Rapid Enhancements of Relativistic Electrons in the Earth's Outer Radiation Belt caused by the Intense Substorms: A Statistical Study

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Key Points:

1. The statistical study of rapid enhancements of relativistic electrons in the outer radiation belt caused by the intense substorms are presented
2. Continuous substorm activities can accelerate electrons to relativistic energies more rapidly (< 9 h) and efficiently
3. MeV electron injections during the intense substorms could contribute to rapid enhancements of MeV electrons in the outer radiation belt

Abstract

Using the data from Van Allen Probe A and B, we investigate rapid enhancements of relativistic electrons in the Earth's outer radiation belt caused by the intense substorms ($AE_{max} > \sim 900$ nT) for 29 events from January 2013 to April 2015. These intense substorms may occur during the storm main phase or recovery phase. Based on the different substorm evolution characteristics, the intense substorms are divided into isolated substorm activities and continuous substorm activities. In this study, we set a criterion for rapid enhancements when the electron phase space densities (PSDs) for = 1096, 2290, and 3311 MeV/G increased by more than 2 times in 9 hours. In the time interval of 9 hours, the local acceleration of chorus waves is the dominant process for accelerating the seed populations (100s keV) up to MeV energies. Our statistical results show that enhanced chorus waves and seed electrons during the intense substorms are observed in the outer radiation belt. Continuous substorm activities can more rapidly (< 9 h) and efficiently accelerate relativistic electrons

in the outer radiation belt than isolated substorm activity. During the intense substorms, MeV electron injections could contribute to rapid enhancements of relativistic electrons in the outer radiation belt. Our statistical study suggests that the intense substorms during geomagnetic storms have a significant effect on the rapid variations of relativistic electron dynamics.

1. Introduction

The extreme and rapid variabilities of relativistic (1 MeV) electrons in the Earth's outer radiation belt are due to the acceleration and loss processes (Reeves et al., 2003). The acceleration mechanisms of relativistic electrons are mainly local acceleration and inward radial diffusion. For the local acceleration process, the seed electrons (~ 100s keV) from substorm injections or magnetospheric convection (e.g., Tang et al., 2009, 2018; Wang et al., 2022) are locally accelerated to relativistic energies by whistler-mode chorus waves (e.g., Horne and Thorne, 1998; Miyoshi et al., 2013; Boyd et al., 2014; Mourenas et al., 2014; Omura et al., 2015). Previous studies have also shown that the local acceleration process involved energetic electrons in nonlinear interactions with chorus waves (e.g., Mozer et al., 2014; Foster et al., 2017). Inward radial diffusion of ultralow-frequency (ULF) waves can also accelerate the seed electrons to relativistic energies or redistribute the accelerated MeV electrons by chorus waves (e.g., Reeves et al., 2013; Su et al., 2015). The acceleration process of relativistic electrons in the outer radiation belt generally requires a long time except for the nonlinear effect of chorus waves. Using the data from the Van Allen Probes and Time History of Events and Macroscale Interactions during Substorms (THEMIS) satellites, Boyd et al. (2018) have shown that local acceleration is the dominant acceleration mechanism for most MeV electron enhancements in the Earth's outer radiation belt. Horne et al. (2005b) estimated that the timescale for accelerating the flux of 1 MeV electrons to an order of magnitude by whistler-mode chorus waves was about 1 day. However, some observations have shown that the time scale of the chorus wave acceleration of ~ 100s keV electrons to MeV energies are ~ 12 h (e.g., Thorne et al., 2013; W. Li et al., 2014; Tang et al., 2017a).

Several other mechanisms can explain rapid enhancements of relativistic electrons in the Earth's outer radiation belt. Previous observations and simulations have shown that relativistic electron injections could lead to rapid enhancements of MeV electrons in the outer radiation belt, which were associated with the intense substorm electric fields or convection electric fields (e.g., Li et al., 1998; Kim et al., 2000; Ingraham et al., 2001; Mithaiwala & Horton, 2005; Ganushkina et al., 2013; Tang et al., 2022; Xiong et al., 2022). In addition, an interplanetary (IP) shock acceleration is also an important mechanism, which is caused by IP shock compressions on the dayside (e.g., Blake et al., 1992; Foster et al., 2015; Kanekal et al., 2016; Schiller et al., 2016; Hudson et al., 2017).

Substorms can provide not only source electrons (or whistler-mode chorus waves) but also seed electrons (e.g., Thorne et al., 2013; Boyd et al., 2014; Tang et al., 2010, 2016a). Tang et al. (2017b) have shown that the intense substorms during the storm recovery phase were crucial to relativistic electron enhancements in the heart of the Earth's outer radiation belt. It is not clear whether the intense substorms (AE_{max} ~ 900 nT) during geomagnetic storms can lead to rapid recovery and enhancements of relativistic electrons in the outer radiation belt. In this study, we will present a statistical study about rapid (< 9 h) enhancements of relativistic electrons in the Earth's outer radiation belt due to the intense substorms.

2. Data and Statistical Method

To examine rapid enhancements of relativistic electrons in the Earth's outer radiation belt due to the intense substorms, we have selected 29 events from January 2013 to April 2015. In this study, we used the electron PSDs for seven values of the first adiabatic invariant (= 100, 209, 302, 630, 1096, 2290, and 3311 MeV/G) and one fixed value of the second adiabatic invariant (K = 0.11 $G^{1/2}R_E$) along the trajectory of Van Allen Probe A. The PSD in terms of adiabatic invariant coordinates (, K, L^*) can represent a net change of the electrons in the outer radiation belt (e.g., Green et al., 2004; Shprits et al., 2006). We also used the magnetic field data and the magnetic spectral density from the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS; Kletzing et al., 2013). Boyd et al. (2014) have shown that the electron PSDs can be calculated using the particle data from the Magnetic Electron-Ion Spectrometer (~ 20–4000 keV) (Blake et al., 2013), Relativistic Electron Proton Telescope (~ 1–20 MeV) (Baker et al., 2013) instruments of the Energetic particle, composition, and Thermal Plasma suite (ECT, Spence et al., 2013), and the magnetic field data from the EMFISIS. For = 100, 209, 302,630, 1096, 2290, and 3311 MeV/G at selected L^* = 5.0, the corresponding electron energy is about 0.20 MeV, 0.36 MeV, 0.45 MeV, 0.85 MeV, 1.23 MeV, 1.96 MeV, and 2.45 MeV, respectively. For K = 0.11 $G^{1/2}R_E$, the corresponding electron pitch angle range is from about 40° to 90° along the drift orbit. L^* value is calculated using the TS04D magnetic field model (Tsyganenko and Sitnov, 2005). In this study, the 1 min averaged interplanetary magnetic field, solar wind electric field, and geomagnetic indices come from CDAWeb (http://cdaweb.gsfc.nasa.gov/). The AE index maximum (AE_{max}) represents the intensity of substorm activity during geomagnetic storms. These intense substorm events are listed in Table 1. Time is the time of occurrence for AE_{max}.

To quantify enhancements of relativistic electrons in the Earth's outer radiation belt due to the intense substorms, we will compare the variations of MeV electron PSDs at selected L^* over one orbital period (about 9 hours). The selected L^* is chosen as the position of the enhanced region of the outer radiation belt, and the selected L^* is not always the L shell where the peak PSDs of relativistic electrons is due to the orbit of the spacecraft (see Table 1). PSD_{10}, PSD_{20}, PSD_{30}, PSD_{40}, PSD_{50}, PSD_{60}, and PSD_{70} are the PSDs of = 100, 209, 302, 630, 1096, 2290, and 3311 MeV/G electrons at selected L^* before or at the onset of the intense substorms, respectively. PSD_{11}, PSD_{21}, PSD_{31}, PSD_{41}, PSD_{51}, PSD_{61}, and PSD_{71} are the PSDs of = 100, 209, 302, 630, 1096, 2290, and 3311

MeV/G electrons at selected L^* after the intense substorms, respectively.

Considering the influences of the time selected by the initial PSDs of relativistic electrons at selected L^* (PSD_{40}, PSD_{50}, PSD_{60}, and PSD_{70}) and different substorm evolution characteristics during the intense substorms on MeV electron PSD variations (PSD_{41}/PSD_{40}, PSD_{51}/PSD_{50}, PSD_{61}/PSD_{60}, and PSD_{71}/PSD_{70}), we categorize the intense substorm events into the three types. The first type is that the initial PSDs of relativistic electrons are selected before the intense substorms and isolated substorm activity occurs during the intense substorms (13 events, labeled as “A” in Table 1). The second type is that the initial MeV electron PSDs are selected at the onset of the intense substorms and isolated substorm activity occurs during the intense substorms (5 events, labeled as “B” in Table 1). The third type is that the initial PSDs of relativistic electrons are selected before the intense substorms and continuous substorm activities occur during the intense substorms (11 events, labeled as “C” in Table 1). The isolated substorm activity is characterized by a peak AE greater than 900 nT, while continuous substorm activities are characterized by two or more substorms with a peak AE greater than 900 nT occurring at a time interval $>$ 0.5 h, and AE is below 500 nT for no more than 2 h at a time. We will analyze the three different types of substorm events in detail next.

3. Case Study and Statistical Analysis

Figure 1 shows an example of A-type events, which occurred during the 8 December 2013 geomagnetic storm. The minimum of the SYM-H index (SYM-H_{min}) for this storm event was –72 nT (Figure 1k). During the storm main phase, solar wind dynamic pressure was up to ~ 20 nPa (not shown). Thus, substantial decreases in the PSDs for various = 302, 630, 1096, 2290, and 3311 MeV/G electrons (Figures 1a–1e) may be due to the magnetopause shadowing effect (e.g., Hudson et al., 2014; Ni et al., 2016; Ozeke et al., 2017). During the storm recovery phase, the interplanetary magnetic field (IMF) B_z component was mainly in a southward direction (Figure 1h), the solar wind electric field E_y component was 3.0 mV/m (Figure 1i), and the intense and isolated substorm activity started to occur at 16:00 UT on 8 December. The AE index reached a maximum of 1,151 nT at 16:20 UT on 8 December (Figure 1j). During the intense substorms, Van Allen Probe A was located at duskside and did not observe the intense chorus waves (Figures 1f and 1g). Van Allen Probe B was located at a perigee (near MLT ~ 1), and also did not observe the intense chorus waves (see “-” of “Wave intensity” in Table 1). After the intense substorms, the seed electrons rapidly enhanced (as indicated by the blue dot in Figure 1a). And, MeV electron PSDs for = 630, 1096, 2290, and 3311 MeV/G were rapidly recovered and enhanced (as indicated by the blue dots in Figures 1b–1e). The PSD_{41}/PSD_{40}, PSD_{51}/PSD_{50}, PSD_{61}/PSD_{60}, and PSD_{71}/PSD_{70} were 49.9, 40.4, 13.2, and 5.0, respectively. During the intense substorms, solar wind dynamic pressure was $<$ 2 nPa (not shown). And, the strong ULF waves were not observed by Van Allen Probe A at selected L^* ~ 5.1 (not shown). Figure S1 in Supporting Information shows the electron PSDs at $K = 0.11\ \mathrm{G}^{1/2}\mathrm{R_E}$

and different (= 209, 302, 630, 1096, 1905, and 3311 MeV/G) as a function of L^* during the time interval from 11:13 UT on 8 December to 02:24 UT on 9 December, which shows the PSD evolution during the recovery phase of the 8 December 2013 geomagnetic storm. At ~ 16:16 UT, the seed electrons rapidly enhanced due to substorm injections (the purple lines in Figures S1a and S1b), while MeV electron injections did not occur (the purple lines in Figures S1c–S1f). Based on the above analysis, inward radial diffusion by ULF waves and MeV electron injections were not responsible for MeV electron enhancements. For rapid enhancements of relativistic electrons at selected $L^* \sim 5.1$, the most likely explanation was the result of the intense whistler-mode chorus waves interaction with the seed electrons during the intense substorms (e.g., Boyd et al. 2014; Su et al., 2014a). Noted that the intense substorms occurred during the storm recovery phase, so this event was labeled as “R” in Table 1.

Figure 2 shows an example of B-type events, which occurred during the 19 May 2013 geomagnetic storm. The $SYM\text{-}H_{min}$ for this storm event was –45 nT (Figure 2k). During the storm main phase, small solar wind dynamic pressure was ~ 1.5 nPa (not shown), the IMF B_z component was –5.0 nT (Figure 2h), the E_y component was 2.0 mV/m (Figure 2i), and the intense substorm activity started to occur at 06:00 UT on 19 May. The AE index reached a maximum of 972 nT at 14:27 UT (Figure 2j). During the intense substorms, Van Allen Probe A and B were located at the perigee and did not observe the intense chorus waves (Figures 1f and 1g, “-” of “Wave intensity” in Table 1). After the intense substorms, the seed electrons had some enhancements (as indicated by the blue dot in Figure 2a). The relativistic electron PSDs for = 630, 1096, 2290, and 3311 MeV/G had also been enhanced (as indicated by the blue dots in Figures 2b–2e). The PSD_{41}/PSD_{40}, PSD_{51}/PSD_{50}, PSD_{61}/PSD_{60}, and PSD_{71}/PSD_{70} were 1.6, 1.7, 1.9, and 1.8, respectively. Noted that the intense substorm activity mainly occurred during the storm main phase, so this event was labeled as “M” in Table 1.

Figure 3 shows an example of C-type events, which occurred during the 1 May 2013 geomagnetic storm. The $SYM\text{-}H_{min}$ for this storm event was –67 nT (Figure 3k). During the storm main phase, solar wind dynamic pressure was about 6.0 nPa (not shown), the IMF B_z component was up to –10 nT (Figure 3h), and the E_y component was ~ 4.0 mV/m (Figure 3i). Thus, some decreases in the PSDs for = 302, 630, 1096, 2290, and 3311 MeV/G electrons (as indicated by the black dots in Figures 3a–3e) may be due to the magnetopause shadowing effect (e.g., Xiang et al., 2018). However, the continuous substorm activities started to occur at 12:00 UT on 1 May ($AE > 500$ nT). The AE index reached a maximum of 1,473 nT at 16:40 UT on 1 May (Figure 3j). During the intense substorms, Van Allen Probe A was located at dawnside and observed the intense chorus waves (Figures 3f and 3g). After the intense substorms, the seed electrons rapidly enhanced (as indicated by the blue dot in Figure 3a). Enhanced relativistic electrons were also observed (as indicated by the blue dots in Figures 3b–3e). The PSD_{41}/PSD_{40}, PSD_{51}/PSD_{50}, PSD_{61}/PSD_{60}, and PSD_{71}/PSD_{70} were 1.7, 4.4, 14.7, and 15.0, respectively.

Using the two-dimensional Storm Time Evolution of Electron Radiation Belt (STEERB) code (Xiao et al., 2009; Su et al., 2010, 2014b), we calculated the diffusion coefficients at ~ 11:40 UT and 19:40 UT (Figures S2–S5). The momentum and cross diffusion rates are pronounced at relatively larger equatorial pitch angles, implying a significant acceleration effect on trapped electrons. Therefore, rapid enhancements of relativistic electrons at selected $L^* \sim 4.75$ during the intense substorms were due to the local acceleration by chorus waves (e.g., W. Li et al., 2014; Xiao et al., 2014). Noted that the continuous substorm activities occurred during the storm main phase, so this event was labeled as "M" in Table 1.

Figure 4 shows the maximum of the AE index (AE_{max}) versus the chorus wave power at selected L^* during the intense substorms for 17 events from January 2013 to April 2015. Because Van Allen Probes may be located at the apogee/perigee or duskside around the time of the AE_{max}, Van Allen Probe A or B did not observe the intense chorus waves ("-" of "Wave intensity" in Table 1). From Figure 4, substorm intensity (AE_{max}) has a good correlation with the chorus wave power at selected L^* during the intense substorms (cc = 0.91). This result indicates that when substorm intensity is stronger, the intensity of chorus waves in the local acceleration region is stronger, which is consistent with previous statistical results (e.g., W. Li et al., 2009; Meredith et al., 2001, 2012; Bingham et al., 2019). Note that the large chorus wave power (>1.0 nT^2) during the event on 17 March 2013 was observed, so rapid enhancements of relativistic electrons at selected $L^* \sim 4.3$ for this event may also be related to the nonlinear wave acceleration (e.g., Foster et al., 2017).

Figure 5 shows substorm intensity (AE_{max}) versus the seed electron PSDs (= 100, and 209 MeV/G) at selected L^* after the intense substorms (PSD_{11} and PSD_{21}) for 29 events from January 2013 to April 2015. Noted that these seed electron PSDs were selected from different L^*, different substorm activities (isolated substorm activity or continuous substorm activities), and different storm phases (main phase or recovery phase). For the event on 29 June 2013, the substorm event was an isolated activity. However, the AE index showed a pulse of enhancement and reached a maximum of 2,000 nT at 11:25 UT on 29 June (not shown). The seed electron PSDs were selected from selected $L^* \sim 4.0$ (the electron PSDs had no values at selected $L^* > 4.0$ due to the Van Allen Probe orbital), so PSD_{11} and PSD_{21} were relatively small (Figures 5a and 5b). For the event on 17 March 2013, continuous substorm activities occurred, and the AE index reached a maximum of 2,500 nT at 16:40 UT on 17 March (not shown). However, the intense substorms occurred during the main phase, which may result in the loss of the seed electrons due to the magnetopause shadowing effect and outward radial diffusion. These events lead to a decrease in the correlation coefficients between substorm intensity and enhanced seed electrons (PSD_{11} and PSD_{21}). The correlation coefficients between substorm intensity and the seed electrons are about 0.5 (the events on 29 June 2013 and 17 March 2013 are not included). This suggests that when substorm intensity is stronger, the seed electron PSDs in the local acceleration region are larger, which is consistent with some previous statistical results (e.g., Turner et al., 2015; Tang et al., 2017a).

Figure 6 shows substorm intensity (AE_{max}) versus the relativistic electron PSD variations for = 630, 1096, 2290, and 3311 MeV/G at selected $L*$ (PSD_{41}/PSD_{40}, PSD_{51}/PSD_{50}, PSD_{61}/PSD_{60}, and PSD_{71}/PSD_{70}) for 29 intense substorm events from January 2013 to April 2015. For = 630 MeV/G electrons, PSD_{41}/PSD_{40} is between 1.0 and 315 (Figure 6a). Among these events with small variations ($PSD_{41}/PSD_{40} < 3$), five events are A-type with smaller AE_{max}, five events are B-type, and two events are C-type occurring during the main phase. While eight A-type events with $AE_{max} > 1000$ nT and nine C-type events have large enhancements ($PSD_{41}/PSD_{40} > 3$). For = 1096 MeV/G electrons, PSD_{51}/PSD_{50} is between 1.4 and 172 (Figure 6b). Among these events with small variations ($PSD_{51}/PSD_{50} < 3$), two events are B-type with smaller $AE_{max.}$ While thirteen A-type events, three B-type events occurring during the recovery phase, and eleven C-type events have large enhancements ($PSD_{51}/PSD_{50} > 3$). For = 2290 MeV/G electrons, PSD_{61}/PSD_{60} is between 1.9 and 163 (Figure 6c). For these events with small variations ($PSD_{61}/PSD_{60} < 3$), two events are B-type with smaller $AE_{max.}$ While thirteen A-type events, three B-type events occurring during the recovery phase, and eleven C-type events have large enhancements ($PSD_{61}/PSD_{60} > 3$). For = 3311 MeV/G electrons, PSD_{71}/PSD_{70} is between 1.8 and 61 (Figure 6d). For these events with small variations ($PSD_{71}/PSD_{70} < 3$), one event is A-type with small AE_{max} and occurring during the storm main phase, and five events are B-type. While twelve A-type events and eleven C-type events have large enhancements ($PSD_{71}/PSD_{70} > 3$). Our statistical results show that MeV electron PSD variations are less for the larger electrons, which is consistent that higher energy electrons during the local acceleration process requiring a longer acceleration time (e.g., Boyd et al., 2014; Tang et al., 2017a). The delayed enhancement of higher energy electrons is a characteristic feature of the local acceleration of chorus waves. The electrons for = 1096, 2290, and 3311 MeV/G have different behaviors than the electrons for = 630 MeV/G. Here, we have set a criterion for rapid enhancements when the electron PSDs for = 1096, 2290, and 3311 MeV/G increased by more than 2 times ($PSD_{51}/PSD_{50} > 3$, $PSD_{61}/PSD_{60} > 3$, $PSD_{71}/PSD_{70} > 3$) in 9 hours. Our statistical results also show that continuous substorm activities can more rapidly (< 9 h) and efficiently accelerate electrons to relativistic energy in the outer radiation belt than isolated substorm activity.

Figure 7 shows the seed electron PSDs for = 302 MeV/G (PSD_{31}) versus the relativistic electron PSDs for = 630, 1096, 2290, and 3311 MeV/G at selected $L*$ after the intense substorms (PSD_{41}, PSD_{51}, PSD_{61}, and PSD_{71}) for 29 events from January 2013 to April 2015. PSD_{31} is well correlated with PSD_{41}, PSD_{51}, PSD_{61}, and PSD_{71} (cc 0.72). This suggests that the seed populations at selected $L*$ can be effectively accelerated during the intense substorms, which can cause rapid enhancements of relativistic electrons in the acceleration region. This is consistent that the local acceleration of whistler-mode chorus waves is the dominant process for the seed populations up to MeV energies (e.g., Horne et al., 2005a, Miyoshi et al., 2013; Thorne et al., 2013; Jaynes et al., 2015; Tang et al., 2017a).

Figure 8 shows the electron PSDs at $K = 0.11$ $G^{1/2}R_E$ and different (= 209, 302, 630, 1096, 2290, and 3311 MeV/G) as a function of $L*$ along the trajectory of Van Allen Probe A during the recovery phase of the 9 October 2013 geomagnetic storm. During the storm main phase, solar wind dynamic pressure was up ~ 25 nPa (not shown). Thus, substantial decreases in the PSDs for = 302, 630, 1096, 2290, and 3311 MeV/G electrons (the black lines in Figures 8a–8f) may be due to the magnetopause shadowing effect. During the storm recovery phase, the continuous substorm activities started to occur at 05:00 UT on 9 October. The AE index reached a maximum of 1,080 nT at 07:22 UT on 9 October (not shown). During the intense substorms, at ~ 08:00 UT on 9 October, the PSD peaks of 209–3311 MeV/G electrons appeared at selected $L*$ ~ 5.0 (the purple lines in Figure 8), which was due to substorm electron injections. Van Allen Probe B was located near noonside and observed the intense chorus waves (not shown). After the intense substorms, the seed electrons rapidly enhanced (the green lines in Figures 8a and 8b). And, MeV electron PSDs for = 630, 1096, 2290, and 3311 MeV/G were also rapidly recovered and enhanced (the green lines in Figures 8c–8f). The PSD_{41}/PSD_{40}, PSD_{51}/PSD_{50}, PSD_{61}/PSD_{60}, and PSD_{71}/PSD_{70} were 85.7, 50.0 16.0, and 7.3, respectively. For rapid enhancements of relativistic electrons at selected $L*$ ~ 5.0, the most probable explanation is the result of a combination of MeV electron injections and strong whistler-mode chorus waves interaction with the seed electrons during the intense substorms.

4. Discussion

Previous studies have shown that the intense substorms are crucial to relativistic electron enhancements in the Earth's outer radiation belt (e.g., Lyons et al., 2005; Kim et al., 2015; Forsyth et al., 2016; Tang et al., 2017b). During the intense substorms, the energetic electrons from the plasma sheet are injected into the Earth's inner magnetosphere. These injected electrons (~ 10s keV) can contribute to the growth of whistler-mode chorus waves near the geomagnetic equator (e.g., Tsurutani and Smith, 1977; Omura et al., 2008). And, these chorus waves were preferentially observed outside the plasmapause on the dawnside (e.g., W. Li et al., 2012; Agapitov et al., 2013; Aryan et al., 2014). The chorus waves are well correlated with substorm intensity (e.g., Meredith et al., 2001, 2012; Agapitov et al., 2013; Kim et al., 2015; D. Wang et al., 2019). During the intense substorms, substorm electron injections or magnetospheric convection also provide the seed populations (e.g., Gabrielse et al., 2012; Tang et al., 2013; Zhao et al., 2016; Khoo et al., 2019; X. Wang et al., 2022), which can be energized to MeV energies by wave-particle interactions (e.g., Thorne et al., 2013; W. Li et al., 2014). However, Meredith et al. (2003) suggested that a prolonged period of substorm activity ($AE > 300$ nT for a total integrated time greater than 0.7 days or >100 nT for a total integrated time greater than 2 days) may cause relativistic electron flux enhancements. Our statistical studies have shown that relativistic electrons in the Earth's outer radiation belt can rapidly enhance (< 9 h) during isolated substorm activities (indicated as the black and the blue squares and dots in Figure 6).

Using the Combined Release and Radiation Effects Satellite (CRRES) data, L. Y. Li et al. (2009) have shown that the continuous intense substorm activity (average $AE > 200$ nT) could lead to the net increases of the relativistic electrons in the outer radiation belt. Using the Geostationary Operational Environment Satellites (GOES) data, Hajra et al. (2015) have studied the relativistic ($E > 0.6$, > 2.0, and > 4.0 MeV) electron acceleration at $L \sim 6.6$ during the high-intensity, long-duration, continuous AE activity (HILDCAA) events. They have found that enhancement of >50% occurred during 100% of HILDCAAs for the $E >$ 2.0 MeV electron fluxes. During the continuous substorm activities, enhanced chorus waves were observed in the accelerated region (Figure 4) and enough seed electrons were continuously injected into the outer radiation belt (indicated as the red squares and dots in Figure 5). These are consistent with previous studies (e.g., Meredith et al., 2002; Rodger et al., 2016). In the present study, we have shown that relativistic electrons could be accelerated rapidly (< 9 h) and efficiently during the continuous substorm activities (indicated as the red squares and dots in Figure 6).

In this study, we use the ratio between MeV electron PSDs at selected L^* after the intense substorms (PSD_{41}, PSD_{51}, PSD_{61}, and PSD_{71}) and those before or at the onset of the intense substorms (PSD_{40}, PSD_{50}, PSD_{60}, and PSD_{70}) to represent the variations of MeV electrons in the outer radiation belt over one orbital period (about 9 hours). Here we briefly discuss some factors that may affect the variations of MeV electron PSDs. The first factor is the selected L^* value. Tang et al. (2017b) have shown that the intense substorms during the storm recovery phase are crucial to relativistic electron enhancements in the heart of the outer radiation belt ($L^* = 4.5 - 5.0$). In this study, the intense substorms occurred during the storm main phase or the storm recovery phase. Also, considering the availability of the PSD data, the selected L^* was between 4.0 and 5.3. The second factor is the selected time of PSD_{40}, PSD_{50}, PSD_{60}, and PSD_{70}. Figure S6 in Supporting Information shows the relationship between the relativistic electron PSDs for = 630, 1096, 2290, and 3311 MeV/G at selected L^* before or at the onset of the intense substorms (PSD_{40}, PSD_{50}, PSD_{60}, and PSD_{70}) and MeV electron PSD variations (PSD_{41}/PSD_{40}, PSD_{51}/PSD_{50}, PSD_{61}/PSD_{60}, and PSD_{71}/PSD_{70}) for 29 intense substorm events from January 2013 to April 2015. From Figure S6, the PSDs for = 630, 1096, 2290, and 3311 MeV/G electrons at selected L^* at the onset of the intense substorms (PSD_{40}, PSD_{50}, PSD_{60}, and PSD_{70}) may be larger for small variations of relativistic electrons (PSD_{41}/PSD_{40}, PSD_{51}/PSD_{50}, PSD_{61}/PSD_{60}, and PSD_{71}/PSD_{70}) (the B-type events, indicated as the blue squares and dots in Figure S6). The third factor is the time of the intense substorms. In this study, some intense substorm events occurred during the early main phase of the geomagnetic storm. So, the initial PSDs for = 630, 1096, 2290, and 3311 MeV/G electrons (PSD_{40},

PSD_{50}, PSD_{60}, and PSD_{70}) may be larger. Thus, the variations of relativistic electrons (PSD_{41}/PSD_{40}, PSD_{51}/PSD_{50}, PSD_{61}/PSD_{60}, and PSD_{71}/PSD_{70}) are relatively smaller (indicated as the squares in Figure S6).

The fourth factor is MeV electron injections during the intense substorms. Recently, some observations from Van Allen Probes have shown that MeV electron injections during the intense substorms can explain rapid enhancements of MeV electrons in the outer radiation belt (e.g., Su et al., 2014b; Dai et al., 2015; Tang et al., 2016b; Kim et al., 2021). In this study, some MeV electron injection events were observed during the intense substorms (Figure 8, and see “Y” of “Injection” in Table 1). Noted that MeV electron injections during some events were not observed by Van Allen Probe A or B due to the positions of Van Allen Probes. During the intense substorms, MeV electron injections occurred at the heart of the outer radiation belt, while Van Allen Probes were located at perigee or apogee. There are also some events in which relativistic electron injections were observed in the outer edge of the outer radiation belt, however, the region we were comparing is the heart of the outer radiation belt (see “-” of “Injection” in Table 1).

6. Conclusions

In this study, we present the statistical study of rapid enhancements of relativistic electrons in the Earth’s outer radiation belt caused by the intense substorms. The main conclusions are summarized as follows:

1. During the intense substorms, enhanced chorus waves and seed electrons are observed in the outer radiation belt.
2. Continuous substorm activities can more rapidly (< 9 h) and efficiently accelerate electrons to relativistic energy in the outer radiation belt than isolated substorm activity.
3. During the intense substorms, MeV electron injections could contribute to rapid enhancements of relativistic electrons in the outer radiation belt.

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Table Captions

Table 1. List of Substorm Events Examined in This study

Figure Captions

Figure 1. (a–e) The electron PSDs for five first adiabatic invariant values (= 302, 630, 1096, 2290, and 3311 MeV/G) and the fixed second adiabatic invariant (K = 0.11 $G^{1/2}R_E$) on Van Allen Probe A. (f) and (g) the magnetic spectral density, and integrated chorus wave power between 0.05 and 0.8 f_{ce}, where f_{ce} is the equatorial electron gyrofrequency. The overlaid white lines in panel (f) denote 0.05, 0.8, and 1.0 f_{ce}. (h–k) solar wind parameters (the interplanetary magnetic field B_z component and solar wind electric field E_y component in the GSM coordinates), and geomagnetic indices (*AE* and *SYM-H*) during the 8 December 2013 geomagnetic storm. The vertical blue dashed line indicates the time of an intense substorm. The black dotted lines in Figures 1a–1e represent the selected L^* value. Note that the black dots denote the PSDs of = 302, 630, 1096, 2290, and 3311 MeV/G electrons at selected L^* before the intense substorms (PSD_{30}, PSD_{40}, PSD_{50}, PSD_{60}, and PSD_{70}), the blue dots denote the PSDs of = 302, 630, 1096, 2290, and 3311 MeV/G electrons at selected L^* after the intense substorms (PSD_{31}, PSD_{41}, PSD_{51}, PSD_{61}, and PSD_{71}).

Figure 2. The same format as Figure 1 but for an example of the initial PSDs of relativistic electrons selected at the onset of the intense substorms and isolated substorm activity occurred during the 19 May 2013 geomagnetic storm.

Figure 3. The same format as Figure 1 but for an example of the initial PSDs of relativistic electrons selected before the intense substorms and continuous substorm activities occurred during the 1 May 2013 geomagnetic storm.

Figure 4. The maximum of the *AE* index (AE_{max}) versus the chorus wave power at selected L^* during the intense substorms for 17 events from January 2013 to April 2015. The correlation coefficient is shown on the panel.

Figure 5. Substorm intensity (AE_{max}) versus the seed electron PSDs (= 100, and 209 MeV/G) at selected L^* after the intense substorms (PSD_{11} and PSD_{21}) for 29 events from January 2013 to April 2015. The black denotes the type-A event, the blue denotes the B-type event, and the red denotes the C-type event, respectively. The squares represent the intense substorms that occurred during the storm main phase, and the dots represent the intense substorms that occurred during the storm recovery phase, respectively.

Figure 6. Substorm intensity (AE_{max}) versus the relativistic electron PSD variations for the various (= 630, 1096, 2290, and 3311 MeV/G) at selected L^* (PSD_{41}/ PSD_{40}, PSD_{51}/ PSD_{50}, PSD_{61}/ PSD_{60}, and PSD_{71}/ PSD_{70}) for 29 intense substorm events from January 2013 to April 2015.

Figure 7. The seed electron PSDs for = 302 MeV/G (PSD_{31}) versus the relativistic electron PSDs for the various (= 630, 1096, 2290, and 3311 MeV/G) at selected L^* after the intense substorms (PSD_{41}, PSD_{51}, PSD_{61}, and PSD_{71}) for 29 events from January 2013 to April 2015. The correlation coefficient is shown on each panel.

Figure 8. The electron PSD at $K = 0.11$ $G^{1/2}R_E$ and different (= 209, 302, 630, 1096, 2290, and 3311 MeV/G) as a function of L^* along the trajectory of Van Allen Probe A during the time interval from 00:01 UT to 21:00 UT on 9 October 2013.