Acceleration of Magnetospheric Relativistic Electrons by Ultra-Low Frequency Waves: A Comparison between Two Cases Observed by Cluster and LANL Satellites

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Abstract. Understanding the origin and acceleration of magnetospheric relativistic electrons (MREs) in the Earth's radiation belt during geomagnetic storms is an important subject and yet one of outstanding questions in space physics. It has been statistically suggested that during geomagnetic storms, ultra-low-frequency (ULF) Pc-5 wave activities in the magnetosphere are correlated with order of magnitude increase of MRE fluxes in the outer radiation belt. Yet, physical and observational understandings of resonant interactions between ULF waves and MREs remain minimum. In this paper, we show two events during storms on September 25, 2001 and November 25, 2001, the solar wind speeds in both cases were > 500 km s⁻¹ while Cluster observations indicate presence of strong ULF waves in the magnetosphere at noon and dusk, respectively, during a ~ 3-hour period. MRE observations by the Los Alamos (LANL) spacecraft show a quadrupling of 1.1-1.5 MeV electron fluxes in the September 25, 2001 event, but only a negligible increase in the November 25, 2001 event. We present a detailed comparison between these two events. Our results suggest that the effectiveness of MRE acceleration during the September 25, 2001 event can be attributed to the compressional wave mode with strong ULF wave activities and the physical origin of MRE acceleration depends more on the distribution of toroidal and poloidal ULF waves in the outer radiation belt.

INTRODUCTION

Magnetospheric relativistic electrons (MREs) in the outer radiation belt can have hazardous space environment effects on space system. More importantly, during geomagnetic storms/substorms, relativistic electrons can be energized and enhanced in Earth's radiation belt and potentially have serious effects on satellites. Understanding the origin and acceleration of magnetospheric relativistic electrons (MREs) in the Earth's radiation belt during geomagnetic storms is an important subject and yet one of outstanding questions in space physics. Most often, MRE enhancements in the outer radiation belt of the magnetosphere (e.g., geosynchronous region) are correlated with geomagnetic storms and high solar wind speed. But not all storms are associated with MRE enhancements [*Reeves* 1998]. It was suggested that during geomagnetic storms, increased ultra-low-frequency (ULF) Pc-5 wave activities in the magnetosphere can enhance the MRE flux by order of magnitude in the outer radiation belt (L = 5-7) and slot region (L = 2-3.5) can be filled with accelerated MeV electrons [*Baker et al.*, 1998; *Rostoker et al.*, 1998; *Green*, 2002].

The connection between ULF waves and MRE acceleration has been statistically established by *Mathie and Mann* [2000], *O'Brien et al.* [2003]. Statistically [e.g., *O'Brien et al.* (2001)], significant MRE enhancement tends to occur during:

- Sustained, high solar wind speed (> 450 km/sec)
- The recovery phase of a magnetic storm
- Long-duration (days) of elevated Pc5 ULF wave power.

In the past, models have been developed to explain MRE acceleration by ULF waves. *Schulz and Lanzerotti* [1974] developed one dimensional radial diffusion model and related diffusion coefficient with magnetic and electric field wave amplitude. *Summers and Ma* [2000] derived a momentum diffusion model of MRE acceleration by stochastic ULF waves based on quasi-linear theory of wave-particle interaction. Both of these models have neglected the azimuthal distributions of ULF waves. Since electrons drifting in an axially symmetric magnetic field cannot be accelerated by uniformly distributed ULF waves over its drift orbit, asymmetric magnetic field and/or wave distributions are needed for the drift-resonant acceleration mechanism to yield a net energy gain for MREs. For example, *Elkington et al.* [1999, 2003] considered a compressed dipole field model with day-night asymmetry to investigate the acceleration of magnetospheric electrons by both toroidal and poloidal mode ULF waves. These ULF waves were found to result in electron energization via the drift-resonant interaction.

Degeling et al. [2007] considered the effect of realistic scenario of asymmetric azimuthal distribution of compressional mode ULF waves on electron acceleration and demonstrated that the poloidal mode wave is more efficient in electron energization because of azimuthal overlap of the poloidal ULF electric field and electron drift orbit on the dayside of magnetosphere through modeling. The poloidal mode electric field (E_ϕ) is related to the compressional mode ULF wave that can transfer wave energy across magnetic field lines. The azimuthally asymmetric wave distribution can be attributed to the dominance of wave power on the dayside due to the solar wind compression. Although modeling work indicates that localized toroidal and poloidal ULF waves play different roles on outer belt MRE acceleration, however, there have not been direct observational evidences to distinguish the efficiencies of drift resonant acceleration of MREs between compressional mode and FLR mode ULF waves.

In this paper, we present two events which occurred on September 25, 2001 and November 25, 2001, respectively, to show that although the statistical result supports the general dependences of MREs on solar wind speeds and ULF activities, individual events can

behave quite differently. Both events were associated with high solar wind speeds and (> 3 hour) strong ULF waves in the magnetosphere. MRE observations by the energetic electron detectors on Los Alamos (LANL) spacecraft showed significant increase MeV electron flux over a 3-hour period in the September 25, 2001 event, but the MRE increase in the November 25, 2001 event was negligible. We suggest that localized toroidal and poloidal ULF waves play important and distinct roles on outer belt MRE acceleration.

## MRE FLUX ENHANCEMENT DURING SEPTEMBER 25, 2001 EVENT
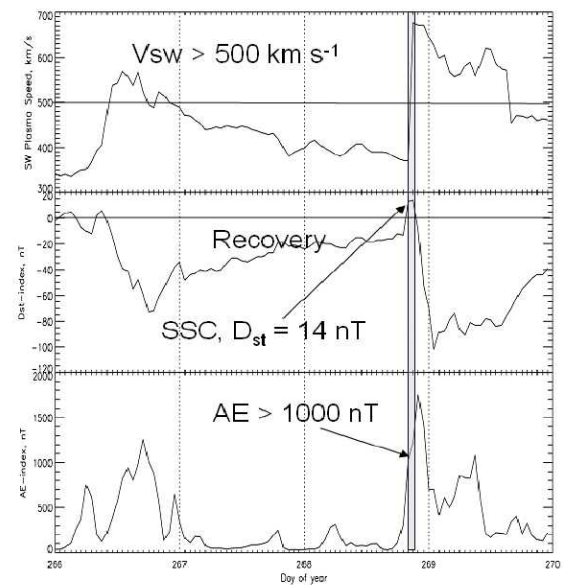
Figure 1: Solar wind speed, Dst index and AE index during Sept. 23- Sept. 26, 2001. The Sept. 25, 2001 [day of year (doy) 268] storm event is marked with shaded area. (Data source: OMNI).

During the September 25, 2001 event, the MRE enhancement occurred together with significant ULF wave activities. Before the Storm Sudden Commencement (SSC) event occurred on September 25, 2001, there was a geomagnetic storm that occurred on Sept. 23 (DOY = 266) with Dst minimum ~ -75 (Figure 1). It is still in the storm recovery phase during the two days (Sept. 24 and 25) following the Sept. 23 magnetic storm. On September 25, an interplanetary shock driven by the CME arrived at the Earth at 20:25 (UT) and caused a powerful SSC event. The solar wind speed after the shock as measured by the Wind spacecraft was 670 km s^{-1}. At the beginning of SSC event the geomagnetic indices were Kp = 6 and AE = 1100 nT. During the interval of our interest (UT 20:00 to 23:00 on Sept. 25, 2001), the Dst maximizes around

14 nT (signature of SSC), hence the event occurred during the onset phase of the Sept. 25 magnetic storm
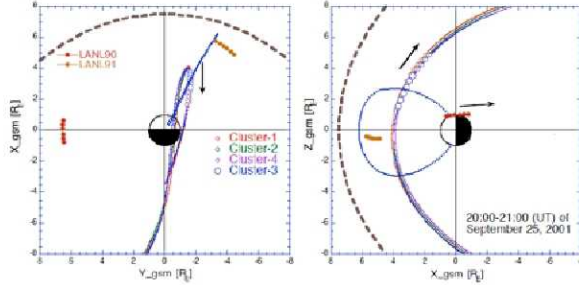
Figure 2: The orbits of the Cluster and LANL90 and 91 spacecrafts at 20:00-21:00 (UT), September 25, 2001. The solid line in the Cluster orbits show the periods when the spacecraft are outside the magnetopause (shown as dashed lines). The dotted blue line (right panel) is a magnetic field line passing through Cluster-3 at 20:30 (UT), computed using the Tsyganenko T89 model.

The SSC event on September 25, 2001 was monitored by Cluster-1 to -4, and Los Alamos 1990-095 (LANL90), and 1991-080 (LANL91) spacecrafts. In Figure 2, the color-coded open/solid circles show the orbits of the Cluster and LANL spacecrafts during 20:00-21:00 (UT) on September 25, 2001. The arrows near the orbits show the directions of spacecraft motion. The Cluster spacecrafts were in geopolar orbit with perigee near noon and thus were in a suitable location for detecting ULF waves and low-energy electrons near local noon during the September 25 SSC event. Also the orbit of Cluster-3 (largest open circles in Figure 2) was at lower latitudes during the event period. As shown in Figure 2, the magnetic field line (dotted line in Figure 2, right panel) traced using the Tsyganenko T89 model, passed through Cluster-3 at 20:30 (UT), indicating an orbit conjunction between Cluster-3 and LANL91. This conjunction enables comparisons of electron flux measurements between these two spacecraft. The omnidirectional electron flux (J_{omn}) data in the electron energy (T_e) range 50 keV -1.5 MeV were collected by LANL spacecrafts. LANL91 was close to noon, and LANL90 was located at dusk

The Cluster spacecrafts provide the dusk electric field (E_{dusk}) data measured in the spin plane perpendicular to the X_{GSE} axis and its power spectra from the measurements during 20.20-21.20 hr (UT) of 25 September 2001 as shown in the top panel of Figure 3a. During the event period, E_{dusk} had a wide-spectral structure. For wave frequency $f_w > 20$ mHz, the
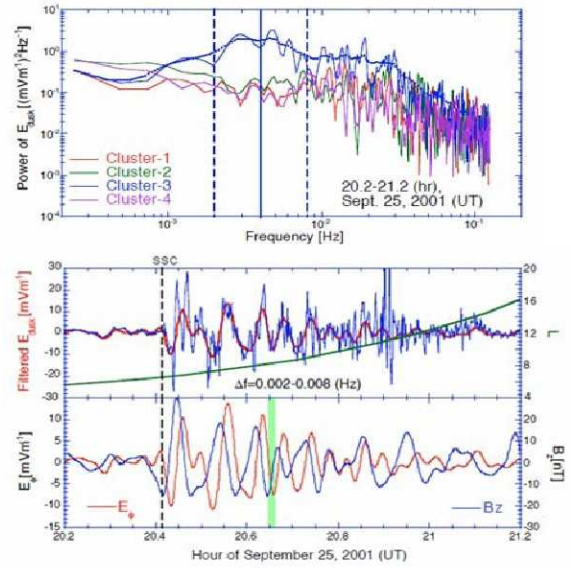
(a)
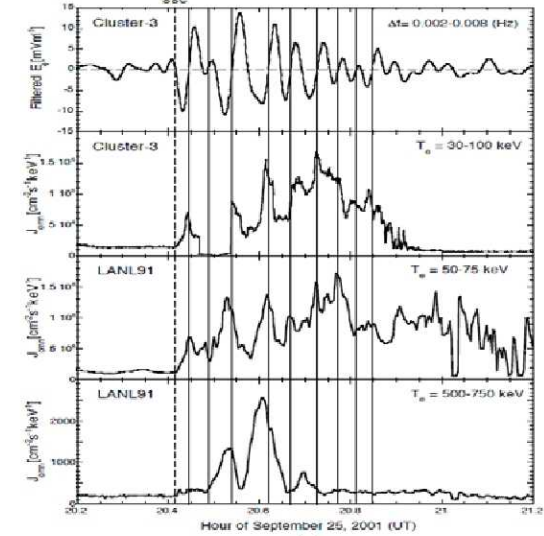
(b)

Figure3: (a) (Top Panel) Power spectra of duskward electric field components from all four Cluster spacecrafts. (Middle Panel) Time profiles of original and filtered E_ϕ, and L values from the Cluster-3 spacecraft observations. (Bottom panel) B_Z and E_ϕ after being filtered with same band-pass filter from the Cluster-3 spacecraft observations. (b) Time profiles of filtered E_ϕ measured by Cluster-3 (top panel), J_{omn} of 30-100 keV electrons measured by Cluster-3 (second panel), J_{omn} of 50-75 keV electrons measured by LANL91 (third panel) and J_{omn} of 500-750 keV electrons measured by LANL91 (bottom panel). The vertical solid lines are the times at which the filtered E_ϕ crosses zero from negative to positive.

observed power spectrum of E_{dusk} by Cluster-1, -2, and -4 are close in magnitude to that on Cluster-3, while at lower frequencies the wave power on Cluster-3 is greater than that on other Cluster spacecrafts by more than one order of magnitude. The power of E_{dusk} measured by Cluster-3 is concentrated in the frequency range of 2-8 mHz (between the dashed lines), which falls right into ULF Pc-5 wave band.

The ULF oscillation of the dusk electric field measured by Cluster-3 is evident in the filtered data of E_{dusk} obtained by using a 2-8 mHz band-pass filter. The time profile of filtered electric field is shown in the middle panel of Figure 3a as the red line along with the original electric field data and the L parameter. Since the Cluster-3 spacecraft was located near noon during the September SSC event, E_{dusk} can be viewed as the azimuthal electric field component and we denote it as E_ϕ in the rest of the paper.

In bottom panel of Figure 3a, we compare the phase of E_ϕ with that of B_z, which is filtered using the same band-pass filter. It can be seen that over the main observation interval between SSC and 20.65 hr (UT) (the shaded green region), B_z led E_ϕ by $\sim \pi/2$, while after 20.65 hr (UT) both phases are gradually close to each other. In addition, the magnetic field amplitude observed by GOES satellite has ULF oscillations [Tan et al., 2010]. These features are consistent with the simulations of compressional mode waves [Degeling et al., 2007, Figure 1]. These waves are poloidal mode waves and are related to radial perturbation of magnetic field line. It is of fast-mode wave nature and is related to the perturbed field components δB_ρ, δE_ϕ and δB_z [Takahashi et al., 1992, 1995].

The modulation of low-energy electron fluxes by the compressional mode ULF waves can be identified using the wave data from Cluster and electron data from Cluster and LANL spacecrafts. In Figure 3b the time profile of filtered E_ϕ oscillations (top panel) is compared with J_{omn} for Cluster-3 30-100 keV electrons (see middle panel of Figure 3b, the differential flux is deduced from Cluster-3 integrated flux data), and for LANL91 50-75 keV electrons (see bottom panel of Figure 3b). Because of the conjunction between Cluster-3 and LANL91 orbits, the phases of J_{omn} measured on both spacecraft matched with each other very well. On the other hand, there is no clear modulation of higher energy (500-750

keV) electron flux as observed by LANL 91 (see bottom panel of Figure 3b).

The acceleration of relativistic electrons can be identified from the omnidirectional electron flux J_{omn} measured by GOES 08-10 and LANL 90 shown in Figure 4a. Figure 4b shows the J_{omn} data over a wide energy range (50 keV-1.5 MeV) as measured by the LANL90 spacecraft located at dusk. It can be seen that low-energy electrons did not have net energy increase, since the resultant level of J_{omn} for LANL90 is nearly equal to the pre-event background value after 21:40 UT at the end of modulation.

After the anomalous increase of J_{omn} during the first hour after the SSC onset, a steady diffusive enhancement of high-energy (e.g., 1.1-1.5 MeV) electron flux was observed ~1.5 hours after the SSC onset. With respect to the pre-event backgound value the electron flux J_{omn} ($T_e = 1.1$-1.5 MeV) enhancements observed by LANL90 is 4 times. There is a threshold $T_e(thr)$ of electron energy, below which the electron fluxes are highly modulated by the ULF waves and the final electron flux doesn't exceed pre-event background value. Above this threshold the electron flux increases diffusively and the final electron flux has a net increase. The electron energy thresholds ($T_e(thr) \sim$ 300 keV) as identified from LANL90 observations are shown as the horizontal purple lines in Figure 4b. The implication of this energy threshold and theory of drift-resonant acceleration of MREs by compressional mode ULF waves can be found in *Tan et al.* [2010].

NOVEMBER 25, 2001 EVENT WITH STRONG ULF WAVE ACTIVITY, BUT NO NET MRE ACCELERATIONS

The November 25, 2001 event occurred during the recovery phase of a large geomagnetic storm as shown by the Dst index in Figure 6b and the associated interval of extremely long-lasting ULF Pc5 pulsations has been analyzed extensively by *Rae et al.* [2005]. *Rae et al.* [2005] reported that these monochromatic large-amplitude ULF
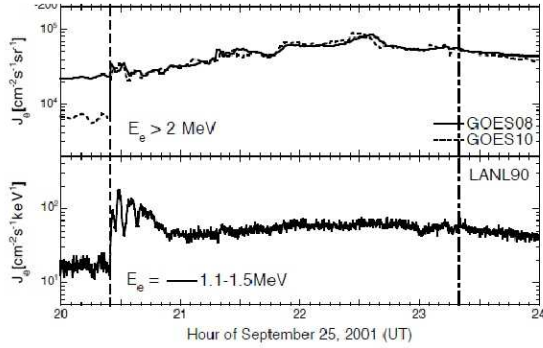
(a)
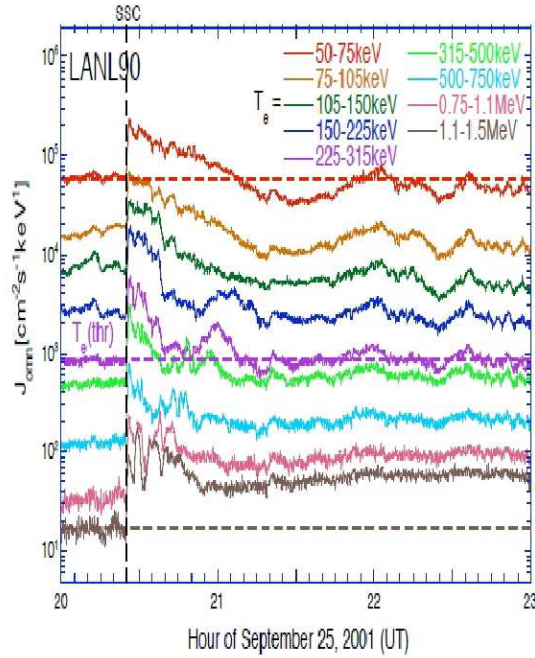
(b)

Figure 4: (a) (Top panel) GOES08 and GOES10 satellite observation of > 2MeV MRE flux enhancement. (Bottom panel) LANL90 satellite observation of 1.1-1.5 MeV MRE flux enhancement. (b) Time profiles of J_{omn} measured by LANL90. The upper, middle and lower horizontal dashed lines indicate the background J_{omn} levels at $T_e = 50$-75 keV, $T_e = 225$-315 keV and $T_e = 1.1$-1.5 MeV, respectively.

pulsations occurred continuously for many hours and were observed throughout the

magnetosphere by the Cluster satellites, and geostationary satellites GOES-8, -9, -10 and -12, and in the dusk-sector ionosphere by the CANOPUS magnetometer chain. The Cluster satellites are in the vicinity of the dusk magnetopause (Figure 7) and show oscillations with the same periodicity as the ground

and geosynchronous pulsations. As an example, the ULF oscillation can be seen from Figure 6d which shows the bandpass-filtered duskward electric field observed by Cluster-4 during the interval. In Figure 8a, low energy electron flux shows ULF modulated oscillation and no net increase.

During this event, there are no monochromatic dynamic pressure variations in the solar wind. It is suggested by *Rae et al.* [2005] that Kelvin-Helmoltz instability at the duskside magnetopause caused magnetopause oscillations, which coupled energy to standing Alfvén waves propagating along the resonant field lines. This explains that ground-based magnetometers observed signatures characteristic of a field-line resonance. The standing Alfven wave is of toroidal mode wave nature and is related to azimuthal perturbation of magnetic field line. It propagates along the magnetic field line and is related to the perturbed field components δB_ϕ and δE_r.
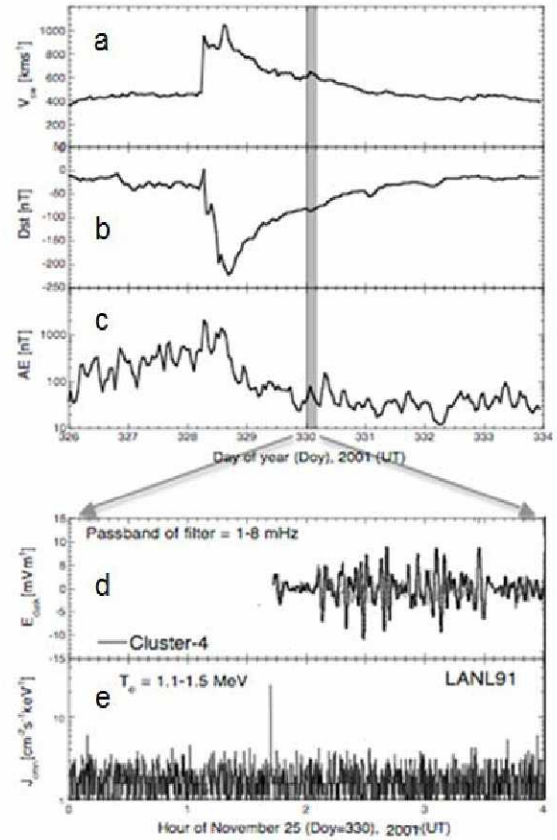

Figure 6: (a-c) Solar wind speed, Dst index and AE index during Nov. 21- Nov. 28, 2001. (Data source: OMNI) (d) Strong ULF wave activities observed by Cluster-4 spacecraft. Earlier data before UT 1:40 was a data gap. (e) No MRE flux enhancement observed by LANL 91.

The evidence of toroidal mode wave can be also seen in Figure 8b, which shows that the radial electric perturbation carried the largest energy spectra as observed by the Cluster-2 spacecraft in the vicinity of duskside magnetopause.
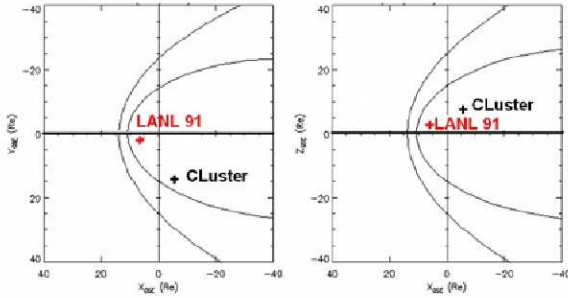
Figure 7: Cluster and LANL 91 spacecraft location during the November 25, 2001 event.
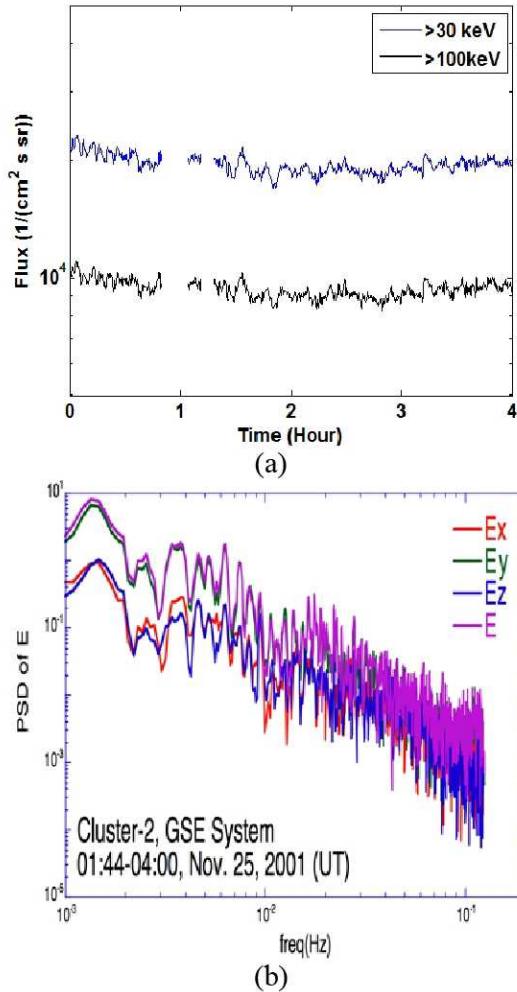
Figure 8: (a) electron flux observed by Cluster-4 spacecraft. (b)Power spectra of electric field components for Cluster-2 spacecraft. Since the Cluster

satellite is located at the dusk side, the dominant electric field component E_y can regarded as E_r.

During this event interval, the solar wind velocity V_{sw} > 500 km/s, and it is during the recovery phase of a large storm with minimum Dst < -200 nT. Also, strong Pc5 ULF activity near 1.5 mHz were observed throughout the magnetosphere and duskside ionosphere. All of these factors meet the criteria derived from the statistical analysis by *O'Brien et al.* [2001], which implies that these conditions will favor MRE acceleration. But, there is no net MRE enhancement observed, i.e. for electron of energy T_e= 1.1-1.5MeV by LANL 91 observation in Figure 6e. Instead, *Rae et al.* [2005] reported coherent low energy (75-315 keV) electron flux modulations by ULF waves from observations of LANL spacecrafts distributed at different local time around the geosynchronous orbit.

COMPARISON BETWEEN SEPTEMBER 25, 2001 AND NOVEMBER 25, 2001 EVENTS

In this section, we do a comparison between September 25, 2001 and November 25, 2001 events and investigate factors affecting efficient MRE accelerations by ULF waves.

Table 1 compares features of the two events we studied. In general, the solar wind velocities are high (> 500 km/s). Also, strong ULF fluctuations are both observed. But, the September 25, 2001 event observed MRE enhancement and the November 25, 2001 event did not. During the first 1.5 hours after SSC onset in September 25, 2001 event, the low-energy electron flux observed by LANL 90 exhibits less modulation as compared to the modulation observed in Figure 3b by LANL 91 on the dayside. This indicates that the ULF wave energy is mainly concentrated in the dawn-noon sector of the dayside where LANL-91 is located and less disturbed at the dusk side where LANL 90 is located. This further suggests that the ULF wave energy is fed through dayside compression rather than Kelvin-Helmholtz instability or other processes at the flanks.

We found that the main difference between these two events are that during the SSC
event of September 25, 2001, the ULF waves are mainly poloidal mode waves and concentrated at and near the outer radiation belt in the dayside magnetosphere; and during the event of November 25, 2001, Kelvin-Helmholtz instabilities due to magnetosheath shear flows excited flank side-

concentrated field line resonance (toroidal mode waves). These findings are consistent with previous observations. For example, *Engebretson et al.* [1998] and *Vennerstrom* [1999] observed that Pc-5 wave power tends to maximize near magnetic local noon and increases more generally with solar wind velocity such

Date	September 25 00-04 UT	November 25 20-24 UT
MRE (~1 MeV) enhancement	Yes	No
Vsw	> 500 km s-1 (implusive)	> 500 km s-1
Enhanced ULF	Yes	Yes
Storm condition	Onset	Recovery
SSC	Yes	No
Bz (GSE)	Mostly < 0	Mostly > 0
Solar wind Pdyn	> 20 nPa	~ 2 nPa
ULF characteristics	Stronger Eφ, Poloidal	Eρ, Weaker Eφ, Toroidal
AE	> 1000 nT	< 100 nT

Table 1: Comparison between the two events.

as during high-speed streams. *Sakurai et al.* [1999] also found that compressional power is superior to that of the transverse resonant oscillations when spacecraft was close to the magnetopause. These oscillations during SSC events have been suggested to be excited by waves or compression regions in the solar wind [*Kepko and Spence*, 2003; *Kessel et al.* 2003; *Kessel and Shao*, 2005]. On the other hand, *Anderson et al.* [1990] observed that storm-time Pc-5 waves (fundamental mode of Field Line Resonance (FLR)) are excited primarily in the dusk and dawn regions and by magnetosheath flows [*Mann et al.* 1999, 2004].

EFFICIENCIES OF DRIFT-RESONANT ACCELERATION BY POLOIDAL AND TOROIDAL ULF WAVES

The electron acceleration by poloidal mode wave (E_ϕ) should be more effective than by toroidal mode wave (E_r). This is because that E_r is perpendicular to the electron drift orbit and its energization effect depends on the drift orbit deviation

Δr due to the magnetospheric compression. Since the main component of electron drift motion is along the azimuthal direction, interaction of electrons with compressional mode waves whose electric field is along the azimuthal direction, can be more effective in generating MREs. We can use a compressed dipole magnetic field to approximate the equatorial magnetic field configuration [*Elkinton et al.*, 2003] and illustrate on this. In the model the magnetic field strength B is a function of the radius r and azimuthal angle ϕ,

$$B(r,\phi) = b_0 + b_1(1 + b_2 \text{c} \quad \phi), \qquad (1)$$

where $b_0 = B_0 R_E^3 / r^3$ ($B_0 = 3.11 \times 10^4$ nT), b_1 and b_2 are model parameters. Alternatively, we can use two new parameters $B_m = b_0 + b_1(1 + b_2)$ and $B_m = b_0 + b_1(1 - b_2)$ to describe the model, which correspond to day-night asymmetry in magnetic field configuration [*Tan et al.*, 2004]. Thus the relative acceleration efficiency of toroidal mode to poloidal mode wave (E_r to E_ϕ) can be related to the factor $\Delta r / r$ using the compressed dipole model,

$$\Delta r / r \sim (b_{max} - b_{min})L^3 / (6B_0). \qquad (2)$$

During September 25, 2001 event, we determined $B_{min} \sim 65$ nT and $B_{max} \sim 190$ nT from the magnetic field B_z component measured by GOES10. Relative acceleration efficiency of E_r to E_ϕ (Eq. 2) has a value of ~0.15 at L = 6. Therefore, in the September 25 event the electron acceleration is mainly due to the poloidal mode electric field E_ϕ. This also explains that the observed lack of MRE enhancement in the November 25, 2001 event is consistent with less effective acceleration by toroidal mode waves.

SUMMARY

In this paper, we compared two magnetic storm events, one with and one without MRE enhancements. We found that either toroidal or poloidal mode can both produce electron flux modulations for low energy electrons. It is suggested that during a sudden storm commencement (SSC), i.e. 2001 September 25. SSC, events tend to produce dayside compressive mode with E_ϕ perturbations, producing (MeV) MRE enhancement. On the other hand, radial electric field oscillations Eρ (e.g., toroidal field line resonances) on the flanks are not effective in producing MREs, as was observed in the 2001 November 25 event. In *Tan et al.* [2010], more detailed theory and analysis on the drift-resonant acceleration of MREs by compressional mode wave as inferred from September 25, 2001 event

will be discussed. A more comprehensive study of the relationships among upstream solar wind and IMF conditions, Ultra-Low-Frequency (ULF) waves, and Magnetospheric Relativistic Electrons (MREs) is needed, in particular, to study the excitation and distribution of ULF waves by upstream solar wind and IMF conditions and the drift resonant acceleration of relativistic electrons by ULF waves.

ACKNOWLEDGEMENTS

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