Outer zone relativistic electron acceleration associated with substorm-enhanced whistler mode chorus

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We present plasma wave and particle data from the CRRES satellite during three case studies to investigate the viability of a local stochastic electron acceleration mechanism to relativistic energies driven by resonant interactions with whistler mode chorus. We first consider a strong geomagnetic storm that contains prolonged substorm activity during its 3-day recovery phase. The recovery phase is characterized by electron injections at subrelativistic energies, enhanced whistler mode chorus amplitudes, and a gradual increase in the flux of relativistic electrons (E > 1 MeV) over the entire outer zone, with fluxes exceeding the prestorm level by an order of magnitude in the region 3.5 < L < 4.5. We next consider a strong geomagnetic storm that contains very little substorm activity during its 3-day recovery phase. Here the recovery phase is characterized by a lack of sustained electron injections at subrelativistic energies, a low level of chorus amplitudes, and a net reduction in the flux of relativistic electrons in the outer zone. Finally, we examine a period of prolonged substorm activity in the absence of a significant storm signature, as measured by Dst. This period is characterized by electron injections at subrelativistic energies, enhanced chorus amplitudes, and a gradual increase in the flux of relativistic electrons in the region 4 < L < 6.5. These results suggest that the gradual acceleration of electrons to relativistic energies seen on a timescale of days during geomagnetic storms can be effective only when there are periods of prolonged substorm activity following the main phase of the geomagnetic storm. Furthermore, gradual electron acceleration to relativistic energies can be obtained during periods of prolonged substorm activity in the absence of a significant storm signature as indicated by Dst. The case studies show that the acceleration mechanism is confined to the region outside of the plasmapause and occurs in the presence of enhanced chorus waves. These results suggest that a local acceleration mechanism involving the energization of a seed population of electrons with energies of the order of a few hundred keV to relativistic energies by wave-particle interactions involving whistler mode chorus contributes to the reformation of the relativistic outer zone population following prolonged substorm activity.

INDEX TERMS: 2788 Magnetospheric Physics: Storms and substorms; 7807 Space Plasma Physics: Charged particle motion and acceleration; 7867 Space Plasma Physics: Wave/particle interactions; KEYWORDS: whistler mode chorus, electron acceleration, relativistic electrons, outer radiation belt, substorms

1. Introduction

[2] The flux of relativistic electrons (E > 1 MeV) in the Earth’s outer radiation belt (3 < L < 7) varies substantially during geomagnetic storms. Typically, the relativistic electron flux may fall by up to 2 or 3 orders of magnitude over a period of several hours at the beginning of the main phase. Subsequently, the flux may rise to peak levels 10–100 times the prestorm values over a period of 2–3 days during the recovery stage. These flux enhancements constitute a potentially serious hazard to satellites and possibly to humans in space. Indeed, satellite anomalies have been directly associated with these enhancements [Baker et al., 1994], and the radiation belt environment is an increasingly important region for space weather forecasting [Baker, 1998]. Moreover, precipitating relativistic electrons can penetrate to low altitudes and affect the ionization, conductivity, electric field, and chemistry of the middle atmosphere (see, for example, review by Lastovicka [1996]).

[3] There are several mechanisms which contribute to the initial flux decrease, including adiabatic effects associated
with the decrease of Dst [Kim and Chan, 1997], loss due to precipitation to the atmosphere during resonant interactions with enhanced plasma waves [e.g., Thorne and Kennel, 1971; Smith et al., 1974], and outward drift and loss via scattering at the magnetopause [Li et al., 1997a]. Observations suggest that the subsequent flux increase cannot be explained by adiabatic effects alone [Li et al., 1997b]. Furthermore, the electron phase space density in the solar wind is too low to supply the outer radiation belt directly [Li et al., 1997b]. These results imply that the increases in the relativistic electron flux are caused by acceleration processes within the magnetosphere itself, although the exact nature of these processes remains elusive.

[4] Enhanced storm time convection electric fields can provide a seed population of electrons with energies of the order of a few hundred keV. Wave-particle interactions then provide a potential mechanism for accelerating this seed population to relativistic values. Horne and Thorne [1998] identified several wave modes which could accelerate electrons to MeV energies via Doppler-shifted cyclotron resonance. In particular, they showed that whistler mode waves are able to resonate with electrons over a wide range of energies, including the important energy range from 100 keV to several MeV, showing that these waves could, in principle, accelerate electrons in the seed population up to MeV energies. In a related paper, Summers et al. [1998] considered the diffusion curves for resonant interactions with parallel propagating whistler mode waves and showed that significant energization can occur during resonant interactions with these waves. Summers and Ma [2000] then developed a model based primarily on a local stochastic acceleration by whistler mode chorus and showed that a necessary requirement was enhanced whistler mode chorus lasting for a period on the order of 1 or 2 days. Relativistic electron flux enhancements which occur on much faster timescales are therefore likely to be due to different acceleration mechanisms. For example, inductive electric fields have been associated with enhancements taking place on a rapid timescale, of the order of minutes [Li et al., 1993], and ULF pulsations have been associated with enhancements occurring over tens of minutes or hours [e.g., Rostoker et al., 1998; Liu et al., 1999]. In this paper we consider the potential contribution of wave-particle interactions involving whistler mode chorus to the gradual acceleration of electrons to relativistic energies seen on a timescale of days.

[5] Blake et al. [1997] showed that a high-speed solar wind stream and a leading pressure pulse can have a strong effect on the energetic electron population when the interplanetary magnetic field (IMF) turns southward. More recently, Iles et al. [2000] have shown that relativistic electron enhancements are correlated with the presence of high-speed solar wind streams and southward IMF during the recovery phase of a geomagnetic storm. This result suggests that substorm activity during the recovery phase may be an important factor in determining whether or not a gradual relativistic electron enhancement will occur. Meredith et al. [2001] recently investigated the substorm dependence of whistler mode chorus amplitudes in the radiation belts and showed that enhanced chorus emissions occur outside of the plasmapause during moderate (100 \(< AE < 300 \) nT) and active (AE > 300 nT) conditions, the extent and magnitude of the enhancements being largest during active conditions. These results suggest that gradual relativistic electron enhancements associated with geomagnetic storms are likely to be correlated with enhanced whistler mode chorus amplitudes during the recovery phase, supporting the suggestion that these waves are involved in the acceleration process.

[6] The majority (~90%) of geomagnetic storms have been found to result in relativistic electron flux enhancements [Reeves, 1998]. However, not all storms show such a response. For example, Meredith et al. [2001] briefly discussed one such response which was associated with the 26 August 1990 geomagnetic storm. In this particular case the IMF Bz turned northward during the recovery phase, and there was very little substorm activity and very little chorus activity, providing further evidence for the suggestion that substorms and chorus activity may be important if electron energization to relativistic energies is to proceed.

[7] Inward radial diffusion also provides a mechanism for accelerating electrons to relativistic energies in the outer zone following the storm time depletion. Brautigam and Albert [2000] performed a detailed phase space density analysis on the 9 October 1990 geomagnetic storm, using data from the CRRES spacecraft. They demonstrated that the temporal variability of the lower-energy electrons (M (\(< p^2\pi^2/2m_eB \) \(< 314 \) MeV G\(^{-1}\)) could be explained purely in terms of variations at the outer boundary (L (\(< 6.6\)) and Kp-dependent radial diffusion. However, the higher-energy electrons (M (\(> 700 \) MeV G\(^{-1}\)) exhibited a decrease in phase space density with increasing L, which is inconsistent with an inward radial diffusion source. The peak in phase space density inside L = 4.5 is indicative of an internal source acting at the heart of the outer belt throughout the storm recovery phase. The authors examined the plasma wave spectrograms for this storm and suggested that enhanced whistler mode chorus seen during the recovery phase could be involved in the acceleration process.

[8] Here we examine the behavior of the whistler mode chorus and electron flux during three specific events to see if the observations are consistent with an acceleration mechanism driven by whistler mode chorus. We begin by examining the 9 October 1990 geomagnetic storm (case 1). This is a strong storm associated with prolonged substorm activity during its recovery phase. We then examine the 26 August 1990 geomagnetic storm (case 2). This is a strong storm which, in contrast to case 1, is associated with little substorm activity during its recovery phase. The results from these two case studies suggest that prolonged substorm activity may be important, and in our final case study (case 3) we examine an extended period (11–16 September 1990) of prolonged substorm activity in the absence of a significant storm signature.

2. Instrumentation

[9] CRRES is particularly well-suited to studies of wave-particle interactions in the radiation belts because of both its orbit and its sophisticated suite of wave and particle instruments. The spacecraft was launched on 25 July 1990 and operated in a highly elliptical geosynchronous transfer orbit with a perigee of 305 km, an apogee of 35,768 km, and an inclination of 18°. The orbital period was ~10 hours, and
the initial apogee was at a magnetic local time of 0800 MLT. The satellite swept through the heart of the radiation belts on average ~5 times per day, providing good coverage of this important region for almost 15 months.

[10] The low-energy electron data used in this study were collected by the low-energy plasma analyser (LEPA) instrument. This instrument consisted of two electrostatic analyzers with microchannel plate detectors, each with a field of view of 120° × 5°, one measuring electrons and the other ions in the energy range 100 eV < E < 30 keV [Hardy et al., 1993]. The analyzers were mounted on the spacecraft with the 120° range covering angles from 30° to 150° with respect to the spacecraft spin axis, the total range being divided into 15 zones 8° wide. The energy was swept through the complete range 64 times per spin, synchronized to the spin period of 30 s. The instrument detected the complete pitch angle range from 0° to 180° every 30 s with a resolution of 5.625° × 8° at 20 energy channels in the range 100 eV < E < 30 keV.

[11] The high-energy electron data used in this study were collected by the Medium Electrons A (MEA) experiment. This instrument, which used momentum analysis in a solenoidal field, had 17 energy channels ranging from 153 keV to 1.582 MeV [Vampola et al., 1992]. The full field of view, coupled with the angular scan of 6° which occurred during the 0.512 s data accumulation period, resulted in a total acceptance angle of 8°–18°, depending on the channel.

[12] The wave data used in this study were provided by the University of Iowa plasma wave experiment. This experiment provided measurements of electric fields from 5.6 Hz to 400 kHz, using a 100-m tip-to-tip long wire antenna, and magnetic fields from 5.6 Hz to 10 kHz, using a search coil magnetometer, with a dynamic range covering a factor of at least 10^4 in amplitude [Anderson et al., 1992]. The electric field detector was thus able to detect waves from below the lower hybrid resonance frequency (f_{LHR}) to well above the upper hybrid resonance frequency (f_{UHR}) for a large fraction of each orbit.

3. Data Analysis

3.1. Electron Flux

[13] Complete pitch angle distributions were determined as a function of half-orbit (outbound or inbound) and L in steps of 0.1L for both LEPA and MEA by averaging the appropriate data over these intervals. The results were then stored together with the time in UT, magnetic latitude \( \lambda_m \), magnetic local time (MLT), and time spent in each bin. This enabled us to present the perpendicular flux in the familiar L versus time plots commonly used to study the temporal evolution of particle data.

[14] The combination of the Earth’s dipole tilt and the inclination of the CRRES orbit restricts the magnetic latitude coverage of the CRRES spacecraft to the range −30° < \( \lambda_m \) < 30°. The observed perpendicular flux will be a function of the magnetic latitude of the spacecraft when the particle distribution function is anisotropic. This can lead to a modulation of the flux with geomagnetic latitude, which should be borne in mind when interpreting the flux versus L plots.

[15] The MLT of apogee of the CRRES spacecraft for the three case studies ranges from 0657 MLT for orbit 75 at 2025 UT on 25 August 1990 to 0450 MLT for orbit 197 at 2308 UT on 14 October 1990, with the outbound and inbound sweeps through the outer radiation belt (L > 3) covering ~4 hours of MLT preapogee and postapogee, respectively. The drift periods for equatorially mirroring electrons at various energies and L are tabulated in Table 1. These periods show that the relativistic electrons complete orbits on timescales which are fast compared to the timescales of geomagnetic storms and drift through the MLT region of the outer radiation belt sampled by CRRES on a timescale of minutes. MLT variations in the region sampled by CRRES at these energies will not affect the analysis. The 214 and 14.3 keV electrons take on the order of 16 min and 3 hours, respectively, to gradient drift through the MLT region of the outer radiation belt sampled by CRRES during each orbit. At the lower energies, E × B drifts also contribute significantly to the rate of azimuthal drifts, with typical transit times across 8 hours of MLT near dawn being of the order of a few hours. Hence MLT variations between the outbound and inbound orbits may be apparent at 14.3 keV.

3.2. Chorus Amplitudes

[16] The wave data were initially corrected for the instrumental background response and smoothed using a running 3-min average to take out the beating effects due to differences in the sampling and the spin rate. Spurious data points, data spikes, and periods of instrumental downtime were flagged and ignored in the analysis. Whistler mode chorus is commonly observed in the range 0.1 → 0.8 f_{ce} [Koons and Roeder, 1990] with a gap occurring at 0.5 f_{ce} [Tsurutani and Smith, 1977]. The emissions were therefore divided into two categories which we refer to as lower- and upper-band chorus. The wave intensities were then defined by integrals of the averaged wave spectral density (V^2 m^-2 Hz^-1) over the frequency range 0.1/f_{ce} < f < 0.5 f_{ce} (lower-band chorus) and 0.5 f_{ce} < f < f_{ce} (upper-band chorus). The electron gyrofrequency f_{ce} was determined from the fluxgate magnetometer instrument on board the spacecraft [Singer et al., 1992]. The corresponding wave amplitudes were obtained by taking the square root of the appropriate integrated spectral densities. The background noise levels for the derived wave amplitudes are on the order of 5 × 10^10 mV m^-1. The amplitudes were then rebinned as a function of half-orbit (outbound or inbound) and L by averaging over steps of 0.1L and recorded together with the time in UT, magnetic latitude \( \lambda_m \), magnetic local time (MLT), and time spent in each bin.

[17] The chorus amplitudes are a sensitive function of location and substorm activity. Meredith et al. [2001] showed that the chorus amplitudes are most enhanced over the largest range of geospace in the lower band during active conditions in the region 4 < L < 7, −15° < \( \lambda_m \) < 15° from 2300 MLT through dawn to 1300 MLT. This enabled

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>L = 3</th>
<th>L = 4</th>
<th>L = 5</th>
<th>L = 6</th>
<th>L = 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.47 MeV</td>
<td>15.8 min</td>
<td>12.0 min</td>
<td>8.64 min</td>
<td>7.92 min</td>
<td>6.77 min</td>
</tr>
<tr>
<td>1.09 MeV</td>
<td>20.4 min</td>
<td>15.3 min</td>
<td>12.2 min</td>
<td>10.2 min</td>
<td>8.78 min</td>
</tr>
<tr>
<td>214 keV</td>
<td>1.34 hours</td>
<td>1.01 hours</td>
<td>48.4 min</td>
<td>40.3 min</td>
<td>34.5 min</td>
</tr>
<tr>
<td>14.3 keV</td>
<td>17.4 hours</td>
<td>13.1 hours</td>
<td>10.1 hours</td>
<td>8.71 hours</td>
<td>7.47 hours</td>
</tr>
</tbody>
</table>
us to determine a quantitative measure of the chorus activity during any given period by averaging the lower-band chorus over this latitude range, referred to as equatorial lower-band chorus, between 2300 and 1300 MLT over unit steps in $L$ centered on 3, 4, 5, and 6. For the three case studies the CRRES spacecraft encountered dusk around perigee, and for $L > 2.5$ the observations were always in the region $0000 \rightarrow 1130$ MLT. In all cases this quantitative measure of the chorus activity was equivalent to the average equatorial lower-band chorus amplitudes.

4. Case Studies

[18] We adopt the original notation of Sugiura and Chapman [1960], recently modified by Loewe and Prolss [1997], to describe the geomagnetic storms as follows: strong when $-200 \text{ nT} < Dst_{\text{min}} < -100 \text{ nT}$, moderate when $-100 \text{ nT} < Dst_{\text{min}} < -50 \text{ nT}$, and weak when $-50 \text{ nT} < Dst_{\text{min}} < -30 \text{ nT}$.

4.1. Case 1: Strong Geomagnetic Storm Followed by Prolonged Substorm Activity in the Recovery Phase

[19] We begin by examining the 9 October 1990 geomagnetic storm. This is a good example of a strong geomagnetic storm, which contains prolonged substorm activity during the recovery phase. Figure 1 shows the geophysical parameters, together with the electron flux, wave amplitudes, and spacecraft location as a function of $L$ and time for this event. Starting at the foot of the plot and moving upward, the panels show the $Kp$ index (color-coded) together with a line plot of the $AE$ index, the $Dst$ index (color-coded), the solar wind speed and interplanetary magnetic field (IMF) $Bz$ from IMP 8, wave amplitudes for lower-band chorus and upper-band chorus, the perpendicular electron fluxes at 14.3 keV, 214 keV, 1.09 MeV, and 1.47 MeV, magnetic latitude, and magnetic local time. The electron fluxes are in the standard units of cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$. The approximate position of the plasmapause, $L_p$, given by the expression

$$L_p = 5.6 - 0.46Kp^*,$$

where $Kp^*$ is the maximum value of $Kp$ in the previous 24 hours [Carpenter and Anderson, 1992], is marked in Figures 1a–1h as a thin white line. Each orbit is defined to start and finish at perigee, so that on these plots one orbit of data is represented by two vertical stripes, corresponding to the outbound and inbound legs, respectively.

[20] The spatial and temporal structure of the perpendicular flux as a function of $L$ may be better quantified using line plots of the former against the latter. These are shown for the perpendicular flux at 1.47 MeV, 1.09 MeV, 214 keV, and 14.3 keV in Figures 2a–2d, respectively, during selected outbound, near-equatorial passes when the CRRES spacecraft traversed the outer radiation belt within $15^\circ$ of the magnetic equator. Using these near-equatorial passes facilitates comparison of the profiles throughout the event by reducing the modulating effect of the changing magnetic latitude of the spacecraft. The profiles are color-coded to identify the associated orbit. For each of the case studies the reader should refer to the detailed overview plots (Figure 1 in this case) unless specific reference is made to the line plots (Figure 2 in this case).

4.1.1. Geophysical parameters

[21] This is a strong geomagnetic storm with a minimum $Dst$ of $-133$ nT, occurring at 0830 UT on 10 October 1990. The main phase of this geomagnetic storm starts at 0030 UT on 10 October and lasts for ~8 hours. During this period the IMF has a strong southward component, and the solar wind speed is $\sim 500$ km s$^{-1}$. The main phase is followed by a long recovery phase containing several subsidiary $Dst$ minima, the $Dst$ index eventually returning to quiet time values after ~3.25 days at 1430 UT on 13 October. The $AE$ index is elevated during the main phase with a peak value of 971 nT just after the $Dst$ minimum at 0930 UT on 10 October. The $AE$ index fluctuates but remains predominantly enhanced during the entire 3.25-day recovery period with values greater than 100 nT for 90% of the time and values greater than 300 nT for 62.5% of the time. This event is thus a clear example of a strong storm with significant substorm activity during the main and recovery phases.

4.1.2. 1.47- and 1.09-MeV electrons

[22] The fluxes of relativistic electrons are initially observed in two zones, separated by a slot region. The measured fluxes of relativistic electrons in the inner zone ($L < 2$) may suffer from proton contamination (A. Vampola, personal communication, 2001) and consequently are not discussed further in this paper. The outer zone flux of 1.47 MeV electrons peaks initially at $\sim 80$ cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ at $L = 4.7$ (dark blue trace in Figure 2a). The outer zone flux of 1.09-MeV electrons peaks initially at $\sim 200$ cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ at $L = 5$ (dark blue trace in Figure 2b). A reduction in the relativistic electron flux in the region $L > 4.5$ is observed following the magnetospheric compression (increase in $Dst$) on 9 October (light blue traces in Figures 2a and 2b). This is not a $Dst$ effect but rather due to loss via scattering at the magnetopause and/or interactions with enhanced plasma waves. This is followed by a dropout in the relativistic electron flux associated with the main phase of the storm caused by the $Dst$ effect and other nonadiabatic loss mechanisms, which almost results in the complete disappearance of the outer zone at the $Dst$ minimum near 0830 UT on 10 October. The main phase is followed by a relatively rapid recovery in the outer zone relativistic electron flux during the next orbit (10 hours later). At 1.47 MeV the fluxes are less than the prestorm values (green trace in Figure 2a), but at 1.09 MeV the fluxes exceed the prestorm values in the region $3.6 < L < 4.8$ but...
are less than the prestorm values in the region $4.8 < L < 6.5$ (green trace in Figure 2b). The peak of the reformed outer zone now occurs nearer to the Earth being located at $L = 4.3$ and $L = 4$ for the 1.47- and 1.09-MeV electrons, respectively. The outer zone relativistic electron flux then gradually increases during the next 2.75 days over the entire outer zone with fluxes eventually exceeding the prestorm values by an order of magnitude in the region $3.5 < L < 4.5$ (red traces in Figures 2a and 2b). The outer zone fluxes of 1.47- and 1.09-MeV electrons now peak at $L = 4.2$ with values of $10^6$ cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$, respectively.

4.1.3. 214-keV electrons

The 214-keV flux is initially observed in two zones, separated by a slot region. The inner zone flux peaks at $10^5$ cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ at $L = 2.0$ and then falls off with increasing $L$, reaching a minimum value of $10^4$ cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ at $L = 3.7$. Thereafter, the flux rises to form the outer zone in the region $L > 3.7$ with a peak flux of $10^5$ cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ at $L = 4.7$ (dark blue trace in Figure 2c). Electron injections associated with the first few hours of the main phase of the storm lead to an increased flux in the region $3 < L < 6$. However, this is followed by a modest reduction in the flux in the region $3 < L < 7$ associated with the $Dst$ minimum. The electron flux in the region $2.5 < L < 7$ increases during the next orbit (10 hours), completely filling the slot region (green trace in Figure 2c).

4.1.4. 14.3-keV electrons

The flux of 14.3-keV electrons is highly variable and is enhanced predominantly outside of the plasmapause in association with substorm activity. Reduced fluxes of 14.3-keV electrons on the order of $10^5$ cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ are seen in the region outside the plasmapause at the beginning of this event, consistent with this period being magnetically quiet and lacking substorm activity. Electron injections associated with the storm main phase then lead to enhanced fluxes outside the plasmapause at a time when the high-energy flux has dropped out. Significant enhancements are also seen at regular intervals during the recovery phase in association with substorm activity. The largest enhancements are being seen during the outbound passes in the predawn sector (see, for example, the light blue, green, and yellow traces in Figure 2d).
4.1.5. Chorus activity

[25] The chorus activity is predominantly enhanced, particularly in the lower band, during both the main phase and the recovery phase. The enhanced chorus emissions lie mainly outside the plasmapause. Moreover, as the plasmapause moves to smaller L during magnetically active periods, the inner edge of the chorus emissions also moves to smaller L and follows the plasmapause position very closely. The average values of the equatorial lower-band chorus amplitudes during the recovery phase are 0.24, 0.77, 0.81, and 0.56 mV m\(^{-1}\) at \(L = 3, 4, 5,\) and 6, respectively.

4.1.6. Event summary

[26] The recovery phase of this storm is associated with a gradual increase in the flux of relativistic electrons over the whole of the outer zone. This is coincident with a period of prolonged substorm activity, injections of subrelativistic electrons and enhanced chorus amplitudes.

4.2. Case 2: Geomagnetic Storm Followed by Little Substorm Activity During the Recovery Phase

[27] We next examine the 26 August 1990 geomagnetic storm. This is an example of a strong geomagnetic storm, which contains little substorm activity during the recovery phase. The geophysical parameters, wave data, electron data, and spacecraft location for this event are shown in Figure 3, and the flux versus \(L\) profiles during the outbound, near-equatorial passes are shown in Figure 4.

4.2.1. Geophysical parameters

[28] This is a strong geomagnetic storm with a minimum \(DST = -113\) nT, occurring at 1330 UT on 26 August. The main phase of this geomagnetic storm starts around 0730 UT on 26 August and lasts for ~6 hours. During this period the IMF is predominantly strongly southward, and the solar wind speed is typically ~700 km s\(^{-1}\). The main phase is followed by a recovery phase which lasts ~3 days during which time the \(AE\) index gradually returns to quiet time values. The \(AE\) index is elevated during the main phase with a peak value of 1109 nT at 0830 UT on 26 August. The \(AE\) index remains elevated with values >500 nT for several hours following the main phase and then falls rapidly to 93 nT at 2030 UT on 26 August. There is a brief recovery to 319 nT at 2330 UT on 26 August which falls back to 63 nT at 0330 on 27 August. The \(AE\) index then remains predominantly below 100 nT for the next 2 days. This is coincident with a period of strong and consistent northward IMF. During the entire 3-day recovery period the \(AE\) index is greater than 100 nT for 32% of the time and greater than 500 nT for 5% of the time. This is a clear example of a strong storm with significant substorm activity during the main phase but with very little substorm activity during the recovery phase.

4.2.2. 1.47- and 1.09-MeV electrons

[29] The outer zone fluxes initially peak at \(L = 3.6\) with values of ~1300 and 2250 cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) keV\(^{-1}\) at 1.47 and 1.09 MeV, respectively (dark blue traces in Figures 4a and 4b). The outer zone fluxes are of the same order of magnitude as those observed by the end of the recovery phase during case 1 and are associated with a moderate geomagnetic storm which occurred 4 days earlier. There is a dropout in the relativistic electron flux associated with the main phase of the storm caused by the \(DST\) effect and other nonadiabatic loss mechanisms. The flux falls throughout the outer zone, but the dropout is largest and of the order of 2 or 3 orders of magnitude in the region 4.7 < \(L < 6.0\), near the \(DST\) minimum at 1330 UT on 26 August. The relativistic electron flux recovers partially during the next 10 hours. This is not purely a \(DST\) effect since the partial recovery takes place before any significant increase in the \(DST\) index. Thereafter, during the remainder of the recovery phase the flux of relativistic electrons stays roughly constant and typically an order of magnitude less than the prestorm values (light blue, green, and yellow traces in Figures 4a and 4b). By the end of the recovery phase the outer zone fluxes of 1.47-and 1.09-MeV electrons peak at \(L = 3.3\) with values of ~500 and 900 cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) keV\(^{-1}\), respectively. This geomagnetic storm is not associated with a flux enhancement of relativistic electrons. On the contrary, the net flux at the end of the recovery phase is less than the prestorm values, and this storm is characterized by electron loss at relativistic energies.

4.2.3. 214-keV electrons

[30] The 214-keV flux is initially enhanced with a filled-in slot region, caused by the previous geomagnetic storm. Here the flux peaks at 10\(^{5}\) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) keV\(^{-1}\) at \(L = 2.5\) and then falls off to ~10\(^{4}\) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) keV\(^{-1}\) at \(L = 6\) (dark blue trace in Figure 4c). There is a dropout in the electron flux associated with the main phase of the storm caused by the \(DST\) effect and other nonadiabatic loss mechanisms. The 214-keV electrons return to their prestorm values very quickly, within the next half orbit and before the \(DST\) index has recovered. This is not purely an adiabatic effect and indicates that some of these electrons have either been injected or accelerated in this region. The flux then stays relatively constant up to 28 August but typically falls by a factor of 2 to 3 in the region 3 < \(L < 5.2\) by the end of the recovery phase (yellow trace in Figure 4c).

4.2.4. 14.3-keV electrons

[31] During the main phase of the storm, enhanced fluxes of 14.3-keV electrons are observed outside the plasmapause which moves inward toward \(L = 2.5\). At the end of the main phase, fluxes of the order of 2 \(	imes\) 10\(^{3}\) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) keV\(^{-1}\) are seen, principally in the region 3.0 < \(L < 5.5\). Enhanced fluxes are also seen outside \(L = 5\) during the first hours of the recovery phase associated with substorm activity occurring around 0000 UT on 27 August (light blue trace in Figure 4d). Thereafter, no significant electron injections are seen during the remainder of the recovery phase. During this period the electron fluxes are typically less than 10\(^{5}\) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) keV\(^{-1}\) (see, for example, the green trace in Figure 4d).

4.2.5. Chorus activity

[32] The chorus activity is enhanced during the period of enhanced \(AE\) activity during the main phase and at the beginning of the recovery phase. The average values of the equatorial lower-band chorus amplitudes during this period of enhanced wave activity are 0.28, 0.52, 0.15, and 0.16 mV m\(^{-1}\) at \(L = 3, 4, 5,\) and 6. These amplitudes are of a similar order of magnitude to those seen during the period of prolonged substorm activity during the recovery phase of case 1 but are smaller at larger \(L\). The chorus activity then falls to quiet time values and remains reduced during the next 2 days while the \(AE\) index is small, during the remainder of the recovery phase of the storm. The
Figure 3. (a–k) Re-binned data and relevant geophysical parameters for case 2 in the same format as Figure 1. See color version of this figure at back of this issue.
average values of the equatorial lower-band chorus amplitudes during this period are 0.052, 0.028, 0.025, and 0.041 mV m\(^{-1}\) at \(L = 3, 4, 5,\) and 6, respectively. These reduced amplitudes are typically an order of magnitude less than those associated with the prolonged substorm activity occurring during the recovery phase of case 1.

**4.2.6. Event summary**

The recovery phase of this storm, in contrast to case 1, is associated with a net reduction in the flux of relativistic electrons in the outer zone and is coincident with a lack of substorm activity, a lack of sustained injections of subrelativistic electrons, and a low level of chorus amplitudes.

**4.2.7. Subsequent electron acceleration to relativistic energies**

The recovery phase of this geomagnetic storm is followed by a period of enhanced \(AE\) activity from 0430 UT on 29 August to 1530 UT on 30 August, which takes place in the absence of any storm signatures in the \(Dst\) index. During this 35-hour period the \(AE\) index is greater than 100 nT for 80% of the time and greater than 300 nT for 33% of the time. Substorm injection signatures are seen at 14.3 keV, and the chorus activity is enhanced. The average values of the equatorial lower-band chorus amplitudes are 0.054, 0.23, 0.43, and 0.13 mV m\(^{-1}\) at \(L = 3, 4, 5,\) and 6, respectively. There is some evidence for an increase in the relativistic electron flux during this period in the region \(5 < L < 6,\) suggesting that it may be possible to obtain electron acceleration to relativistic energies by periods of enhanced chorus activity in the absence of a geomagnetic storm. This idea is investigated in more detail in a separate and clearer case study in section 5.

A moderate geomagnetic storm then follows with a minimum \(Dst\) of \(-54\) nT at 1730 UT on 30 August. The \(Dst\) index then gradually returns to quiet time values over a period of 1.5 days. The \(AE\) index reaches a value of 689 nT at \(Dst\) minimum and is enhanced during a large fraction of the recovery phase with values above 100 nT for 69% of the time and above 300 nT for 28% of the time. Substorm injection signatures are seen at subrelativistic energies, and the chorus activity is enhanced. The average values of the equatorial lower-band chorus amplitudes are 0.13, 0.44, 1.0, and 0.63 mV m\(^{-1}\) at \(L = 3, 4, 5,\) and 6, respectively, comparable with those observed during the period of prolonged substorm activity during the recovery phase of case 1. The flux of relativistic electrons in the region \(4.0 < L < 6.5\) (outside the plasmapause) then continues to increase to maximum values which occur at the beginning of 1 September (red traces in Figures 4a and 4b). In sharp contrast, the flux of relativistic electrons at lower \(L (2.8 < L < 4)\) continues to decrease during this same period. This flux reduction, which is inside the plasmapause, may be
associated with pitch angle scattering by enhanced plasmaspheric hiss and/or electromagnetic ion cyclotron (EMIC) waves.

4.3. Case 3: Prolonged Substorm Activity in the Absence of a Significant Storm Signature

[36] Here we examine an event associated with prolonged substorm activity in the absence of a significant storm signature as measured by $\Delta$St. The geophysical parameters, wave data, electron data, and spacecraft location for this event are shown in Figure 5, and the flux versus $L$ profiles during the outbound, near-equatorial passes are shown in Figure 6.

4.3.1. Geophysical parameters

[37] The $\Delta$St index is predominantly greater than $-30$ nT during this interval although some excursions below $-30$ nT are encountered, indicative of weak storm activity. Thus we would not identify this event as a significant storm event. However, the $AE$ index is predominantly enhanced during the 5-day period between 11–16 September 1990, with values greater than 100 nT for 89% of this period and values greater than 300 nT for 52% of this period.

4.3.2. 1.47- and 1.09-MeV electrons

[38] The outer zone flux of 1.47-MeV electrons initially peaks at $\sim120$ cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ at $L = 5$ (dark blue trace in Figure 2a). The outer zone flux of 1.09-MeV electrons initially peaks at $\sim300$ cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ at $L = 5.2$ (dark blue trace in Figure 2b). There is a flux dropout at relativistic energies in the outer zone, principally in the region $4 < L < 6$ associated with the plasmaspheric compression (an increase in $\Delta$St) at 0600 UT on 11 September. The relativistic electron flux then increases gradually in the region $L > 4$ over the next few days to levels which eventually exceed the precompression levels in the range $4 < L < 5.5$. By the end of this period of enhanced substorm activity the outer zone fluxes of 1.47- and 1.09-MeV electrons peak at $L = 4.7$ with values of $\sim300$ and 800 cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$, respectively (red traces in Figures 6a and 6b). There is evidence for a gradual reduction in the flux of relativistic electrons in the region $2.8 < L < 3.8$. This reduction occurs inside the plasmapause and is most likely associated with pitch angle scattering via enhanced plasmaspheric hiss and/or EMIC waves.

4.3.3. 214-keV electrons

[39] The 214-keV flux is initially observed in two zones, separated by a slot region. The inner zone flux peaks at $\sim8 \times 10^4$ cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ at $L = 2.0$ and then falls off with increasing $L$, reaching a minimum value of $\sim600$ cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ at $L = 3.9$ (dark blue trace in Figure 6c). Thereafter, the flux rises to form the outer zone in the region $L > 3.9$ with a peak flux of $\sim9000$ cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ at $L = 6$. There is a sharp flux increase in the region $5 < L < 6$ at 0000 UT on 11 September. This is followed by a flux dropout in the region outside of the plasmapause associated with the compression. The flux then increases by 0000 UT on 12 September and partially fills the slot region. The flux then remains enhanced with fluxes $\geq10^4$ cm$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$ in the region $4 < L < 6$ throughout the remainder of the period.

4.3.4. 14.3-keV electrons

[40] Electron injections associated with the enhanced level of magnetic activity lead to an enhanced fluxes outside the plasmapause in the region $L > 4$. The flux is stronger during the outbound passes when CRRES is in the predawn sector. The near-equatorial outbound orbits show that the flux is enhanced by greater than an order of magnitude over the precompression levels in the range $4 < L < 6$ (compare, for example, the dark blue trace with the other traces in Figure 6d).

4.3.5. Chorus activity

[41] The chorus activity is predominantly enhanced during this period, in the region outside of the plasmapause, with average values of the equatorial lower-band chorus amplitudes of 0.098, 0.55, 0.73, and 0.69 mV m$^{-1}$ at $L = 3, 4, 5$, and 6, respectively. These amplitudes are of a similar order of magnitude to those seen during the period of prolonged substorm activity during the recovery phase of case 1.

4.3.6. Event summary

[42] This event is associated with a period of gradual electron acceleration over a large fraction of the outer zone that is not associated with a significant geomagnetic storm but which is coincident with a period of prolonged substorm activity, injections of subrelativistic electrons, and enhanced chorus amplitudes.

5. Discussion

[43] We use plasma wave and particle data from the CRRES satellite to investigate the role of wave-particle interactions involving whistler mode chorus in the gradual acceleration of outer zone electrons to relativistic energies, occurring over a time period of several days.

[44] We begin by studying the strong geomagnetic storm of 9 October 1990. This geomagnetic storm is followed by a 3-day recovery phase associated with sustained substorm activity. Our experimental analysis shows that this period is associated with the gradual acceleration of electrons to relativistic energies over the entire outer zone ($3.2 < L < 7$). Bruegmann and Albert [2000] applied a detailed phase space density analysis to this geomagnetic storm and showed that the gradual acceleration of $>1$ MeV electrons in the storm recovery cannot be due to radial diffusion alone and that some other process must be operating to accelerate the electrons. They suggested that enhanced whistler mode chorus could play a role. Our analysis of the waves and particles during the recovery phase of this storm shows that this period is associated with sustained injections of subrelativistic electrons and enhanced chorus amplitudes. These signatures are seen primarily outside of the plasmapause which for this event was located around $L = 3$ in the postmidnight sector. The chorus amplitudes are thus enhanced over the same region of geospace as the gradual acceleration. Moreover, R. B. Home et al. (Evolution of energetic electron pitch angle distributions during storm time electron acceleration to MeV energies, submitted to Journal of Geophysical Research, 2001), (hereinafter referred to as Home et al., submitted manuscript, 2001) have recently studied the evolution of the electron pitch angle distributions in the energy range from 0.15 to 1.58 MeV for this event. They observed energy-dependent flat top distributions during the recovery phase, consistent with resonant interactions with whistler mode chorus.
Figure 5. (a–k) Rebinned data and relevant geophysical parameters for case 3 in the same format as Figure 1. See color version of this figure at back of this issue.
We then study the strong geomagnetic storm of 26 August 1990. This geomagnetic storm contains little substorm activity during its recovery phase, enabling us to test the importance of sustained substorm activity during the recovery phase. This period is associated with no significant injections of subrelativistic electrons, reduced chorus amplitudes, and a lack of electron acceleration to relativistic energies. A moderate storm follows on 30 August 1990, the recovery phase of which is associated with injections of subrelativistic electrons, enhanced chorus amplitudes, and a gradual increase in the flux of relativistic electrons outside of the plasmapause in the region $4.0 < L < 6.5$.

These results suggest that prolonged substorm activity (identified by $AE > 100$ nT) during the recovery phase is required for a gradual enhancement to proceed. This raises the interesting possibility that electron acceleration to relativistic energies may occur in the presence of prolonged substorms outside of a geomagnetic storm. Therefore, for our third case study we examine an extended period of prolonged substorm activity that occurs in the absence of any significant storm signatures. This period is associated with injections of subrelativistic electrons, enhanced chorus amplitudes, and a gradual acceleration of electrons to relativistic energies.

More generally, enhanced chorus amplitudes are observed outside of the plasmapause and are largely substorm dependent. They are principally observed in two regions. Within $15^\circ$ of the magnetic equator the amplitudes are most enhanced in the region $3 < L < 7$ from 2300 MLT through dawn to 1300 MLT [Meredith et al., 2001], consistent with keV electron injection from substorms near midnight and subsequent drift around dawn to the dayside. At higher latitudes the chorus amplitudes are most enhanced on the dayside in the region $3 < L < 7$ from 0600 to 1500 MLT [Meredith et al., 2001], consistent with wave generation in the horns of the magnetosphere [Tsurutani and Smith, 1977]. The chorus amplitudes in both regions are significantly enhanced during substorms and may thus both contribute to the acceleration of relativistic electrons.

The results from the three case studies show that the gradual acceleration of electrons to relativistic energies seen on a timescale of days is associated with prolonged substorm activity, injections of subrelativistic electrons, and enhanced chorus amplitudes. These enhanced chorus waves can resonate with electrons over a wide range of energies, including the important energy range from 100 keV to several MeV [Horne and Thorne, 1998] and may cause significant energization of a seed population of electrons with energies on the order of a few hundred keV [Summers et al., 1998] on a timescale of days [Summers and Ma, 2000].
Here we have used the Dst index to define a magnetic storm. However, the Kp index may also be used as an index for storms and is frequently used to describe the overall geomagnetic condition. The rate of radial diffusion is known to be closely correlated with Kp [see, e.g., Brautigam and Albert, 2000, and references therein]. Furthermore, extended periods of elevated geomagnetic activity levels of Kp of 3–3.5 have been associated with relativistic electron flux enhancements at GPS L = 4.2 [Hilmer et al., 2000]. The observations presented here are also consistent with Kp being a critical parameter since the enhancements all occur during periods of elevated Kp. However, Brautigam and Albert [2000] have shown that the relativistic electron flux enhancements observed during case 1 cannot be explained solely in terms of radial diffusion. Furthermore, the flat-topped pitch angle distributions observed after the acceleration events would appear to be inconsistent with radial diffusion (Horne et al., submitted manuscript, 2001) and provide further evidence for local stochastic acceleration by whistler mode chorus.

The CRRES results presented here provide evidence of enhanced substorm activity and whistler mode chorus associated with electron acceleration to relativistic energies in the outer radiation belt and provide strong circumstantial evidence for the theory of local stochastic electron acceleration to relativistic energies driven by resonant wave-particle interactions with whistler mode chorus. However, further detailed analysis will be required to determine the relative roles of radial diffusion and local stochastic acceleration in the energization process.

6. Conclusions

We present plasma wave and particle data from the CRRES satellite during three case studies to investigate the viability of a local stochastic electron acceleration mechanism to relativistic energies driven by resonant interactions with whistler mode chorus. We examine two strong geomagnetic storms: one with and one without prolonged substorm activity in the recovery phase and a period of prolonged substorm activity in the absence of a significant geomagnetic storm. Our main conclusions are as follows:

1. Prolonged substorm activity, occurring over a period of days, is associated with the gradual acceleration of electrons to relativistic energies seen on these timescales during the recovery phase of geomagnetic storms.

2. Gradual acceleration of electrons to relativistic energies can also be obtained by periods of prolonged substorm activity in the absence of a significant geomagnetic storm as indicated by the Dst index.

3. Periods of prolonged substorm activity are associated with enhanced fluxes of injected subrelativistic electrons and enhanced whistler mode chorus amplitudes.

4. The CRRES observations provide strong circumstantial evidence for the local stochastic acceleration of electrons to relativistic energies driven by wave-particle interactions involving whistler mode chorus.

Although radial diffusion should also be enhanced during the extended periods of substorm activity, Brautigam and Albert [2000] have shown that it cannot fully explain the relativistic flux enhancements seen during case 1. Further data analysis will be required to quantify the relative roles of radial diffusion and local stochastic acceleration in the energization of electrons to relativistic energies.

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Figure 1. (opposite) (a–k) Rebinned data and relevant geophysical parameters for case 1. Starting at the foot of the plot and moving upward, the panels show the $K_p$ index (color-coded) together with a line plot of the $AE$ index, the $Dst$ index (color-coded), the solar wind speed and interplanetary magnetic field (IMF) $B_z$ from IMP 8, the wave amplitudes for lower-band chorus and upper-band chorus, the perpendicular electron flux at 14.3 keV, 214 keV, 1.09 MeV, and 1.47 MeV, magnetic latitude, and magnetic local time. Note that the electron fluxes are in the standard units of $cm^{-2}s^{-1}sr^{-1}keV^{-1}$. The empirical position of the plasmapause is marked in Figures 1a–1h as a solid white line.

Figure 2. Temporal evolution of the $L$ profiles of the perpendicular flux at (a) 1.47 MeV, (b) 1.09 MeV, (c) 214 keV, and (d) 14.3 keV during case 1 from selected outbound, near-equatorial passes. The profiles are color-coded to identify the associated orbit. The $AE$, $K_p$, and $Dst$ indices are included in the same format as Figure 1.
Figure 3. (a–k) Rebinned data and relevant geophysical parameters for case 2 in the same format as Figure 1.
Figure 4. Temporal evolution of the $L$ profiles of the perpendicular flux at (a) 1.47 MeV, (b) 1.09 MeV, (c) 214 keV, and (d) 14.3 keV during case 2 from selected outbound, near-equatorial passes. The profiles are color-coded to identify the associated orbit. The $AE$, $Kp$, and $Dst$ indices are included in the same format as Figure 3.
Figure 5. (a–k) Rebinned data and relevant geophysical parameters for case 3 in the same format as Figure 1.
Figure 6. Temporal evolution of the $L$ profiles of the perpendicular flux at (a) 1.47 MeV, (b) 1.09 MeV, (c) 214 keV, and (d) 14.3 keV during case 3 from selected outbound, near-equatorial passes. The profiles are color-coded to identify the associated orbit. The $AE$, $Kp$, and $Dst$ indices are included in the same format as Figure 5.