Inward shift of outer radiation belt electrons as a function of Dst index and the influence of the solar wind on electron injections into the slot region

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[1] The radial positioning of radiation belt electrons as a function of the Dst index and the controlling solar wind parameters for deep penetration of energetic electrons into the inner magnetosphere are investigated. Using 2–6 MeV electron data from the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) from January 1995 to June 2004, we examine the L location of energetic electron deepest penetration, L location of the maximum flux, and L location of the maximum flux enhancement and variation over the duration of 119 moderate and strong isolated geomagnetic storms. We find that the L location of deepest penetration, L location of the maximum flux at the end of electron injections, and L location of the maximum flux variation have strong correlations with the minimum Dst index. Although the variation and radial positioning of radiation belt electrons is clearly associated with the Dst index, their deep penetration into the slot region (2 < L < 3) is not directly correlated with the Dst index in an obvious way. It is also known that the Dst index can be accurately predicted based on solar wind parameters. Thus, the necessary and sufficient combination of solar wind conditions for the occurrence of injection events into the slot region, between L = 2–3, are also investigated. We find a total of 23 injection events at L = 2.5 from 1995 to 2004 and that when certain solar wind conditions are met, an injection event at L = 2.5 is ensured. We also find that the electron flux preconditioning is an important factor influencing electron injections at L = 2.5.

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1. Introduction

[2] Relativistic electrons in the inner magnetosphere are distributed into two regions: the inner radiation belt and the outer radiation belt. The inner radiation belt is relatively stable, while the outer radiation belt is highly dynamic and can exhibit great changes during geomagnetic storms. Geomagnetic storms can either increase or decrease relativistic electron fluxes in the outer radiation belt [Reeves et al., 2003]. Tverskaya et al. [2003] investigated storm-injected relativistic electrons during selected geomagnetic storms in 1993, 1997, 1998, and a great storm in April 2000 using SAMPEX, Polar, and the highly elliptical orbit (HEO) 1997-068 observations and found a strong correlation between the absolute value of the minimum Dst index (Dstmin) and the radial position of the intensity peak of injected electrons during the recovery phase of a storm. The radial position is referred to as L location, where L is the projected equatorial distance mapping dipole field lines in units of Earth radii. Iles et al. [2002] also confirmed that the L location of the peak electron count rate enhancement during geomagnetic storms from January 1995 to March 1998 has a dependence on Dst* by using data from microsatellites the Space Technology Research Vehicle (STRV). More recently, Zheng et al. [2006], using SAMPEX 2–6 MeV electron data, showed that the penetration distance of 2–6 MeV electrons during intense storms (with Dstmin < −130 nT) from 1992 to 2004 has a good correlation with Dstmin delayed by 3 d.

[3] Separating the inner and outer radiation belts (2 < L < 3) is a region called the slot region, which is usually devoid of relativistic electrons. The formation of the slot region is believed to be due to the balance between the inward transport of electrons and pitch angle diffusion [Lyons and Thorne, 1972]. During intense solar wind conditions however, the slot region can be filled with relativistic electrons [Blake et al., 1992; Li et al., 1993; Baker et al., 2004a]. After filling, the electrons in the slot region subsequently decay. In the slot region, the lifetimes of electrons of different energies can be quite different [Fennell et al., 2005]. For 2–6 MeV electrons, it can vary from several days to a few weeks at different L [Baker et al., 2007]; in the center of the slot region
which greatly influence 2–6 MeV electron fluxes during geomagnetic storms, we examine daily averaged data from SAMPEX of 2–6 MeV electrons from 1995 to 2004. We define $L_{\text{lowest}}$ as the lowest $L$ on which the flux changes by at least one order of magnitude, and $I_{\text{flux}}^\text{max}$ as the $L$ on which the flux at the end of injection is the largest. Also, we define $I_{\text{variation}}^\text{max}$ (by percentage/value) as the $L$ of the maximum flux enhancement, that is, the $L$ on which the flux increases most by percentage/value from the beginning of the storm to the end of injection; $I_{\text{variation}}^\text{min}$ (by percentage/value) is defined as the $L$ of the maximum flux variation, that is, the $L$ on which the flux increases most by percentage/value from the point of the lowest flux during the storm to the end of injection. Figure 1 shows an example of how to calculate the flux enhancement and variation. The dashed line marks the middle of the day of $DSt_{\text{min}}$. We define the flux at the end of an injection as the averaged flux 2–4 d after the day of $DSt_{\text{min}}$ and this time period is indicated by the gray block on the right of Figure 1; the flux at the beginning of the storm is defined as the averaged flux 1–3 d before the day of $DSt_{\text{min}}$ indicated by the gray block on the left of Figure 1. The colored asterisks represent the lowest fluxes during the storm at corresponding $L$ shells. As Figure 1 shows, the lowest fluxes during the storm at different $L$ shells can occur at different days; at $L = 2.5$, the flux variation is similar in magnitude to the flux enhancement, but at $L = 4$ or $L = 6$, the flux variations are much larger than the flux enhancements.

In this study, we broaden the size of storms and enlarge the number of selected storms from previous studies [e.g., Tverskaya et al., 2003] by using all moderate and strong storms (with $DSt_{\text{min}} < -50$ nT) during 1995–2004. To avoid the influence of multiple storms, we use only isolated storms in this study. We set the criteria for isolated storms as the following: first, only those storms with no other storms occurring within 7 d before or 4 d after are included; for some strong storms, the electron flux is not likely to be significantly influenced by much smaller storms nearby, thus we also include those intense storms that are much larger than other storms (with $\Delta DSt_{\text{min}} > 100$ nT) that happen within 7 d before and 4 d after. Figure 2 shows an example of the storm selection criteria. In April 2000, three storms meet our criteria, as marked with red asterisks. For storms on 16 April and 24 April, no other storms occur within 7 d before or 4 d after, so these two storms are included; the storm on 5 April, marked with the green asterisk, is not counted as an isolated storm because 2 d later another large storm occurred. The storm on 7 April, however, is included despite being only 2 d after a storm because it is much larger than the nearby storm. From January 1995 to June 2004, a total of 124 storms

![Figure 1](image1.png)

**Figure 1.** An example of how to calculate the flux enhancement and the flux variation during an isolated storm based on daily averaged 2–6 MeV electron flux data from SAMPEX. The dashed line marks the middle of the day of $DSt_{\text{min}}$. The fluxes averaged over the 3 d periods indicated by two gray blocks are defined to be the flux at the beginning of the storm (left) and the flux at the end of injection (right), respectively. The asterisks represent the lowest fluxes during the storm at corresponding $L$ shells.

$L = 2.5$, the lifetime of 2–6 MeV electrons is about 3.6 ± 1.6 d [Meredith et al., 2009].

In this study, we examine the relationship between different definitions of $L$ location of 2–6 MeV electron injections and minimum $DSt$ during all moderate and intense isolated storms from 1995 to 2004. The data we use are daily averaged 2–6 MeV electron flux measurements from SAMPEX, which operates in a near-circular orbit with an altitude of 520 by 670 km and an 82° inclination [Baker et al., 1993].

The electron flux data are sorted by $L$ shell, which corresponds to radial distance in Earth radii at the equator by mapping magnetic field lines, with $\Delta L = 0.1$. By using a wide intensity range of storms, with $DSt_{\text{min}}$ from −50 nT to around −400 nT, and multiple $L$ location definitions, we show the correlation between $L$ location and $DSt$ index in more depth than previous work. We also investigate electron flux during isolated storms at each $L$ shell and the sum of electron fluxes throughout the slot region and the outer belt, and find that almost all storms show flux enhancements at some $L$ shell, but only about 40% of the storms cause increases of the total electron flux between $L = 2$ and $L = 7$, 20% cause decreases, and 40% produce no change. Additionally, using daily averaged 2–6 MeV electron flux data and 5 min solar wind data from OMNIWeb, we perform a survey of the relationship between 2 and 6 MeV electron injections into the slot region and solar wind conditions, comparing the relative effectiveness of solar wind parameters and their combinations. In addition to solar wind conditions, we find another important factor, electron flux preconditioning, which greatly influences the likelihood of electron injections into the slot region.

### 2. Storm-Injected Relativistic Electrons and $DSt$ Index

To investigate the relationship between the $L$ location of 2–6 MeV electron injections and the minimum $DSt$ index during geomagnetic storms, we examine daily averaged data from SAMPEX of 2–6 MeV electrons from 1995 to 2004. We define $L_{\text{lowest}}$ as the lowest $L$ on which the flux changes

![Figure 2](image2.png)

**Figure 2.** Selected isolated geomagnetic storms in April 2000. Three storms, marked with red asterisks, are selected according to our criteria, while the storm with the green asterisk is not included.
met these requirements; 10 of them were large storms with much smaller storms nearby, and among these 10 storms the closest smaller storm occurred about 1 d before. Excluding storms during which the SAMPEX data are not available, a total of 119 storms are investigated; also excluding storms during which the \( \text{flux} \) did not increase at any \( \text{L shell} \) from \( \text{L}=2 \) to \( \text{L}=7 \), finally, a total of 117 storms are used in the following study.

Figure 3 shows the six different \( \text{L} \) locations defined previously versus \( |\text{Dst}_{\text{min}}| \) during 117 storms from 1995 to 2004. The magnitudes of the maximum flux, flux enhancement, and flux variation (by percentage/value) for each storm are also shown in Figure 3. \( L_{\text{lowest}} \), \( \text{flux}_{\text{max}} \) and \( \text{variation}_{\text{max}} \) (by value) have the highest correlations with \( |\text{Dst}_{\text{min}}| \), with correlation coefficients of 0.78, 0.83, and 0.87, respectively. For intense storms (\( |\text{Dst}_{\text{min}}| < -100 \text{ nT} \)), the magnitudes of the maximum flux enhancement and variation are generally higher than for moderate storms (\( -50 \text{ nT} < |\text{Dst}_{\text{min}}| < -100 \text{ nT} \)). The results indicate that the location of relativistic electron deepest penetration, location of the maximum flux at the end of injection, and location of the highest flux variation by value during geomagnetic storms have strong correlations with \( \text{Dst} \) index and thus the intensity of the storm. The stronger the storm, the further inward electrons can penetrate. Compared to the deepest penetration and \( \text{L} \) location of the maximum flux and flux variation, the correlation coefficients between \( \text{flux}_{\text{max}} \) (by percentage/value) and \( |\text{Dst}_{\text{min}}| \) are not as high (0.48 and 0.53, respectively). Reeves et al. [2003] investigated relativistic electron fluxes in the outer radiation belt during geomagnetic storms and showed that during about half of geomagnetic storms, the flux at a given \( \text{L} \) shell in the outer radiation belt increases, while for another half, the electron flux either remains the same or decreases, and that this result is independent of the specific \( \text{L} \) shell investigated. This explains the weak correlation between \( \text{flux}_{\text{max}} \) (by percentage/value) and \( |\text{Dst}_{\text{min}}| \). During some geomagnetic storms, especially some moderate storms, the flux at the outer radiation belt decreases, while at lower or even higher \( \text{L} \) the electron flux does not change or increases slightly, thus a lower or higher \( \text{L} \) shell would become the \( \text{L} \) shell on which the flux “increases” the most. As indicated in Figure 3d, the magnitudes of the maximum flux enhancement during some storms are quite low, and for these storms the \( \text{L} \) shell of the maximum flux enhancement is usually very low or very high. On the other hand, the \( \text{L} \) location of the maximum flux variation during the storm does have a strong correlation...
We are examining the correlation between IMF magnitude and injection events at different L shells. By examining data during 1995–2004, we find that IMF $B_z$ shows good correlation with injection events at $L = 2.5$, and shown that IMF $B_z$ is greater than 24 nT during these injection events. The maximum IMF magnitude ($B_{max}$) of each event is greater than 24 nT; IMF $B_z$ remains less than −10 nT for more than 1 h; the maximum $E_y$ ($E_{y,\text{max}}$) is larger than 8 mV/m, while 21 of 23 events occurred with $E_{y,\text{max}} > 9$ mV/m. There is also some correlation between solar wind speed ($V_{sw}$) and injection events. During most events (22 of 23) the maximum $V_{sw}$ ($V_{sw,\text{max}}$) is greater than 500 km/s. Solar wind density and dynamic pressure, however, show no obvious correlation with injection events.

We find that the sufficient conditions for injection events at $L = 2.5$ are: $B_{max} > 24$ nT, $E_{y,\text{max}} > 9$ mV/m, and $E_y \times t$ (time during which $E_y > 0.5$ mV/m) > 7 mV/m*d. Here $E_y \times t$ is calculated within 1.5 d before and after $E_{y,\text{max}}$, and calculated only when $E_y > 0.5$ mV/m, which means it only includes the positive part of $E_y$. For the period 1995–2004, there are a total of 10 intervals during which the solar wind conditions met these sufficient conditions, and an injection event occurred for each of these intervals.

The sufficient and necessary conditions for injection events at $L = 2.5$ are summarized in Table 1. There are some research suggesting injections in the slot region are caused by strong storms [e.g., Miyoshi and Kataoka, 2005]. Indeed, the results we found show that most injection events at $L = 2.5$ (22 of 23) occurred during intense storms, with $Dst_{\text{min}} < -140$ nT; however, there is still one event that happened under a moderate storm ($Dst_{\text{min}} = -87$ nT). Furthermore, intense storms do not always lead to injection events in the slot region: there are 10 storms for the period 1995–2004 with $Dst_{\text{min}} < -140$ nT that did not cause injection events at $L = 2.5$.

### 3. Relativistic Electron Injections Into the Slot Region and Correlation With Solar Wind Parameters

#### 3.1. Injection Events in the Slot Region

In the previous section, we showed that there is a strong correlation between electron injections and $Dst$ index. In this section, we will show the relationship between electron injections into the slot region and solar wind parameters. To examine electron injections into the slot region, we define injection events in the slot region ($L = 2–3$), according to daily averaged SAMPEX 2–6 MeV electron flux data from 1995 to 2004, as follows: at $L = 2/2.1/\ldots/3$, if the daily averaged 2–6 MeV electron flux increases monotonically by one order or more within 3 d, we call it an injection event at $L = 2/2.1/\ldots/3$. From 1995 to 2004, we find, for example, a total of 3 injection events at $L = 2$, 23 events at $L = 2.5$, and 34 events at $L = 3$. Figure 4 shows the number of injection events at $L = 2-3$.

#### 3.2. Solar Wind Conditions for Electron Injections Into the Slot Region

##### 3.2.1. Solar Wind Conditions for Injection Events at $L = 2.5$

To show the correlation between solar wind parameters, including interplanetary magnetic field (IMF), and injection events in the slot region, we choose to focus on the center of the slot region, $L = 2.5$, because the electron flux at $L = 2.5$ is usually the lowest within the slot region according to SAMPEX data. By examining data during 1995–2004, we find a total of 23 injection events at $L = 2.5$. The results show good correlation between IMF magnitude, IMF $B_z$ in geocentric solar magnetospheric coordinates, solar wind electric field $E_y$, and injection events at $L = 2.5$ using 5 min solar wind data from OMNIWeb. During these injection events, the maximum IMF magnitude ($B_{max}$) of each event is greater than 24 nT; IMF $B_z$ remains less than −10 nT for more than 1 h; the maximum $E_y$ ($E_{y,\text{max}}$) is larger than 8 mV/m, while 21 of 23 events occurred with $E_{y,\text{max}} > 9$ mV/m. There is also some correlation between solar wind speed ($V_{sw}$) and injection events. During most events (22 of 23) the maximum $V_{sw}$ ($V_{sw,\text{max}}$) is greater than 500 km/s. Solar wind density and dynamic pressure, however, show no obvious correlation with injection events.

We find that the sufficient conditions for injection events at $L = 2.5$ are: $B_{max} > 24$ nT, $E_{y,\text{max}} > 9$ mV/m, and $E_y \times t$ (time during which $E_y > 0.5$ mV/m) > 7 mV/m*d. Here $E_y \times t$ is calculated within 1.5 d before and after $E_{y,\text{max}}$, and calculated only when $E_y > 0.5$ mV/m, which means it only includes the positive part of $E_y$. For the period 1995–2004, there are a total of 10 intervals during which the solar wind conditions met these sufficient conditions, and an injection event occurred for each of these intervals.

We find the sufficiency and necessary conditions for injection events at $L = 2.5$ are: $B_{max} > 24$ nT, $E_{y,\text{max}} > 9$ mV/m, $E_y \times t$ (time during which $E_y > 0.5$ mV/m) > 7 mV/m*d. For the period 1995–2004, there are a total of 3 intervals during which these criteria are fulfilled, and 21 of them caused injection events at $L = 2.5$. There are two exceptions during which the necessary conditions are not fulfilled. During one event, the solar wind parameters are not fully available; during the other event, the solar wind conditions are quite mild compared to other events, and this event (on 28 March 2001) will be discussed in the next subsection. The sufficient and necessary conditions for injection events at $L = 2.5$ are summarized in Table 1.

#### Table 1. The Sufficient and Necessary Solar Wind Conditions for Injection Events at $L = 2.5$

<table>
<thead>
<tr>
<th>Sufficient Conditions</th>
<th>Necessary Conditions (Except for Two Events)</th>
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<tbody>
<tr>
<td>$B_{max} &gt; 24$ nT</td>
<td>$B_{max} &gt; 24$ nT</td>
</tr>
<tr>
<td>$E_{y,\text{max}} &gt; 9$ mV/m</td>
<td>$B_z &lt; -10$ nT lasting for $&gt; 3$ h</td>
</tr>
<tr>
<td>$E_y \times t &gt; 7$ mV/m*d (when $E_y &gt; 0.5$ mV/m)</td>
<td>$E_{y,\text{max}} &gt; 9$ mV/m</td>
</tr>
<tr>
<td>$E_y \times t &gt; 3.5$ mV/m*d (when $E_y &gt; 0.5$ mV/m)</td>
<td></td>
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*The resolution of solar wind data is 5 min.
and solar wind electric field have good correlations with injection events. Here we also want to examine the correlation between the magnitude of flux enhancement at $L = 2.5$ and solar wind parameters using a larger database of events. Because the $Dst$ index can be predicted by solar wind parameters accurately [Temerin and Li, 2002, 2006], we use $Dst$ index to identify those events for convenience. We choose to use storms with $Dst_{\text{min}} < -50$ nT during 1995–2004, and for multiple storms happening within 2 d, we choose the most intense one. There are a total of 209 events that meet these criteria.

We calculate the electron flux enhancement at $L = 2.5$ as the ratio of the flux at the end of the event to the flux at the beginning of the event. Because now we focus only on flux enhancements at $L = 2.5$, we use different definitions of the beginning and the end of the event from section 2. The beginning of the event here is defined to be 0 or 1 d before $Dst$ reaches its minimum, depending on which day the electron flux at $L = 2.5$ is lower, while the end of the event is defined to be 3 d after the beginning of the event. There is a time delay between solar wind impact and the electron flux enhancements in the slot region and we find it usually takes 2–3 d from the beginning of the event for electron flux to reach its peak value at $L = 2.5$, which is also consistent with previously published results [e.g., Zheng et al., 2006]. Here we choose solar wind parameters during the time period of 2 d before $Dst$ reaches its minimum and 1 d after that to investigate their correlations with the enhancement of the electron flux at $L = 2.5$.

Figure 5 shows the relationship between solar wind parameters and electron flux enhancements at $L = 2.5$ during the 209 events from 1995 to 2004. The results show good correlations between solar wind parameters $E_y$, IMF $B_z$, $B$, and flux enhancement magnitude. The correlation coefficients of $E_{y,\text{max}}, B_{z,\text{min}}$, and $B_{\text{max}}$ with the logarithm of the flux enhancement magnitude are 0.68, –0.64, and 0.61, respectively. $E_y \times \text{time}$ (when $E_y > 0.5 \text{ mV/m}$) has the highest correlation coefficient with the logarithm of the flux enhancement (0.71). On the other hand, solar wind speed, which is widely believed to be the parameter most strongly correlated with electron flux enhancements in the outer belt [e.g., Li et al., 2001, 2011], has a relatively weaker correlation with flux enhancements in the slot region (0.42). These results indicate that solar wind parameters have good correlations with electron flux enhancements in the slot region, and solar wind electric field is the most important parameter for controlling the magnitude of electron flux enhancements in the slot region.

3.3. Electron Flux Preconditioning for Electron Injections Into the Slot Region

3.3.1. Electron Flux Preconditioning

In section 3.2.1, we discussed sufficient and necessary solar wind conditions for injection events at $L = 2.5$. We mentioned one event during which the solar wind conditions are quite mild compared to others. Figure 6 (left) shows this event on 28 March 2001. The red dashed line shows the beginning of this event. The most likely explanation for why this event caused an injection at $L = 2.5$ despite the mild solar wind conditions is that the electron flux at $L$ greater than 2.5 is already high due to an intense storm on 19 March, while the flux at $L = 2.5$ is still low. Thus, the steep electron flux gradient makes it easier for these electrons preexisting around $L = 3$ to penetrate into $L = 2.5$. According to this, we define a preconditioned event as when the $2–6 \text{ MeV}$ electron flux at $L = 3$ is at least two orders higher than the flux at $L = 2.5$ prior to an event. Figure 6 (right) also shows a nonpreconditioned event on 7 April 2000, which also caused an injection event at $L = 2.5$. Comparing these two events, we find that for the nonpreconditioned event, much more intense solar wind conditions are required to cause a flux increase in the slot region. The minimum IMF $B_z$ for the nonpreconditioned event on 7 April 2000 is about $–30$ nT, and maximum $E_y$ is about $17 \text{ mV/m}$; while for the preconditioned event on 28 March 2001, $B_{z,\text{min}}$ and $E_{y,\text{max}}$ are just roughly $–13$ nT and 8 mV/m, respectively. Thus, electron flux preconditioning is a very important factor for electron injection into the slot region. It is worth mentioning that the flux after the event in March 2001 is relatively lower, with a post-event flux of less than 10 electrons/cm$^2$/sr/MeV. However, an electron flux enhancement of one order is quite significant at $L = 2.5$ and among all other 22 injection events at $L = 2.5$, 9 of them have similar post-event flux levels to this March 2001 event. Among these nine injection events, some are caused by quite intense solar

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**Figure 5.** IMF and solar wind parameters versus logarithm of flux enhancement at $L = 2.5$ during 209 events from 1995 to 2004. Dashed lines are linear fits to the points.

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wind conditions and strong storms, with \( |Dst_{\text{min}}| \) up to \(~ 250 \text{nT} \); but because the ratios of the electron flux at \( L = 3 \) to \( L = 2.5 \) before these injection events are lower than that before the preconditioned event in March 2001, the post-event flux levels for these events are just similar to the March 2001 event, which also confirms the importance of electron flux preconditioning.

### 3.3.2. Electron Flux Preconditioning of Injection Events at \( L = 2–3 \)

In the previous subsection, we focused primarily on injection events at \( L = 2.5 \). In this subsection, to investigate the influence of electron flux preconditioning, we use all injection events occurring in the slot region, from \( L = 2 \) to \( L = 3 \). Based on the definition of preconditioned events above, we divide injection events into preconditioned events and non-preconditioned events according to the flux profile at the beginning of the event. The definition of the beginning of the event here is the same as the one in section 3.2.2. We then plot the lowest \( L \) shell on which electron flux increased by at least one order (that is, the lowest \( L \) shell on which the injection event occurred based on our definition) versus \( |Dst_{\text{min}}| \) during the injection event (Figure 7). Figure 7 shows that for non-preconditioned events, the storm must be much stronger than preconditioned events to cause injections in the slot region. This suggests that with proper preconditioning, such as defined above, relativistic electrons are more likely to be injected into the center of the slot region, \( L = 2.5 \), while without preconditioning, it is also possible for electrons to move inward but much larger storms and thus much more intense solar wind conditions are required.

### 4. Discussion

Figure 3 shows the \( L-Dst \) dependence based on 117 geomagnetic storms during 1995–2004. It is worth noting that SAMPEX data may have saturation issues, and there may be some uncertainties in the \( L \)-location calculation. However, we demonstrate here that these uncertainties do not significantly affect the results in this \( L-Dst \) dependence study. For each storm, we examine the uncertainty in the \( L \) location of the maximum flux at the end of injection. Figure 8 shows the uncertainties in the \( L \) location of the maximum flux previously examined in Figure 3b. Red lines represent where the electron flux is greater than 90% of the maximum flux at the end of injection. Figure 8 shows that even considering these uncertainties, the \( L \) shell of the maximum flux at the end of injection still has a strong correlation with \( Dst \).

![Figure 6. Daily averaged 2–6 MeV electron fluxes in the slot region, IMF magnitude, IMF Bz, solar wind electric field, solar wind speed, and Dst index on 18–30 March 2001 (left) and 1–13 April 2000 (right). Red dashed lines mark the beginning of these injection events at \( L = 2.5 \).](image)

![Figure 7. Lowest \( L \) shell on which 2–6 MeV electron flux increased by at least one order of magnitude versus \( |Dst_{\text{min}}| \) during injection events that occurred at \( L = 2–3 \). Red points represent preconditioned events; black points represent non-preconditioned events. The dashed line shows \( L = 2.5 \).](image)
Figure 8. $L$ shell of the maximum electron flux at the end of injection versus $|\text{Dst}_{\text{min}}|$ for 117 storms during 1995–2004. Red lines represent where the flux is greater than 90% of the maximum flux. The dashed line is the linear fit to the points, and the dotted line shows the equation derived by Tverskaya [1986].

index, and thus these uncertainties do not significantly affect the result of $L$-$\text{Dst}$ dependence.

[20] The result of Figure 3 indicates that the $L$ location of relativistic electron injections is greatly influenced by geomagnetic activity, confirming previous studies [e.g., Tverskaya, 1986, 2003]. Tverskaya [1986] investigated the relationship between the minimum $\text{Dst}$ index and the $L$ location of peak intensity of storm-injected relativistic electrons during storms and gave the following formula:

$$|\text{Dst}|_{\text{max}} = 2.75 \times 10^4/L_{\text{max}}^4.$$  \hspace{1cm} (1)

[21] The dotted line in Figure 8 shows the relationship between $L_{\text{max}}$ and $|\text{Dst}_{\text{min}}|$ indicated by this equation. To compare with this equation, we also plot the dashed line, which is the linear fit to the points in Figure 8. It is apparent that although both the results from Tverskaya [1986] and our study show clear $L$-$\text{Dst}$ dependence, our result shows a deeper electron injection during storm time. Compared with previous studies [e.g., Tverskaya, 1986, 2003], our study gives clear criteria for storm selection and clear definition of $L_{\text{max}}$, which are much easier to follow and are reproducible by others. Furthermore, by using a larger database of storms and six different definitions of $L_{\text{max}}$, we examine the $L$-$\text{Dst}$ dependence in more detail. The results show that besides the $L$ location of the maximum flux, the $L$ location of deepest penetration, the $L$ location of the maximum flux enhancement, and flux variation during isolated geomagnetic storms all correlate well with the minimum $\text{Dst}$ index.

[22] Additionally, as Figure 7 shows, the $L$ value of the lowest penetration into the slot region for non-preconditioned events has a clear dependence on the minimum $\text{Dst}$ index. This is because the $L$ shell of the lowest penetration during a storm has a strong correlation with the storm intensity. For the preconditioned events, there is still a dependence of the $L$ shell of lowest penetration on minimum $\text{Dst}$ but it is not as clear. This may be because when the defined electron flux precondition is fulfilled, it is easier for energetic electrons to penetrate into $L = 2.5$, and if the ratio of electron flux at $L = 3$ to $L = 2.5$ before the event is higher, the penetration into $L = 2.5$ would be easier. Among the preconditioned events, some of them are better preconditioned than others with a higher ratio of flux at $L = 3$ to $L = 2.5$; thus, for these events, it is much easier to penetrate into the center of the slot region.

[23] Also, our choice to use 3 d averaged flux at the beginning of the storm and at the end of injection may have some influence on the result of $L$-$\text{Dst}$ dependence. To investigate in more detail, we try using different definitions for pre-storm flux and post-storm flux. For example, we use the flux of the day before $\text{Dst}_{\text{min}}$ as the flux at the beginning of the storm, and use the flux of 3 d after $\text{Dst}_{\text{min}}$ as the flux at the end of injection; we also try using the maximum flux 1–3 d before $\text{Dst}_{\text{min}}$ and the maximum flux 2–4 d after $\text{Dst}_{\text{min}}$. The results derived from these two different definitions are nearly identical with results showed in section 2.

[24] It is worth mentioning that among all isolated storms with $\text{Dst}_{\text{min}} < -50$ nT from 1995 to 2004, there are only two storms during which the 2–6 MeV electron flux at the end of the injection is lower than the flux at the beginning of the storm. This result suggests that the total electron flux at some $L$ shells increased compared to pre-storm levels, although the increase may be very slight. The results of Reeves et al. [2003] showed that only about half of all storms produced an increase in relativistic electron flux, one quarter decreased the fluxes and one quarter produced little change. However, they focused only on one $L$ shell at a time, between $L = 4$ and $L = 7$, while we investigate the flux enhancement at each $L$ shell from $L = 2$ to $L = 7$ during the storm. Based on our study, besides those two storms during which the flux decreased at all $L$ from $L = 2$ to $L = 7$, only 17 isolated storms (14%) produced little increase across all $L$ shells, by a factor of less than 2. This indicates that most isolated geomagnetic storms (84%) do produce significant relativistic electron flux enhancements at some $L$, although the $L$ location of peak enhancement may vary. Also, Reeves et al. [2003] suggested that the flux increase at a fixed $L$ shell is independent of $L$ size. We find, however, that the magnitude of the maximum flux enhancement among all $L$ shells from $L = 2$ to $L = 7$ does have a correlation with minimum $\text{Dst}$ index. Figure 9 shows the magnitude of the maximum flux enhancement by percentage versus $|\text{Dst}_{\text{min}}|$ during the 117 storms investigated, and the correlation coefficient between them is 0.52. This indicates that although the position of peak enhancement may change, larger storms are more likely to produce greater flux enhancements at some $L$ shell.

[25] On the other hand, we also sum up 2–6 MeV electron fluxes between $L = 2$ and $L = 7$ at the beginning of the storm and at the end of injection, respectively, and use these summations as rough estimates of the total number of electrons throughout the slot region and the outer radiation belt, similar to Baker et al. [2004b]. We find, however, that among all 119 storms, 47 storms (40%) caused increases in this total electron flux, 26 storms (20%) caused decreases, 46 storms (40%) produced little net change (within a factor of 2), and that the total flux enhancement has no correlation with storm intensity. This may be because larger storms are also more likely to produce greater losses.
Our results are not contradictory with Reeves et al. [2003], because they only focus on one \( L \) shell at a time, while we focus on all \( L \) shells from \( L = 2 \) to \( L = 7 \). It shows that although at a fixed \( L \) shell, about half of storms produce no change or decreases in the relativistic electron flux, throughout the slot region and the outer radiation belt, almost all storms will cause a flux enhancement at some \( L \) shell, and around 84% of them will produce significant increases at some \( L \) shell. However, only around 40% of storms will produce net increases in the total number of electrons throughout the slot region and the outer belt, 40% will produce little net change, and around 20% will cause net decreases. It should also be noted that the relativistic electron flux data we use is only derived from the SAMPEX satellite, while the Reeves et al. [2003] study uses multiple satellites, including the Los Alamos National Laboratory (LANL) space environment monitors and Polar. Also, because we focus on multiple \( L \) shells at a time and the SAMPEX satellite has limited differential energy measurements, it is difficult to derive phase space density data for a large range of \( L \), so we look only at fluxes rather than phase space densities.

We also check the difference between geomagnetic storms driven by coronal mass ejections (CMEs) and corotating interaction regions (CIRs) in the \( L - \text{Dst} \) dependence and the flux enhancement of energetic electrons. By using CME- and CIR-driven storms lists from Turner et al. [2009, and references therein], we find that among 119 isolated geomagnetic storms from January 1995 to June 2004, there are 54 CME-driven storms and 42 CIR-driven storms. Comparing the \( L - \text{Dst} \) dependence of CME- and CIR-driven storms, we find that there is no significant difference between them except that the CIR-driven storms are smaller relatively. For electron flux enhancements from \( L = 2 \) to \( L = 7 \), the difference between CME- and CIR-driven storms is still not significant. Among 54 CME-driven storms, only 6 storms (11%) produced little increase across all \( L \) shells by a factor of less than 2, all other storms (89%) produced significant increase at some \( L \) shell between \( L = 2 \) and \( L = 7 \); while among 42 CIR-driven storms, 2 storms (5%) decreased the flux at all \( L \) shells, 7 storms (17%) produced little increase across all \( L \), and 33 storms (78%) increased the flux at some \( L \) shell significantly. The CIR-driven storms appear to produce less flux enhancement; however, this is mainly due to the fact that CIR-driven storms are relatively smaller than CME-driven storms in terms of minimum \( \text{Dst} \), and as Figure 9 shows, the maximum flux enhancements among \( L = 2 - 7 \) are correlated with the minimum \( \text{Dst} \) index. Also, comparing the total flux enhancement between \( L = 2 \) and \( L = 7 \), both CME- and CIR-driven storms produced net flux increases, decreases and little change, and there is no significant difference between them.

We also investigate the relationship between flux enhancements in the slot region and solar wind-magnetosphere coupling. Newell et al. [2007] examined the interaction between solar wind and the magnetosphere and found that the function that represents the rate of magnetic flux opened at the magnetopause correlates quite well with multiple geomagnetic indices and some variables characterizing magnetospheric activity. This function, which is called the universal solar wind-magnetosphere coupling function, can be expressed as

\[
\frac{d\Phi_{\text{MP}}}{dt} = \nu^{4/3} B_T^{2/3} \sin^{5/3} (\theta_c/2)
\]

Here, \( d\Phi_{\text{MP}}/dt \) represents the rate of magnetic flux opened at the magnetopause, \( \nu \) represents the solar wind velocity, \( B_T \) represents the interplanetary magnetic field component perpendicular to the solar wind velocity, and \( \theta_c \) represents the IMF clock angle, which is given by \( \tan (\theta_c) = B_y/B_z \). Figure 10 shows the relationship between this universal coupling function and the logarithm of flux enhancement at \( L = 2.5 \). The universal coupling function is calculated by using 1 h solar wind data from OMNIWeb, which is suggested by Newell et al. [2007], and averaged over 3 d (same time period used in section 3.2.2 for calculation of solar wind parameters). The linear trend in Figure 10 is quite clear, with a correlation coefficient of 0.70. It suggests that relativistic electron flux enhancements

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**Figure 9.** The magnitude of the maximum flux enhancement among \( L = 2 - 7 \) (by percentage) versus \( |\text{Dst}_{\text{min}}| \) during 117 isolated storms from 1995 to 2004.

**Figure 10.** The universal solar wind-magnetosphere coupling function (averaged) versus logarithm of flux enhancement at \( L = 2.5 \) during 209 events from 1995 to 2004. Dashed line is the linear fit to the points.
in the slot region are greatly influenced by solar wind-magnetosphere coupling and energy transfer.

5. Conclusion

We have examined the relationship between Dst index and the L location of 2–6 MeV electron deepest penetration, maximum electron flux, maximum flux enhancement, and maximum flux variation during 119 moderate and strong isolated geomagnetic storms from 1995 to 2004 using daily averaged 2–6 MeV electron flux data from SAMPEX. Also, we have defined injection events in the slot region and investigated the correlation between electron injections at L = 2.5 and solar wind parameters. Moreover, we have found that electron flux preconditioning is also an important factor for injections in the slot region. The results are summarized as follows:

1. The L location of deepest penetration, the L location of the maximum flux at the end of injection, and the L location of the maximum flux variation (by value) during the storm have strong correlations with minimum Dst index during isolated geomagnetic storms, with correlation coefficients of 0.78, 0.83, and 0.87, respectively.

2. From 1995 to 2004, only two isolated storms produced 2–6 MeV electron flux decreases at all L shells from L = 2 to L = 7, and 17 storms (14%) produced little increase in electron flux at any L shell. Most isolated storms (84%) produced significant increases in 2–6 MeV electron flux at some L shell, and the magnitude of the maximum flux enhancement during the storm is correlated with the storm size. However, the sum of fluxes throughout the slot region and the outer belt, a rough measurement of the total number of electrons, increased during around 40% of storms, decreased during around 20% of storms, and did not change much during the other 40%. Moreover, the total flux enhancement has no correlation with storm size.

3. During 1995–2004, according to SAMPEX 2–6 MeV electron flux data, there are a total of 23 injection events during which the electron flux at L = 2.5 increases by at least one order of magnitude within 3 d. IMF magnitude, IMF Bz, solar wind electric field, and solar wind speed are correlated with injection events. The solar wind electric field and $E_v \times \text{time}$ (when $E_v > 0.5 \text{ mV/m}$) are the most effective parameters for injections into the slot region.

4. By examining injection events at L = 2.5, we find the sufficient and necessary solar wind conditions to cause injection events, as shown in Table 1. For the period 1995–2004, there are a total of 10 intervals during which the sufficient conditions are fulfilled and injection events occurred for each interval; a total of 30 intervals exist during which the necessary conditions are met, and 21 of these caused injection events at L = 2.5.

5. Injection events in the slot region are not only caused by extreme solar wind conditions; for events meeting defined electron flux preconditioning, it is much easier for electrons to penetrate into the center of the slot region (L = 2.5). Under the defined preconditioning, injections into the slot region can be caused by relatively mild solar wind condition.

References


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