Dropouts of the outer electron radiation belt in response to solar wind stream interfaces: global positioning system observations

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We present a statistical study of relativistic electron counts in the electron radiation belt across a range of drift shells ($L^* > 4$) combining data from nine combined X-ray dosimeters (CXD) on the global positioning system (GPS) constellation. The response of the electron counts as functions of time, energy and drift shell are examined statistically for 67 solar wind stream interfaces (SIs); two-dimensional superposed epoch analysis is performed with the CXD data. For these epochs we study the radiation belt dropouts and concurrent variations in key geophysical parameters.

At higher $L^*$ we observe a tendency for a gradual drop in the electron counts over the day preceding the SI, consistent with outward diffusion and magnetopause shadowing. At all $L^*$, dropouts occur with a median time scale of $\sim 7$ h and median counts fall by 0.4–1.8 orders of magnitude. The central tendencies of radiation belt dropout and recovery depend on both $L^*$ and energy. For $\sim 70$ per cent of epochs Sym-H more than $-30$ nT, yet only three of 67 SIs did not have an associated dropout in the electron data. Statistical maps of electron precipitation suggest that chorus-driven relativistic electron microbursts might be major contributors to radiation belt losses under high-speed stream driving.

Keywords: radiation belt; relativistic electrons; global positioning system; solar wind

1. Introduction

(a) The outer electron radiation belt

The outer electron radiation belt, located between radial distances of 3–7 Earth radii ($R_E$), is highly dynamic and currently concluded to be driven in large part by variations in the solar wind (e.g. Paulikas & Blake 1979; Li et al. 2005). Though geomagnetic storms have been known to cause large increases in relativistic electron fluxes, Reeves et al. (2003) showed, using a full solar cycle of data,

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that approximately a quarter of all storms actually resulted in net decreases in the relativistic electron fluxes. The majority of previous studies of the outer radiation belt have looked at enhancements in the relativistic electron fluxes, few have concentrated on the losses.

A number of observational studies have examined the variations of outer radiation belt electron fluxes using both geosynchronous and low-Earth orbit (LEO) satellite measurements. Onsager et al. (2002) showed an example of radiation belt electron flux dropout that manifested over all local times (as seen at geosynchronous orbit for more than 2 MeV electrons) over about 10h, though local dropouts occurred more rapidly with time scales of less than 4h. A statistical analysis of rapid dropouts of relativistic electron flux at geostationary orbit by Green et al. (2004) showed localized depletions in more than 2 MeV electron flux occurring over 1–2 h, spreading to all local times by $\simeq 8$ h after the start of the dropout. Bortnik et al. (2006) have analysed a radiation belt dropout that showed a rapid, non-adiabatic loss of relativistic electrons from a range of L-shells. They found that the rapid losses were both energy and L-shell dependent, for a range of electron energies more than 0.63 MeV, occurring on time scales of less than 6 h near geosynchronous orbit and $\simeq 12$ h closer to $L = 4$.

Observed flux decreases can arise from adiabatic motion, loss through the magnetopause (magnetopause shadowing, e.g. Ohtani et al. 2009 and outward diffusion) or precipitation into the upper atmosphere (e.g. reviews by Friedel et al. 2002; Millan & Thorne 2007; Shprits et al. 2008). Candidate mechanisms for the scattering of relativistic electrons into the loss cone include whistler-mode chorus waves (Thorne et al. 2005; Bortnik & Thorne 2007), plasmaspheric hiss (Summers et al. 2007; Bortnik et al. 2008) and electromagnetic ion-cyclotron (EMIC) waves (Loto’aniu et al. 2006; Rodger et al. 2008). Estimates of the time scales required for these mechanisms to deplete the outer electron radiation belt are well described in the literature and we summarize these time scales here.

(b) Loss time scales

Radial diffusion has been shown to be important in the loss of relativistic electrons as a transport mechanism to open drift shells (Shprits et al. 2006). The radial diffusion coefficient $D_{LL}$ increases with both radial distance and magnetospheric activity; Brautigam & Albert (2000) presented a $K_p$-dependent parameterization of $D_{LL}$ such that for $K_p = 2$, $D_{LL}(L = 4) = 5 \times 10^{-3} d^{-1}$ and $D_{LL}(L = 6.6) = 0.76 d^{-1}$. For increased magnetospheric activity ($K_p = 5$) these coefficients become 0.17 and 25 d$^{-1}$, respectively. Thus at geosynchronous orbit, the transport time scale approaches approximately 1 h during enhanced magnetospheric convection. The time scales at $L = 4 R_E$ are of the order of several days. We note that the coefficients are independent of the gradient of phase space density; knowledge of the net effect on transport would require solution of the diffusion equation. Shprits et al. (2006) concluded that outward radial diffusion can be responsible for depletions in electron fluxes deep in the radiation belt across a typical storm main phase, though this result was derived from a study of quite intense geomagnetic activity.

It has been shown that the minimum energy for pitch-angle scattering of electrons by EMIC waves is typically above 2 MeV, but can fall below this for a small fraction of wave events, at a limited range of local times, occurring during
Electron radiation belt dropouts

intervals of enhanced ring current (Meredith et al. 2002, 2003). The drift-averaged scattering lifetimes are also expected to lie in the range of several hours to a day (see also Summers & Thorne 2003). Meredith et al. (2002) and Summers & Thorne (2003) also report a tendency for the minimum energy to fall below 2 MeV during more geomagnetically active conditions, with higher cold plasma concentrations and stronger ring current (more negative $D_{st}$ or Sym-H indices).

Interaction between whistler-mode chorus waves and relativistic electrons outside the plasmapause can lead to intense relativistic electron microbursts. Thorne et al. (2005) report that for wave powers observed during active intervals the effective lifetimes of MeV electrons are of the order of one day, and do not depend strongly on $L$. Inside the plasmasphere, a candidate mechanism for relativistic electron loss is pitch-angle scattering by resonant interaction with plasmaspheric hiss (e.g. Bortnik et al. 2008). The loss time scales have been shown to be dependent on both energy and $L$ (e.g. Summers et al. 2007) and the combined action of chorus, hiss and EMIC have been estimated at more than 14 h (more than 2 h) for electron energies of 1 MeV (300 keV).

(c) Solar wind stream interfaces

During the declining phase of the approximately 11 year solar activity cycle, coronal holes can extend from the polar regions towards the ecliptic plane. These coronal holes are the source of fast solar wind (Wang & Sheeley 1991), characterized by typical speeds of 500–800 km s$^{-1}$. As the Sun rotates, the coronal holes pass across the Sun–Earth line, and the Earth encounters streams of high-speed solar wind for periods typically lasting several days (Tsurutani et al. 2006; Denton et al. 2009). As the high-speed solar wind streams (HSSs) are emitted from the Sun they catch up with slow solar wind ($V_{sw} < 500$ km s$^{-1}$) and form a compressed interface in the interplanetary medium called a stream interaction region—if these recur they are known as corotating interaction regions. The stream interface (SI) identifies the transition from compressed slow wind to compressed fast wind.

Recently the effects of HSSs on the magnetosphere have been an active topic of study; e.g. Denton et al. (2009) and other papers in that issue. There are a great number of papers in the literature that describe the correlation between solar wind velocity and radiation belt relativistic electron fluxes (e.g. Paulikas & Blake 1979; Li et al. 2001, 2005; Lyatsky & Khazanov 2008), particularly with regard to energization. Several papers have also directly examined the effect of SIs on radiation belt populations (Miyoshi & Kataoka 2008; McPherron et al. 2009), using either low-altitude or geosynchronous satellite data, and their results showed that the enhancement of relativistic electron fluxes is dependent on the Russell–McPherron effect (Russell & McPherron 1973). McPherron et al. (2009) also noted the tendency for a rapid dropout in electron fluxes at geosynchronous orbit, of 0.8–2 orders of magnitude, directly after the arrival of a SI.

(d) Present work

In this paper, we present a statistical survey of observations from the combined X-ray dosimeters (CXDs) flown on the global positioning system (GPS) constellation showing a consistent response of the electron radiation belts to the
arrival at Earth of solar wind SIs. Through this study we address whether there is a consistent radiation belt response to SI, and also how the response varies with drift shell. We also present average maps of riometer absorption for intervals centred on the set of SI to indicate regions of precipitation.

2. The GPS constellation

Los Alamos National Laboratory has been flying energetic particle detectors on GPS spacecraft since 1983, with 11 spacecraft currently carrying Los Alamos instruments, nine of which are CXD instruments. The GPS orbit is a circular $4 \, R_E$ orbit with a nominal 12h period and a 55° inclination. It crosses the equator at $L \sim 4.2$ and moves to higher magnetic latitudes at higher $L$ shells, and near $L = 6.6$ GPS only samples particles within approximately 30° of field-aligned equatorial pitch angles. The GPS satellites orbit in six different planes, each of which has the same period and inclination, but are rotated by 60° about the Earth’s spin axis with respect to each other.

For this study we use data from nine identical CXD instruments (Distel et al. 1999), which are inter-calibrated to a very high degree, allowing us to combine data from all instruments in magnetic coordinate space to provide an unprecedented hourly temporal and 0.2 $R_E$ spatial resolution in the region from $L = 4–8$. The CXD instrument measures electrons at energies from $\sim 140 \text{keV}$ to $\sim 10 \text{MeV}$. We report here data, in counts per second, from the following nominal CXD energy channels: 230–410 keV; 0.77–1.25 MeV; and 1.7–2.2 MeV. We use counts per second instead of flux for two reasons—firstly, this paper primarily focuses on temporal and spatial variations, and, secondly, the CXD instrumental response is difficult to invert to flux without assuming a spectral form. The CXD channels are a mixture of differential and integral response types, depending on the spectral shape. Soft spectra get measured more differentially; hard spectra are measured more in an integral manner. For the events in this paper the spectral type is mostly soft—the higher energy channels drop out and stay low for longer—so the interpretation of the energy channels should be ‘approximately differential’.

The use of GPS data, even with its orbital peculiarities, has one large advantage over the use of LEO data. Over the range of $L$ covered by the GPS mission LEO satellites measure at most approximately 6° of the equatorial pitch angle distribution at $L = 4$ and approximately 2° at $L = 6.6$, all close to the loss cone. GPS can sample a much wider range of equatorial pitch angles—all pitch angles at $L^* = 4$, and to within 30° of the field-aligned direction at $L = 6.6$. LEO observations are dominated by processes occurring near the loss cone, which can lead to variations of orders of magnitude while the main trapped population is affected minimally. By including a large fraction of measurements away from the local loss cone the GPS data are much more dominated by the trapped particle distribution. However, basic limitations in the use of GPS data remain: at higher $L$ the GPS data are not sensitive to processes that affect near-90° pitch angle particles.

The GPS measurements presented here are ordered by the parameter $L^*$. $L^*$ is a magnetic drift invariant (Roederer 1970); under adiabatic changes to the geomagnetic field $L^*$ is a conserved quantity, thus $L^*$ is often used in radiation
Electron radiation belt dropouts

Table 1. Selected details of global positioning system satellites carrying Los Alamos combined X-ray dosimeters (CXD) used in this study. The columns give, in order, the NORAD tracking number, the space vehicle number, the international designation, the orbital plane and the date from which CXD data are available.

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belt studies; ordering by \( L^* \) should better organize data from different magnetic local times than using a radial distance or McIlwain L-value. In a dipole magnetic field \( L^* = L \) is the distance from the centre of the Earth to the equatorial crossing point of a given field line. For this paper we calculate \( L^* \) with the ONERA library\(^1\) using the T89 model (Tsyganenko 1989) and the calculation is truncated at \( L^* = 9 \). As the CXD instrument gives no pitch angle information we here calculate \( L^* \) for \( \alpha = 90^\circ \). The T89 model is parameterized by \( K_p \); its use for this study is justified as the GPS data are at hourly resolution and the ring current response is small.

In this paper, we present the first statistical study combining energetic particle measurements from multiple GPS satellites. This provides unprecedented \emph{in situ} coverage of the inner magnetosphere at 1 hourly temporal and 0.2 \( R_E \) of spatial resolution. This approach removes any orbital aliasing (over the temporal resolution of the measurements). Selected details of the satellites used in this study are given in table 1.

3. Stream interfaces

A SI delineates the leading slow solar wind and trailing fast solar wind (Burlaga 1974). The data from the ACE MAG and SWEPAM instruments were inspected for a simultaneous increase in the radial solar wind velocity and a west–east deflection in the azimuthal solar wind flow. The solar wind data were then inspected for evidence of a compression region, including increased magnetic flux density, enhanced proton temperature and increased proton number density. The time of the SI was taken as the time at which the sense of the east–west flow deflection reversed. Each SI was then identified in the NASA OMNI dataset and the time of arrival at Earth’s bow shock nose was recorded. The times of SI arrival so identified are given in table 2. Any SI with another interface within 2 days were

\(^1\)http://craterre.oncert.fr/home.html.
Table 2. Epoch times for the SI (propagated to Earth’s bow shock nose) identified between January 2005 and December 2008 used in this study. All epochs are identified to the nearest 30 min.

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excluded from our list of epochs, as were interfaces that had clearly identifiable solar ejecta entrained by the compression region (e.g. Richardson 2006; Rouillard et al. 2009).

Superposed epoch analysis is a technique used to reveal consistent responses, relative to some repeatable phenomenon, in noisy data (Chree 1908). Time series of the variables under investigation are extracted from a window around the epoch (here the SI) and all data at a given time relative to epoch form the sample of events at that lag. The data at each time lag are then averaged so that fluctuations not consistent about the epoch cancel. While this is a powerful technique, care

must be taken in the interpretation as a consistent response about an epoch does not imply causality—the response could arise from, say, a common driver. A bias in epoch selection can also give results that are difficult to interpret (e.g. Freeman & Morley 2009).

In many superposed epoch analyses the mean of the data, at each time relative to epoch, is used to represent the central tendency. In this paper we use the median, since this measure of central tendency is robust and not affected by outliers. We also present the interquartile range (IQR) as a robust measure of the spread of the data. As the IQR only uses 50 per cent of the data, and thus is perhaps not the most complete measure of spread, it is very easy to interpret and has been widely used in superposed epoch studies in the literature (e.g. O’Brien et al. 2001; Borovsky & Denton 2009; Freeman & Morley 2009; McPherron et al. 2009). Since we here have a relatively small sample of only 67 events, we have calculated bootstrapped 95% confidence interval (CI) for the median and IQR (e.g. Wilks 2006; Morley & Freeman 2007).

Figure 1 shows superposed epoch plots of both solar wind and magnetospheric properties for the set of 67 SIs. In each panel the superposed epoch median—that is, the median of values at the given time relative to epoch—of the quantity is given by a black line. The bootstrapped 95% CI for the median is given by the red band. The darker blue band marks the IQR and the bootstrapped 95% CI about it is shown as a lighter blue band. The lower three panels give the solar wind radial velocity, azimuthal velocity (GSE coordinates), and the proton number density. These show the expected properties of the SI used as the epoch for this study, and indicate both the similarities and the variability between streams. It can be seen from these panels that the SI is extremely well organized about the chosen epochs, giving good confidence in the event selection. Shown in the upper two panels are the $D_{st}$ index (a measure of the ring current; e.g. Gonzalez et al. 1994), and the $K_p$ index (a measure of magnetospheric convection; Thomsen 2004). It can be seen from these panels that there is a consistent pattern of magnetospheric response to the SI, as gauged by these indices. The increase in $D_{st}$ prior to the arrival of the SI is a well-known effect of magnetopause currents contaminating the $D_{st}$ index, and the depression of the index shows the strengthening of the ring current (e.g. Loewe & Prölss 1997). Typical classifications of geomagnetic storms use the minimum of the $D_{st}$ index to determine the size of the storm, by these classifications $\simeq 70$ per cent of these events would not qualify as even a small geomagnetic storm (Loewe & Prölss 1997). At the first HSSs and geospace interactions (HSS-GI) workshop, held in 2007, the continued classification of geomagnetically disturbed intervals by $D_{st}$ alone was called the ‘$D_{st}$ mistake’ (see Denton et al. 2009). For these intervals driven by high-speed solar wind the ring current is typically weak, but the level of magnetospheric convection (as shown by the index) indicates a moderate level of magnetospheric activity. In fact, the median value of maximum $K_p$ is $3^+$.  

4. Superposed epoch analysis of CXD data

Figures 2–7 show the central tendency of the superposed energetic electron data to magnetospheric driving by SI. In figures 2, 4 and 6 superposed epoch medians of the measured counts per second are displayed as functions of both time relative
Figure 1. Superposed epoch plots of solar wind and magnetospheric properties for the set of 67 SIs given in table 2. In each panel the superposed epoch median of the quantity is given by a black line. The 95% CI for the median is given by the red band. The blue bands mark the interquartile range (IQR; dark blue) and the 95% CI about it (light blue). Shown here are the (a) \( D_{st} \) index, (b) \( K_p \) index, (c) the solar wind radial velocity, (d) the solar wind azimuthal velocity (GSE coordinates), and (e) the solar wind proton number density.

to epoch and \( L^* \). Overplotted in red is the magnetopause standoff distance calculated using the Shue et al. (1997) model—note that this location is not directly comparable with the electron counts as the standoff distance is given in \( R_E \) and the electron counts are given in \( L^* \).
Electron radiation belt dropouts

Figure 2. Two-dimensional superposed epoch analysis of CXD electron counts as functions of L*. The abscissa is the time relative to epoch and the ordinate is L*, calculated using the T89 magnetic field model and the ONERA library. The colourmap shows the electron counts from the 230–410 keV energy channel on a log scale. The overplotted red line shows the median standoff location from the Shue et al. (1997) (in R_E).

One-dimensional cuts at fixed L* (=6.5, 5.5, 4.5) are given in figures 3, 5 and 7. The variability and uncertainty are displayed in figures 3 and 7 following the same format as figure 1. In the 230–410 keV band (figures 2 and 3) we see a strong tendency for electron counts to drop out at the arrival of the SI with a minimum in counts about 2 h after the SI. The effect is less pronounced deeper in the magnetosphere; the median dropout magnitude at this energy ranges from 0.4 orders of magnitude at L* = 4.5 to 1.4 orders of magnitude at L* = 6.5. The electron counts tend to recover to pre-event levels in about a day. The median response at L* = 4.5 shows a tendency to increased counts (figure 1a) within several hours. This can arise through inward diffusion from the plasmasheet, or may represent the increased population of ring current electrons via increased magnetospheric convection, or through the action of magnetospheric substorms. Recurrent substorms are known to be common under high-speed stream driving (e.g. Morley et al. 2009b).

Figures 4 and 5 give superposed epoch data for the 0.77–1.25 MeV energy channel. The time of minimum electron counts is approximately 4–5 h after the epoch. This is delayed with respect to the lower energy channel by 2–3 h. The dropout also appears to move to lower L* over several hours (on average), in contrast to the 230–410 keV channel where the dropout is nearly simultaneous across all L*.

Figure 3. Superposed epoch plots of 230–410 keV CXD counts per sec at fixed $L^*$ $((a)-(c))$. $L^* = 6.5, 5.5, 4.5$) for the set of I. The format is the same as figure 1.

At $L^* = 6.5$ the electron counts only recover, on average, to their pre-event level. For this energy range the recovery takes an average of $\simeq 2$ days, but increases slightly with $L^*$.

The response in the 1.7–2.2 MeV energy channel (figures 6 and 7) is different again. We continue to observe a tendency to drop out, which remains pronounced to $L^* = 4$. The counts are near the noise floor from $L^* > 5.5$, but the time of recovery...
minimum electron counts at $L^* = 4.5$ is about 7 h after epoch. The median dropout magnitude at this energy ranges from about 0.8 orders of magnitude at $L^* = 4.5$ to 1.8 orders of magnitude at $L^* = 5.5$. The recovery of these populations is also different. The time scale for recovery is much extended beyond 3 days.

It is also clear that the temporal evolution of the losses from the outer edge of the electron radiation belt are correlated with the median magnetopause standoff distance. As the magnetopause moves closer to the Earth we note that the calculation of $L^*$ fails as the last closed drift shell moves inside $L^* = 9$. This is shown by the missing pixels near $L^* = 9$ in figures 2, 4 and 6.

To check whether or not the observed tendency for electron dropout was merely a tendency or a consistent relationship, we inspected the data for all selected epochs. Only three out of 67 epochs show no indication of any dropout; however, the time lag between the estimated arrival of the SI and the dropout is variable. In many cases these are concurrent (or nearly so), but for a few events the dropout occurred up to 1.5 days before (or after) the arrival of the SI. It should also be remembered that we here present averaged data; however, for this dataset we can be sure that our superposed epoch plots actually represent the majority of events.

5. Riometer observations

Ground-based riometers provide a means of detecting high-energy (more than 30 keV) electron precipitation. Riometers, in general, respond to changes in ionospheric free electron density at heights where the electron motion is collision
dominated (Sen & Wyller 1960). The absorption measured by riometers is therefore sensitive to any incident particle population capable of reaching the D-region (approx. 90 km) of the ionosphere, which has empirically been determined to be more than 30 keV electrons and/or MeV protons. Since the

Figure 5. Superposed epoch plots of 0.77–1.25 MeV at fixed $L^*$ corresponding to figure 4. The format is the same as figure 3.
total absorption recorded by riometers is related to the total energy flux of the precipitation particle population, the riometers provide little information about the number flux or energy of the particle population. Instead, we use the presence (or absence) of riometer absorption as a robust indicator of precipitation of high energy electrons. With large arrays of these instruments deployed in Canada and Europe it is also possible to get a sense of the large-scale precipitation patterns associated with various processes.

For this analysis we have used riometers from the Canadian GeoSpace Monitoring (CGSM) and Sodankylä Geophysical Observatory (SGO) networks. The CGSM riometer network covers Canada, with good instrument density, giving coverage over a wide range of both latitude and longitude (e.g. Spanswick et al. 2006). The SGO network comprises a latitudinal chain of riometers in Finland (e.g. Aminaei et al. 2006; Longden et al. 2007) with additional instruments in Norway and Svalbard, thus providing good latitudinal coverage with limited longitudinal coverage. We used these data for a superposed epoch analysis of riometer absorption using the timings of SI presented in table 2.

Figure 8 shows a map of the absorption from riometers across the northern hemisphere. The absorption is shown in bins of magnetic latitude and magnetic local time (MLT) in figure 8. The bin size is 30 min of MLT and 5° of magnetic latitude. All panels show a three hourly average for each spatial bin. Use of three hourly averages gives an increased spatial coverage, due to the rotation of the Earth by 15° every hour. Combining the resultant maps for all 67 events thus gives excellent coverage across the Northern Hemisphere.

Absorption appears to increase (indicating the precipitation of more than 30 keV electrons) around the time of epoch, and the precipitation becomes more strongly organized approximately 3 h after the SI and peaks in the morning sector (9 MLT; 60–65 MLat). The morning sector absorption remains elevated.
for at least 12 h after the arrival of the SI. Inspection of the individual riometer time series shows that the absorption occurs in a very bursty manner (data not shown).

6. Discussion

Between $t_e - 4$ and $t_e + 3$ a rapid loss of energetic electrons is observed across a wide range of $L^*$. As the SIs are only measured to the nearest half hour, and the interface regions display varying geoeffective parameters, we expect that this
time scale only reflects the central tendency. It is most likely that the dropouts occur over a range of time scales, which may be governed by the characteristics of the interface region, and we are currently further investigating this. At least one of the SI in our list of epochs displays a loss across a wide range of $L^*$ in less than 3 h (Morley et al. 2010). The observed dropouts are coincident with the arrival of a SI and can continue through the subsequent HSSs. At $L^* \simeq 5.5$ and higher we also see a more gradual drop in the electron counts over the 12–24 h preceding the SI, increasing past 1 day at $L^* \simeq 6.5$. Inside $L^* \simeq 5.5$ we still see a gradual decrease, but only over 0–12 h before epoch. During the day before the arrival of the SI, the magnetosphere is immersed in compressed slow solar wind. Coincident with this gradual loss the $K_p$ index starts to rise, as does the solar wind proton number density. The resultant increase in ram pressure causes the magnetopause to move inward from its quiet-time median standoff distance of $\simeq 10.8 \, R_E$ to a median standoff distance of $\simeq 8.4 \, R_E$. These gradual losses are consistent with a combination of loss mechanisms; the compression of the magnetopause to a stand-off distance of approximately $8.4 \, R_E$ is compatible with the gradual loss of relativistic electrons from the higher radial distances (i.e. near to and beyond geosynchronous orbit), provided that the outward radial diffusion also takes place.

The results of this analysis are qualitatively similar when organized by $L$ rather than $L^*$. As sorting by $L^*$ removes adiabatic changes, we take these data as being more physically meaningful.

Using geosynchronous measurements of more than 2 MeV electrons from the GOES satellites and more than 300 keV electrons from the low-altitude NOAA POES satellites (organized by $L$), Miyoshi & Kataoka (2008) studied the dependence of the radiation belt electron fluxes on the solar wind speed and the Russell–McPherron effect (Russell & McPherron 1973). They also briefly noted the existence of a reduction in fluxes near the arrival of the SI, but did not discuss the dropouts further. However, inspection of their figures 3 and 6 reveals that the epochs used in their study also penetrate to approximately $L = 4$. The time scales of the dropouts are also similar. The data shown in our figures 2, 3 and the upper panel of figure 7, thus broadly agree with Miyoshi & Kataoka (2008). In this context, we note that when interpreting the $L^*$-dependence of the response of the CXD data it is important to take account of the effects of the GPS orbit—namely that at a given $L^*$ the GPS spacecraft are always roughly at the same magnetic latitude. Only near perigee ($L^* = 4$) does GPS sample the full equatorial pitch angle distribution; at higher $L^*$ GPS is at higher latitudes and measures an increasingly smaller fraction of the near-90° equatorial particles. Though it may be possible to imagine processes operating in pitch angle space (i.e. pitch angle diffusion) that have just the right characteristics to reproduce the observations at different $L^*$, the broad similarities between the GPS data and the low-altitude observations make this an unlikely explanation.

Similarly, a superposed epoch analysis of geosynchronous data (using only data from the GOES satellites) by McPherron et al. (2009) showed a tendency for an initial dropout in electron fluxes directly after the arrival of a SI. They stated that it ‘is apparent that relativistic electrons at synchronous orbit rapidly disappear during the passage of a CIR (interface ±12 h)’. While the data presented in this paper are consistent with the observations of these authors, we note that
these authors focused on the flux enhancements after the SI and did not look in detail at the dropouts. Additionally, we present in situ measurements from a range of geomagnetic latitudes and local times, organized by drift shell, whereas McPherron et al. (2009) used data from two geosynchronous satellites. We therefore expect that our characterization is more representative of the dropout, but we have not investigated any dependence of the dropout properties on solar wind parameters or the Russell–McPherron effect (Russell & McPherron 1973).

The formation of a plasmaspheric drainage plume can be expected at the onset of enhanced convection (e.g. Goldstein & Sandel 2005), and typically lasts (under high-speed driving) about 4 days (Borovsky & Denton 2008). The presence of a plume will provide ideal conditions for EMIC wave growth (Horne & Thorne 1993; Erlandson & Ukhorskiy 2001). However, EMIC are unlikely to form the dominant loss mechanism here as the minimum resonant energy would have to fall to approximately 230–410 keV, simultaneously across a wide range of \( L^* \), to account for the losses across all energies. The superposed riometer data also show no absorption feature in the afternoon sector where precipitation from EMIC would be expected—we note that this does not exclude EMIC from being a potential loss mechanism, just that we see no evidence for EMIC providing a consistent response following SI. Both Morley et al. (2009a) and Fraser et al. (in press) have shown EMIC occurrence during the main and recovery phases of geomagnetic storms driven by corotating interaction regions.

Borovsky & Denton (2009) have postulated that the formation of the super-dense ion plasmasheet, and its interaction with a plasmaspheric plume, may lead to significant EMIC wave growth and thus a dropout in relativistic electrons. Denton & Borovsky (2009) show that the plasmasheet density increase is first observed at geosynchronous orbit (near midnight) 5.9 h after the solar wind density increases in the compression region. They reported the solar wind density rise as occurring 6.5 h prior to storm onset. Thus, the rise in plasmasheet density occurs a mean of 0.6 h prior to storm onset. In their studies, the SI occurs a mean of 3 h after the storm onset and thus the midnight plasmasheet density rises 3.6 h prior to the arrival of the SI at Earth. The transport time scales for the super-dense ion plasmasheet to penetrate to dusk and 9 MLT are reported as \( \simeq 3.5 \) and 6–9 h, respectively. So for the mechanism suggested by Borovsky & Denton (2009) to be the cause of the rapid loss of relativistic electrons we require that the rapid loss begins at, or after, the time of SI arrival. In this paper, we see the rapid loss from \( \simeq 4 \) h prior to the arrival of the SI. We also see no riometer signature in the afternoon-dusk sector that would indicate a consistent EMIC-related precipitation response to the arrival of a SI—thus our results appear to be initially incompatible with the suggestion of Borovsky & Denton (2009). However, that study selected high-speed stream-driven storms based on a clear response in the \( K_p \) index and each of the selected storms had to be recurring. We have selected our epochs based solely on the solar wind conditions to examine, without bias to an observed geomagnetic response, the effect of SI on the occurrence of electron dropouts. The disagreement may result from a bias in epoch selection or the use of storm onset as epoch (compared to SI). The possibility that EMIC may be a significant loss mechanism for the more geoeffective SIs warrants further investigation.
At energies below approximately 0.5 MeV, there is a strong recovery in the electron population after about a day (these energies have a plasmasheet source and may recover by inward diffusion or substorm injection). This effect is diminished at progressively higher energies with an effective lack of recovery at energies above 1.25 MeV. Additionally, electrons with energies of 100 to 300 keV are believed to form a ‘seed’ population (e.g. Obara et al. 2000) for subsequent acceleration to relativistic energies by magnetospheric processes including enhanced inward radial diffusion driven by ULF waves (Shprits et al. 2006) and chorus-driven energization (Summers et al. 2007). However, on average there is no significant recovery observed in the 1.7–2.2 MeV data. This suggests that acceleration processes are either weak or dominated by loss processes for the higher electron energies.

The riometer data suggest that the radiation belt losses can, at least in part, be explained for \(5 < L < 6\) by a rapid and bursty precipitation mechanism that is active in the late morning sector. A likely candidate is relativistic electron microbursts—as these microbursts occur outside the plasmapause; if they are an active mechanism in SI-driven then the plasmapause must be close to Earth. As the peak absorption is seen from about 3 h after the epoch, and the magnetospheric convection peaks about an hour after the impact of the SI, it is quite likely that the outer layers of the plasmasphere could have been stripped off and begun to convect to the magnetopause in a plasmaspheric drainage plume. Thus it is probable that the observed precipitation is in the plasmatrough. A detailed investigation of this is planned.

As the riometer cannot discriminate between different energies of precipitating electrons, we cannot be certain that the absorption observed is due to relativistic electrons. However the bursty nature of the absorption and the spatial location are suggestive of electron microbursts driven by high-latitude chorus waves, which are generated off the magnetic equator in the late morning and on the dayside. We intend to further investigate this possibility. Due to the timing of the rise in riometer absorption, relative to the losses observed at GPS, we cannot attribute the rapid dropout to this mechanism—at least on a statistical basis. The peak absorption is observed from approximately 3 h after the arrival of the SI, and thus coincides with the end of the interval of rapid loss. It may be that we can only attribute part of the rapid losses to whatever loss mechanism causes the implied precipitation in the late morning sector. In that context we note that Rodger et al. (2008) point out that riometer absorption is expected to be less strong for relativistic electron precipitation where the peak ionization is well below the altitude of peak riometer sensitivity. Further study is required to explain the observed losses over the wide range of \(L^*\) at which they are observed, and their relationship with the measured riometer absorption (see also Lam et al. 2010).

The results discussed in this manuscript arise from a statistical technique, and to confirm their validity the data for each epoch were visually inspected. About 4.5 per cent (three out of 67) epochs from our list showed no dropout at or near the time of arrival of the SI. Work is ongoing to address the distributions of dropout and recovery time scales, and closer investigation of those events that did not display a dropout will be performed to elucidate the necessary conditions for the arrival of a stream interaction region (and attendent HSS) to initiate a dropout in the outer electron radiation belt.
7. Conclusions

— At $L^* \simeq 5.5$ and higher we observe a tendency for a gradual drop in the electron counts over the 12–24 h preceding the SI, while the magnetosphere is in compressed slow solar wind. We interpret this as being consistent with outward diffusion and magnetopause shadowing.

— Between $t_e - 4$ and $t_e + 3$ rapid loss of energetic electrons is observed across a wide range of $L^*$. At all $L^*$, dropouts in the relativistic electrons are seen over a median time scale of $\simeq 7$ h, with median counts falling by 0.4–1.8 orders of magnitude. This dropout is faster than reported by previous statistical studies and may be due to the better data density afforded by the GPS constellation.

— The central tendencies of radiation belt dropout and recovery are dependent on both $L^*$ and energy. Only three of 67 SIs did not have an associated dropout in the electron counts.

— For this set of SIs, in $\simeq 70$ per cent of events $\text{Sym-H}$ remains above $-30$ nT, yet there is a strong tendency for radiation belt dropouts that penetrate to small $L^*$. Defining quiet-time or storm using $D_{st}$ or $\text{Sym-H}$ does not necessarily reflect the state of magnetospheric activity (see also Denton et al. 2009).

— Electron precipitation at energies more than 30 keV, inferred from riometer absorption, at and after the arrival of a SI is unstructured and bursty. From approximately 3 h after the arrival of a SI the precipitation is localized in the morning sector ($\approx 5 < L < 6$). This is suggestive of chorus-driven relativistic electron microbursts being major contributors to radiation belt losses under high-speed stream driving, though we cannot directly attribute the rapid dropout to this mechanism.

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Electron radiation belt dropouts


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