A review of recent observations of relativistic electron energization in the Earth's outer Van Allen radiation belt

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Abstract. The energization to relativistic energies of electrons in the Earth's inner magnetosphere is still not fully understood. Current models of electron energization in the Earth's magnetosphere may be broadly classified into two types. One class of models emphasize in-situ processes such as resonant or stochastic wave particle interactions and the second class invokes particle transport process such as enhanced radial diffusion as the dominant mechanism. We present a review of recent observations of relativistic electrons made by spacecraft such as SAMPEX, and Polar. Our observations elucidate the solar cycle dependence upon electron energization characteristics by comparing high speed solar wind driven events with coronal mass ejection driven events. These solar drivers are predominant during the descending and ascending phases of a solar cycle, respectively. We present observational results such as the global and coherent nature of electron energization which constrain set by the proposed physical models of energization. We also present measurements of electron spectra and flux isotropization time scales during electron energization events. Data collected by detectors onboard SAMPEX in low earth orbit and Polar which measures electron fluxes at a much higher altitude are used to measure spectra and flux isotropization. Pulse height analyzed data from the PET detector onboard SAMPEX are used to measure electron spectra, whereas flux isotropization is measured by comparing SAMPEX and Polar fluxes.

Index Terms. Electron energization, relativistic energies, Van Allen radiation belts

1. Introduction

The Earth's magnetosphere is known to energize electrons to relativistic energies in the outer zone ($L \geq 3.0$) (Paulikas and Blake, 1979; Baker et al., 1989). These electron fluxes are highly variable and dynamic, showing enhancements of several orders of magnitude occurring on timescales of about a day (Baker et al., 1994). Electron energization is associated with increased solar wind velocity (Paulikas and Blake, 1979) and the southward turning of the interplanetary field (Blake et al., 1997). The energized electrons result from a seed population of low energy electrons (approximately hundreds of keV) provided by substorms (Baker et al., 1998). The fundamental causative agents for the energization of electrons, namely high solar wind speeds and a strong southward component of the interplanetary magnetic field have been well established although the detailed mechanisms of electron energization remain to be fully understood.

Relativistic electron enhancements are driven by high-speed solar wind streams, and by, coronal mass ejections, during declining and ascending phases of a solar cycle (Baker et al., 1994; Kanekal et al., 1999) respectively. These drivers may have differing characteristics and thus may result in electron enhancements with differences, such as, rise times and decay times (see Fig. 5).

Physical models proposed for the acceleration of electrons in the magnetosphere are of two broad classes, emphasizing either particle transport or in-situ energization. Some of the proposed models of the former type include simple radial diffusion (Schulz and Lanzerotti, 1974), diffusion in both radial and pitch angle degrees of freedom such as the recirculation (Nishida, 1976) model while the latter class includes energization due to wave-particle interactions (Hudson et al., 1999; Liu et al., 1999; Summers et al., 1998).These processes could be operating simultaneously, with both types of processes contributing more or less equally or one class being the dominant in any given event. It may be possible to distinguish between the two types of mechanisms through observations of characteristic features of energization events such as pitch angle distributions and flux isotropization time scales.

In this study we review the observations of characteristic features of electron energization events as well as their dependence upon solar cycle phase. We have reported previously on the comparison of daily averaged electron fluxes measured by the Polar and SAMPEX satellites and found that the low-altitude and high-altitude fluxes track each other remarkably well (Kanekal et al., 1999). That study suggested that electron acceleration and isotropization are occurring on timescales of about a day and that the two are intimately connected. However, it may still be possible, as has been suggested by (Reeves et al., 1998), that relativistic electrons of large equatorial pitch angles may be energized earlier followed by rapid isotropization.

2. Spacecraft and instrumentation

Sensors from, Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX), and Polar, provide data used in this study. SAMPEX is in a low-Earth polar orbit at an altitude of about 600 km and an inclination of 82 degrees (Baker et al., 1993). Polar is at a much higher altitude in highly elliptical orbit with apogee of 2 R_E a perigee of 9 R_E and an orbital period of about 17 hours. The Proton Electron Telescope (PET) on board SAMPEX measures electrons in the energy range of 0.4-30 MeV (Cook et al., 1993). The High Sensitivity Telescope (HIST) on board Polar measures electrons of energies up to 10 MeV (Blake et al., 1995). This study mostly uses energetic electrons from the 2-6 MeV channel from PET, the >2 MeV channel from HIST.

3. Observational features of relativistic electron events

An overview of the electron observations is displayed in Fig. 1 which shows the logarithm of 30-day running-average of electron fluxes. The top panel shows 2.- to 6.- MeV electrons measured by the PET detector onboard SAMPEX and the bottom panel shows the >2 MeV electrons measured by the HIST detector onboard Polar. Fluxes are shown as a function of the L value and year. The electron fluxes are color-coded with the highest intensities shown in red. The data cover a period of over 11 years from 1992 to the end of 2004. A model calculation of the location of the plasma pause times a factor of 1.3 is shown superposed as a blue trace.

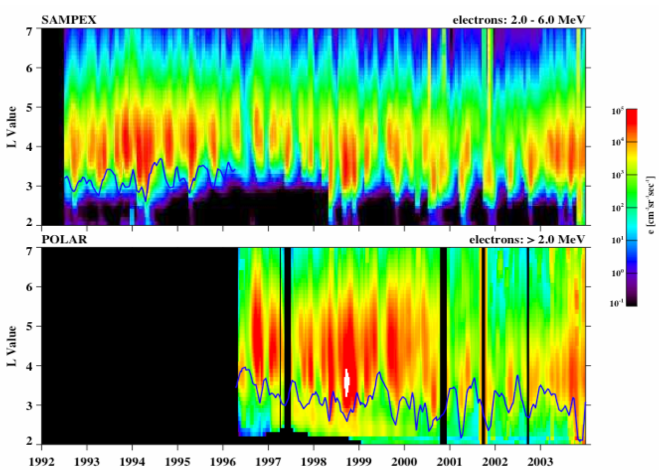

Fig. 1. Relativistic electron flux as function of L shell, for the years 1992 to the end of 2003. Daily averaged fluxes of 2.- to 6.- MeV (top panel) and >2.0 MeV electrons (bottom panel) are smoothed with a 30-day running box-car average method and are color-coded in intensity as shown by the color bar to the right. The superposed blue trace is a model calculated location of the plasmapause multiplied by a factor of 1.3 (1.3 XL_{pp}).

The dynamic nature of the outer zone electrons is evident from the data, which show many electron flux intensification events in the outer zone. An examination of the flux intensification events, using data with a higher time resolution of a day (data not shown), reveals that the energization of electrons, occur rather rapidly, within about a day. However, the fluxes reach their peak value usually only after several days. The energized electrons appear over most of the outer zone (3.5 < L < 6.5) nearly simultaneously. These observations suggest that, the underlying energization processes may be of a global nature and operate over a large spatial extent in the magnetosphere. Moreover, the location of flux maximum appears to be strongly correlated with the location of the plasmapause. For energization models invoking in-situ wave-particle interactions, such a correlation would be natural since the plasma density variation at the plasmapause location would favor wave growth.

A second noteworthy feature of electron energization is its intimate connection with pitch angle scattering. Comparison of the low-altitude (SAMPEX) with the high-altitude flux measurements (Polar) shown Fig. 1, clearly indicates that the flux enhancement events are observed by both spacecrafts. Using electron flux measurements with a higher time resolution, earlier studies have reported that relativistic electron enhancement events exhibit coherent behavior (Kanekal et al., 2005). The temporal behavior of both high- and low-altitude fluxes is nearly identical with regard to rise- and decay- times, during all the observed electron enhancements. This coherent behavior exists at all times, except when the fluxes are decaying away for somewhat long periods of time without any intervening flux enhancements.

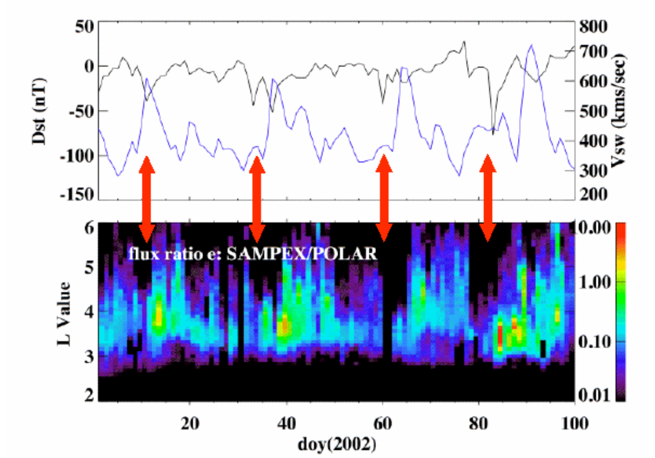

Fig. 2. Ratio of low- to high-altitude electron fluxes as a function of L shell for first 100 days of year 2002. The top panel shows solar wind velocity (blue) and the D_{st} index (black). Red solid arrows indicate electron energization events. The flux ratio is color-coded as shown in color bar to the right.

Fig. 2 shows the ratio of low-altitude (SAMPEX) to the high-altitude (Polar) electron fluxes in the bottom panel and the Dst index and the solar wind velocity in the top panel. The data clearly show that the low-altitude to high-altitude flux ratio increases during electron enhancement events driven by increased solar wind velocity. This implies that a fraction of the high-altitude electron flux is being continually pitch angle scattered during acceleration events and is observed at low altitudes. Note also that the isotropization is highest at the position of the flux maximum, L_{max} and tapers off in L, suggesting that isotropization is strongest at the location of the flux maximum.

Fig. 3 shows electron spectra measured during the main and the recovery phases respectively, for several geomagnetic storms. For each storm, measured spectra are shown for an arbitrarily chosen day during the main (blue) and recovery (red) phases. These spectra are obtained using pulse-height analyzed data from the PET detector onboard SAMPEX. The data correspond to six geomagnetic storms of varying intensity with the minimum value of the D_{st} index ranging from –75 nT to –173 nT. In each case, it is clear that the electron spectra harden during the recovery phase indicating electron energization; however there appears to be no correlation between the strength of the geomagnetic storm and the extent to which electron spectra harden.

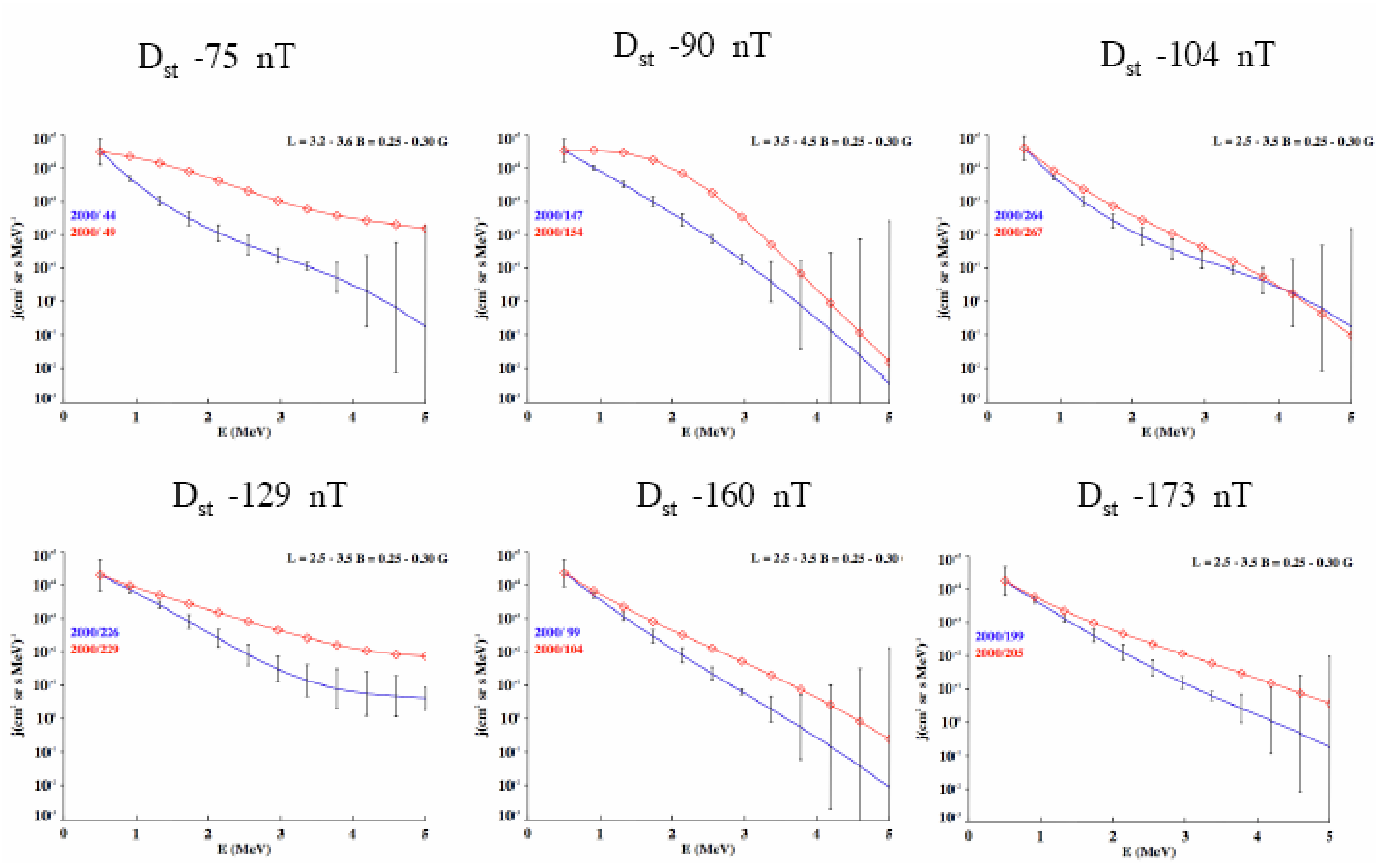

Fig. 3. Electron spectra measured during six geomagnetic storms of year 2000. Each panel shows two spectra measured on arbitrary days during the main phase (blue) and the recovery phase (red) of each storm respectively. The minimum value of the D_{st} index for each storm is also indicated.

4. Solar cycle dependence of relativistic electron events

It is well known that, usually, high-speed solar wind streams drive relativistic electron enhancement events during the declining phase of the solar cycle (Baker et al., 1994), and by coronal mass ejections during the ascending phase of the solar cycle (Kanekal et al., 1999).

Fig. 4 shows the normalized annual total relativistic electron flux for the entire outer zone (here defined as $2.5 < L < 6.5$) for nearly a complete solar cycle. The figure shows that during the declining phase of the solar cycle electron fluxes are much more intense than during the ascending phase. This is due to the fact that high speed solar wind streams are well established and recur with a 27-(13-) day periodicity during the declining phase, where as coronal mass ejection events are much more sporadic.

In order to examine the driver dependence of electron energization, we have performed a superposed epoch analysis of electron energization events. There are about 20 events of each type corresponding to the declining and ascending parts of the solar cycle, respectively. Additional selection criteria were applied to each event class to ensure that they were indeed driven by high-speed stream (HSS) or coronal mass ejection (CME) events. Criteria included requirements such as presence of counter-streaming electrons for CME events and co-rotating interaction regions (CIR) for HSS events. In addition electron events were required to be well separated from each other. The peak solar wind velocity was required to be > 500 km/sec and > 450 km/sec for HSS events and CME events respectively. The HSS driven events were observed during the years 1994 and 1995 and the CME driven events were measured during the years 1997 and 1998.

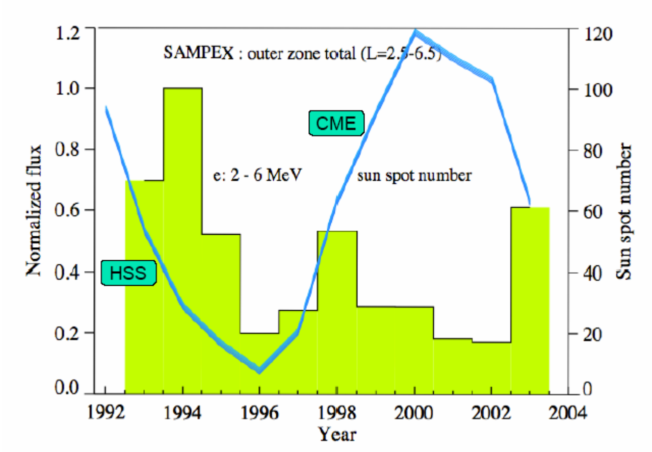

Fig. 4. Normalized annual electron fluxes for the years 1992 to 2003. Annual sunspot numbers are indicated as a thick blue line. The times of high-speed streams and coronal mass ejection events are also indicated.

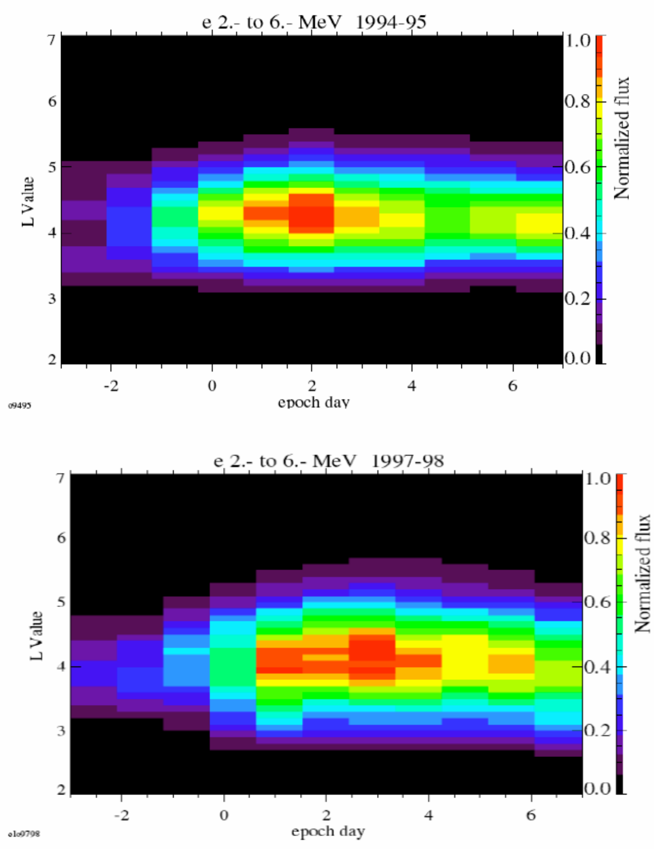

Fig. 5. Superposed epoch analysis of HSS driven events (top) and CME driven events (bottom) for 2.- to 6.- MeV electrons. The zero epoch is chosen to be the day with the highest value of the solar wind velocity. Fluxes are normalized according to the color bar at the right.

Fig. 5 shows the results of the superposed epoch study for 2. - to 6.- MeV electrons. The top panel shows the results for the HSS driven events and the bottom panel shows the results for CME driven events. The zero epoch is set to the day of the highest solar wind velocity. The electron fluxes presented are daily averages measured by the PET detector onboard SAMPEX. The Figure shows that both types of events indicate that the electron fluxes start to increase about two days prior to the epoch day. However the HSS events appear to decay faster that the CME driven events despite the fact that higher velocities of solar wind persist for longer periods during HSS events (Fig. 6).

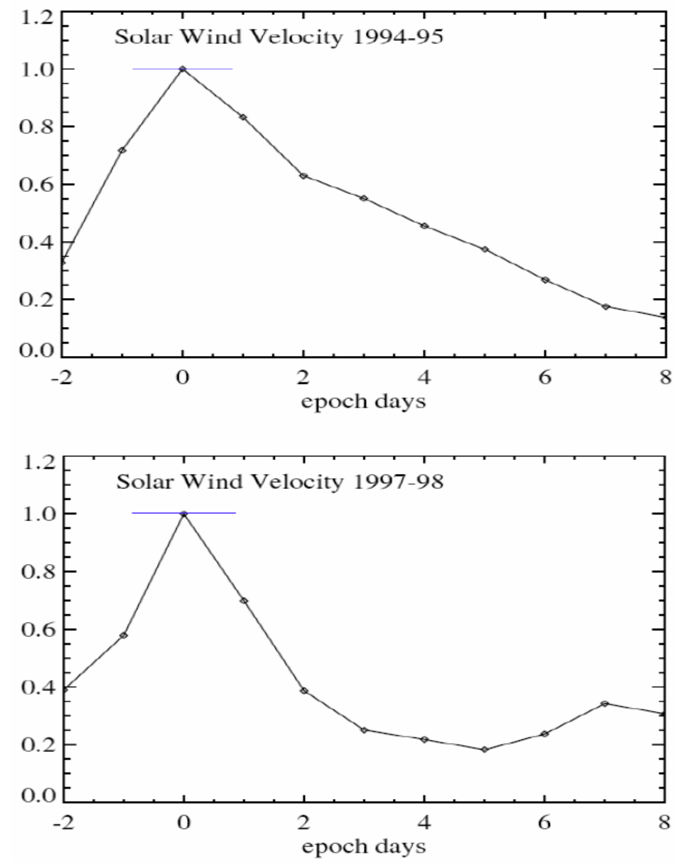

Fig. 6. Superposed epoch analysis of solar wind velocity for HSS events (top) and CME events (bottom).

Fig. 6 shows the superposed epoch plots of the solar wind driver for electron event periods corresponding to the HSS and CME time periods respectively. Note that the solar wind velocity falls off much more rapidly for the latter class of events. The mean values of solar wind velocity were 685 ± 81 km/sec and 556 ± 83 km/sec for the HSS and CME events respectively. The minimum values of the D_{st} index were -43 ± 18 nT and -69 ± 34 nT for HSS and CME events respectively.

Fig. 7 shows the results if the superposed epoch study for low energy electrons (> 25 keV) which may provide the seed population which is energized to relativistic energies. Note that these measurements are taken by the micro-channell plates of the LICA detector and are sensitive to all particles including ions. Therefore some care must be exercised in interpreting these data. However, in the outer zone region during electron enhancement events, it is quite likely that the observed flux is predominantly electrons.

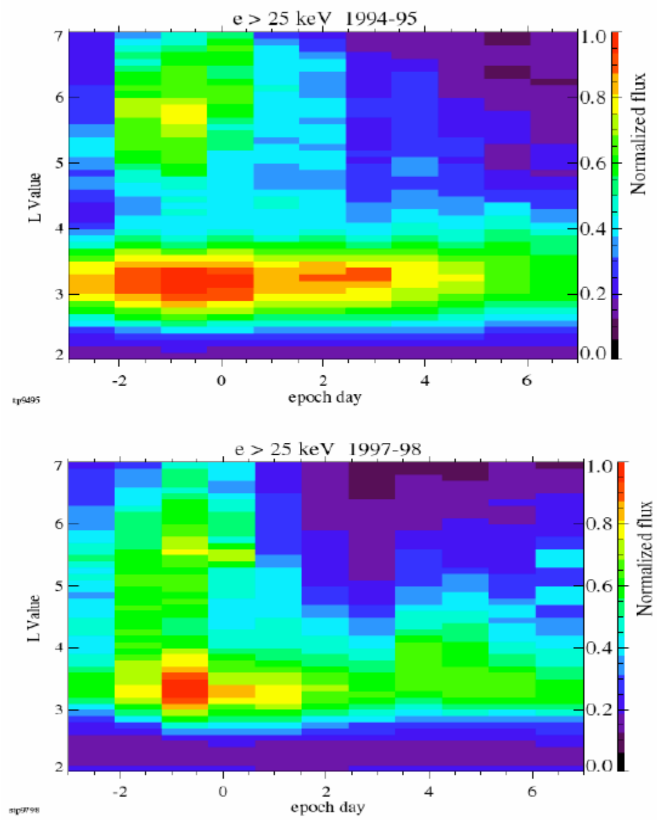

Fig. 7. Superposed epoch analysis of HSS driven events (top) and CME driven events (bottom) for low energy (>25 keV) electrons. The zero epoch is chosen to be the day with the highest value of the solar wind velocity. Fluxes are normalized according to the color bar at the right.

It is evident from the Figure that during HSS driven events the low energy electrons persist for longer duration at both lower L shells (about L=3) and at higher L shells (4< L <7). Thus both the driver conditions and the seed population seem to favor the expectation that high speed driven events ought to have higher and more prolonged levels of relativistic electron fluxes, in contrast to the observations (fig. 5).

5. Summary and conclusions

We have presented observations of relativistic electron energization events spanning over almost an entire solar cycle. We have shown that these events are global and coherent in nature occurring over a large region of the outer zone of the Earth's magnetosphere. The energization of electrons appears to be intimately associated with rapid flux isotropization, suggesting that pitch angle scattering occurs concomitantly with energization, or that, the energization process itself operates on electrons of almost all pitch angles.

We have measured the electron spectral evolution during these events and have found that the spectra harden during the recovery phase of geomagnetic storms when electrons are energized. The extent of spectral hardening appears to be independent of the strength of the geomagnetic storms. These observations impose important constraints on the proposed physical models of electron energization in the Earth's magnetosphere.

We have investigated the driver dependence of electron energization by investigating relativistic electron ehancements occurring during different times of a solar cycle. A superposed epoch analysis compared two sets of events occurring during the declining and ascending parts of the solar cycle respectively. These events are usually driven by high speed solar wind streams in the former case and by coronal mass ejection events in the latter. The results suggest that the coronal mass ejections result in energized electrons which persist for a somewhat longer duration as compared to high speed stream driven events. This seems puzzling since the high-speed solar wind driven events appear not only to have higher fluxes of a longer-lasting seed population, but also a longer duration of higher solar wind velocity.

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