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A case study to determine the relationship of relativistic electron events to substorm injections and ULF power

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[1] We study the two storm events of 1997: one in May that was accompanied by a relativistic electron event (REE) and the other in September, with a more profound Dst decrease, but with no significant flux increase of relativistic electrons. We find that a larger amount of seed electrons was present in the May event compared to that of the September storm, whereas the ULF (ultra low frequency) power was more enhanced and the particle spectrum was harder in the September event. Hence, we demonstrate that a larger storm does not necessarily produce more seed electrons and that the amount of seed electrons is an important factor in an actual increase in REE flux levels. We note that whistler mode chorus was enhanced in the May event and could also contribute to the acceleration of electrons. *INDEX TERMS:* 2716 Magnetospheric Physics: Energetic particles, precipitating; 2720 Magnetospheric Physics: Energetic particles, trapped; 2731 Magnetospheric Physics: Magnetosphere—outer; 2788 Magnetospheric Physics: Storms and substorms; 2736 Magnetospheric Physics: Magnetosphere/ionosphere interactions. **Citation:** Hwang, J., K. W. Min, E. Lee, C. Lee, and D. Y. Lee (2004), A case study to determine the relationship of relativistic electron events to substorm injections and ULF power, *Geophys. Res. Lett.*, *31*, L23801, doi:10.1029/2004GL021544.

1. Introduction

[2] Global effects of magnetic storms include electric fields that disturb plasma populations and magnetic fields throughout the larger part of the magnetosphere that penetrate deep into the ionosphere [*Lee et al.*, 2002]. One of the well-known effects associated with magnetic storms is a dramatic increase of relativistic electrons in the outer radiation belt. Enhancements of high energy electron flux were reported during the early stages of space exploration [*Paulikas and Blake*, 1979], but such enhancements have recently received renewed attention because of their harmful effects on satellite operations [*Baker et al.*, 1994].

[3] The relativistic electrons in the outer radiation belt exhibit a decrease in flux when monitored at a geosynchronous orbit during the main phase of a magnetic storm. Then, the flux level increases during the recovery phase, quite often rising beyond that of the pre-storm level. A number of correlation studies have shown that relativistic electron events (REEs) are generally related to high-speed solar wind streams [*Li et al.*, 1997; *O'Brien et al.*, 2001] and a southward turning of the interplanetary magnetic field [*Blake et al.*, 1997]. However, the phase space density of 20–200 keV solar wind electrons is too low to account for the flux increase of the outer radiation belt electrons and a local acceleration mechanism within the magnetosphere seems necessary for the generation of seed electrons [*Li et al.*, 1997; *Reeves et al.*, 1998].

[4] Recently, it has been argued that wave-particle interactions such as ultra-low frequency MHD modes or whistler mode chorus, could provide sufficient energy to generate relativistic electrons [*Rostoker et al.*, 1998; *Summers et al.*, 1998, 2002; *Elkington et al.*, 1999; *Meredith et al.*, 2001; *O'Brien et al.*, 2003]. One senario that may explain REEs is that strong substorm activity, caused by a prolonged southward IMF (Interplanetary magnetic field), generates seed electrons that are accelerated and transported inward, due to the strong convective electric fields, and then further energized to relativistic energies by wave-particle interactions [*Li et al.*, 1998; *Summers et al.*, 1998; *Obara et al.*, 2000].

[5] As substorm injections occur rather frequently, it is natural that previous studies regarding REEs concentrated on the acceleration mechanisms. In contrast, there have been only a limited number of studies regarding the importance of seed electrons [*Buhler et al.*, 1998; *Obara et al.*, 2000; *Meredith et al.*, 2003a]. By comparing the two storm events of 1997, this paper attempts to show the following: (1) that an intense storm, with a large Dst decrease, does not necessarily generate a large population of seed electrons and, thus, that an REE is apparently absent, even with strong ULF activity after the loss of a significant amount of relativistic electrons; whereas, (2) a less intense storm may produce an REE with a softer spectrum, by providing a large population of seed electrons. The results presented in this paper may provide some insight into the question of why REEs do not occur during all intense storms [*Reeves et al.*, 2003]. While whistler mode waves can also contribute to the acceleration of electrons, available observations did not cover the entire region of interest during the two storm events. Nevertheless, it is seen that the May event was associated with intense whistler wave activities, which could provide an acceleration mechanism for the observed REE.

2. Effect of Seed Electrons on REEs

[6] Let us compare the two storm events shown in Figure 1, which describes the changes of the flux of relativistic electrons observed by GOES 9 in relation to the Dst index. It should be noted the storm on the left of May 1, 1997 produced a large REE while the one on the right of September 2, 1997 did not produce a large REE, while the minimum Dst was more profound for the storm

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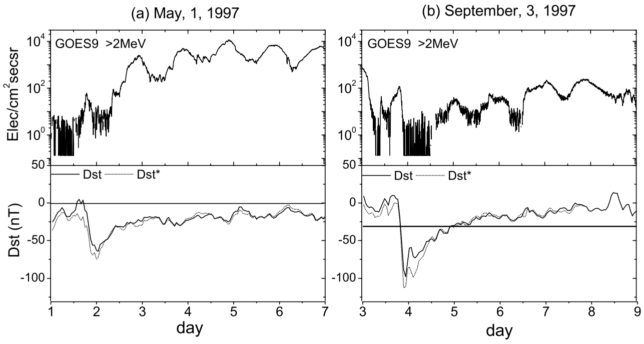

Figure 1. Comparison of the two storm events: (a) one accompanied by an REE on May 1, 1997, and (b) the other with no observed REE on September 3, 1997. The first panel shows relativistic electrons observed by GOES 9 in the >2 MeV channel. The second panel shows Dst index.

event of September 3 than for the one of May 1. It is interesting that we observe an REE associated with a relatively weak storm on May 1, while we observe no REE with a relatively strong storm on September 3. This apparent inconsistency could possibly be related to the flux level of seed electrons or to the level of associated wave activities. First, we compare the substorm particle injections measured by the Los Alamos National Laboratory's (LANL) geosynchronous satellite 1994-084 in Figure 2. We calculate the flux ratios of the seed electrons of the two events for the 105–150 and the 150–225 keV energy channels, since seed electrons are regarded as having energies of 100 keV [*O'Brien et al.*, 2001; *Obara et al.*, 2000]. We take 30-minute averages of the post- and pre-injection flux levels, separated by twenty four hours at local time, and calculate their ratios. More specifically, all flux levels are obtained at approximately the same local time, 10:30 UT (17:24 LT); May 1 and May 2 are taken as the pre- and post-injection levels for the May event and September 3 and September 4 are taken as the pre- and post-injection levels for the September event. The post-injection flux levels for the May event are, respectively, $1.2 \times 10^4/\mathrm{cm}^2 \cdot \mathrm{sec} \cdot \mathrm{sr}$(105–150 keV) and $7.3 \times 10^3/\mathrm{cm}^2 \cdot \mathrm{sec} \cdot \mathrm{sr}$(150–225 keV), increasing by factors of 3.1 and 4.2 compared to the pre-injection levels. The post-injection flux levels for the September event are, respectively, $5.9 \times 10^3/\mathrm{cm}^2 \cdot \mathrm{sec} \cdot \mathrm{sr}$(105–150 keV) and $2.7 \times 10^3/\mathrm{cm}^2 \cdot \mathrm{sec} \cdot \mathrm{sr}$(150–225 keV), increasing by factors of 1.6 and 1.8 compared to the pre-injection levels. The higher flux levels of the May event are more or less maintained throughout the recovery phase except at occasional drops, as seen in Figure 2. These observations verify that the difference in the amount of seed electrons is indeed consistent with the fact that the storm on May 1 was accompanied by an REE, while the storm on September 3 was not.

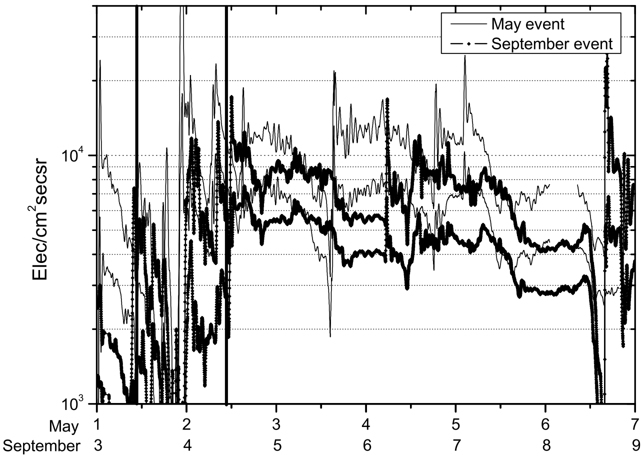

Figure 2. Comparison of the seed electron flux levels in the two energy channels, 105–150 keV and 150–225 keV, measured by LANL 1994-084. The thin gray line represents the May event and the thick black line represents the September event, corresponding to the two storm events shown in Figure 1.

[7] As the observation from geosynchronous satellites provides information only for a limited spatial region, we would like to confirm the validity of our assertion from a more global perspective by investigating the same events using data from the polar orbiting SAMPEX and NOAA satellites. Figure 3 shows relativistic electron fluxes observed from the SAMPEX PET (The Proton/Electron Telescope), sorted according to the L-values. The response of relativistic electrons is seen as global in both events as the fluxes are affected for the L values from 7 to 4, though the level of change decreases with decreasing L value. Figure 3 also clearly shows (1) that the level of relativistic electron flux increases significantly during the recovery phase of the May event and (2) that the level of relativistic electrons flux does not fully return to the pre-storm state after the large dropout during the main phase in the September event. We compare these findings with seed electron fluxes, using the 100–300 keV electron data of NOAA-12 MEPED (Medium Energy Proton and Electron Detector). Only the data with a look direction, perpendicular to the field line was chosen, to accurately represent the trapped particle fluxes. The result of this comparison is shown in Figure 4. We calculated the fluence (integration of the flux in time) over one day after the start of the storm recovery phase. The total fluences measured were $1.6 \times 10^6/\mathrm{cm}^2 \cdot \mathrm{sr}(5 < L < 6)$ and $1.5 \times 10^6/\mathrm{cm}^2 \cdot \mathrm{sr}(6 < L < 7)$ for the May event, and $5.3 \times 10^5/\mathrm{cm}^2 \cdot \mathrm{sr}(5 < L < 6)$ and $7.1 \times 10^5/\mathrm{cm}^2 \cdot \mathrm{sr}(6 < L < 7)$ for the September event. These

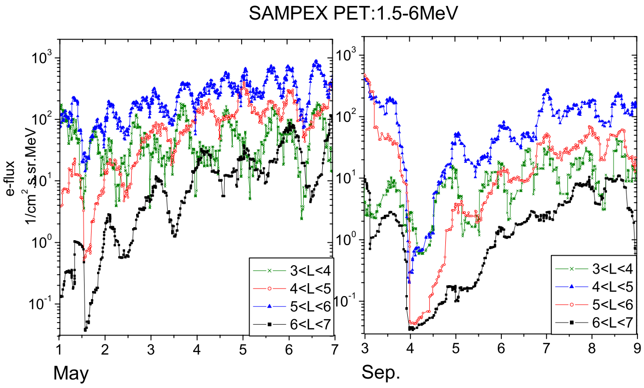

Figure 3. Relativistic electrons observed by SAMPEX for 1.5–6 MeV channel, corresponding to the two storm events depicted in Figure 1.

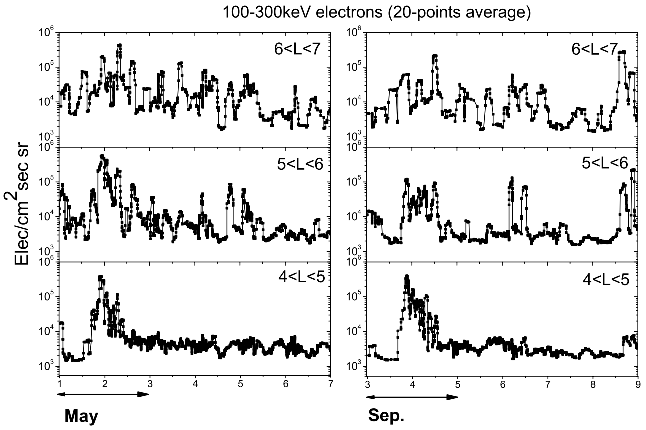

Figure 4. Electron fluxes for the 100–300 keV energy channel of the NOAA-12 satellite MEPED, corresponding to the two storm events depicted in Figure 1.

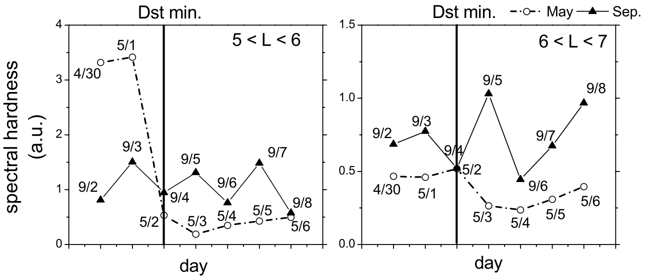

Figure 6. Change of spectral hardness over time, corresponding to the two storm events depicted in Figure 1. The vertical line indicates the dates of the storm main phases for the two events.

measurements were consistent with the previous results from the LANL data, with higher values for the May event than for the September event.

3. Association of REEs With Wave Activities

[8] Because ULF waves have been proposed as one of the possible acceleration mechanisms for REEs, we plot the ULF wave amplitudes measured for the two magnetic storm events under consideration. Figure 5 shows that the stronger September event is indeed associated with more intense ULF wave activities than the less intense May storm is, with a peak amplitude of 175 nT, compared to a peak amplitude of 41 nT for the May event. With a smaller population of seed electrons, the larger ULF activities of the September event should generate a harder particle spectrum than the May event, if ULF is responsible for the acceleration of electrons and other conditions are similar. Using the NOAA-12 data, we calculated the spectral hardness, defined as the flux in the 300–2500 keV channel divided by the flux in the 100–300 keV channel. Figure 6 shows that the electron spectrum of the September event remains more or less the same, maintaining a hard spectrum, while that of the May event becomes soft after the start of the storm. This result is consistent with the theory of ULF acceleration of seed electrons.

[9] As a whistler mode wave is also regarded as a viable candidate of the possible acceleration mechanisms for REEs, we would like to briefly mention its characteristics in the two storms of 1997. According to *Meredith et al.* [2003b], the favored region of chorus acceleration is between 03:00 and 10:00 MLT (magnetic local time) for the equatorial region of $4 < L < 6$ and between 06:00 and 14:00 MLT for the mid-latitude region of $4 < L < 6$. We sorted the POLAR PWI (Plasma Wave Investigation) data according to the L-values for two wave bands, 207–1577 Hz and 1659–12662 Hz. During the two storm events, POLAR crossed the equatorial region only for $L < 4$ and the magnetic latitudes corresponding to $4 < L < 6$ are between +15 and +30, which is the mid-latitude region. The POLAR's orbits passed through the favored region of chorus acceleration during the May event with local times 11:00 MLT (May 2) and 10:30 MLT (May 3), while during the September event, they slightly missed the region with local times 14:30 MLT (September 4) and 14:50 MLT (September 5). Indeed, Figure 7 shows that whistler mode waves are enhanced with the start of the storm in the May event, which may have contributed to the acceleration of electrons and produced a notable REE. The wave intensities of the September event are seen much weaker than those of

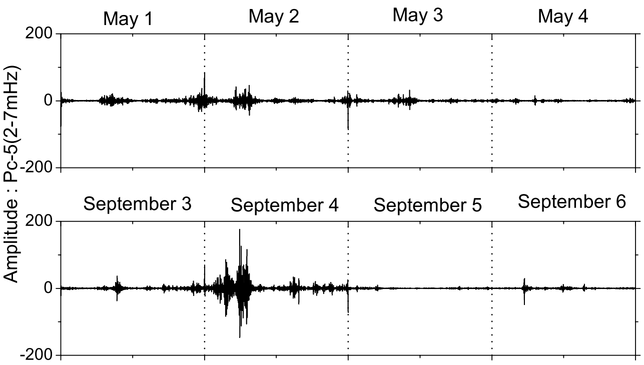

Figure 5. ULF Pc-5 amplitudes obtained at the MCMU site (L = 5.49) of the CANOPUS array, corresponding to the two storm events depicted in Figure 1.

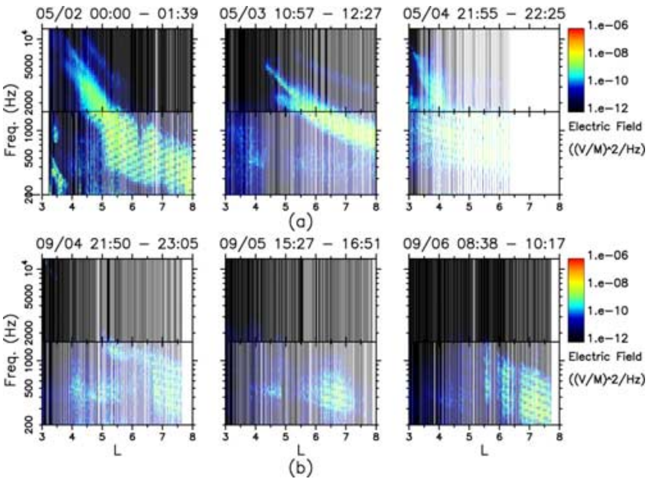

Figure 7. Whistler wave intensities observed from POLAR PWI corresponding to the two events in Figure 1.

the May event. However, it is difficult to estimate how much the whistler mode contributes to the acceleration of the relativistic electrons, since POLAR might have missed the region of intense whistler modes during the September event.

4. Discussion and Summary

[10] Several papers have suggested the importance of seed electrons in REEs. For example, *Green and Kivelson* [2001] showed that ULF wave power alone is not sufficient to account for REEs, and *Reeves et al.* [2003] reported only half of magnetic storms are accompanied by REEs. *Buhler et al.* [1998] noted that the injection of electrons into the trapping region could be crucial for the large enhancement of relativistic electron flux in their study of a 10 January, 1997 CME event. Based on their statistical study, *Meredith et al.* [2003a] reported that storms with a large increase of relativistic electron flux also have a large population of low energy electrons. However, it has not been demonstrated that a substantial population of low energy electrons injected during substorms is a necessary prerequisite for a large increase of relativistic electron flux during storms.

[11] In this study, we have examined two storm cases in 1997 to determine the role, if any, of seed electrons by studying their fluxes observed at geosynchronous orbits, as well as from polar orbiting satellites. The May 1997 storm accompanied by a REE was found to have a larger flux increase of seed electrons than that of the more intense September storm with no accompanying REE. This finding implies that a larger storm does not necessarily produce more seed electrons. It was found that the particle spectrum was harder for the September storm than for the May storm, a finding that is consistent with the more significant ULF Pc-5 activity in the September event than in the May event. The present study demonstrates the importance of seed electron fluxes for the apparent occurrence of REEs and acceleration mechanisms such as ULF can harden particle spectra without causing an apparent REE. We attempted to investigate the role of whistler mode acceleration in the present study. Though the lack of sufficient data, especially for the region of interest, prevented us from reaching any conclusion regarding this, it was seen that the wave was enhanced in the May event. Hence, the REE seen during the May event could be a result of combination of the enhanced seed electron flux and the enhanced whistler activities.

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