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Time correlation of low-altitude relativistic trapped electron fluxes with solar wind speeds

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Abstract. We present the results from a study of time correlation between the low-altitude relativistic trapped electron fluxes and the solar wind speeds. Our trapped electron observations in the energy range of 0.19-3.2 MeV were obtained by the OHZORA spacecraft in an altitude range of 350-850 km, near a solar minimum period (1984-87). The solar wind data with a 5-minute time resolution were obtained from IMP-8 observations. Linear correlation analyses between the two data sets have been performed for relative time lags varying from 12 minutes to 60 days. The 2.5-day, 13-day, 27-day and 54-day correlation peaks previously reported for energetic electrons near geosynchronous orbits are clearly seen in our results. However, the use of higher time resolution solar wind data than in previous studies allows correlation analyses to be performed at shorter time lags. We report here correlation at shorter time lags (<10 hrs) exists and that while such correlation is stronger than those observed at longer lag times, it cannot be entirely attributed to storm or substorm injections. The correlation is also found to decrease with drift shell magnetic equatorial radii, r. In addition, local-time and radial variations in the responses of different drift shells to solar wind speed enhancements indicate that the energetic electron population enters the inner magnetosphere predominantly through the midnight sector.

Introduction

It is well known that relativistic electron fluxes near geosynchronous orbits are correlated with solar wind speeds [Paulikas and Blake, 1976; 1979; Baker et al., 1986]. Later studies also showed that few-MeV electron flux enhancements tend to recur about 27 days, strongly suggestive of their connection with high-speed solar wind streams originating from persistent coronal holes tied to the solar surface. Such correlation also suggests that relativistic electrons are somehow driven or transported into the magnetosphere during passages of high-speed solar wind streams.

Similar correlation between daily-averaged electron fluxes and solar wind speeds has also been found at 2.5-day, 13-day, and 54-day time lags [Baker et al., 1990; Blake et al., 1997]. The latter two cases appear to be related to sub-harmonic and the second harmonic of a solar rotation, respectively, while the 2.5-day delay is related to the overall time scale of electron acceleration and transport from the solar wind to the inner magnetosphere [Baker et al., 1990; Gorchakov and Mineev, 1996; Li et al., 1997].

The present study focuses on the time correlation of solar wind speeds with relativistic electron fluxes observed at low altitudes. In particular, we have found that correlation exists at time scales much shorter than those reported earlier. While geomagnetic storm and substorm injections may account for some of the short-time rises in electron fluxes, these processes however cannot account for all the relativistic electron enhancements which are correlated with solar wind speed increases. Using the magnetic equatorial radius of a drift shell r, or its projected value Lm at noon, to organize the low-altitude trapped electron observations taken by the OHZORA spacecraft, we show evidence of particle entry predominantly in the midnight sector and effect of radial diffusion.

Low-Altitude OHZORA Observations

The Japanese OHZORA (EXOS-C) spacecraft was launched on February 14, 1984, into a 350 km×850 km orbit with a 75°-inclination. The mission operated continuously until March 1987. The high energy particle (HEP) instrument on board had two identical orthogonal telescopes (Sensors 1 and 2). The OHZORA spacecraft was non-spinning (except for a five-day period) such that Sensor 1 was fixed in the anti-sunward direction (the z-axis) and Sensor 2 in the x-y plane.

Electron identification was achieved by analyzing the signal from the AE detector, which has a 180 keV-threshold discrimination level for electrons. Further details of the spacecraft and sensors are given in Nagata et al [1985] and Kohno et al [1990]. By fitting the measurements from the two telescopes with a “sinαxα-profile” (where α is the local pitch angle), omni-directional electron fluxes are calculated for the entire OHZORA HEP data set [Fung et al., 1997].

Magnetic Drift-Shell Equatorial Radius, r_t or L_{tn}

A suitable parameter (coordinate) is needed to properly organize low-altitude electron fluxes into drift shell structures. The McIlwain L-parameter is a perfect example in the dipole magnetic field case [McIlwain, 1961]. In a realistic field geometry in which the geomagnetic field is often distorted by the solar wind and external magnetospheric currents, L actually varies along a field line [McIlwain, 1966] and can no longer be used to visualize drift shell structures in real space.

Low-altitude mirroring particles encounter large mirroring fields B_m (>1000 nT) and are less affected by shell splitting [Roederer, 1970]. Their drift shells are then fairly well defined by their second adiabatic invariants I, which is effectively given by the length of the field line on which they execute their bounce motions. At a given magnetic local time (MLT), the field line length is scaled by its magnetic equatorial radius.
such that a field line is uniquely identified by \((r_t, \text{MLT})\). Due to the inherent asymmetry of the realistic geomagnetic field, \(r_t\) at different \(\text{MLT}\) are not confined to the dipole equator plane and will vary with \(\text{MLT}\) along a given drift shell. We denote the special case of \(r_t(\text{MLT}=12\text{hr})=L_{tn}\).

Analogous to the Mcllwain \(L\) and \(L_r\) of Roederer and Schulz [1969], \(L_{tn}\) is the radial distance (in RE) to the magnetic minimum on a given field line at noon. Given a realistic field model, \(r_t\) and \(L_{tn}\) can be computed by tracing the field lines. Since \(I\) is computed by integrating along a magnetic field line [Walt, 1994], a relatively general empirical relationship (e.g., \(I = a + br_t + cr_t^2\)) can be established between \(I\) and \(r_t\) at each \(\text{MLT}\), only with the coefficients \((a, b, c)\) varying with \(\text{MLT}\). A drift shell is then identified by simply connecting \(r_t\) at different \(\text{MLT}\) but with the same \(I\). Thus, \(r_t\) at any \(\text{MLT}\) can be mapped (by following the variations of the coefficients) to its corresponding noon-value \(L_{tn}\), which can then be used as a label for the drift shell. In this study, the IGRF (1985) internal field and the T89c [Tsyganenko, 1989] external field have been used to model a realistic geomagnetic field. Figure 1 shows the projections of the loci of \(r_t\) as a function of \(\text{MLT}\) under different solar wind dynamic pressure and \(K_p\) conditions. Each drift shell is clearly identified by its \(L_{tn}\) value.

**Correlation with Solar Wind Speeds**

Relativistic electron fluxes at low altitudes have been shown to be quite dynamic [Baker et al, 1994]. In addition, Li et al., [1997] show that increases in electron fluxes (2-6 MeV) at low altitudes (< 675 km) in 6 < \(L\) < 7 are correlated with similar electron enhancements in the geosynchronous region. Therefore, it may be expected that the time correlation between the solar wind speeds and relativistic electron fluxes seen in geosynchronous observations should also appear in low-altitude observations [e.g., Imhof et al., 1994].

**Figure 2.** Correlations of low-altitude relativistic electron fluxes (0.19-3.2 MeV) observed by OHZORA (350-850 km; 1984-87) at \(L_{tn} = 7-8\) in different local time sectors and solar wind speeds obtained by the IMP-8 spacecraft. A lag time of 4 hours was assumed between the electron measurements and solar wind measurements (propagated to \(X_{GS M} = 0\)).

Using the OHZORA energetic electron observations (350-850 km) taken during a solar minimum period (1984-87) and the IMP-8 solar wind measurements at 5-minute resolution, we have performed correlation analyses on the electron and solar wind data. Figure 2 shows an example of the linear correlation between 5-minute averages of low-altitude electron fluxes at 7 < \(L_{tn}\) < 8 and solar wind speeds. Also, shown separately for the four local-time sectors are the linear correlation coefficient \(r\) and the corresponding probability of no correlation \(P_r\) [Bevington, 1969]. The tendency for \(r\) at lag times < 10 hrs to decrease with increasing local times may be due to the fact that these time lags are short compared to the time scales of processes by which local-time asymmetry in the electron fluxes are homogenized.

**Correlation at Different Time Lags**

Correlation analyses have been performed for different time lags ranging from 12 minutes (about twice the time resolution of the solar wind data) to 60 days. To discern any short-time lag correlation which may be caused by substorm activities, we have performed our analyses for different \(AE\) levels. For the OHZORA data interval (1984-87), the median \(AE\) is 160 nT. The first two panels in Figure 3 show the linear correlation coefficients as a function of lag time when the electron data were taken during quiet (\(AE < 160\) nT) and substorm (\(AE > 160\) nT) conditions, respectively. Both cases show strong correlation at lag times < 1 day. Previously observed correlation at longer time lags (2.5-days, 27 days, and to some extent, 54 days) is also observed. Insofar as the correlation at longer lag times is significant, we can conclude that the short-time scale (< 1 day) correlation is even more important for the
Figure 3. Coefficient of correlation between OHOZORA energetic electron measurements (Jomne) and solar wind speeds at X_GSM=0 for different time lags from the solar wind arrival time during quiet (AE < 160 nT; top panel) and substorm (AE > 160 nT; middle panel) conditions. Different color traces indicate the responses of different drift shells. The lower panel shows that there exists little correlation between Jomne and the Akasofu's \( \varepsilon \)-parameter.

Figure 4. Correlation coefficient as a function of time lag of OHOZORA energetic electron measurements from solar wind arrival times at X_GSM=0. Different color traces indicate the responses at different local time sectors along a drift shell range at \( L_m = 5-6 \) (upper panel), 6-7 (middle panel, and 7-8 (lower panel).

Local-Time and Radial Variations

By analyzing the electron flux data organized by \( L_m \), we can also examine the local-time and radial variations in the response of a drift shell to solar wind velocity enhancements. The combined effects of azimuthal drift and radial diffusion of energetic electrons are summarized in Figure 4. As seen above, the magnetosphere in the range of \( 4 \leq L_m \leq 8 \) responds fairly uniformly to solar wind velocity enhancements for lag times \( \geq 50 \) hrs as a result of radial diffusion. In addition, the correlation at lags < 10 hrs tends to decrease with increasing local time from midnight (last panel). This is consistent with the energetic electrons entering the magnetosphere in the midnight sector and drifting in increasing \( MLT \) around the Earth. Since the drift periods of the energetic electrons (\( \geq 200 \) keV) are \( \approx 1 \) hr [Walt, 1994], any local-time asymmetry in the electron fluxes is likely to be destroyed after multiple drift periods (~10 hrs). Inside geostationary orbit (top panel), however, the correlation becomes uniform in local time, indicating the smoothing effects of drift and radial transport.

It is interesting to note also that both the 27-day and 54-day peaks appear in all three panels and at all local times shown in Figure 4. The 13-day peak, apparently quite transitory however, is seen only in the midnight sector when the data in a given drift shell were properly organized by \( L_m \). As seen in the lower panel, it diminishes rapidly as \( MLT \) increases and \( L_m \) decreases (upper and middle panels). This transitory nature could account for the relatively weak 13-day correlation observed previously by using only daily-averaged fluxes taken by geostationary spacecraft [Baker et al, 1990]. Moreover, correlation at short lag times is highest in the midnight and dawn sectors in the outer drift shells (\( L_m = 7-8 \)), consistent with an external source for the electrons. These observations suggest that particle acceleration and entry to the inner magnetosphere occur predominantly near midnight.

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It is of interest to investigate also the possible correlation of the low-altitude relativistic electron environment ([Baker et al, 1994]). It is important to note the very significant short-time scale correlation (< 2 hrs) despite the absence of substorm activities (see Figure 3 top panel).

Figure 3 indicates also that different \( L_m \)-drift shells have similar response at lags greater than ~50 hrs. For long lag times, the energetic electron fluxes are essentially the same over a large region of the magnetosphere (\( 4 \leq L_m \leq 8 \)). This suggests that radial transport and azimuthal drifts of the energetic electrons have effectively homogenized the range of \( L_m \)-shells over time scales of 50 hours or longer. Contrastingly, Figure 3 also shows that the correlation at lags < 50 hrs actually decreases with \( L_m \). Therefore, on short time scales the lower \( L_m \) regions (< 5) are less affected by processes associated with increases in solar wind speeds.

It is of interest to investigate also the possible correlation of the low-altitude electron fluxes with the \( \varepsilon \)-parameter [Akasofu, 1981] and compare the results with the solar wind speed correlation. The bottom panel of Figure 3 shows the linear correlation coefficient \( r \) as a function of time lag for the \( \varepsilon \)-parameter correlation. No significant correlation (\( r < 0.3 \)) is observed in this case for all lag times considered.

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Summary and Conclusions

We have carried out time-correlation studies of low-altitude (350-850 km) relativistic electron fluxes obtained by the OHZORA satellite (1984-87) and solar wind speeds by the IMP-8 spacecraft. Using the magnetic equatorial radius $L_{eq}$ at noon, the low-altitude electron fluxes were organized into well-defined drift shell bins in real space and were found to correlate with solar wind speeds (see Figures 3 and 4) as found in geosynchronous observations [e.g., Baker et al., 1990].

More importantly, since higher time resolution (5-min) solar wind data were used in the present study, we have performed correlation analyses at time lags shorter (< 50 hrs) than earlier studies [Baker et al., 1990; Blake et al., 1997]. Strong correlation was found to exist at lag times much shorter (< 10 hrs; see Figures 3 and 4) than previously found. The short-time lag correlation indicates the importance of local acceleration and field-aligned transport processes in affecting the dynamics of energetic electrons in the inner magnetosphere [Baker et al., 1994]. In fact, Chen et al. [1998] and Sheldon et al. [1998] have recently suggested the possibility of electrons being accelerated and trapped in the cusp region. From their simulation results, Sheldon et al. have noted that trapping of 0.005 - 6 MeV electrons could last as long as 300 s if electric field effects are ignored, and have inferred that the radiation belts could be filled by scattering and diffusion processes. Thus besides substorms, the cusp could be a source of energetic electrons observed at low altitudes. Finally, virtually no correlation is found between relativistic electrons and the Akasofu $t$-parameter (Figure 3).

The correlation at time lags up to 10 times the electron drift periods (~ 1 hr) also exhibits local-time variations that may be ordered by the electron drift motions (Figure 4). These results suggest that electrons are accelerated and enter the inner magnetosphere mainly in the high $L_{eq}$-shell ($L_{eq}$ > 7) midnight sector. The local acceleration and field-aligned transport processes (e.g., Imhof et al., [1994] and Sheldon et al., [1998]) must operate predominantly in the magnetotail or mantle in conjunction with the arrival of high-speed solar wind streams, leading to quick electron enhancements at low altitudes prior to drifting in MLT and diffusing radially. Investigations of these processes will elucidate the overall solar wind-magnetosphere coupling [Baker et al., 1997].

At longer lag times (> 50 hrs), cross-field or radial transport processes would have homogenized the responses of a range of drift shells. Thus the radial transport time scale is about 50 hrs (Figures 3 and 4). This corresponds to the “2.5-day” correlation-peak observed in the geostationary data. The 13-day peak correlation, observed only in the midnight sector (Figure 4), is likely degraded by the combined effects of drift and radial diffusion, resulting only in weak correlation in the daily-averaged data [Baker et al., 1990]. Finally, Belian et al. [1996] have noticed poor correlation of daily electron fluxes with solar wind speeds during 1987-1994. It will be of interest to study the short-time correlation in that period.

Acknowledgments. We thank the NASA National Space Science Data Center (NSSDC) for providing the OHZORA and IMP-8 data used in this study. We are also indebted to Dr. T. Kohno and K. Nagata for archiving their HEP data from OHZORA at the NSSDC. Work by L. C. Tan at RSTX was supported by NASA contract NAS5-97059.

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(Received May 1, 1998; accepted May 7, 1998)