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Radial gradients of phase space density of the outer radiation belt electrons prior to sudden solar wind pressure enhancements

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[1] When Earth's magnetosphere is impacted by a sudden solar wind pressure enhancement, dayside trapped electrons are transported radially inwards, conserving their first and second adiabatic invariants (μ and K). Thus, with magnetic field and particle flux measurements at geosynchronous orbit (GEO) before and after the impact, the phase space density (PSD) radial gradients of the particles prior to the impact can be reconstructed. We show two examples, in which the PSD of low-μ electrons, which correspond to energies less than $\sim$100 keV, increases slightly with increasing radial distance for one event and remains unchanged for the other, while that of high-μ electrons decreases significantly with increasing radial distance from GEO for both events. These results suggest that the PSD radial gradients are μ dependent, and a significant heating, which violates μ and K, occurs inside GEO for the high energy electrons for the two cases examined. **Citation:** Turner, D. L., and X. Li (2008), Radial gradients of phase space density of the outer radiation belt electrons prior to sudden solar wind pressure enhancements, *Geophys. Res. Lett.*, *35*, L18101, doi:10.1029/2008GL034866.

1. Introduction

[2] Phase space density radial gradients are suggestive of the source regions of the outer belt electrons and thus, the dominant acceleration mechanisms as well. These gradients have been investigated intensively [e.g., *Selesnick and Blake*, 2000; *Green and Kivelson*, 2004; *Onsager et al.*, 2004; *Iles et al.*, 2006; *Chen et al.*, 2005, 2006, 2007]. A critical process in determining the magnitude of the PSD radial gradient is to calculate the L^* (L^* throughout is the Roederer L^* parameter and is related to the third adiabatic invariant) on which the electrons are assumed to drift while conserving their first and second adiabatic invariants. Most researchers apply empirical magnetic field models to calculate L^*, but it is known that empirical models have some uncertainties. For example, using different empirical models may lead to different values of L^* for the same events [e.g., *Green and Kivelson*, 2004; *McCollough et al.*, 2008]. Multi-satellite techniques [i.e., *Onsager et al.*, 2004; *Chen et al.*, 2005, 2006, 2007], which are used to determine instantaneous values of the PSD radial gradient, are field model dependent since a corresponding L^* must be calculated for each spacecraft, and single satellite techniques [i.e., *Selesnick and Blake*, 2000; *Green and Kivelson*, 2004; *Iles et al.*, 2006], which are used to determine values of the PSD radial gradient over a portion of the spacecraft orbit, are also field model dependent and assume that changes during the spacecraft transit time are insignificant. *Onsager et al.* [2004], utilizing the fact that two GOES satellites are at different L^* because of their different magnetic latitudes, studied the PSD of electrons with $\mu = 6000$ MeV/G, and they found that the PSD radial gradient is positive around GEO. However, other researchers, as referenced above, found that the PSD for high-μ electrons usually peaks inside of GEO. We have developed a new method that determines the direction of the PSD radial gradient nearly instantaneously and without relying on a magnetic field model to determine the actual L^*. This method is complementary to the above mentioned studies, and results from it are consistent with the results of several of these previous studies.

[3] Here, we demonstrate this new method, which determines the direction of the electron PSD radial gradient at and beyond GEO prior to a sudden solar wind pressure impact based on the fact that such an event causes a magnetic field compression and dayside trapped particles to be transported radially inwards, conserving μ and K [*Li et al.*, 1993, 2003; *Lee et al.*, 2005; Y. Shi et al., Features of energetic particle radial profiles inferred from geosynchronous responses to solar wind dynamic pressure enhancements, submitted to *Annales Geophysicae,* 2008]. As we know, a satellite at dayside GEO measures electrons initially at larger L^* immediately after the impact and electrons at a smaller L^* before the impact. Based on the electron measurements as well as the magnetic information before and after the impact, a PSD radial gradient prior to the impact can be reconstructed. Using this method, we have investigated several events, and we present the results from two of them here. From these, we find that the PSD radial gradients are μ (or energy) dependent. For low-μ electrons, corresponding to energies less than $\sim$100 keV at GEO, the PSD increases slightly or stays relatively constant with increasing radial distance, while that of high-μ electrons, which correspond to energies greater than $\sim$200 keV, generally decreases with increasing radial distance from GEO. For the remainder of this discussion, a gradient that increases with increasing radial distance shall be referred to as a positive gradient, while one that decreases with increasing radial distance shall be referred to as a negative gradient.

2. Analysis Method

[4] We use two solar wind pressure enhancement events to determine the PSD radial gradient for electrons at and beyond GEO. Figure 1 shows the Dst index and B_z, V, and dynamic pressure of the solar wind from ACE measurements for 12 hour periods before and after sudden solar

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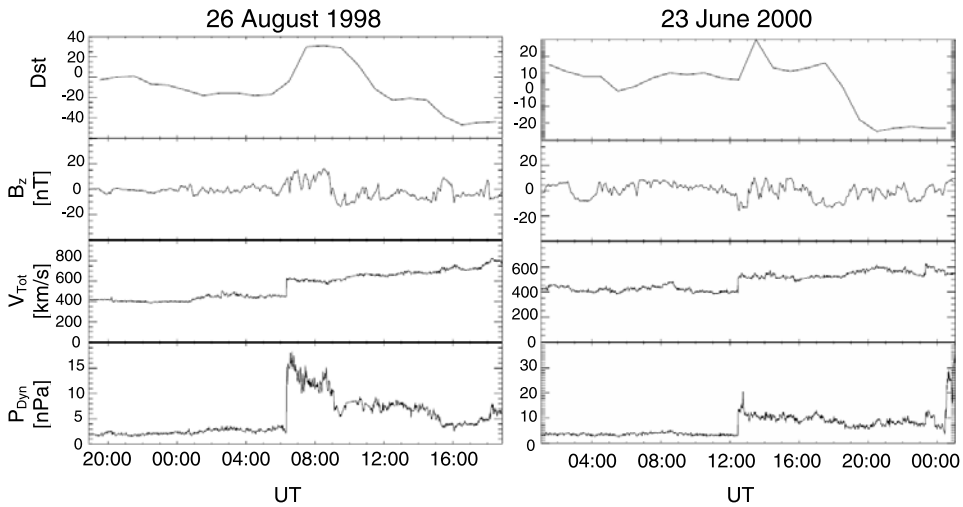

Figure 1. DST and ACE solar wind data for both events. Note that the date at the top of Figures 1 (left) and 1 (right) is that of the event itself, but both show a time range of more than one day.

wind pressure enhancements on 26 August 1998 and 23 June 2000. To employ this method, the sudden pressure enhancements should occur on timescales much shorter than the drift periods of the particles being studied to ensure that the particle measurements accurately reflect particles from the same local time but a different L^*. Also, note that the solar wind conditions prior to the events are relatively calm. This is not necessarily an event criterion, but for these events, it does correspond to a more uniform magnetic field response, which makes the μ calculation easier and is further discussed below.

[5] For particle data, we use energetic electron flux measurements from the Los Alamos National Laboratory (LANL) satellites in GEO. The LANL satellites' SOPA instruments have nine differential electron flux channels, and we use 10-second resolution SOPA flux data for this study. Flux measurements from several energy channels at this resolution for two hours before and after the events are shown in Figure 2. Here, we only show the measurements from three LANL satellites for each event. For the 1998 event, all three satellites shown are on the dayside, and for the 2000 event, only the three satellites with data available are shown, of which two are also on the dayside. In Figure 2, event times are marked with a vertical dashed line. Note how the response varies for each satellite, yet most see a flux increase in the lowest energy channels and a decrease in the higher energy channels immediately following the solar wind pressure impact. However, because the local magnetic field is compressed by the solar wind pressure enhancement, one cannot infer the PSD radial gradient just based on the flux variations. The PSD has to be carefully calculated as described below.

[6] To capture only these initial effects and mitigate ambiguity due to particle drifts, we use only the flux

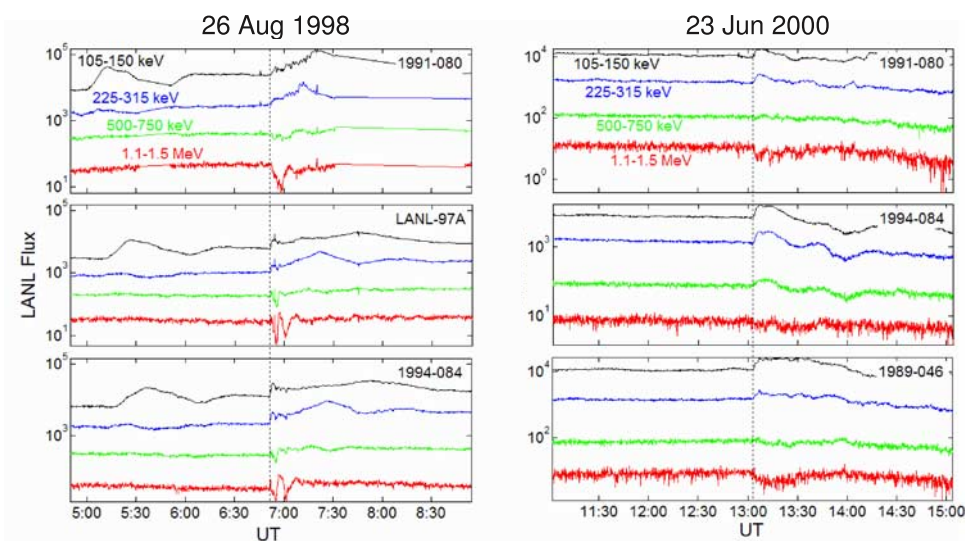

Figure 2. LANL flux [cm^{-2} $s^{-1}sr^{-1}keV^{-1}$] measurements for both events. Event times are shown with dotted lines. For the 1998 event, 1991–080, LANL-97A, and 1994–084 are at 07:27, 11:30, and 13:45 local time (LT) respectively, and for the 2000 event, 1991–080, 1994–084, and 1989–046 are at 13:36, 19:59, and 02:01 LT respectively.

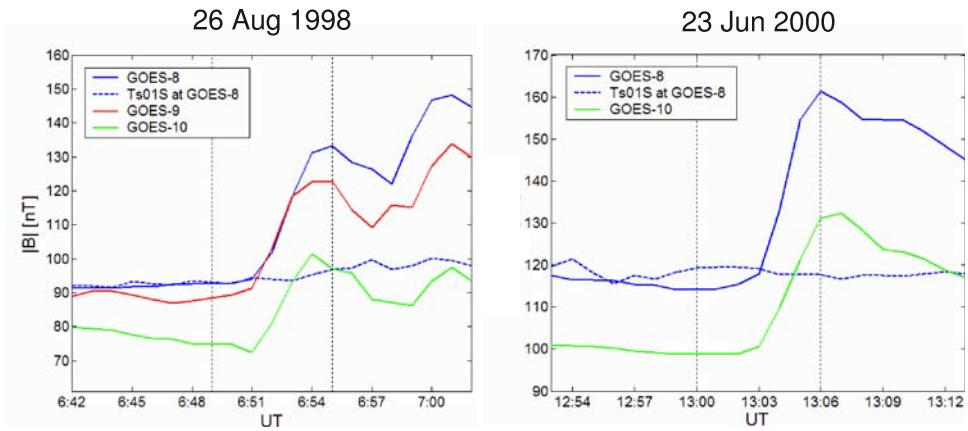

Figure 3. GOES B-fields for both events. Tsyganenko 2001-Storm model results for GOES-8 are shown with the dashed blue lines for both events. Dotted vertical lines show the times used for this study. For the 1998 event, GOES-8, −9, and −10 are at ∼02:50, ∼00:50, and ∼22:50 LT respectively, and for the 2000 event, GOES-8 and −10 are at ∼09:00 and ∼05:00 LT respectively.

measured three minutes before and after the pressure enhancement. The fluxes from the nine differential energy channels from each satellite are fit with a power law using the equivalent energy for each channel:

$$E_{ch} = \sqrt{E^{ch}_{\min} \cdot E^{ch}_{\max}} \tag{1}$$

where the *min* and *max* energies are the lower and upper bounds of the channel as discussed by *Chen et al.* [2005]. The power law fit provides a good approximation of the energy spectrum at each time and allows us to determine a flux for any given energy. PSD is then calculated for each time from these fluxes using:

$$f = 3.325 \times 10^{-8} \frac{j}{E(E + 2m_0c^2)} \left[\left(\frac{c}{MeV \cdot cm} \right)^3 \right] \tag{2}$$

where f is PSD in units seen in brackets, j is flux in units of $cm^{-2}s^{-1}sr^{-1}keV^{-1}$, E is energy in MeV, m_0 is the rest mass of an electron, and c is the speed of light in a vacuum. For detail of the equation form, see *Chen et al.* [2005].

[7] To calculate μ, the magnitude of the magnetic field is required, but LANL satellites do not have onboard magnetometers. Before the pressure impacts, magnetic field models such as the Tsyganenko 2001-storm (Ts01-S) model [*Tsyganenko et al.*, 2003] prove to be quite accurate when compared to GOES magnetic field measurements. However, during and after the pressure impacts, all field models are unable to capture the resulting compression of the field, and as has been mentioned in much of the previous research, accurate PSD results are highly dependent on the accuracy of the field model [*Selesnick and Blake*, 2000; *Green and Kivelson*, 2004]. Figure 3 shows the GOES magnetic field measurements during both events. These field measurements are 1-minute resolution data from the Coordinated Data Analysis Web (CDAWeb) and NOAA's SPIDR data archive (see Acknowledgments for site URLs), and the known offsets for GOES-8 and GOES-10 measurements [*Tsyganenko et al.*, 2003] are corrected. For both events, the Ts01-S model was run at GOES-8 positions, and the results are shown by the dotted blue line. Notice that before the event, the Ts01-S model and the GOES-8 measurements are very close, but when the event occurs, the Ts01-S model does not capture the immediate field enhancement.

[8] We have chosen events in which the magnetic field response is similar at different local times, meaning that the GOES satellites see very similar relative increases in the magnitude of the magnetic field. For the 26 August 1998 event, the percent increases observed by GOES 8 and 10 differ by ∼2%, while GOES 8 and 9 and 9 and 10 increases differ by ∼1%. For the 23 June 2000 event, GOES 8 and 10 percent increases differ by ∼4%. Since the fields measured by GOES behave very similarly during the event, we assume the same relative change for the magnetic fields at the LANL locations. To approximate the field strength at the LANL spacecraft positions, we use the Ts01-S model before the event and scale the compressed field from the nearest GOES measurements for the rest of the event. First, GOES field measurements are interpolated from their 1-min resolution to the same 10-s resolution as the LANL particle measurements. The scaling then involves calculating the ratio of the Ts01-S field at the LANL spacecraft to the initial measured field at GOES and multiplying the remaining GOES measurements with this ratio to get the field at the corresponding times for the LANL satellite:

$$B(t_i)_{LANL} = \left(\frac{B(t_0)_{T_{s01-S}}}{B(t_0)_{GOES}} \right) B(t_i)_{GOES} \tag{3}$$

where t_i is a time index with t_0 being the initial time, $B(t)_{GOES}$ is the GOES measured field, $B(t_0)_{Ts01\text{-}S}$ is the Ts01-S result at the LANL spacecraft position prior to the event, and $B(t)_{LANL}$ is the scaled field at the LANL position throughout the event. Given this, we can now compute μ for each time step with:

$$\mu = \frac{E(E + 2m_oc^2)\sin^2\alpha}{B_{LANL}(2m_oc^2)} \times 10^5 \left[\frac{MeV}{G} \right] \tag{4}$$

where B_{LANL} is the field magnitude in nT, α is the pitch angle, and the other parameters are as defined for equation (2). Note that for this study, we are calculating this for equatorial electrons with pitch angles close to

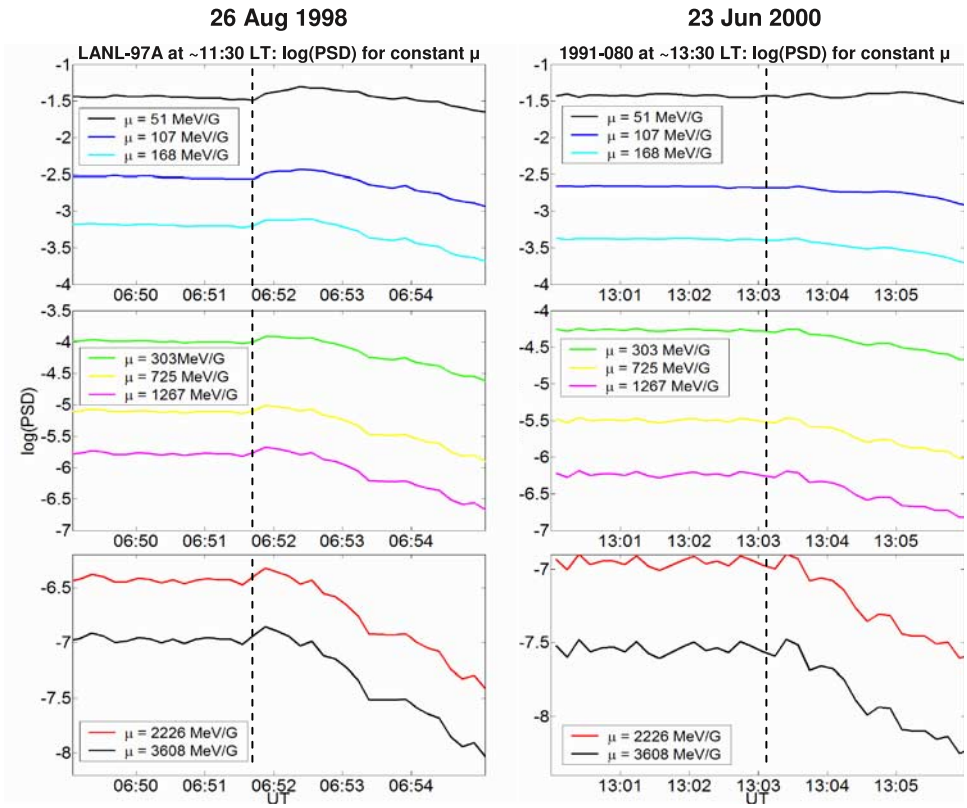

Figure 4. PSD results from the LANL satellite closest to noon for each event. Colored lines show the logarithm of PSD for constant values of μ for three minutes before and after each event, the times of which are shown with dashed lines.

90 degrees, which is representative of the majority of dayside energetic electrons [*Gannon et al.*, 2007].

3. Results and Discussion

[9] Figure 4 shows the results for both events. Each event is displayed with three plots showing the logarithm of PSD for fixed values of μ. These are the results derived from the LANL satellites closest to noon: LANL-97A at ~11:30 LT for the 1998 event and 1991-080 at ~13:30 LT for the 2000 event. We only show the results from the satellites closest to noon since it is there that the electrons are most likely transported radially inwards. Event times are displayed with the dashed vertical lines, and the time scale for all is six minutes. It is evident in the first event that the PSD for high μ (results above ~100 MeV/G) drops significantly, up to a full order of magnitude for the PSD of μ = 3608 MeV/G, after the event, but for μ = 51 MeV/G, the PSD slightly increases after the event and then returns to approximately initial levels. This low-μ behavior is markedly different from that of higher μ's, and the results from the other two LANL satellites for this event have similar features. Thus, it is apparent that immediately prior to this event the PSD radial gradient for fixed μ above ~100 MeV/G is negative, while for lower μ's, it is relatively flat.

[10] For the 2000 event, 1991-080 observes similar results. The PSD for low μ (51 and 107 MeV/G) is unchanged after the shock's impact, while that for the highest μ's (2226 and 3608 MeV/G) decrease drastically after the event. In general, a flat PSD radial profile could be the result of two different reasons: one in which the profile reflects a steady situation with no PSD radial gradient and another in which diffusion may have been so strong that it has smoothed out any gradients in the PSD. For the PSD with μ = 168 MeV/G, a slight decrease is observed, and this decrease is also seen in the PSD for all μ's higher than this, with the decrease in PSD for μ = 3608 MeV/G being almost an order of magnitude. The behavior is distinctly different between the PSD for lowest and highest μ's. Similar to the 1998 event, immediately prior to this event, the PSD gradient for fixed μ above ~110 MeV/G is negative, while the gradient for fixed μ lower than this is relatively flat.

[11] We have investigated more than 15 other events using this new method, and we have found that in most cases, the results are similar to the ones presented here. In two cases, the low μ gradient is also negative. In some others cases, the gradient for high μ electrons is relatively flat, and there is one case in which the PSD gradient is positive for high μ electrons. However, in the majority of cases for high μ electrons, the PSD radial gradient is negative. Also, in the vast majority of cases, there is a distinctive difference in the behavior of electrons with μ less than ~100-200 MeV/G when compared to those with μ greater than ~200-300 MeV/G.

[12] Overall, we find for the cases presented here that the dayside PSD radial profile immediately prior to two sudden solar wind pressure enhancements decreases with increasing radial distance for electrons with μ greater than around 100-200 MeV/G and is relatively flat for lower μ's. These results imply that the PSD for μ greater than a couple of hundred MeV/G peaks inside of GEO prior to these events.

These results are consistent with those of *Chen et al.* [2005, 2006, 2007] and *Iles et al.* [2006]. *Chen et al.* [2005, 2007] find that for both quiet and storm times, the electron PSD gradient for L-shells centered about L^* ~6 is negative for high energy electrons. These results are somewhat consistent with those of *Brautigam and Albert* [2000] as well; they find for one storm that electrons with μ < ~315 MeV/G can be modeled well by radial diffusion, while those with μ > ~700 MeV/G cannot. They suggest that wave particle heating, which would cause a negative PSD radial gradient beyond GEO, might explain the inconsistency for the high-μ electrons. It is also interesting to note here the findings of *Bortnik and Thorne* [2007]; they discuss an "anchor point" energy at a couple of hundred keV at which whistler-mode chorus tends to accelerate electrons with greater energy and scatter those with lower energy. This too is consistent with our findings here; for electrons at GEO, μ of ~200 MeV/G corresponds to energy of a couple of hundred keV.

4. Conclusion

[13] Here, we have discussed a new method for calculating the direction of the equatorial PSD radial gradient immediately prior to sudden solar wind pressure enhancements using particle and magnetic field data from spacecraft in GEO. Based on the results of this method applied to two events in 1998 and 2000, we found that the PSD radial gradient is μ dependent; it is negative for electrons with μ greater than ~100-200 MeV/G and either slightly positive or flat for electrons with μ lower than this. These results are consistent with those of several previous independent studies and suggest that prior to these events higher energy electrons had a PSD peak inside of GEO, implying a significant heating occurs for these high energy electrons.

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