Characterization of relativistic electron flux rise times during the recovery phase of geomagnetic storms as measured by the NS41 GPS satellite

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1. Introduction

Radiation belt studies in the last 10 years have been focusing on source, loss and transport processes acting on the trapped relativistic electron population. Identifying these processes and the region and time that they occur, are the subject of ongoing studies (see reviews by Li and Temerin, 2001; Friedel et al., 2002; Horne, 2002).

Relativistic electron fluxes usually decrease during the main phase of a storm and then either increase or stay low during the recovery phase (Reeves et al., 2003). Radial transport across magnetic field lines conserving the particle's first and second adiabatic invariants has been identified very early as a key mechanism for the trapped electron dynamics (Schulz and Lanzerotti, 1974).
diffusion could be sufficient to explain the electron radiation belt dynamics if we consider adiabatic effects to be responsible for the main phase flux decrease during a storm (Kim and Chan, 1997) and higher post-storm fluxes to be due to enhanced storm-time radial diffusion transporting particles to the inner magnetosphere from an external source and energizing them at the same time.

However, recent observational studies have shown that radial transport alone cannot explain all observed features (Brautigam and Albert, 2000; Horne et al., 2003a,b; Miyoshi et al., 2003; Green and Kivelson, 2004; Shprits and Thorne, 2004; Chen et al., 2006; Fox et al., 2006; Iles et al., 2006). There are various loss, source and transport mechanisms acting on the trapped MeV electron population, which are enhanced during active magnetospheric conditions.

Electron–wave interactions are believed to be one of the predominant physical mechanisms acting both as a loss and a source for MeV radiation belt electrons (Thorne et al., 2005; Horne et al., 2006). Different waves are present in different regions of the inner magnetosphere and they act on different timescales (e.g., Horne et al., 2005a; Shprits et al., 2006a). Plasmaspheric hiss is believed to be responsible for relativistic electron losses due to pitch angle scattering on timescales of 5–10 days inside the plasmasphere, where the plasma density is high (Lyons et al., 1972; Abel and Thorne, 1998; Meredith et al., 2006). EMIC waves are also present in this high-density environment, especially in plasmaspheric plumes formed during the storm’s main phase (e.g., Erlandson and Ukhorskiy, 2001). They are believed to cause important MeV electron losses, by pitch angle scattering near the loss cone, in high-density regions, during the main phase on timescales of hours (Thorne and Kennel, 1971; Albert, 2003; Meredith et al., 2003c; Summers and Thorne, 2003). Whistler-mode chorus waves interact with electrons principally outside the plasmapause in a low-density plasma environment (Meredith et al., 2003a). These waves can act as an important local source (by energy diffusion) and loss (by pitch angle scattering) mechanism for relativistic electrons on timescales of the order of several hours to a day (Horne and Thorne, 1998; Summers et al., 1998, 2002, 2007; Horne et al., 2003a, 2005a,b; Glauert and Horne, 2005).

In addition to these processes, we should consider losses to the Earth’s magnetopause, which have been found to contribute to rapid outer radiation belt depletions on the timescale of hours (Desorgher et al., 2000; Green et al., 2004; Shprits et al., 2006b). These losses can be very important in the case of intense storms where the Earth’s magnetosphere is greatly compressed and drift paths are very distorted (Ukhorskiy et al., 2006).

Bortnik et al. (2006) investigated loss mechanisms during the November 20, 2003 radiation belt dropout event using various spacecraft data. They suggested that for electrons of energy greater than 0.5 MeV the dropout was due to losses to the magnetopause in the high L-shell region (L > 5) and to losses from EMIC wave pitch angle scattering at lower L-shells (L < 5).

In an effort to understand (and perhaps predict) the dynamics of the Earth’s radiation environment, we need to take all these physical processes into account. Theoretical predictions may be tested using in situ measurements. The motivation to study MeV electron flux rise times during the recovery phase of magnetic storms comes from the realization that different processes act on different timescales and that the occurrence of some of them is limited to a certain region inside the radiation belts.

Timescales for relativistic electron enhancements during the recovery phase of storms have been reported previously. Baker et al. (1994) used SAMPEX low-altitude data to show that MeV electron fluxes rise fast, on a timescale of 1–2 days or less, for 2.5 ≤ L ≤ 5. They found that low L-shells would have such a prominent response remarkable and tried to explain this rapid increase by associating it to high solar wind speed streams observed during these events. However, low-altitude measurements are limited by the fact that the main population, located at the equator, cannot be sampled.

More recent studies have used CRRES near-equatorial particle and wave data to show that relativistic electron enhancements coincide with enhanced whistler-mode chorus wave activity (Meredith et al., 2002a,b, 2003b). More evidence has been provided by theoretical work estimating MeV electron flux rise times due to energization of lower-energy electrons from whistler-mode chorus waves (i.e., that matched observed flux rise times). Horne et al. (2005a) used chorus wave spatial distributions measured by CRRES and estimated—by applying wave–particle quasi-linear theory—that the timescale for an order of magnitude increase of the electron flux at 1 MeV is about 24 h at L = 4.5. Timescales of the same order have been observed for MeV electron fluxes measured by CRRES (Meredith et al., 2002a,b). These theoretical calculations set the lower limit of expected electron flux rise timescales in this region of space—since radial diffusion is slower than that found here.

Relativistic electron fluxes near geosynchronous orbit have been seen to rise on timescales of the order of 2–3 days and these rises are shown to be well correlated with high solar wind speed (O’Brien et al., 2001; Iles et al., 2002; Dmitriev et al., 2005; Kataoka and Miyoshi, 2006; Vassiliadis et al., 2005). At the geosynchronous orbit (L = 6.6) radial diffusion—enhanced by ULF wave activity (Elkington et al., 1999; Mathie and Mann, 2000)—is expected to have an important effect on radiation belt electron dynamics (O’Brien et al., 2001). But as we move inwards towards the Earth, in regions where the effect of radial diffusion becomes weaker, we should be able to differentiate better between source mechanisms.

Almost all in-situ energetic particle studies performed in the equatorial L = 4–6 region have been based on data from CRRES obtained during ~1 year. Equatorial measurements are of interest because it is the region where the whole particle distribution can be observed and studied. Results from these studies have shown that this region is of great importance to radiation belt dynamics as a whole, since it is where various source, loss and transport mechanisms are acting. The Global Positioning System (GPS) orbit is covering this region but not many studies have been published where energetic electron dynamics
has been studied (Reeves et al., 1998; Hilmer et al., 2000; McAdams et al., 2001). The orbit crosses the equator at $L \sim 4$ and higher-magnetic latitudes at higher $L$-shells. Depending on magnetospheric activity, equatorial passes of GPS can be inside or outside the high-density environment of the plasmasphere, thus sampling the effect of different processes in each case. When high-activity conditions occur, GPS satellites sample the region where chorus waves may act as a local source for relativistic electrons and EMIC waves in plasmaspheric plumes on the dusk-side may act as an important loss mechanism. Fast rising flux profiles would be expected if measurements are taken in the region and at the time when a local source is acting. Reeves et al. (1998) reported rise times as fast as 12 h for 1.6 MeV electrons at $L = 4.6$ from their study of the January 1997 magnetic cloud event.

Here we present first results from a statistical study of electron flux rise times using equatorial data from the $E > 1.22$ MeV channel of GPS satellite NS41 (Cayton et al., 1998). In Section 2, we describe the event selection criteria and present the resulting flux rise time distributions. In Section 3, a superposed epoch analysis of electron fluxes is performed for different event categories. Section 4 presents the results of a superposed epoch study of corresponding magnetospheric and solar wind parameters. Finally, we discuss the results and their limitations in Section 5 and summarize the results and conclusions of our study in Section 6.

2. Selection of events and resulting rise time distributions

We have analyzed 5.1 years (2001–August 2006) of energetic electron data from the Block IIR Burst Detection Dosimeter (BDD-IIR) instrument on board GPS NS41 satellite and have determined flux rise times for 40 events. The GPS orbit is a circular $4R_E$ orbit with a 12 h period and a 50° inclination. It crosses the equator at $L = 4.2$ and moves to higher-magnetic latitudes at higher $L$ shells. Currently, there are eight GPS satellites in space which have operating energetic particle instruments, constituting a real constellation mission in the inner magnetosphere. Energetic electron detectors measure particles for energies $E = 100$ keV to 10 MeV. Since the period of the orbit is 12 h, the best time resolution we can have with one satellite for a given $L$ shell is 6 h.

The BDD-IIR (Cayton et al., 1998) is a multipurpose silicon detector system now operating on GPS satellite NS41, and also is scheduled to fly on one other space vehicle of the GPS replenishment series (identified by the designation, Block IIR). BDD-IIR is the successor of two previous models of this instrument, the BDD-I (Drake et al., 1993; Cayton et al., 1992) and BDD-II (Feldman et al., 1985), that flew on Block I and Block II GPS satellites, respectively. Like its predecessors, BDD-IIR measures energetic-particle fluxes impinging on the GPS space vehicle, and records its data in on-board memory for downloading during routine contact with the space vehicle (once per day). Absorbers located in front of eight separate silicon sensors determine the energy thresholds for measuring the incident particle fluxes, and the magnitude of energy loss in each sensor provides an imperfect but good separation between ions and electrons over a wide range of incident energies. The deposited-energy thresholds were calibrated carefully (Cayton et al., 1998); these were used to evaluate electron response functions for the channels by detailed modeling (Tuszewski et al., 2002) of the instrument by Monte Carlo methods.

Following a path similar to the one paved for BDD-I data (Cayton and Pongratz, 2005), BDD-IIR data are processed at Los Alamos National Laboratory: First, the observed counting rates are extracted from the raw data. Second, the input or true counting rate (the observed counting rate corrected for deadtime) for each channel is modeled as a sum of two contributions: non-electron background counts plus counts that result from a spectrum of incident electrons. (When folded with the BDD-IIR instrument response functions mentioned above the model spectrum yields predictions for the counting rates in all channels as a consequence of the incident electrons.) Third, best-fit values for the parameters of the model spectrum are inferred by the method of least squares, minimizing the sum of the squared deviations between the sets of true and predicted counting rates for each data record. Fourth, either integral or differential electron fluxes at eight standard energies are evaluated from the best-fitting spectrum. Commonly observed spectral features (remarkably exponential shapes) of relativistic electrons in the outer radiation zone (Reagan et al., 1981; Baker et al., 1986) guided our selection of the relativistic Maxwellian as a functional form of the model spectrum.

For the selection of the events we looked at equatorial flux observations from the $E > 1.22$ MeV channel. We chose to study equatorial fluxes because then the full particle distribution on a field line can be sampled and we avoid mapping approximations that depend on magnetic field and pitch angle assumptions (we have no pitch angle information from the instrument on the NS41 satellite). Equatorial GPS observations can also be compared to GEO measurements, which are also taken at the equator.

To select the magnetic storm events, the following criteria were used: (a) fluxes should have reached their maximum value before another magnetic storm takes place and (b) the ratio of the maximum to the minimum (at the storm’s main phase) flux value should be at least equal to 5. The first criterion is satisfied if fluxes start decreasing or if they stay constant for a day before another storm occurs.

To avoid mixing adiabatic and non-adiabatic effects we used $L^*$ instead of $L$. The $L^*$ represents the equivalent radius of the drift shell at the magnetic equator in a simple dipole field (Roederer, 1970) in units of Earth radii. This is a very important part of our analysis, especially during the main phase and early recovery of a storm. Due to the enhanced ring current during storms, particles move outwards to conserve their third adiabatic invariant, the magnetic flux (Kim and Chan, 1997). Thus the satellite can be at $L = 4$ but measuring particles from $L = 3$ (i.e., for that period of time the $L^*$ of the satellite is equal to 3).
Once the Dst has recovered, particles move inwards again. The $L^*$ calculation was done using the Tsyganenko 2001 storm magnetic field model with dynamic inputs (Tsyganenko, 2002a, b), which has recently been shown to be the most representative model for storm times (Chen et al., 2006).

To limit our study to the equator only fluxes for $L^* = 4–4.5$ were considered. We obtained two data points per orbit by averaging fluxes in this $L^*$ range.

To calculate flux rise times we define time $T = 0$ at $\text{Dst}_{\text{min}}$. The time of $\text{Dst}_{\text{min}}$ has been selected as the epoch time because it is a clear signature of the storm and generally corresponds to times of minimum fluxes in the radiation belts. We have estimated four rise times: the time it takes to reach 90% of the maximum flux value (we are neglecting 10% of the flux variation which is due to statistical errors), the time to half the maximum flux value and the time to 10 and 100 times the minimum flux value as measured at the main phase of the storm. By estimating all four rise times mentioned above, we may get a more complete picture of the rising flux profiles in different phases of the recovery. The method used to estimate rise times is illustrated in Fig. 1 for the November 24, 2001 event. Shown in panels (a) and (b) are the Dst and Kp indices. In panel (c) $E > 1.22$ MeV electron fluxes are plotted versus time for $L^*$ values between 4 and 4.5. Time (1) is epoch time zero which corresponds to $\text{Dst}_{\text{min}}$. Times 2–5 are the rise times described above: (2) time to 10 times the minimum flux, (3) time to 100 times the minimum flux, (4) time to half the maximum flux and (5) time to 90% the maximum flux.

NS41 was launched at the end of 2000, which corresponds to the start of the declining phase of the solar cycle. From the selected events, 20 are ICME-related (Interplanetary Coronal Mass Ejections), 19 are CIR-related (Corotating Interaction Regions) and one event does not relate to any particular structure in the solar wind apart from Bz being negative. Our statistical study includes 21 intense storms ($\text{Dst} \leq -100 \text{nT}$) out of which four are super-storms ($\text{Dst} \leq -250 \text{nT}$), 14 moderate storms ($-100 < \text{Dst} \leq -50 \text{nT}$) and five weak storms ($\text{Dst} > -50 \text{nT}$). The selected 40 events, together with their geomagnetic indices, solar wind characteristics and characteristic rise times are summarized in Table 1. Characterization of an event as a ICME- or a CIR-related event was done based on visual inspection of solar wind data from ACE SWEPAM (McComas et al., 1997).

The distributions we obtain for the rise time to the maximum flux ($f_{\text{max}}$—90% of the maximum value) and to half the maximum flux ($f_{1/2\text{max}}$) are shown in Fig. 2. In this figure the number of events is plotted versus epoch time, from 1 day before $\text{Dst}_{\text{min}}$, to 7 days after $\text{Dst}_{\text{min}}$. Rise times have been binned into 12 h intervals and the estimated average rise time value for each bin corresponds to the time value of each data point plotted.

First, we note that the $f_{\text{max}}$ rise time distribution does not present any characteristic peak, and that it extends from less than a day to more than 6 days. In this wide distribution, more than half of the events (23 events) lie in the 2–4 days interval, which agrees well with observations made at geosynchronous orbit (Kataoka and Miyoshi, 2006; Vassiliadis et al., 2005).

The $f_{1/2\text{max}}$ rise time distribution peaks at less than 2 days. More than 80% of the events (33 events) reach half the maximum flux value in less than 2 days and 40% (15 events) of them reach it in less than 1 day. The difference between the two curves plotted in Fig. 2 is important considering that there is only a factor of ~2 between them (and remember that $f_{\text{max}}$ is actually 90% of the measured maximum flux value). We conclude that flux profiles in the range $4 < L^* < 4.5$ typically have an initial fast increase followed by a slower increase over few days towards the peak value.

In Fig. 3, we plot the distribution of rise times to 10 times the minimum flux value ($f_{10}$) and to 100 times the minimum flux value ($f_{100}$). Here again the number of events is plotted versus epoch time. The binning of data is the same as in Fig. 2. Note that for this figure, the $f_{10}$ rise time distribution is made from 38 events for which the ratio $f_{\text{max}}/f_{\text{min}}$ reaches values equal to or higher than 10 and the $f_{100}$ rise time distribution is made from 17 events for which the ratio reaches values equal to or higher than 100. Less than half of the events presented in Table 1 have a ratio $f_{\text{max}}/f_{\text{min}} > 100$, but this ratio can reach values of up to 5 orders of magnitude, as shown in Fig. 4 for the May 15, 2005 event.

In this figure, like in Fig. 1, Dst and Kp are plotted in the first two panels and $E > 1.22$ MeV electron fluxes are plotted in the third panel. All these parameters are plotted versus time. From the third panel we observe flux increase by more than 5 orders of magnitude during the recovery phase of the storm, starting from $8 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ and reaching $3 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$.

The $f_{10}$ rise time distribution has a peak at less than 1 day—80% of the events show one order of magnitude flux increase in less than a day. We also notice that for five events the minimum flux value and the following increase by one order of magnitude are reached before or exactly at the time of $\text{Dst}_{\text{min}}$. The $f_{100}$ distribution has the same characteristics as the $f_{10}$ distribution but with a less pronounced peak at less than a day. It is interesting to note that a 2 order of magnitude increase can happen in less than 12 h from $\text{Dst}_{\text{min}}$ (5 events). We have looked at the time of minimum flux for these events and found that it occurs on average at $t \leq 4 \text{ h}$ before or after $\text{Dst}_{\text{min}}$. Rise times can therefore be faster than those expected from quasi-linear theory using average wave characteristics for AE $> 500 \text{nT}$ (Horne et al., 2005a). The faster rise times could be due to a number of factors including, exceptionally high wave activity during extreme events (Horne et al., 2005b), non-linear wave particle interactions, or other wave processes (Li et al., 1993).

Based on these results, we conclude that the initial flux rise profile is in general fast and it is in this time interval that fluxes rise the most. This phase is followed by a slower increase in the peak value. These observations agree well on average with the theory that chorus waves, enhanced during high geomagnetic activity provide a local source of MeV electrons producing fast rising flux profiles (Horne et al., 2005a). When conditions become calm,
Chorus waves become less active; then, only slower radial diffusion may be acting. An additional contributing mechanism is the movement of the plasmapause during the recovery phase of a storm. When the plasmapause extends beyond $L^* = 4.5$, local acceleration will stop in this region. However, local acceleration may well continue outside of $L^* = 4.5$ and lead to a further gradual increase in the flux via inward radial diffusion.

3. Superposed epoch analysis of electron fluxes at GPS

Based on the distributions presented in Figs. 2 and 3, we categorized events as a function of their rise times. We first compare events that rise to $f_{1/2\text{max}}$ in a day or less (Group 1) to events that rise to $f_{1/2\text{max}}$ in more than 2 days (Group 2). Here we focus on the analysis of the $f_{1/2\text{max}}$ rise time distribution rather than the $f_{\text{max}}$ distribution because...
we think it is more representative of the processes that are responsible for the initial fast rise of the electron fluxes.

In order to compare the shape of the rising flux profiles independently of the maximum value they reach, we normalized fluxes in logarithmic space to a maximum value of 1 and then calculated the average profile of each group. Events have different time resolution because of data availability, so that we interpolated on a basis of one data point every 6 h and calculated the average fluxes.

 normalized fluxes in logarithmic space to a maximum value of 1 and then calculated the average profile of each group. Events have different time resolution because of data availability, so that we interpolated on a basis of one data point every 6 h and calculated the average fluxes.

The first panel in Fig. 5 shows the results of this analysis where normalized fluxes are presented as a function of epoch time (time = 0 is the time of Dst_{min}) and the third panel shows the average Dst index, as a reference. For both panels the blue line shows the average profile for Group 1 events and the red line shows the average profile for Group 2 events. Dash–dot lines in the first panel show the envelope (minimum to maximum values measured) of the distribution for both groups at each time step. We will discuss the Dst variation in more detail in the next section.

The two curves in the first panel are very distinct. The ‘fast’ events of Group 1 (solid blue line) have a small flux increase during the main phase of the storm and fast increase during the early recovery. The start of the flux increase coincides well with the start of the storm’s recovery phase. In the case of ‘slow’ events from Group 2 (solid red line), fluxes keep decreasing after Dst_{min} is reached. The minimum flux is lower and is reached 12 h after Dst_{min}—this is true not only for the average but for all events in Group 2. The increase towards the maximum flux is much slower.

From the first panel in Fig. 5 we may speculate that in the case of ‘fast’ events source processes are dominant over loss processes and that source mechanisms are acting.
on timescales of a day or less. In the case of ‘slow’ rising events, loss processes seem to be dominating initially over sources in the region that GPS is sampling causing a deeper and longer flux decrease. Later, sources dominate leading to rising fluxes on a timescale of ~3 days.

By contrast to the normalized fluxes of panel (a), panel (b) shows the average flux profile of each group as a function of epoch time relative to Dst_min. The average flux level reached by each group is not very different (there is a factor of two between the two curves) if we consider the variation shown by the envelope of the distribution (dash–dot lines). Even if it takes longer for events from Group 2 to reach the maximum value, this value is overall similar to the one reached during the ‘fast’ events from Group 1. The argument that a factor of two is not an important difference is supported by the study presented by Friedel et al. (2005) in which the authors showed that the best accuracy for fluxes that we can achieve with the current instrumentation is within a factor of two.

Another interesting feature of the event database is that there are events where flux variations cover two or more orders of magnitude, while few events do not reach a factor of 10. We now categorize events with a two or more orders of magnitude flux increase during the recovery phase (Group 3) and those for which the increase is less than two orders of magnitude (Group 4). For these two groups, we performed the same analysis as above. In Fig. 6, normalized fluxes in logarithmic space (panel a), average fluxes (panel b) and the Dst index (panel c) for both groups are plotted versus epoch time. Dash–dot lines illustrate the envelope of the two distributions at each time step. There are 17 events in Group 3 and 23 events in Group 4 (Table 1).

Events from Group 3 (red line) show a much deeper decrease during the main phase of the storm. This is confirmed by looking at the average fluxes of each group plotted as a function of epoch time in panel (b). Fluxes from Group 3 (red line) show an important decrease (fluxes decrease by a factor of 10) during the main phase but reach very similar maximum values as fluxes in Group 4. They seem to experience more intense losses during the main phase of the storm and very intense source processes seem to be acting during the recovery phase, increasing fluxes by two or more orders of magnitude on timescales of 2–3 days.

Five out of seven events with rise time to $f_{\text{max}}$ equal or more than 4 days (Fig. 2) belong to Group 3. They constitute a big part of the high end of the distribution. From Fig. 6 we realize that there is more to these events that distinguishes them from the others. Fluxes experience a much larger dropout during the storm’s main phase and so it takes longer to reach the maximum flux which is of the same level as for the other events. Categorization of events as ‘slow’ or ‘fast’ seems to be a difficult task since we can obtain different conclusions by categorizing them in different ways.

4. Superposed epoch analysis of solar wind and geomagnetic parameters

The correlation between solar wind parameters and relativistic electron enhancements in the inner magnetosphere has been well studied for the geosynchronous orbit (O’Brien et al., 2001; Dmitriev et al., 2005; Miyoshi and Kataoka, 2005; Borovsky and Denton, 2006; Borovsky and Steinberg, 2006; Kataoka and Miyoshi, 2006; Kim et al., 2006). Iles et al. (2002) and Vassiliadis et al. (2005) studied the same correlation inside geosynchronous orbit also and found that for $3.5 < L < 6.5$ and $4.1 < L < 7.5$, respectively, MeV electron enhancements were well correlated with high solar wind speed. Iles et al. (2002) found that significant relativistic electron flux enhancements were associated with an extended interval (2 days or more) of fast solar wind speed and an IMF Bz that is fluctuating about zero or more predominantly southward during the recovery phase. Here we investigate the
correlation of geomagnetic indices and solar wind parameters with MeV electron rise timescales at the GPS orbit.

We performed a superposed epoch analysis of geomagnetic indices (Kp and Dst) and solar wind parameters (pressure, density, speed, IMF amplitude and Bz) for all four groups presented in Section 3. Fig. 7 shows the average of these parameters as a function of epoch time, where \( t = 0 \) is the time of Dst\(_{\text{min}}\) for Groups 1 and 2. The blue line corresponds to Group 1 (rise time to \( f_{1/2\text{max}} \leq 1 \text{ day} \)) and the red line to Group 2 (rise time to \( f_{1/2\text{max}} \geq 2 \text{ days} \)).

Fig. 7 shows that the ‘slower’ events of Group 2 are related to larger storms. Dst\(_{\text{min}}\) for Group 2 reaches much lower values (around \(-200 \text{nT}\)), while for Group 1 it decreases to around \(-100 \text{nT}\). Dst for Group 2 has on average an initial fast recovery followed by a slower one, while MeV electron fluxes shown in Fig. 5 continue to decrease when Dst starts recovering. The variation of Dst and electron fluxes are thus not completely correlated. This is further discussed in Section 5. In agreement with the Dst variation, the Kp index during the storms main phase is higher for Group 2 than for Group 1.

Solar wind parameters for Group 2 show the following characteristics: pressure and density are higher before and during the storm’s main phase, the magnetic field amplitude is 1.5 times higher than for Group 1 and \(|Bz|\) is larger too (both negative and positive portions of Bz).
and solar wind speed averages rise fast before $\text{Dst}_{\text{min}}$. It is interesting to notice that $B_z$ turns predominantly northward during the early recovery phase of Group 2 storms, suggesting inhibited substorm activity during this period. Group 2 comprises five ICME events and two CIR while Group 1 is made of six ICME events and nine CIR.

The same study is performed for events from Groups 3 (events where $f_{\text{max}}/f_{\text{min}} \geq 100$) and 4 (events where $f_{\text{max}}/f_{\text{min}} < 100$) and is presented in Fig. 8. The blue line corresponds to Group 4 and the red line to Group 3. The first five panels illustrate the solar wind parameters: pressure (panel a), density (panel b), speed (panel c), IMF amplitude (panel d) and $B_z$ (panel e) and the last two illustrate the geomagnetic indices: $\text{Dst}$ (panel f) and $K_p$ (panel g).

Events from Group 3 correspond to larger storms (larger $\text{Dst}_{\text{min}}$ and $K_p$ max values) and to the passage of ICMEs in majority (Table 1). The solar wind speed is higher for these events, rising fast at the beginning of the storm's main phase. In addition, $B_z$ is turning northward in the early recovery phase, as observed for Group 2 storms; however, in this case it stays northward for a smaller amount of time. Group 3 comprises 10 ICME and 7 CIR while Group 4 is made of 11 ICME and 12 CIR.

In Groups 2 and 3 we have more ICME-related events. However, our statistics are not large enough to conclude that these two Groups are mostly associated with ICME. From a forecasting point of view, knowing an ICME will hit the Earth is not sufficient, from our results, to indicate whether it will lead to a fast rising or a slow rising event at
Other studies, however, corroborate this possibility (Miyoshi and Kataoka, 2005; Kataoka and Miyoshi, 2006).

5. Discussion

Based on the previous results, we now discuss the following topics: (1) the mechanisms responsible for the fast increase of Group 1 fluxes, (2) the mechanisms responsible for the large dropouts of fluxes from Groups 2 and 3 during the main phase and early recovery, and (3) the mechanisms that cause fluxes from Group 3 to rise to the same level as fluxes from Group 4.

For the first topic we need to identify source mechanisms that have a timescale of less than or equal to a day. As mentioned before, estimated timescales agree well—on average—with the predicted timescale of energy diffusion of low-energy electrons to MeV energies, due to electron-chorus resonant interactions outside the plasmasphere (24 h at $L = 4.5$). The other possible mechanism is radial diffusion which energizes particles while they are transported to inner regions of the magnetosphere. If we consider radial diffusion coefficients estimated by Brautigam and Albert (2000), those coefficients would lead to rise timescales of the order of 2 days for active conditions at $L \sim 4$ (timescale estimated as the inverse of the radial diffusion coefficient value).

The second topic is harder to address. There is more than one possible explanation for the large dropout of fluxes taking place on a timescale of the order of a day.

Fig. 6. (a) Normalized average fluxes in logarithmic space, (b) average fluxes and (c) the average Dst index for Groups 3 (red line) and 4 (blue line), as a function of epoch time. The envelopes of both distributions of fluxes are also plotted (dash/dot lines).
First, we consider the possibility that the flux dropout is due to intense losses driven by electron-wave resonant interactions. EMIC waves in plasmaspheric plumes can produce electron losses on timescales of hours and whistler-mode chorus waves can produce electron losses on timescales of a day. Recent studies have shown that the combined effect of EMIC and whistler-mode waves (chorus and hiss) can lead to a noticeable decrease of equatorial fluxes (Shprits et al., 2006a). GPS instruments do not measure pitch angle distributions so we cannot investigate this further.

Another important loss mechanism for large storms is loss to the magnetopause. The magnetopause is known to move inwards down to geosynchronous orbit or even closer to the Earth during large storms (Shprits et al., 2006b). Losses to the magnetopause at the GPS orbit constitute a separate study and will be further investigated in the future.

The combined effect of the above mechanisms can lead to large MeV electron dropouts, as suggested by Bortnik et al. (2006) for the case of the November 20, 2003 storm (storm included in our study).

The fact that events with larger dropouts are related to larger Dst events makes us wonder about the validity of the magnetic field model. If the T01 storm model used for the $L^*$ calculation was not able to capture the realistic variations of the geomagnetic field, then what we are actually observing is the Dst effect (Dessler and Karplus, 1961; Kim and Chan, 1997). In this case, flux profiles would be expected to be similar to the Dst index profile.

However, in Fig. 4, during the May 15, 2005 event where $Dst_{min} = -256$ nT, fluxes stay low during the first day of the recovery phase while Dst recovers fast to $\sim -100$ nT. Then, fluxes increase fast at the beginning of the second day, while Dst recovers slowly. In addition, Fig. 5 shows that fluxes continue to decrease even when Dst starts recovering, which is inconsistent with the Dst effect. A possibility is that the observed flux dropouts are a combination of all explanations presented above, but the

![Fig. 7. Superposed epoch analysis of solar wind and magnetospheric parameters corresponding to Groups 1 (blue line) and 2 (red line): (a) solar wind pressure, (b) solar wind density, (c) solar wind speed, (d) IMF amplitude, (e) Bz amplitude, (f) Dst and (g) Kp. The black line in all panels corresponds to the average value of each parameter for all events (40 events).]
Dst effect alone cannot explain the dropouts. Intense losses must occur as well.

Concerning the continuously decreasing fluxes of Group 2 (slow events) during the early recovery phase in Fig. 5, we notice (in Fig. 7) that Bz is turning northward during this period for these events. This will inhibit substorm activity, lead to a reduction in the amplitude of the chorus waves and thus severely limit local acceleration by whistler-mode chorus waves. On the contrary, during the fast events and the small flux variation events the IMF is more predominantly southward during the initial part of the recovery phase.

Finally, we consider two possibilities to address the third topic (i.e., similarity of final average flux levels for all groups). The first possibility is that during the recovery phase there is continuing activity taking place which could give rise to chorus waves outside the plasmapause leading to the increase of MeV electron fluxes. From the last panel in Fig. 8, we see that there is continuing activity during the recovery phase for Group 3 events (red line). The average Kp value for this group rises above Kp = 4 during the first day after Dstmin, followed by a Kp~3 during the second day. Fluxes rise on a timescale of 3 days which could suggest that the source predominance over loss is not extreme or that GPS is not sampling the region where the local source is acting. In the latter case, fluxes would rise as a result of radial diffusion diffusing particles away from the source region, presumably located outside the GPS orbit. However, the ~3 day flux rise timescale is in good agreement with a source driven by radial diffusion as estimated by Brautigam and Albert (2000). However, if we were to attribute this large flux increase (2–5 orders of magnitude in ~3 days) to radial diffusion, that would require the presence of a constant high external source, which is not usually observed (Chen et al., 2006).

Our study has some limitations. Interpretation of the conditions that lead to the ‘slow’ rise flux profile becomes complicated if we consider the possibility that the

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**Fig. 8.** Superposed epoch analysis of solar wind and magnetospheric parameters corresponding to Groups 3 (red line) and 4 (blue line): (a) solar wind pressure, (b) solar wind density, (c) solar wind speed, (d) IMF amplitude, (e) Bz amplitude, (f) Dst and (g) Kp. The black line in all panels corresponds to the average value of each parameter for all events (40 events).
magnetic field model used for the \( L^* \) calculation was not able to capture the configuration of the disturbed geomagnetic field—especially for the larger storms. In this case we would be mixing adiabatic and non-adiabatic effects in our analysis, in particular during the main phase and early recovery phases. However, as noted above, comparison between the ‘slow’ flux profile and the average Dst profile shows more differences than similarities, indicating that the observed profile cannot be the simple result of the Dst effect. Moreover, in a case of a super-storm (Fig. 4) we showed that the Dst profile during the recovery phase is very different from the flux profile.

Even if the model performs well, the number of data points depends on the availability of dynamic inputs, which in the case of T01 storm model is solar wind dynamic pressure and density. Especially at the storms main phase, the absence of data points can give a false picture of the timing and value of the minimum flux value reached.

Also, at \( L \sim 4 \) the satellite is measuring the inner edge of the MeV population, where the radial phase space density gradient is steep. An important variation in the \( L^* \) position would correspond to sampling a region with much less particles.

The large variety of event behaviors hardly allows simple explanations and points to the limits of data analysis alone. The flux rise profile is largely influenced by the presence of a local source. This source can be acting outside this region and the flux profile would have a different form. Differences in the flux profiles can be tested with the use of radiation belt codes where all these processes are included (Varotsou et al., 2005).

6. Summary and conclusions

We have presented for the first time MeV electron flux rise time distributions at the equator as measured by the NS41 GPS satellite. Because different processes are acting on different timescales, we have categorized 40 storms from the period 2001–2006 according to the rise time distribution of \( E > 1.22 \) MeV electron fluxes, relatively to the Dst\(_{\text{min}}\) (epoch time \( t = 0 \)). Four different rise times were estimated: the time needed to reach 90% of the maximum flux value, \( f_{\text{max}} \), the time needed to reach half the maximum flux value, \( f_{1/2\text{max}} \), the time needed for fluxes to rise by an order of magnitude after the main phase dropout, \( f_{10} \), and the time needed for fluxes to rise by two orders of magnitude, \( f_{100} \).

The main results of our study are the following:

(a) The \( f_{\text{max}} \) rise time distribution extends from \( t \leq 1 \) day to \( t > 6 \) days while the one for \( f_{1/2\text{max}} \) extends from less than 1 day to a bit more than 2 days.
(b) The \( f_{10} \) rise time distribution is very narrow and peaked at rise times of less than a day. The \( f_{100} \) rise time distribution was found to extend mainly from \( t \leq 1 \) day to \( t \sim 2 \) days (one event reached \( f_{100} \) in a bit more than 3 days).
(c) Fluxes can increase by two orders of magnitude in as little as 12 h from Dst\(_{\text{min}}\) (five events).
(d) ‘Fast’ events show a small dropout during the main phase and a very fast increase, on a timescale of the order of a day or less, during the recovery phase.
(e) ‘Slow’ events have a larger and longer flux dropout during the storm’s main phase, which often extends later than Dst\(_{\text{min}}\) and is followed by a 3-day increase to similar flux level as is reached during the ‘fast’ events.
(f) ‘Fast’ events are related to moderate intensity storms and comprise six ICME-related events and nine CIR-related events.
(g) ‘Slow’ events and events with large dropouts are related to much larger storms and comprise five ICMEs and two CIRs and 10 ICMEs and seven CIRs, respectively.

From the above results we have concluded that

(a) Flux profiles typically present an initial fast rise followed by a slower rise to the maximum flux value. The first rise is where most of the flux increase takes place, while during the second slower phase fluxes only gain a factor of two or so.
(b) In the case of ‘fast’ rising events, flux rise timescales agree well on average with predicted timescales for energization of lower-energy electrons to MeV energies by chorus waves. It is possible that for these events the NS41 satellite at \( L^* \sim 4.2 \) may be sampling the region where chorus waves are acting as a local source for MeV electrons.
(c) Measured electron flux rise times can, for given events, be much faster than electron energization timescales from chorus waves as predicted by quasi-linear theory using average wave characteristics for AE > 500 nT. Exceptionally high wave activity during extreme events, non-linear wave particle interactions or other wave processes may have to be considered in these cases.
(d) The large dropouts during part of the events are not simply the result of a Dst effect since the variations of flux and Dst curves do not correlate on average during such events.
(e) Electron fluxes for ‘slow’ rising events and events with large dropouts experience enhanced losses during the main phase of storms and enhanced sources during the recovery phase. The flux increase occurs on a timescale of \( \sim 3 \) days during which eventually fluxes reach high levels. This observation may be explained by radial diffusion only if a constant external source existed, which is not what has been usually observed (Chen et al., 2006). On the other hand, a local source could be acting but this source would have to be either of low intensity or acting in a close by region with radial diffusion transporting particles to \( L = 4 \).
(f) The direction of the IMF Bz could be an important parameter in determining the behavior of the flux of relativistic electrons during the recovery phase, consistent with the findings of Iles et al. (2002). Northward IMF Bz during the storm’s recovery will inhibit substorm activity, lead to a reduction in the amplitude
of the chorus waves and thus severely limit local acceleration by whistler-mode chorus waves.

(g) From a forecasting point of view we cannot say, based on our results, which group of electron enhancement events will be observed at $L \sim 4$, at the equatorial plane, if an ICME or a CIR is observed in the solar wind. Our statistics shows that there is almost equal possibility for a fast or slow event to occur for either of the two solar wind configurations.

In the future, we are planning to continue our study using data from the new instruments on board seven GPS satellites which are currently in orbit. By using a larger number of satellites we can have better time and space resolution and separate different processes better. Future studies will also focus on losses which are not well understood and not many data exist for the $L$ shells covered by GPS.

Further study is also required to show which solar wind parameters might be associated with different groups of events at the GPS altitude.

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