Low-altitude Measurements of 2-6 MeV Electron Trapping Lifetimes at $1.5 \leq L \leq 2.5$

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Abstract

During the Halloween Storm period (October-November 2003), a new Van Allen belt electron population was powerfully accelerated. The inner belt of electrons formed in this process decayed over a period of days to years. We have examined quantitatively the decay rates for electrons seen in the region of $1.5 \leq L \leq 2.5$ using SAMPEX satellite observations. At L=1.5 the e-folding lifetime for 2-6 MeV electrons was τ~180 days. On the other hand, for the half-dozen distinct acceleration (or enhancement) events seen during late-2003 through 2005 at L~2.0, the lifetimes ranged from τ~8 days to τ~35 days. We compare these loss rates to those expected from prior studies. We find that lifetimes at L=2.0 are much shorter than the average 100-200 days that present theoretical estimates would suggest for the overall L=2 electron population. Additional wave-particle interaction aspects must be included in theoretical treatments and we describe such possibilities here.

Introduction

Radiation belt electron loss processes are relatively poorly understood. It is clear that adiabatic changes resulting from the gradual buildup of the ring current (Kim and Chan, 1997), as well as magnetopause shadowing of closed electron drift paths (Wilken et al., 1986; Shprits et al., 2006a), are insufficient to account for the observed losses throughout most of the trapping region. Currently, the most promising mechanism for MeV electron loss is VLF wave scattering

(Lorentzen et al., 2001) into the loss cone. Although field line stretching probably plays a role in the local time dependence of loss (Onsager et al., 2002; Green et al., 2004) at higher L-values, recent evidence suggests that wave scattering may be the most important overall loss process (Millan and Thorne, 2007).

It is significant that the L-shell of the maximum outer radiation belt flux correlates well with the statistical location of the plasmapause as a function of Dst (e.g., Li et al., 2006). This suggests that the cold plasma density in the plasmasphere plays an important role in controlling the L-dependent inward penetration of the outer radiation belts. While progress has been made in understanding the action of some loss processes and their consequences for controlling outer radiation belt morphology, in-situ measurements from throughout the inner magnetosphere are critical to the development of an understanding of how radiation belt particles are lost (Meredith et al., 2006). This paper utilizes such an approach.

Interior to the plasmapause, a variety of waves contribute to electron decay rates (Abel and Thorne, 1998). These include whistler-mode waves from plasmaspheric hiss, from lightning, and from ground-based transmitters that leak out into the magnetosphere. Just outside the plasmapause, chorus is thought to produce electron microburst precipitation (Lorentzen et al., 2001) and other electron scattering (Shprits et al., 2007). The competition between acceleration and loss over an extended region near the plasmapause must be resolved in order to understand electron dynamics in the heart of the radiation belts. The plasmapause often resides in the region near 5 R_E. However, during disturbed times it typically moves to lower L. The plasmapause moves within 3.5 R_E approximately 5-40 times per year, depending on the specific solar cycle, with more than 20 occurrences in most years (based on model calculations). During the 2003 Halloween storm the plasmapause was displaced inside 2 R_E and remained at this compressed location for several days (Baker et al., 2004).

As will be described in this paper, the 2003 Halloween Storm was a remarkable “active” experiment performed by nature. It produced a “new” radiation belt inside the magnetosphere (Baker et al., 2004), caused by wave acceleration by whistler mode chorus (Horne et al., 2005; Shprits et al., 2006b) which could then be observed to decay over the subsequent days and weeks. The powerful storm that occurred just three weeks after the Halloween Storm (on 20 November 2003) produced a distinctive set of electron acceleration and loss processes that have been studied previously in some detail (Bortnik et al., 2006).

In the present paper we examine several specific acceleration, or enhancement, events that were observed after the 2003 Halloween Storm period during the years 2003-2005. We focus on the range $1.5 \leq L \leq 2.5$ in the inner magnetosphere and we determine empirical electron lifetimes by observing flux decay timescales. These lifetimes are compared and contrasted with prior results and theoretical expectations.

1. Data Selection

The primary data set used in this paper is the E=2-6 MeV electron channel of the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) Proton/Electron Telescope (PET) experiment (see Baker et al., 1993). SAMPEX operates in a roughly circular 600-km altitude, 82°-inclination orbit. For the present study, we use daily averages of electron data sorted according to magnetic L-shells. The L-values correspond roughly to the geocentric radial distance in Earth radii (1 R_E = 6372 km) that a magnetic field line crosses the equatorial plane. L-values are determined using the IGRF magnetic field model. It is recognized that for higher L-values (e.g., L ≥ 5.0), there can be significant distortion away from a dipole configuration. Here we focus on relatively low L-values where the IGRF approximation is quite good.

In order to place SAMPEX particle measurements into context, we have also used upstream solar wind data from the Advanced Composition Explorer (ACE) spacecraft and ground-based geomagnetic information (such as Kp and Dst). These data show that the events analyzed here are associated with significant geomagnetic storms. However, the principal point is specifically to examine inner zone and radiation belt slot region enhancements in their own right, irrespective of ring current, solar wind, or other geomagnetic variations.

It is recognized that low-altitude measurements of electron fluxes may be subject to some ambiguity in timing as compared to measurements near the magnetic equator. However, the "remarkable coherence" seen between near-equatorial platforms and the low-altitude SAMPEX measurements (e.g., Kanekal et al., 2001) suggests that this is not generally a severe problem. We therefore start with the assumption that the lifetimes derived from SAMPEX data are indicative of the inner zone and slot-region relativistic electron populations as a whole.

2. Observations

Figure 1 summarizes solar wind speed and relativistic electron (2-6 MeV) intensities for the years 2003 through 2005, inclusive. Fig. 1a shows daily averages of the solar wind speed measured by ACE sensors. The dashed horizontal line at V_{sw}=500 km/s emphasizes the widely-recognized fact that solar wind speeds above this level almost always "drive" relativistic electron production throughout the outer radiation zone (e.g., Baker et al., 1998). V_{sw} was, on average, above 500 km/s for most of 2003 and for the early part of 2004, due to the presence of recurrent high-speed solar wind streams. For the latter part of 2004, the solar wind speed was quite low and throughout 2005, the value of V_{sw} was mixed.

Figure 1b shows a color-coded representation of the 2-6 MeV electron flux measured by the SAMPEX PET sensors. The vertical scale shows L-values and the horizontal scale is time (in Day of Year [DOY], measured from the beginning of 2003). The logarithm of the directional flux of 2-6 MeV electrons is shown by color as indicated by the color bar to the right of the figure.

As would be expected based on the high solar wind speeds in 2003, the overall radiation belt population was persistently elevated from DOY 1 through DOY~500, or so. Through the latter part of 2004 and for much of 2005 (DOY~500 to DOY~850) the electron intensities were often quite low for $3 \leq L \leq 8$. Notable exceptions were seen at DOY~580 (July 2004) and DOY~680 (November 2004) when powerful storms occurred, V_{sw} increased dramatically, and major relativistic electron events were initiated.

One of the most striking features seen in Fig. 1b was the slot-filling event and the creation of a “new” population of relativistic electrons in the inner zone ($1.0 \leq L \leq 2.0$) in association with the 2003 Halloween Storm period (Baker et al., 2004). This belt of electrons appeared rather suddenly on DOY~305 and persisted through the end of 2005 (i.e., DOY~1100). The inner zone belt of electrons was seen to be enhanced by several of the storms (DOY=580, DOY=680, etc. that were noted in the previous paragraph.

In order to better time and quantify the electron flux increases at various L-values, we have taken “cuts” in L from L=1.5 to L=2.2. These flux values for each L are shown by the different colored lines in Fig. 2. This representation shows that the Halloween Storms enhanced the electron flux at L=1.5 by a factor of ~50 or more. This inner zone flux then remained very elevated to the end of 2005 (decaying gradually over time). On the other hand, the flux values at L=2.0 ± 0.2 increased by as much as five orders-of-magnitude and then decayed quite rapidly in each case back to pre-Halloween values. At least 5 electron enhancement events can be easily identified following the large October-November 2003 event.

3. Analysis and Interpretation

The abrupt rises and more gradual decays of electron fluxes seen in several events in Fig. 2 suggest that we can make empirical determinations of electron lifetimes assuming the fluxes to decay exponentially. We have performed such analyses for the six distinct enhancement-decay episodes seen from November 2003 through the end of 2005 by performing least-squares fits for each decay interval to obtain life times.

Figure 3 shows detailed examples for three of the intervals. Figure 3a is for the Halloween Storm (and, in addition, the 20 November 2003 storm, since their effects were commingled). The red curve shows the flux profile for L=1.5, while the blue curve shows the L=2.0 profile. The black dashed lines show exponential decay (least-squares) fits to the data trends. At L=1.5, we find that $J=Ke^{-t/\tau}$ with τ~180 days. (This same decay rate applies for essentially all of the L=1.5 data through the end of 2005). For the L=2.0 data we have specifically fit the data points for 305 ≤ DOY ≤ 410. This fit gives τ=18.6 days. Note that from DOY~410 to DOY~560, the decay rate was slower with a decay lifetime in excess of 30 days. Thus, the apparent electron lifetimes depend on the length of interval chosen for analysis. We have typically examined periods of ~100 day duration.

Fig. 3b shows the next major storm enhancement event that commenced on DOY~570 (~23 July 2004). This corresponded to a complex, multi-step geomagnetic storm that reached Dst~ -

200 nT. We have fit the decay of this event at L=2.0 for the period $575 \leq \mathrm{DOY} \leq 675$ and find τ=13.4 days. As a final illustrative example, a much weaker event that commenced about DOY=970 (late August 2005) is shown in Fig. 3c. For this event we find a much more gradual decay. For the interval $970 \leq \mathrm{DOY} \leq 1090$, we find τ =26.5 days.

Table 1 shows the six intervals analyzed and the e-folding times for each interval at L=2.0. As noted previously, for L=1.5 a steady value of τ~180d describes the decay throughout the entire period of time, aside from small bump-ups of flux associated with the major storms. On average for L=2.0, we find a decay rate for all events to be $< \tau >$=20.2d ± 8.7. This is short compared to previous theoretical estimates (e.g., Abel and Thorne, 1998).

4. Summary and Discussion

To summarize our key findings we note that:

1. The Halloween 2003 storms produced a ‘new’ inner zone relativistic (2-6 MeV) electron belt that persisted for years at L~1.5.
2. The gradual decay of the new belt was highly L-dependent:
    - At L=1.5, the decay was seen to be J=K exp(-t/τ) with τ~180d.
    - At L=2.0, the decay exhibited τ~18d.
3. Several subsequent storms in 2004-2005 produced clear flux enhancements in the inner zone (6 events were readily identified).
4. The decay of the L=1.5 population continued throughout; the L=2.0 populations decayed with $7.9 \leq \tau \leq 34.8$d.

5. Theoretical estimates suggest that τ-values at L=2.0 and E=2 MeV should be τ~100d due to plasmaspheric hiss.

The specifications of electron decay lifetimes are complicated due to the fact that there are several competing wave-particle interaction mechanisms that can be operative. Inside the plasmasphere, losses are mostly due to scattering caused by plasmaspheric hiss waves, by magnetospherically-reflecting (MR) whistler waves, and by coulomb collisions (Abel and Thorne, 1998). Such loss had previously been estimated to lead to characteristic lifetimes of ~100 days at E~1.5 MeV energies. There were expected to be strong L- and energy-dependences. The Abel and Thorne (1998) calculations included the effects of losses due to VLF transmitters as well as hiss, MR whistlers, and Coulomb collisions The assumptions made concerning VLF transmitters could be a source of discrepancy between observations and models.

Outside the plasmasphere, chorus emissions would produce very fast pitch angle scattering leading to lifetimes of order one day or less (Horne et al., 2005; Albert, 2005). Electromagnetic ion cyclotron (EMIC) waves can possibly provide even faster losses of electrons with E>500 keV (Summers and Thorne, 2003). Some estimates for EMIC losses – although quite localized spatially – would give lifetimes of just hours. However, these waves need frequencies with high values of f_{pe}/f_{ce} to resonate with ~2 MeV electrons. The ratio of f_{pe}/f_{ce} tends to become smaller as one goes to lower L inside the plasmapause (e.g., from 4 to 2). Thus, the EMIC waves will tend to resonate with higher energy electrons, which probably become too high for the energies we observe here. Since these waves are generated by anisotropic proton distributions associated with the ring current, and the ring current does not usually penetrate to L=2, it is unclear how they can be generated near L=2.

For the results reported here, we have focused on the spatial region inside L~3.0 and have quantitatively assessed loss lifetimes for L~1.5-2.0. Under most circumstances (other than, say, the period right after the Halloween Storm), the L-values examined here would be well within the plasmasphere. Thus, we would expect the hiss lifetimes to be the applicable ones.

As noted in Section 2 above, we believe that our determination of L-value for SAMPEX data sorting is relatively accurate. Thus, this should provide a solid basis for theoretical comparison. We know that the chosen energy channel responds to a broad range of electrons and there could be some ambiguity in this matter. However, from our analyses (not shown here) we find the energy spectra around L=2.0 to be strongly falling ($J=KE^{-\gamma}$, with $\gamma\sim 2.5$). Thus, the data we have shown would be dominated by electrons with E~2.0 MeV.

In very recent work (Meredith et al., 2007), estimates have been made of electron lifetimes as a function of energy, L-value and geomagnetic activity levels. The analyses examine lifetimes due to hiss, ducted whistlers, and magnetospherically reflecting whistlers. It is found that at L=2.0 and E~2 MeV, the lifetime for electrons would be at least τ~100-200 days. The L-dependence, however, is very strong such that τ drops precipitously to 1-10 days at L=2.5. From the Meredith et al. (2007) modeling, the lifetime also drops rapidly with increasing energy. Thus, the experimental results we have presented here (with τ ~20d) have to be considered in the context of great sensitivity to L position and the broad range (2-6 MeV) of our analyzed energy range. We note that the lifetimes of about 100 days in the Meredith et al. (2007) paper assume AE* > 500nT during the decay. They are longer for AE* < 100 nT, particularly for 5 MeV electrons.

One possible explanation for the very short apparent electron lifetimes reported here lies in the fact that plasmaspheric hiss is mainly responsible for the loss of 2-6 MeV electrons at equatorial pitch angles <65° at L=2. Detailed model results show that it takes much longer to scatter electrons at larger equatorial pitch angles into the loss come. At L=2 and at 600 km, a 90° pitch angle particle at SAMPEX corresponds to approximately an 18° particle at the equator in a dipole field. In a careful analysis motivated by the present observations, we find that the pitch angle diffusion rates for 2 MeV electrons at L=2 due to plasmaspheric hiss show a deep minimum for pitch angles greater than 65°. This means that electrons at larger equatorial pitch angles take much longer to diffuse into the loss cone. This analysis also provides the decay rate of the electron distribution function at the same energy. The initial condition assumed for the modeling is a flat pitch angle distribution. The distribution function decays more quickly at small pitch angles than at 90°, as expected. The timescales for loss at 18° equatorial pitch angle, corresponding to that which would be observed by SAMPEX, is 23 days, whereas the timescale for the whole distribution to decay is 284 days (Meredith et al., 2007), assuming quiet magnetic activity (as represented by AE* <100 nT). Thus there is good agreement with the observations presented here for the particles at pitch angles measured by SAMPEX. At higher L shells (L=2.5 and larger) there is no deep minimum in the diffusion rates in the model. This would explain why we tend to get such a high degree of global coherence at higher L values (Kanekal et al., 2001).

In a paper in preparation, we pursue the issues raised here and we make more detailed comparisons between observations and theoretical models. This continuing work should help further clarify electron lifetime expectations in this key region of the inner magnetosphere.

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Table 1. Empirical Electron Trapping Lifetimes

$2 \le E \le 6$ MeV; L~2.0	
DOY (2003)	e-folding Lifetime (d)
305-410	18.6 ± 1.8
575-675	13.4 ± 1.1
680-720	7.9 ± 0.8
760-860	19.9 ±2.1
860-970	34.8 ±3.1
970-1090	26.5 ±2.3

$< \tau > = 20.2$d (± 8.7)

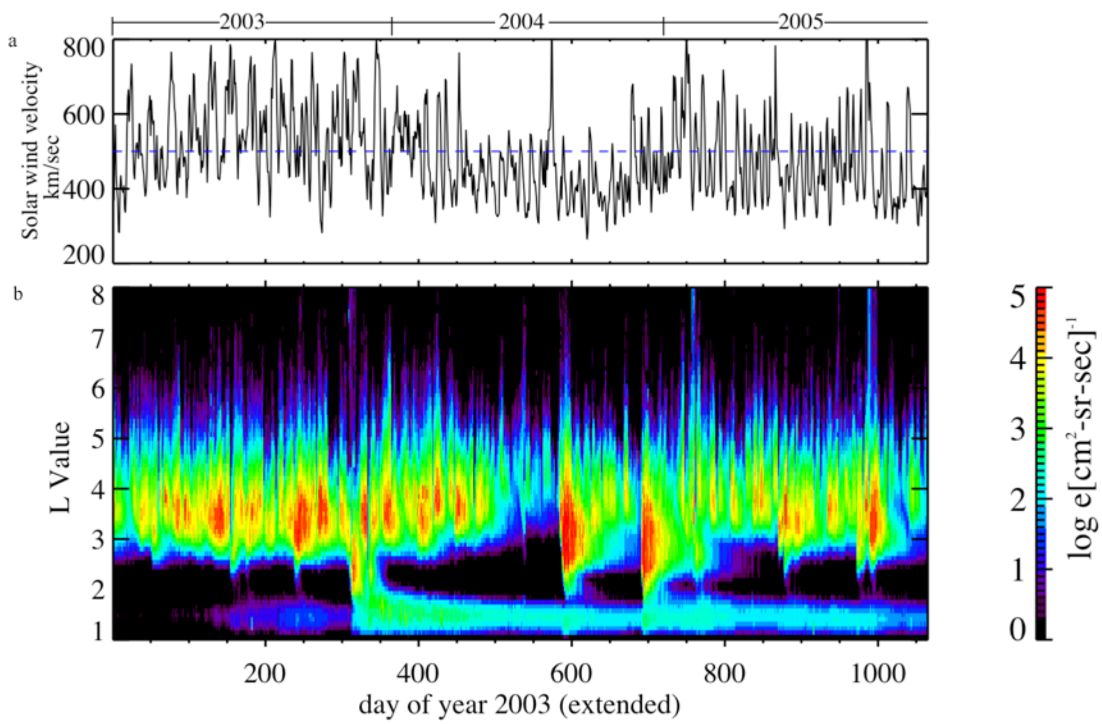

Figure 1

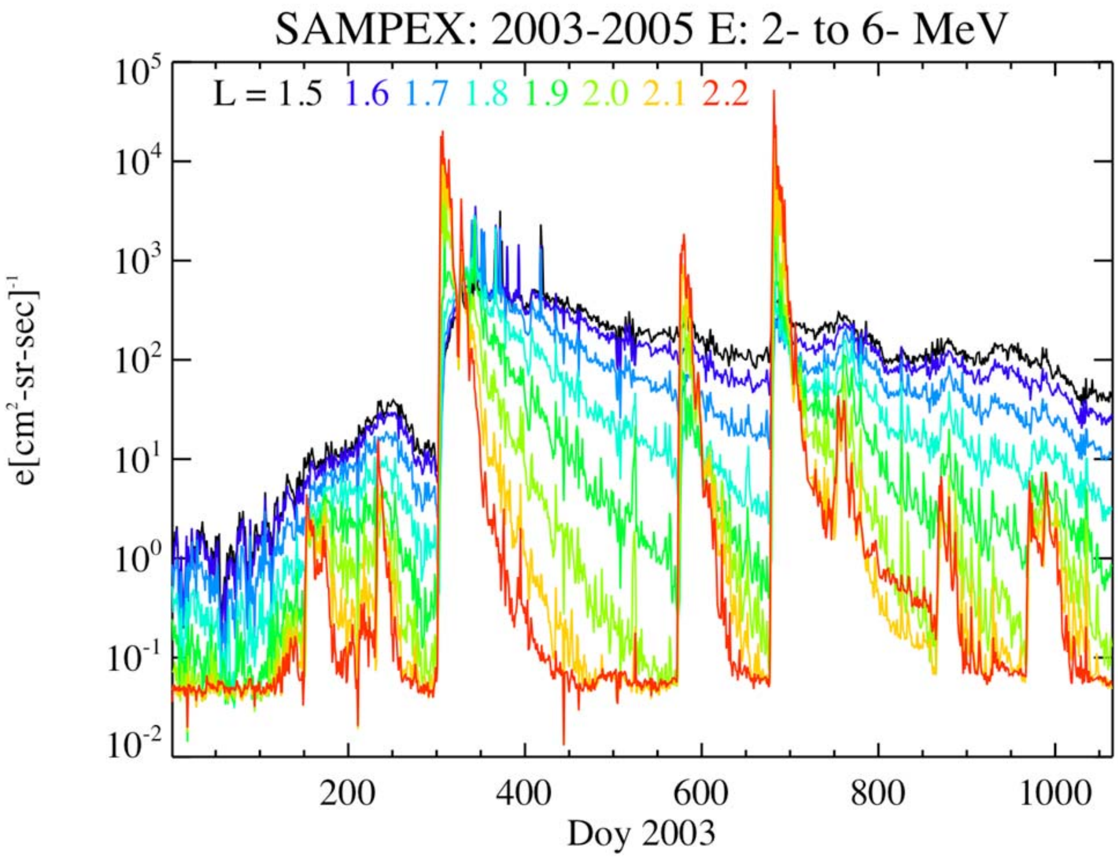
SAMPEX: 2003-2005 E: 2- to 6- MeV
L = 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2
e[cm²-sr-sec]⁻¹
Doy 2003
200
400
600
800
1000

Figure 2

a

b

c

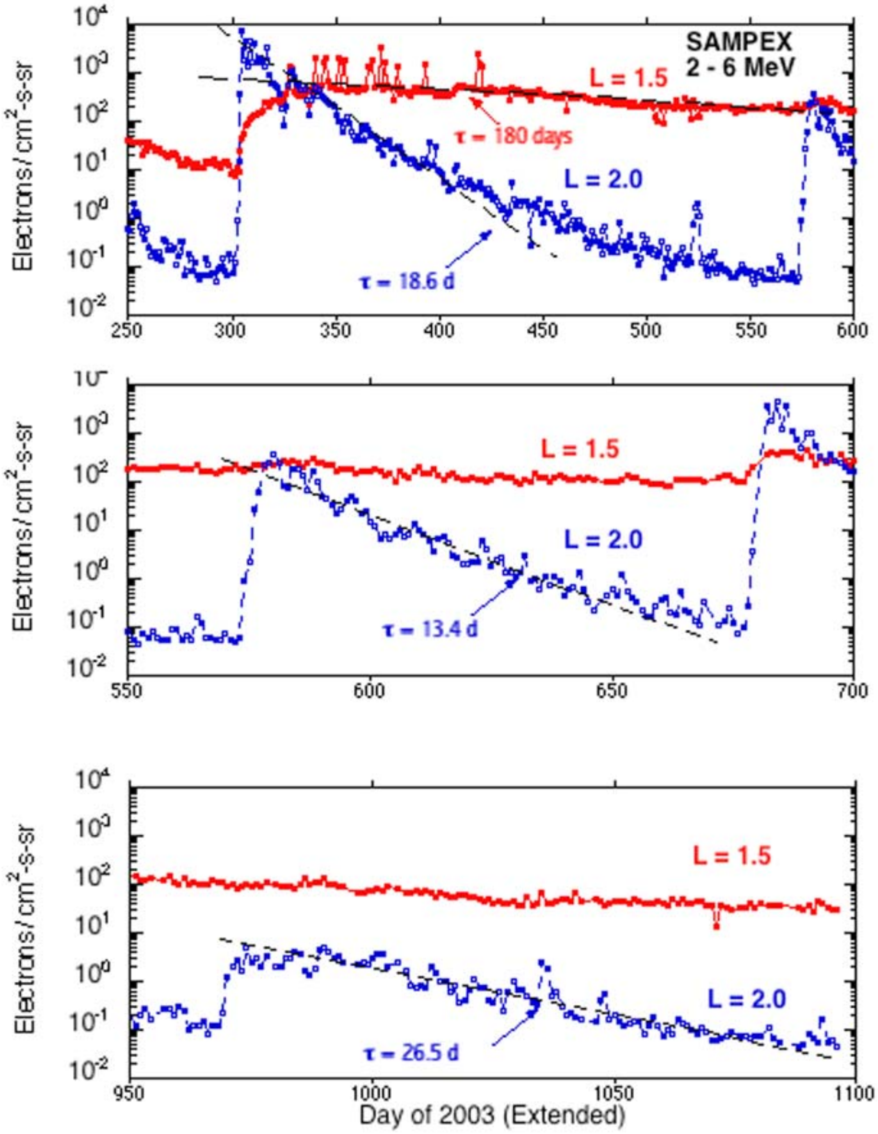
SAMPEX
2 - 6 MeV
L = 1.5
τ = 180 days
L = 2.0
τ = 18.6 d
τ = 13.4 d
τ = 26.5 d
Electrons / cm²-s-sr
Day of 2003 (Extended)

Figure 3

Figure Captions

Fig. 1. Daily-averaged data for the years 2003-2005 inclusive. (a) Solar wind speeds measured by instruments onboard the ACE spacecraft upstream of the Earth's magnetosphere. (b) Relativistic (2-6 MeV) electron fluxes for the range $1 \leq L \leq 8$ in a logarithmic color-coded format as shown by the color bar to the right. Data were obtained from instruments onboard the SAMPEX spacecraft.

Fig. 2. Cuts taken for several different fixed L-values (delineated near the top of the figure) for the period 2003-2005 inclusive. The vertical axis is directional particle intensity and the horizontal axis is time reckoned in days (Day of Year) from the beginning of 2003. Several flux enhancement events are evident.

Fig. 3. Details of several electron enhancement events (as seen in Fig. 2). The red curves correspond to fluxes measured at L=1.5, while the blue curves show measurements at L=2.0. The black dashed lines show least-squares empirical fits. (a) Data for DOY 250-600 of 2003 (extended). (b) Data for DOY 550 – 700 inclusive. (c) Data for DOY 950 – 1096 inclusive.