] showed that the DMSP F6 and F7 spacecraft could charge to voltages < -100 V when the following conditions were met: 1) the spacecraft was in darkness, 2) the plasma density was less than 10^4 cm^{-3}, and 3) there was a high integral number flux (> 10^8 electrons cm^{-2} s^{-1} sr^{-1}) of high energy (> 14 keV) electrons.

Anderson and Koons [1996] reported the occurrence of an anomaly associated with low-altitude, high-level surface charging on the DMSP F13 spacecraft. To our knowledge, this was the first published report of the observation of an anomaly associated with spacecraft charging in low-earth orbit. Three other similar events were subsequently discovered. The anomalies were attributed to electrical malfunctions caused by electrostatic discharges on the vehicle. They occurred during intense energetic electron precipitation events (auroral arcs) within regions of very low plasma density in the auroral zone. Plasma measurements indicate that in each event, the spacecraft frame charged to several hundred volts negative in the approximate time required to charge the ungrounded thermal blankets covering the top of the spacecraft to discharge voltage.

Anderson [1997] presented results of a 1.5-year study during the last solar minimum in which he found several hundred charging events on three DMSP spacecraft, in which the spacecraft frame charged to more than 100 V negative. He attributed the high rate of occurrence on the lack of ionization at DMSP altitudes due to the significantly reduced solar UV output associated with the solar minimum. We have expanded on this study to include 12 years of data, 1989 - 2001, from 7 satellites, thus covering an entire solar cycle.

2. Spacecraft and Instrumentation

The DMSP spacecraft are a series of low-altitude, polar-orbiting satellites whose primary mission is to observe the tropospheric weather. Their secondary mission is to observe the space environment using a set of three instruments: the special sensor for ions, electrons, and scintillation (SSIES), the precipitating energetic particle spectrometer (SSJ/4), and the vector magnetometer (SSM). Seven DMSP satellites were used in this study, all of which fly in sun-synchronous, ~99°-inclination orbits at ~840 km altitude with orbital periods of ~101 min. F8, F11, and F13 fly in dawn-to-dusk orbits while F9, F10, F12, and F14 fly in premidnight-to-prenoon orbits.

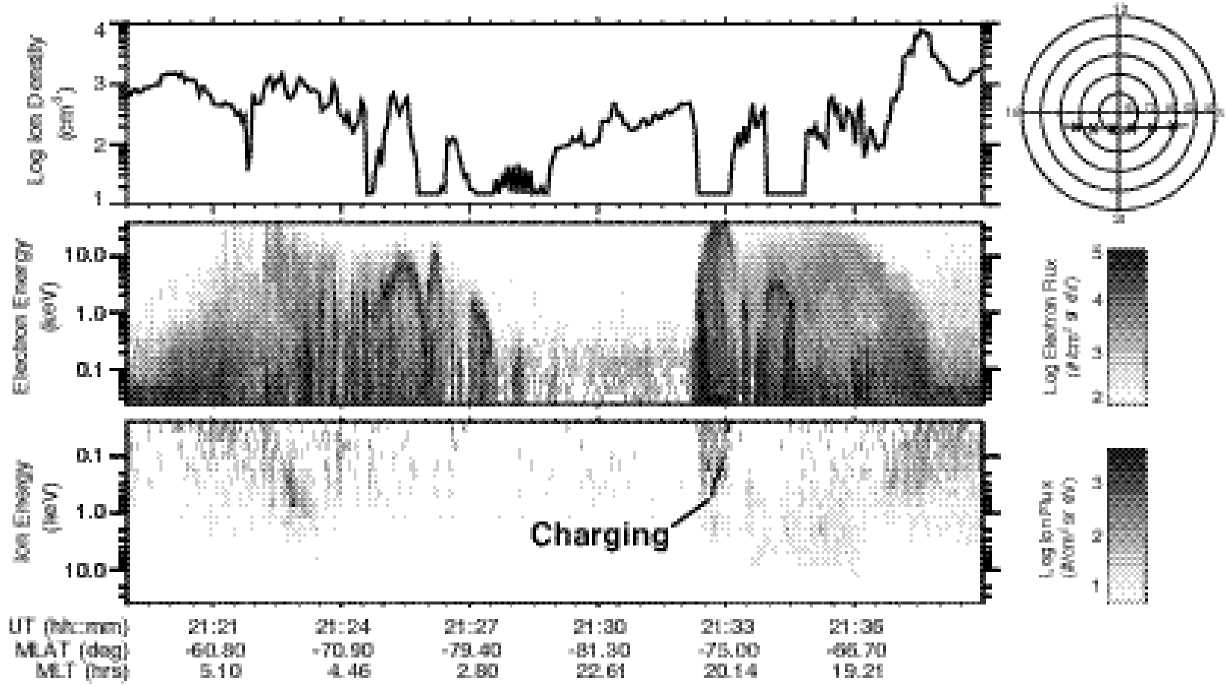

Figure 1. The environmental parameters associated with a typical charging event: the ion (electron) density (top panel), the precipitating electron number flux spectrogram (middle panel), and the precipitating ion number flux spectrogram (bottom panel). The ion spectrogram is plotted with low energy at the top and high energy at the bottom. The polar dial at the top right indicates the spacecraft orbit track in MLT and MLAT.

The instruments of interest here are the SSIES and the SSJ/4. The SSIES measures the *in situ* ion and electron temperatures and the plasma density, fluctuation, composition, and bulk flow velocity. The SSJ/4 measures precipitating energetic electrons and ions in the energy range from 30 eV to 31 keV with downward flight paths within a few degrees of local vertical.

2. Environmental Measurements

Charging events were identified using the ion portion of the SSJ/4 detector. The sensor aperture is grounded to the spacecraft frame so that when the frame charges to some large voltage, the ambient thermal ions (which have energies less than 1 eV) are accelerated to the

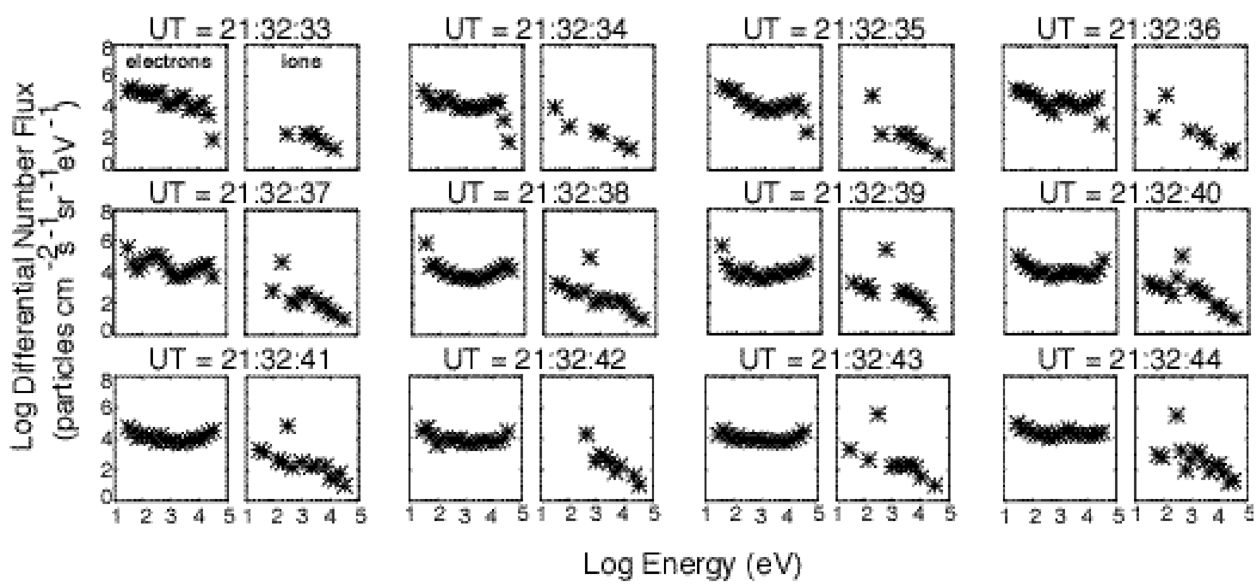

Figure 2. The individual, 1-second electron and ion spectra at the time of the charging event shown in Figure 1.

spacecraft frame voltage as they pass through the plasma sheath in front of the aperture. Therefore a large flux is observed in the ion channel with energy range spanning the frame voltage, generally a much larger flux than from ambient precipitating ions and thus easily identifiable.

Figure 1 shows an example of the environmental parameters associated with a typical charging event. The top panel is the ion (electron) density, the middle panel is the precipitating electron number flux spectrogram, and the bottom panel is the precipitating ion number flux spectrogram with energy plotted from top down. The charging is identified by the large flux in a single ion channel as indicated on the plot. The density remained below the *Gussenhoven et al.* [1985] requirement of 10^4 cm^{-3} during the entire polar pass with excursions below the sensitivity of the instrument associated with 5 separate auroral arcs. (These density depletions are called auroral cavities and are common features of auroral arcs.) However, the only charging occurred within the arc where the peak energy exceeded 10 keV. This is because of strong secondary electron production for electrons below 10 keV. Figure 2 shows an example of several of the individual 1-sec electron and ion spectra acquired during the event shown in Figure 1. The spacecraft frame (instrument aperture) voltage is indicated by the high ion flux in a single channel. (The ion fluxes seen at energies below the peak are actually contamination from high energy electrons.) The electron spectra show strong field-aligned acceleration, indicated by the spectral peak at high energies and sharp falloff at higher energies.

3. Distribution of Charging Events

For this study, a charging event was identified as an event in which the spacecraft frame charged to more than 100 V negative during a auroral crossing. Multiple charging periods during a single auroral crossing were classified as one event. During the period of the study, January 1, 1989 - December 31, 2000, 10368 1-sec spectra were identified as indicating spacecraft charging, giving 1253 total events. Most of the events showed spacecraft frame charging in the few hundred volt range, with one event in which the frame charged to almost 2000 V negative. Figure 3 shows the MLT and magnetic latitude (MLAT) distribution of the 10368 1-sec SSJ/4 sweeps. The majority of the events occurred in the 1800 - 2400 MLT sector between about 65° and 75° MLAT.

Figure 4 shows the distribution of events for the entire period of the study. The events were separated by spacecraft and by hemisphere. There was a strong seasonal dependence driven by the requirement that the spacecraft be in darkness (because of the production of photoelectrons) with the events centered on winter solstice and the absence of events during summer solstice. Near southern winter solstice in 1995, there were multiple events almost daily. (Events occurred on 26 of 31 days during May, 1995). There was a large preponderance of events in the southern hemisphere (80%) and considerable differences in the distribution of events from satellite to satellite. These were largely driven by the local time of the orbit tilt (F8, F11, and F13

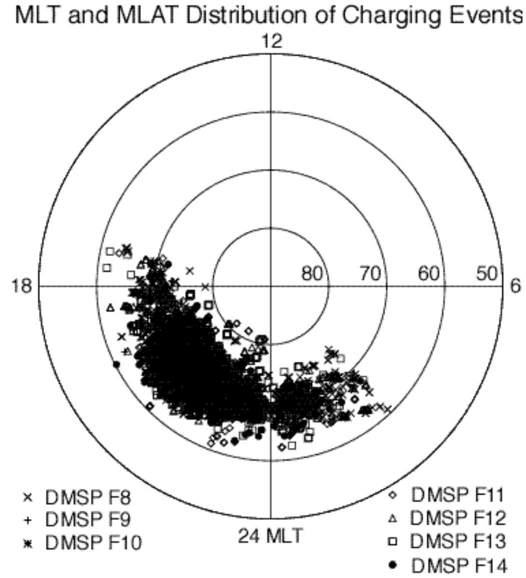

Figure 3. MLT and MLAT distribution of 10386 1-second SSJ/4 sweeps associated with the 1253 charging events.

are in dawn-to-dusk orbits and F9, F10, F12, and F14 are of in premidnight-to-postnoon orbits) and the seasonal dependence of the angle between the spacecraft orbit plane and Earth's axial. Note that a preponderance events occurred on F8 in the northern hemisphere; F8 is in a retrograde orbit with respect to F11 and F13.

There was a strong solar cycle dependence with no events occurring in 1989 and 1990 in the last sunspot maximum, a few events occurring in 2000 during the present sunspot maximum, and several hundred events occurring during sunspot minimum around 1995 - 1996. This is illustrated more clearly in Figure 5 which shows a plot of the monthly distribution of charging events divided by the number of satellites operating, and the monthly average of the sunspot number. The greatest number of events occurred in 1995 near the minimum in the solar cycle. This might seem contrary to intuition as the intense auroral arcs causing these charging events are associated with geomagnetic activity, strongest during sunspot maximum. However, the solar cycle dependence was driven by the variation in the plasma density associated with variations in the solar UV output.

This is illustrated in Figures 6a and 6b which show the daily averages of the ion density measured by the SSIES between 65° and 75° MLAT in the dusk/premidnight sector for the dawn-to-dusk satellites (6a) and the premidnight-to-prenoon satellites (6b), and the average monthly sunspot number. The data are separated in the plots by hemisphere. There was a strong seasonal variation in the density in both hemispheres with the minimum occurring near winter solstice; in the southern hemisphere near sunspot minimum, the difference approached three orders of magnitude. There was a significant hemispherical asymmetry in the minimum densities, particularly for the dawn-to-dusk satellites, reaching more than an order of magnitude near sunspot minimum. Note that the sunspot number suddenly dropped by ~100 in 1992. At the same time, the density

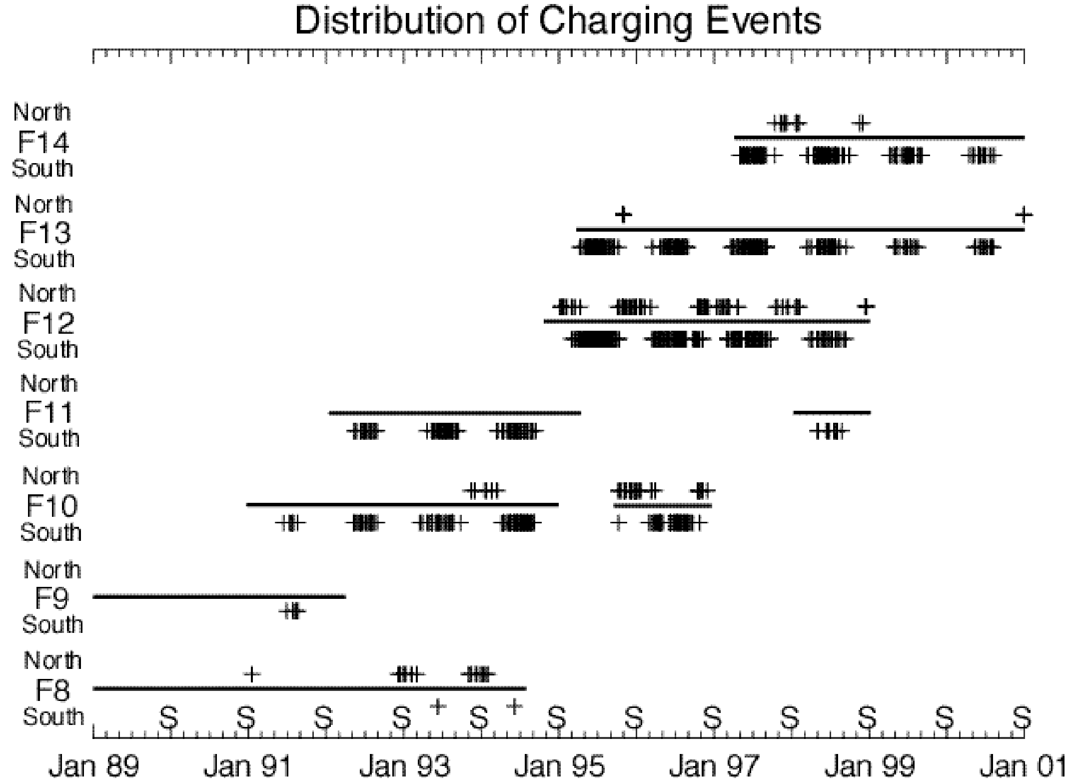

Figure 4. Distribution of events over the time period of the study, separated by hemisphere (above and below the solid line). The northern winter solstices are indicated by the S's at the bottom of the plot.

at southern winter solstice dropped by an order of magnitude and the event occurrence frequency increased dramatically. Also note that the sunspot number in 2000 during the present sunspot maximum was smaller than that during the last solar minimum. This led to significantly smaller densities during winter solstice and the occurrence of several events, unlike during the previous sunspot maximum. The variation in spacecraft

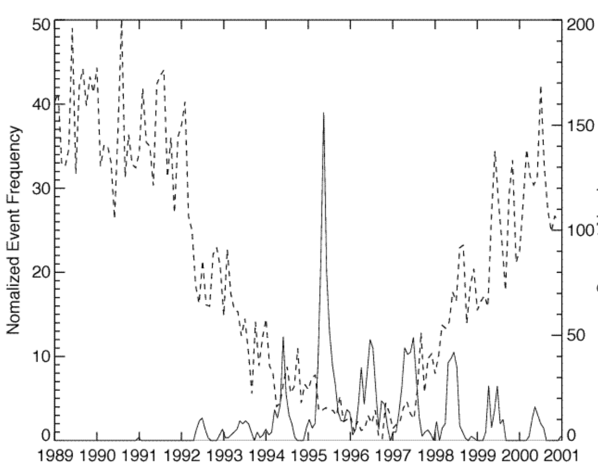

Figure 5. The dashed line shows the distribution of events over the 12-year sec. The solid line shows the sunspot number plotted using the scale to the right.

charging occurrence frequency with season, hemisphere, and solar cycle are clearly all driven by solar illumination and the ambient plasma density.

4. Charging Durations

Auroral arcs are nominally aligned with constant magnetic latitude; therefore a polar spacecraft will generally cut horizontally across an arc thus minimizing its time within the arc. The average charging event duration on the DMSP spacecraft was on the order of 8 However, a lower inclination satellite, and even a polar satellite under the right orbital and magnetic field study nomalized by the number of satellites acquiring data. The solid lines are the monthly averaged sunspot numbers plotted using the scale to the right. configurations, can skim along nearly constant magnetic latitude within the auroral zone. The DMSP spacecraft often experience charging durations exceeding 60 sec. The particle data from the longest duration event found is shown in Figure 7. In this example, the spacecraft charged to over 100 V negative for over 4 minutes.

4. Conclusions

We have found a significant number of high-voltage charging events (1253) on the DMSP spacecraft during a 12-year period covering the most recent solar cycle, much greater than previously expected. The majority of events occurred between 1800 and 2400 MLT and between about 65° and 75° MLAT. The frequency of occurrence was strongly anti-

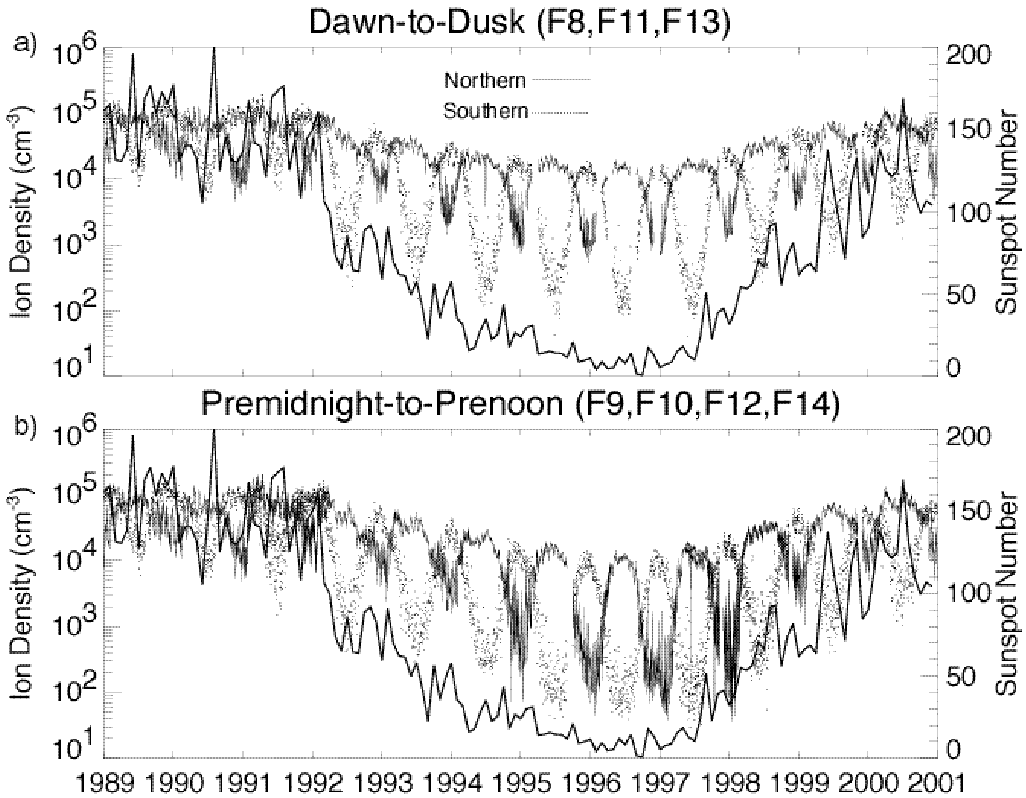

Figure 6. Daily averages of the ion density between 65° and 75° MLAT in the dusk/premidnight sector for the dawn-to-dusk satellites (6a) and the premidnight-to-prenoon satellites (6b). The solid lines are the monthly averaged sunspot numbers plotted using the scale to the right.

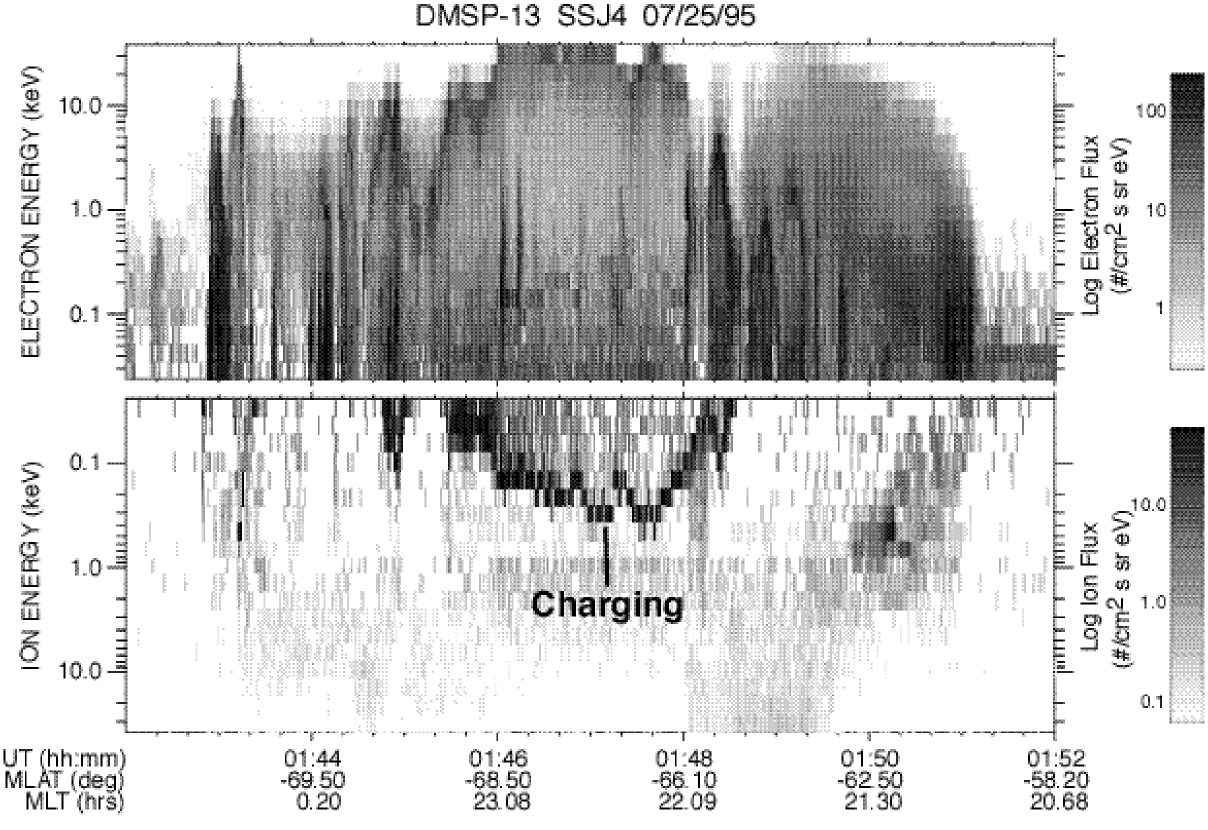

Figure 7. The environmental parameters associated with a charging event that lasted for almost 3 minutes.

correlated with the sunspot number, due to the greatly reduced thermal plasma density in the ionosphere associated with the reduced UV output from the sun. Conditions conducive to spacecraft charging in the DMSP orbits existed a significant fraction of the time, particularly at southern winter solstice, such that high-level charging events occurred almost daily on the DMSP spacecraft.

The requirement that the spacecraft be in darkness led to a seasonal dependence with most of the events occurring around winter solstice. There was a strong anisotropy between frequency of occurrence in opposite hemispheres; 80% of the events occurred in the southern hemisphere. This is due to the seasonal dependence of the angle between the spacecraft orbital plane and Earth's axial tilt.

Anderson et al. [1996] showed that the ungrounded multi-layer thermal blankets covering most of the surface of the spacecraft could easily charge to several kilovolts in a few seconds and recommended that the top layer of the thermal blankets be grounded. This would lead to an increase by a factor of 20 in the required charging time. However, there were events in which the spacecraft charged to high negative values for several 10s of seconds. Such considerations are very important when designing low-altitude satellites, despite the typically large plasma densities. Polar satellites orbiting in the altitude regime a few hundred km above the DMSP orbit, where the plasma density is smaller, will experience very similar conditions to those experienced during the DMSP charging events and lower inclination satellites could remain in auroral arcs and charge for considerable periods of time. The International Space Station's (ISS) ~52° inclination orbit will carry it into the auroral region due to the 11° offset between Earth's magnetic axis and it's spin axis. Although at a much lower altitude where the plasma density is greater, the ISS will experience conditions conducive to charging in its very large wake where the plasma density is considerably depleted.

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