# A Study of Intense Auroral Electron Precipitation Events

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## Introduction

Some of the more stressful environmental situations encountered by high-inclination, low-Earth-orbiting (LEO) spacecraft are transits through intense auroral particle precipitation events over Earth's polar regions. The energy fluxes carried toward the atmosphere by these energetic particles (almost exclusively electrons) often exceed 0.1 $Wm^{-2}$ and may, on occasion, exceed 1.0 $Wm^{-2}$. These electrons have energies of order 10 kilo-electron-Volts (keV); under particularly unfavorable sunlight and local plasma conditions, they may charge spacecraft surfaces to equivalent electrostatic potentials. Moreover, the electrons producing such intense auroral events carry an electrical current outward from the ionosphere, along the geomagnetic field, toward the magnetosphere. These current densities are often sufficiently large that the local geomagnetic field is perturbed from its quiescent direction, and attitude control systems that depend upon the geomagnetic field as a reference may malfunction.

For these reasons a study of intense auroral electron events was undertaken using auroral particle energy flux observations performed by the Total Energy Detector (TED) included in the Space Environment Monitor (SEM) package regularly flown on the NOAA/TIROS series of near-polar-orbiting, low-altitude (850 km) meteorological spacecraft. The objectives of the study included the determination of the size distribution of auroral electron energy fluxes that may be encountered; the distribution in latitudinal extents over which intense energy fluxes extend; the energy distribution of the precipitating electrons in such intense events; the magnetic field-aligned electrical current density distribution associated with such events, and an estimate of their perturbation on the geomagnetic field; the frequency-of-occurrence variation of intense events with respect to the solar cycle and geomagnetic activity; and a specification of the absolute probabilities of encountering an intense event as a function of magnetic latitude and magnetic local time.

The full characterization of the properties of intense auroral precipitation events may assist spacecraft designers by providing them with a worst-case situation for design purposes and an assessment of how often and where in the orbit their systems might be required to operate under such potentially stressful conditions. Satellite operators may also benefit because these results quantify those locations and geophysical conditions where encounters with intense auroral particle fluxes are most likely.

## The Instrument and the Data

The TED instrument is designed to monitor the energy fluxes carried toward the atmosphere by electrons and positive ions integrated over the energy range 0.3 to 20.0 keV. The measurements are made separately for electrons and positive ions and at two different angles with respect to the local geomagnetic field; the observations are then combined in ground processing to produce the "total energy flux." A full measurement cycle requires 2 s (about 11.4 km of satellite travel referenced to the ground). During the first second, electron data are acquired; ion data are obtained over the second half of the instrument cycle.

In addition to the energy flux moments, the instrument provides a measure of the particle energy band within which the sensor response is maximized during the course of each energy sweep. This particle energy, termed the "characteristic energy," is roughly the average energy of the particles contributing to the incident precipitation. Detailed electron or ion energy spectra are obtained from the instrument only at a low-duty cycle and so do not represent primary data from the TED. The TED is capable of monitoring integrated energy fluxes from a threshold of about .01 $mWm^{-2}$ to a design maximum of 300 $mWm^{-2}$ (although, when the characteristic particle energies are above 10 keV, the instrument capability extends to 500 $mWm^{-2}$).

In the course of ground processing, each instance of an integrated energy flux exceeding 60 $mWm^{-2}$ is identified and a 56 s span of observations centered at that event is extracted and stored. An auroral particle energy flux of 60 $mWm^{-2}$ is capable of producing unusually bright auroras approaching 100 kR intensity of 557.7 nm emission from the atmosphere.

This analysis is based on more than 12,000 such observations of intense auroral particle energy fluxes during the period between November 1978 and December 1993. There is a gap in the records between mid 1985 (when the performance of the TED on NOAA–6 degenerated) and June 1991 (when NOAA–12 was launched). The TED instrument aboard NOAA–10, which was to provide observations between October 1986 and June 1991, deteriorated rapidly after launch, and so no useful data on intense auroral events were obtained by that instrument.

## An Intense Auroral Particle Event

Figure 1 displays 56 s of data centered at an intense auroral particle event. In this instance there was a maximum flux of nearly 250 $mWm^{-2}$, followed within seconds by an observation of 150 $mWm^{-2}$. The four previous and four subsequent transits of the satellite through the auroral zone displayed no single measurement greater than 10 $mWm^{-2}$, which indicates how unusual such large energy fluxes are. The event in Figure 1 was located in the southern hemisphere at a corrected magnetic latitude (CML) of 67.1° and a magnetic local time (MLT) of 22 hr.

The latitudinal extent of an intense feature is defined by the locations where the energy flux falls to 10% of the maximum value (24 $mWm^{-2}$ in this instance). By this definition, the event in Figure 1 lasted for 8 seconds and had a latitudinal extent of about 0.2°.

A study of a large number of intense auroral energy flux events shows that each exhibits the following characteristics.

1. The energy fluxes are carried exclusively by incident energetic electrons. Energetic ions usually contribute less than $10^{-3}$, and often less than $10^{-4}$, to the integrated energy fluxes. Positive ions rarely contribute as much as 1% to the total energy flux.
2. The energy distribution of the incident electrons usually exhibits a peak. That is to say, 20%–50% of the integrated energy flux is carried by electrons of energies within one of the 11 logarithmically spaced energy-band samples during an instrument energy sweep.
3. The angular distribution of the incident electrons, as observed at 850 km, is usually aligned to the geomagnetic field; the greatest intensities are seen at low pitch angles. This suggests that the electrons are energized by a magnetic-field-aligned electric potential above the satellite.

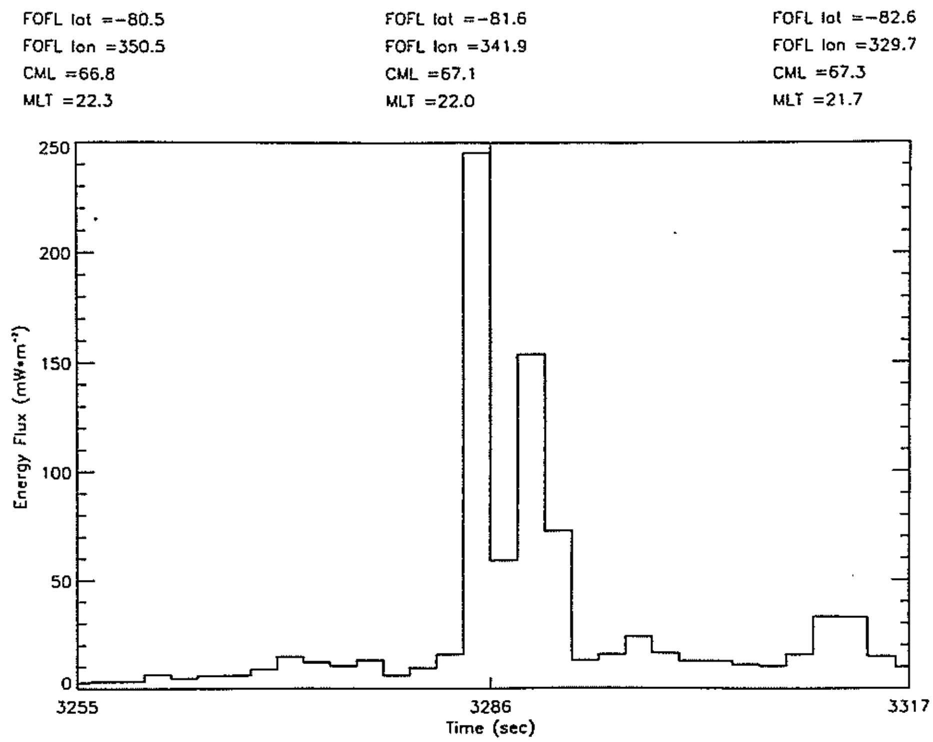


**Figure 1. An intense auroral particle precipitation event observed in the southern hemisphere. FOFL is the "Foot of the Field Line;" the FOFL lat and FOFL lon define the geographic location of the intense aurora that is created by these precipitating particles. The corrected magnetic latitude (CML) and magnetic local time (MLT) of the event are also given. This event lasted 8 s and was about 0.2° in latitudinal extent.**

Together, these properties indicate that the intense auroral particle energy fluxes encountered by the NOAA/TIROS spacecraft are the same as the exceptionally bright discrete auroral arcs observed from the ground.

## The Statistical Characteristics of ~12,000 Intense Auroral Particle Events

The set of more than 12,000 intense auroral energy flux events, accumulated over the major portion of a full solar cycle, offers the opportunity to conduct a thorough statistical analysis of their properties.

Figure 2 displays the integral distribution of large event magnitudes for each of the five satellites that carried a properly operating TED. (The number of events accumulated by NOAA–8 is rather low, both because of the short life of this satellite and because those data were obtained largely during solar minimum.) Each of these distributions can be fit over the energy flux range, between 60 $mWm^{-2}$ and 300 $mWm^{-2}$, to a power-law curve such that the number of events of energy flux value greater than $F$ is roughly proportional to $F^{-3}$. The distributions tend to fall off faster than $F^{-3}$ at energy fluxes above 300 $mWm^{-2}$, but this may reflect sensor saturation at greater energy fluxes. The $F^{-3}$ relationship indicates that the probability of encountering auroral particle energy fluxes above a given threshold decreases by a factor of 8 for each doubling of that threshold (e.g. the probability of encountering energy fluxes exceeding 300 $mWm^{-2}$ is about 125 times less than encountering those at 60 $mWm^{-2}$).

Figure 3 shows the distribution of characteristic electron energies associated with large energy fluxes. About 50% of all instances have characteristic energies between 3.5 and 13.0 keV. The size of each energy bin in Figure 3 is the width of the instrument energy bands and, as stated above,

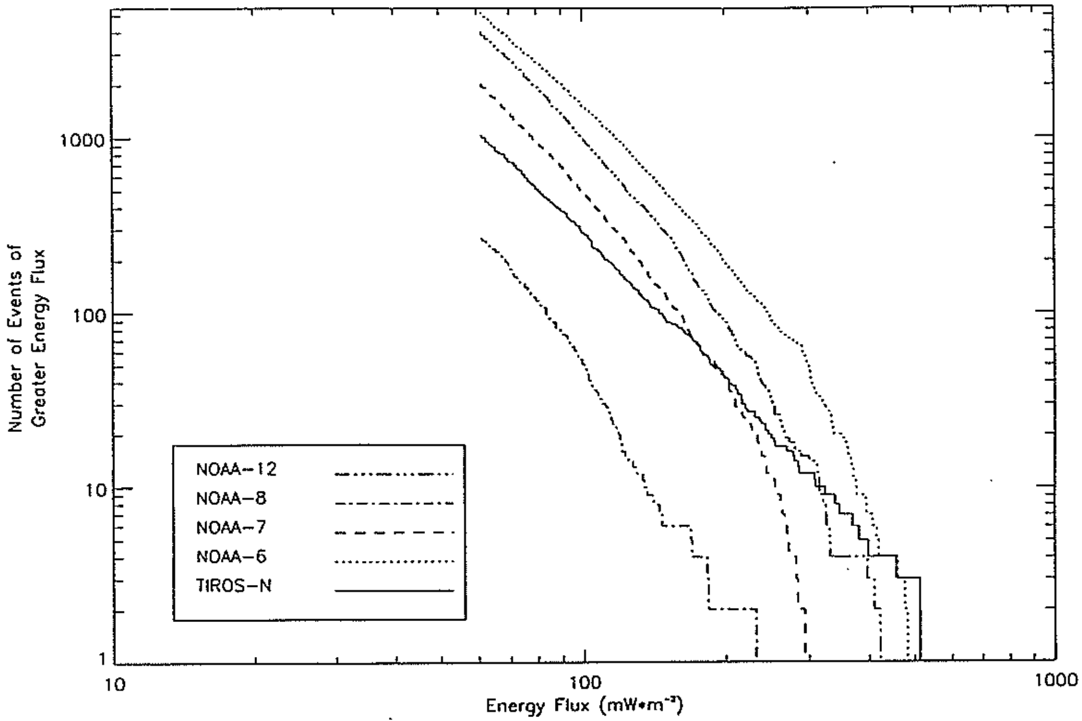


**Figure 2. The integral distribution of large event sizes observed by instruments aboard five satellites. Between 60 $mWm^{-2}$ and 300 $mWm^{-2}$ the curves roughly follow a power law such that *N*, the number of energy fluxes greater than a value *F*, is proportional to $F^{-3}$ .The more rapid decrease in the curves a thigher energy fluxes may reflect the instrument's saturation at fluxes above 300 $mWm^{-2}$.**

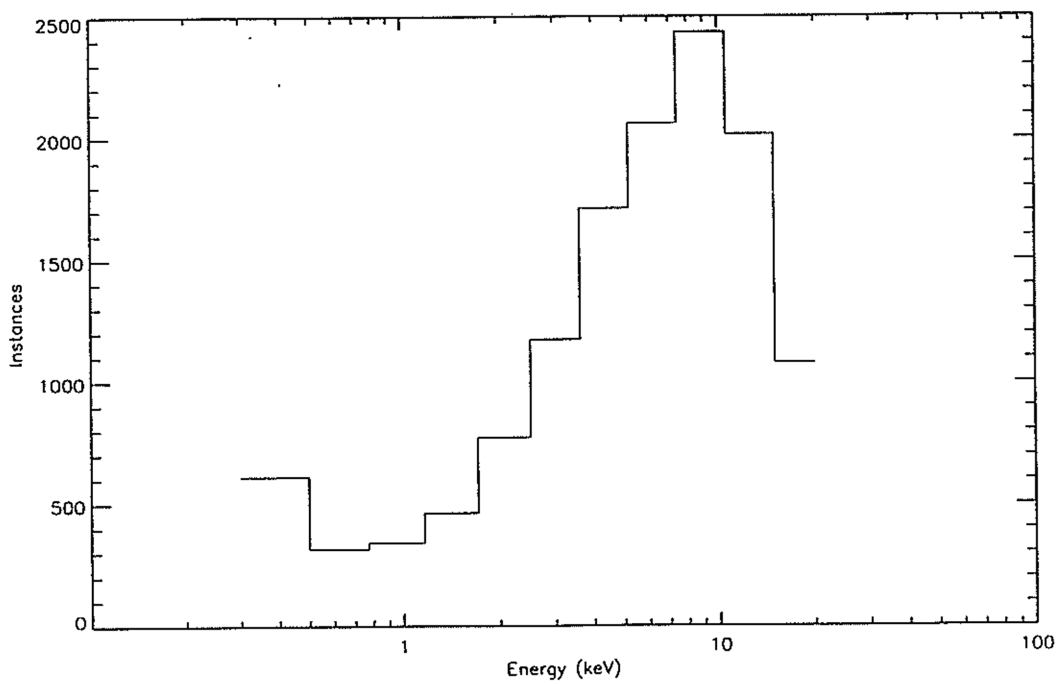


**Figure 3. The distribution of "characteristic electron energies" during intense energy flux observations. The energy width of each point in the bar graph is the size of the energy band sampled during the instrument energy sweep. Typically, 20% to 50% of the total energy flux in a large event is carried by electrons having energies within the energy band identified as the "characteristic electron energy."**

20%-50% of all the energy in a large event is typically contained in a single such energy band. These electron energies are insufficient to produce bulk charging of dielectrics, but they can rapidly charge insulated surfaces.

As described above, the latitudinal extent of an event may be determined by noting the corrected magnetic latitudes at the edges of the event, defined by where the energy flux falls to below 10% of its maximum value (the event being viewed as a spatial feature sampled by a moving spacecraft as opposed to a purely temporal feature). Figure 4 shows the latitudinal extent distribution of all intense energy flux features. Typically these features are less than 0.3° (~30 km) wide in latitude, and there is evidence that some are narrower than the 11.5 km resolution of the measurements. A polar orbiting satellite transiting orthogonally over such a thin feature will encounter large energy fluxes for only a few seconds. However, some intense energy flux events have latitudinal widths in excess of 2° and, because the satellite may transit the feature obliquely rather than straight across, the time spent within an intense event may approach 60 s.

Because it is clear that the intense energy fluxes observed from NOAA/TIROS are associated with bright auroral arcs, and because the energization of the electrons producing such arcs is believed to be due to acceleration through a magnetic field-aligned electric potential, the observation of energy flux to the atmosphere (power input) and the characteristic electron energy (to first order equivalent to the magnitude of that potential) it is possible to estimate the magnetic field-aligned electrical current flow at these times. Figure 5 displays the distribution of magnetic field-aligned current densities calculated from the ratio of power input flux to accelerating potential difference. Typically currents of 10 $\mu Am^{-2}$ are associated with intense energy fluxes, but densities in excess of 40 $\mu Am^{-2}$ are not uncommon. If a current of 40 $\mu Am^{-2}$ existed over a latitudinal dimension of 60 km, a shift of about 5° in the direction of the magnetic field vector would occur during a satellite overflight.

Exceptionally large energy fluxes tend to be connected with increasing geomagnetic activity. Table 1 quantifies this association through the probability of observing an instance of an energy flux greater than 60 $mWm^{-2}$, as a function of the Kp magnetic activity index, during a single NOAA/TIROS transit over the polar regions. There is a monotonic increase in this probability, from 4 instances per 1000 passes at Kp=0 to over 500 instances per 1000 passes at Kp=7. However, it is also clear that modest levels of magnetic activity do not mean that intense auroral energy fluxes are of no concern. Nearly 25% of all >60 mWm-2 instances were encountered at a Kp=3.

Figure 6 shows, in a similar fashion as Table 1, the variation in the probability of encountering a large energy flux as a function of the solar cycle. In Figure 6 the probability of observing such an energy flux during a single pass (averaged over 10 days) is plotted as a function of time since 1978. (The lengthy gap between 1985 and 1991 is a result of the NOAA-6 instrument degradation and the NOAA-10 instrument failure.) Also plotted in Figure 6 is the sunspot number from 1978 to mid-1993 (dashed curve). It is apparent that the probability of encountering intense energy fluxes tends maximize during the 1–2 years at the declining phase of the solar cycle (the frequency of auroral displays shows a similar effect). The overall amplitude of the variation in probability of encountering intense energy fluxes indicates that at sunspot minimum the probability is about a factor of 4 lower and at sunspot maximum about a factor of 4 higher than the overall average. It might be noted that during the first 3 months of 1994, well into the declining phase of the current solar cycle, energy fluxes exceeding 60 $mWm^{-2}$ have been encountered very frequently—in about 300 to 400 instances per 1000 satellite transits over the polar regions.

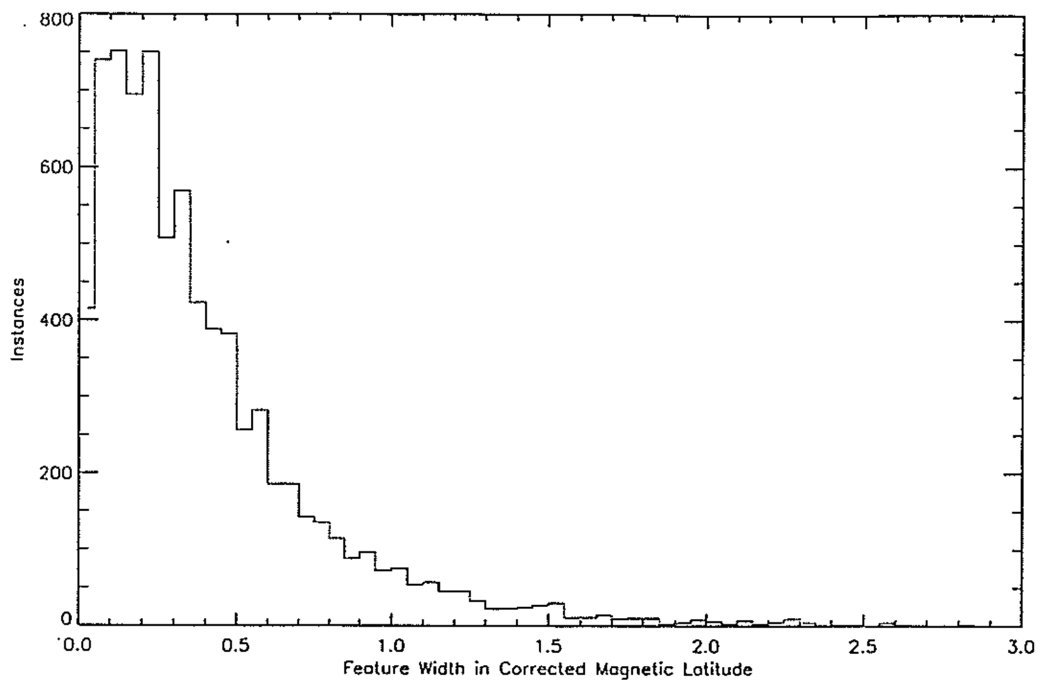


**Figure 4.** The latitudinal extent distribution of intense energy flux events. The latitudinal extent is defined by the corrected magnetic latitudes where the energy flux falls below 10% of its maximum value in the event. The great majority of such events extend than 0.6° (about 60 km), but unusual ones can extend beyond 2°. A low-Earth-orbit satellite will usually transit over such spatial structures within about 10 s, although instances of transit times as long as 60 s have been observed.

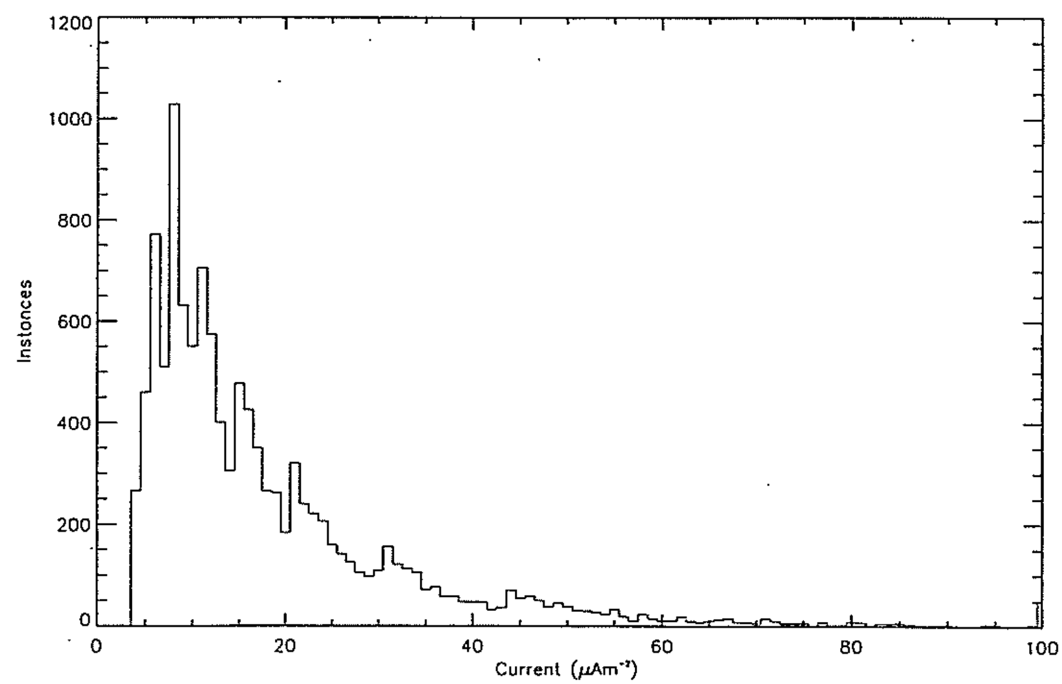


**Figure 5.** The distribution of magnetic field-aligned current density carried by the intense fluxes of precipitating electrons during large events. The current density is calculated assuming that most of the power flux to the atmosphere is a result of electron acceleration through a electric potential difference. In this case, the current density is roughly the ratio between the observed power flux and the "characteristic electron energy," which provides a measure of the accelerating potential. Field-aligned current densities in excess of 40 $\mu Am^{-2}$, if they exist over dimensions of 60 km or more, will change the direction of the local geomagnetic field by about 5°.

**Table 1. How large auroral events correlate with magnetic activity**

| Kp index | Number of satellite passes | Number of $\leq 60$ mWm$^{-2}$ observations | Number per pass |
|---|---|---|---|
| 0 | 5201 | 19 | .004 |
| 1 | 23675 | 368 | .016 |
| 2 | 32800 | 1239 | .038 |
| 3 | 31507 | 2952 | .094 |
| 4 | 19286 | 3591 | .186 |
| 5 | 8442 | 2401 | .284 |
| 6 | 3029 | 1416 | .467 |
| 7 | 1056 | 600 | .568 |
| 8 | 395 | 334 | .846 |
| 9 | 41 | 42 | 1.024 |

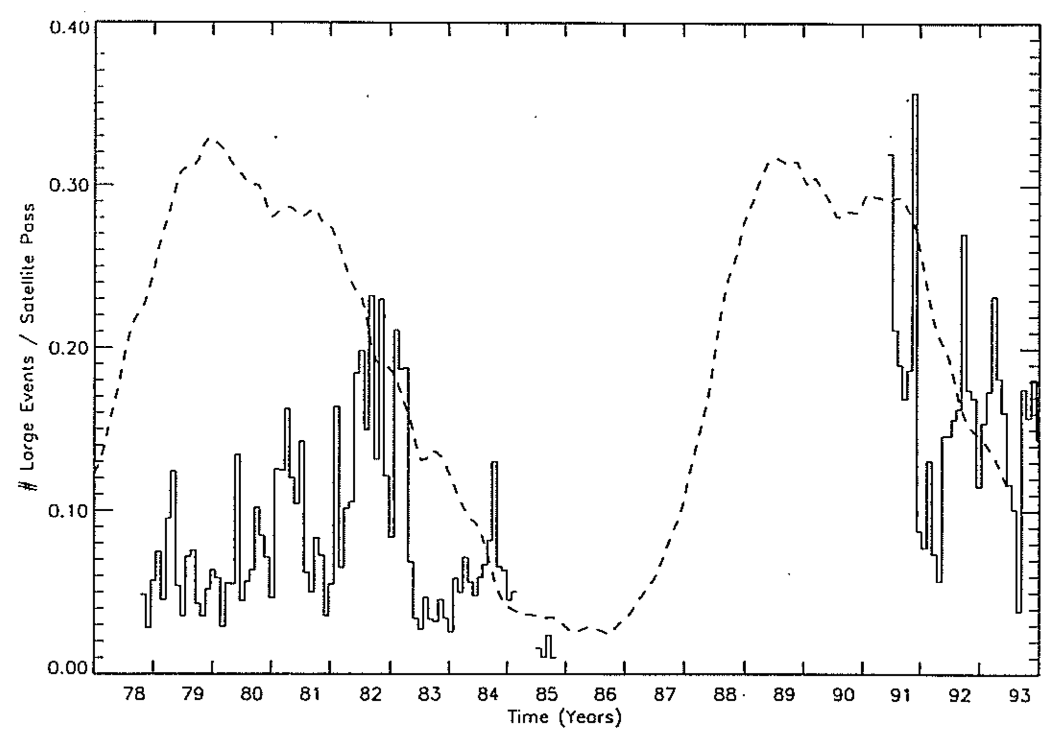


**Figure 6. The solar cycle variation in the probability of observing intense auroral particle energy fluxes. This probability is expressed as the number of instances of an energy flux exceeding 60 mWm$^{-2}$ per satellite transit over the polar regions, averaged over 10 days. The dashed line is the sunspot number that defines the solar cycle. The probability of encountering large events varies by a factor of $\pm 4$ over the course of the solar cycle and is at a maximum during the declining phase of the cycle.**

## Absolute Probabilities of Encountering Large Energy Fluxes as a Function of Location in Magnetic Coordinates

Large energy fluxes are basically auroral phenomena, and auroras are not well ordered in a geographic coordinate system. For this reason, the calculation of absolute probabilities must be done in a corrected magnetic latitude and magnetic local time coordinate system. All NOAA/TIROS orbits for which data are available were transformed to this coordinate system. For purposes of computing probabilities, the orbital data as well as the large-event observations were binned into pixels of 1° in corrected magnetic latitude by 8 min in magnetic local time.

Probabilities were computed in two ways. The first method was a determination of the ratio between the number of encounters with energy fluxes exceeding 60 $mWm^{-2}$ within a CML–MLT bin and the number of transits through that bin by the satellite. This method provides an absolute probability of encountering an intense energy flux at a given location. The second method was a computation of the ratio between the total number of seconds when the energy flux exceeded 60 $mWm^{-2}$ within a CML–MLT bin and the total number of seconds when the satellite was gathering data within that bin. This method provides a measure of the percentage of time at a given location in which intense energy fluxes might be encountered.

All available data were used to compute absolute probabilities, and so the results represent an average over all magnetic and solar activity conditions. However, first-order corrections to these averaged probabilities for changing activity conditions can be made by using the results shown in Table 1 and in Figure 6.

Figure 7 displays, in color-coded, polar format, the absolute probability of encountering intense auroral energy fluxes. The latitude range in Figure 7 is from 90° corrected magnetic down to 45° corrected magnetic. The magnetic local time coordinate ranges from midnight (at the bottom of the plot ) through dawn (at the right), noon (at the top) and dusk (at the left). The maximum probability of encountering an intense energy flux is about .01 at a location of 65°–66° CML and 21 hr MLT. A polar-orbiting low-altitude satellite traversing though the magnetic latitude range 60°–70° in the pre-midnight sector would have about a 10% chance of encountering an intense auroral particle energy flux at some point along its trajectory. The probabilities decrease dramatically after magnetic midnight and through the morning hours. A satellite transit over the polar regions in the pre-noon hours would have a very small chance of encountering a large auroral particle energy flux.

Figure 8 displays, in a similar format, the percentage of time at a given magnetic latitude-magnetic local time location when auroral particle energy fluxes would be expected to exceed 60 $mWm^{-2}$. The overall pattern is very similar to that in Figure 7: about 0.3% of the time, intense energy fluxes are seen at 60°–70° latitude and 21 hr; they then decrease dramatically in the post-midnight and morning hours.

It is possible to transform these probability patterns from magnetic coordinates to geographic coordinates once a universal time of day is chosen. Presentations in terms of geographic coordinates are generally more meaningful to users who are unfamiliar with corrected magnetic latitudes and magnetic local times but are very comfortable with satellite orbits relative to geographic features. Figure 9 presents the Figure 7 information in geographic coordinates, assuming a universal time of 06 hr (midnight in central North America).

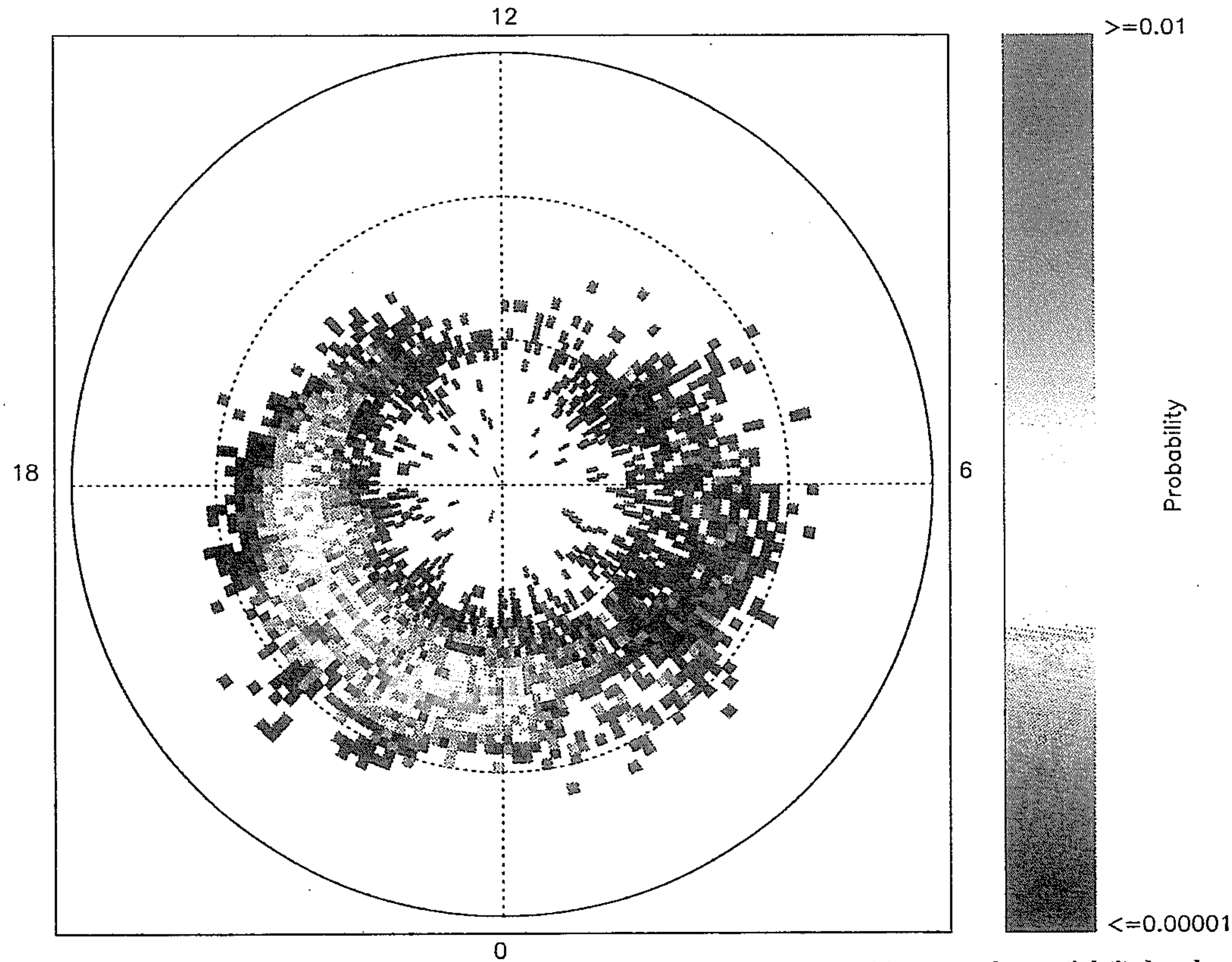


**Figure 7.** The absolute probability of a satellite encountering a large energy flux event as a function of the corrected magnetic latitude and magnetic local time of the satellite's location. The maximum probability within a 1° by 8 min pixel is about .01 at latitudes near 65° in the late evening hours. A satellite passing over the late evening polar sector would have about a 10% chance of encountering a large energy flux. The probability of an encounter decreases rapidly after midnight and throughout the morning hours.

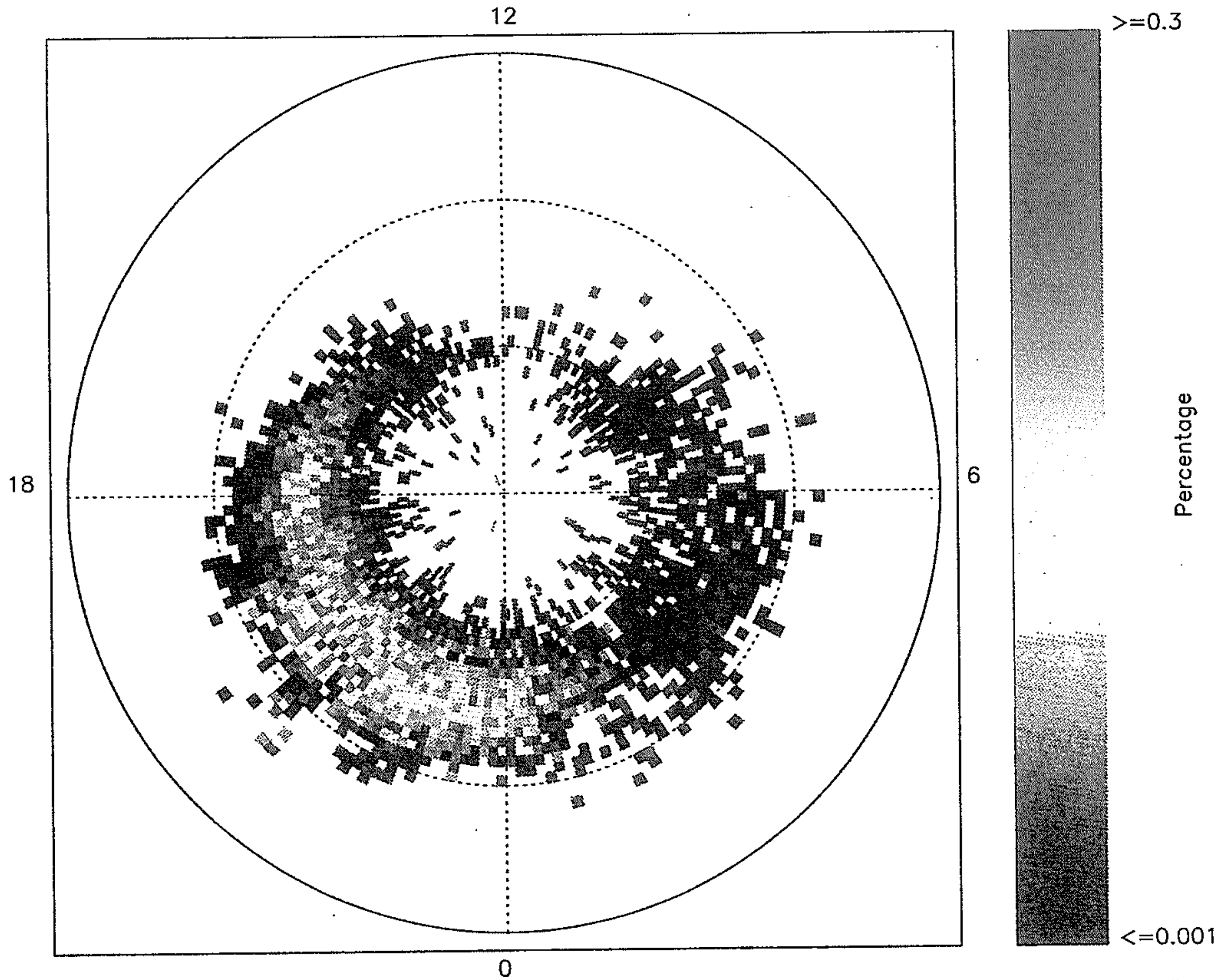


**Figure 8.** Similar to Figure 7, except that the color-coded parameter is the percentage of time within a 1° by 8 min pixel in which energy fluxes exceeding 60 $\mu W m^{-2}$ would be present.

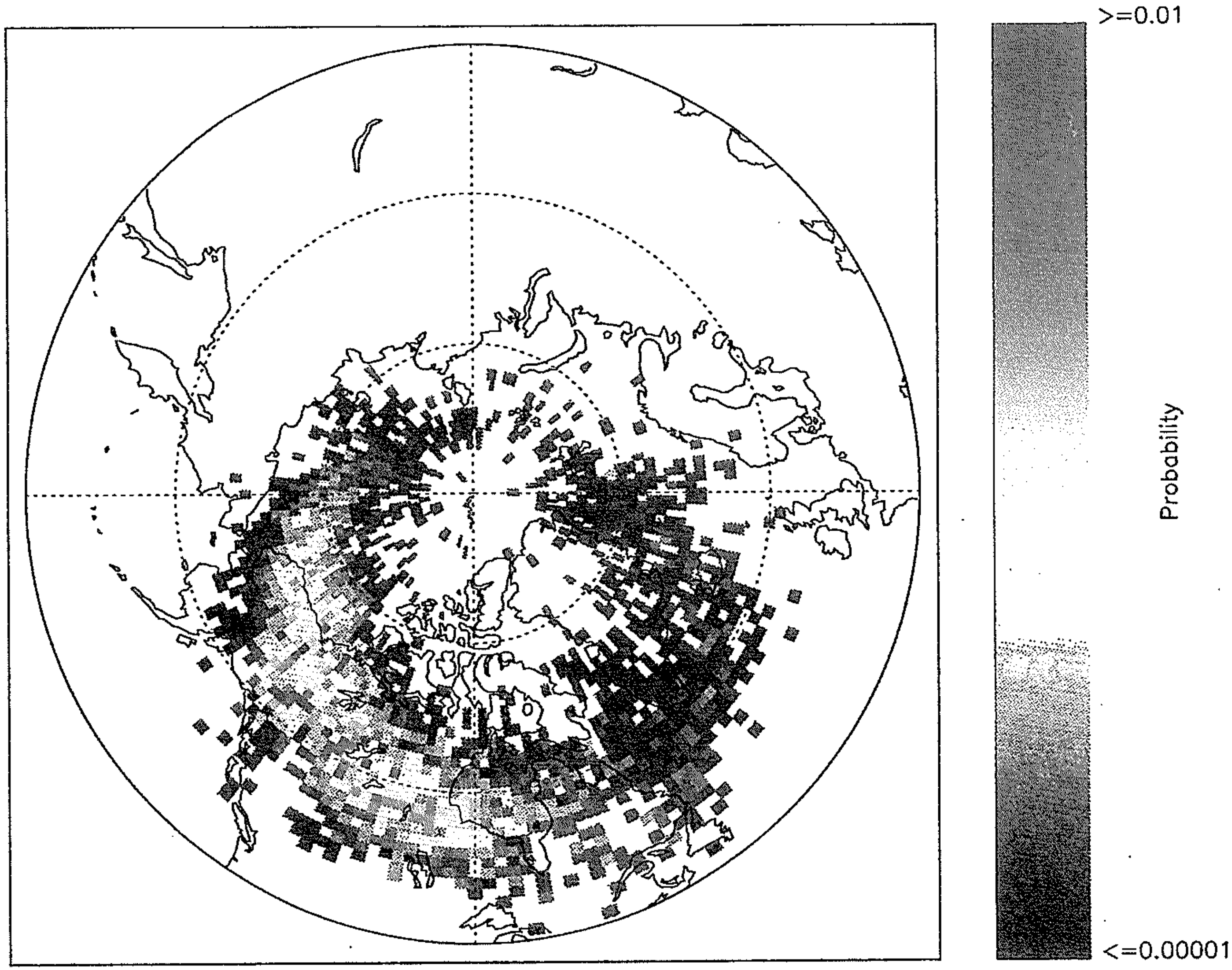


**Figure 9.** The color-coded absolute probabilities of encountering an intense auroral particle energy flux (the same parameter displayed in Figure 7), plotted in geographic coordinates, assuming that the universal time of day was 06 hr (midnight in central North America). The geographic map is included to aid in referencing the probability of large energy fluxes to specific geographic regions. At this time of day, the most intense energy fluxes will be encountered during satellite passes over Alaska and Western Canada.

## Summary

The objective of the SEL study of intense auroral particle fluxes was primarily to characterize the environmentally stressful conditions that accompany such events. In this context, the important results of the study may be summarized by the following points:

1. Intense auroral particle energy fluxes are exclusively energetic electrons.
2. The energy of the electrons is typically concentrated in the 5 to 15 keV range; these energies are capable of charging exposed surfaces to kilovolt electric potentials.
3. The frequency of encountering auroral particle energy fluxes greater than a threshold value $F$ varies as $F^{-3}$.
4. The probability of encountering auroral particle energy fluxes greater than 60 $mWm^{-2}$ increases monotonically with increasing magnetic activity and is virtually 100% at the highest levels of activity.
5. The probability of encountering auroral particle energy fluxes greater than 60 $mWm^{-2}$ varies by a factor of $\pm$ 4 over the course of a solar cycle; the maximum probability occurs a few years after the cycle maximum.
6. The latitudinal extent of regions of intense auroral particle energy fluxes is very limited, with 80% of such events being less than 0.6° ($\sim$60 km) in extent; low-Earth-orbit satellites would transit such a region in about 10 s. Instances of latitudinal extents greater than 2° or transit times greater than 30 s are very rare.
7. Regions of intense auroral particle energy fluxes are associated with field aligned current densities exceeding 10 $\mu Am^{-2}$. Extreme cases, in which field-aligned currents greater than 40 $\mu Am^{-2}$ extend over 60 km, will produce a change of about 5° in the direction of the geomagnetic field at satellite altitudes.
8. The probability that a low-Earth-orbit satellite transiting the polar regions in the pre-midnight hours will encounter an energy flux exceeding 60 $mWm^{-2}$ is about 10%.
9. Low-Earth-orbit spacecraft with inclinations below 45° will very rarely encounter intense auroral particle energy fluxes. Space stations at an inclination of 51° will encounter intense energy fluxes whenever the maximum latitudes are reached in the pre-midnight hours *and* at geographic longitudes near 90°W in the northern hemisphere or 90°E in the southern hemisphere.

## Acknowledgments

The contibution of Ms. Sue Greer in developing the data plots and displays in this work is gratefully acknowledged. For additional information about the space environment and its effects upon space systems, the reader is referred to the *Handbook of Geophysics and the Space Environment* (especially Ch. 7), Adolph S. Jursa, ed., Air Force Geophysics Laboratory. This book is available through National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161