Energetic electrons, 50 keV – 6 MeV, at geosynchronous orbit: their responses to solar wind variations

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Abstract. Using simultaneous measurements of the upstream solar wind and of energetic electrons at geosynchronous orbit, we analyze the response of electrons over a wide energy range, 50 keV - 6 MeV, to solar wind variations. Enhancements of energetic electron fluxes over this whole energy range are modulated by the solar wind speed and the polarity of the interplanetary magnetic field (IMF). The solar wind speed seems to be a dominant controlling parameter for electrons of all energy. Electron enhancements occur after solar wind speed enhancements with a time delay that increases with energy and that also depends on the average polarity of the IMF. The electron enhancements have a shorter delay if the IMF $B_Z < 0$ and a longer delay if the IMF $B_Z > 0$ during the solar wind speed enhancement. The dependence on solar wind condition varies for different energy electrons, with lower energy electrons ($<$ 200 keV) responding more to the polarity of the IMF and higher energy electrons ($>$1 MeV) responding more to the solar wind speed. The variations of different energy electrons are well correlated among themselves. For five years, 1995-1999, the correlation coefficients of 1.1-1.5 MeV electrons with lower energy electrons: 50-75 keV, 105-150 keV, 225-315 keV, and 500-750 keV, are 0.55, 0.64, 0.74, and 0.90. This correlation is enhanced if a time-shift proportional to their energy difference is included. The optimal time-shifts and the corresponding correlation coefficients for the four lower energy electrons are 36, 32, 13, 7 hours and 0.75, 0.77, 0.81, 0.92, respectively.

Introduction

The intimate connection between the variation of radiation belt electrons and the solar wind speed was identified soon after the solar wind was measured and understood as a magnetized plasma emitted by the Sun and flowing outward through the solar system [Williams, 1966]. This connection was demonstrated by the existence of the 27-day periodicity (the averaged solar spin period, a.k.a Carrington Rotation Period) in the intensities of trapped electrons in the outer radiation belt for the two energy channels: $>$280 keV and $>$1.2 MeV [Williams, 1966]. Since then, the correlation between the solar wind speed and radiation belt electrons has been a focal point in the study of energetic particle dynamics in the Earth's magnetosphere. Paulikas and Blake [1979] showed quantitatively that the MeV electron flux at geosynchronous orbit enhances 1-2 days following passages of high speed solar wind streams. The correlation of relativistic electron fluxes with interplanetary parameters, including the interplanetary magnetic field, IMF, were further analyzed [Blake et al., 1997; Fung and Tan, 1998; Obara et al., 2000; Friedel et al., 2002]. It was found that high speed solar wind streams with southward IMF's are more effective in enhancing relativistic electrons that solar wind streams with northward IMF's.

Larger solar wind velocities also drive fluctuations at the magnetopause and produce more intense ULF waves within the magnetosphere [Engebretson et al., 1998; Vennerstrom, 1999]. It was suggested that certain specific ULF waves were especially important in driving radial diffusion of relativistic electrons leading to the observed enhancements [Rostoker et al., 1998; Hudson et al., 1999; Baker et al., 1998a]. Elkington et al. [1999] was able to use MHD simulations to determine the response of the magnetosphere to the solar wind and to trace test particles in the MHD fields to determine the response of radiation belt electrons to ULF waves. Mathie and Mann [2000; 2001] further analyzed the correlations among solar wind speed, ULF waves, and radiation belt electron intensities. These studies not only showed that variations of relativistic electrons in the magnetosphere are well correlated with the solar wind but also indicated the physical process likely responsible for the correlation: enhanced radial diffusion due to enhanced ULF waves.

Based on the correlation between solar wind speed and relativistic electrons, Baker et al. [1990], using the solar wind speed as the input, developed a linear filter model to predict MeV electrons at geosynchronous orbit. A good measure of the relative accuracy of predictions is called 'prediction efficiency (PE),' which is defined as [1-(mean squared residual)/(variance of data)] where the residual is the difference between the data and the prediction. The linear prediction filter method achieved a PE of 52% in their three-month sample period [Baker et al., 1990]. More recently, Li et al. [2001a] have developed a radial diffusion model to predict MeV electrons at geosynchronous orbit based on solar wind speed, speed fluctuations, and the z-component of IMF. They achieved a PE of 81% for a two-year sample period. They concluded, among other things, that the solar wind speed is the most important parameter governing relativistic electron fluxes at geosynchronous orbit and that, in addition, the IMF orientation significantly influences the electron flux enhancing it when the IMF polarity is predominately southward ($B_Z < 0$).

The above studies focused on relativistic electrons (the rest mass of an electron is 511 keV, so an electron with a kinetic energy of $\sim$200 keV would be considered relativistic). Exposure to relativistic electrons can cause deep dielectric discharging and subsequent discharging in spacecraft subsystem leading to spacecraft anomalies or even total failure. However, non-relativistic electrons (a few keV to 10s' keV), because of their higher fluxes, are also of considerable practical importance because of their surface charging effect on the spacecraft [Gussenhoven et al., 1987; Fennell et al., 2001]. Here we emphasize that variations of both non-relativistic electrons and relativistic electrons, 50 keV-6 MeV, at geosynchronous orbit are strongly modulated by the solar wind speed as well as by the polarity of the IMF. We show that their responses are qualitatively similar but quantitatively different depending on their energies. In the following, we will first present observations of the solar wind measurements and of electrons at geosynchronous orbit together with correlations among different energy electrons. We provide a statistical analysis of the response of different energy electrons for different solar conditions, and then discuss the observations with a focus on the acceleration mechanisms for high energy electrons ($>$1 MeV).

Observations and Discussion

Figure 1 shows, for the first half of 1995, the solar wind speed, the positive part of ($-V$xB_Z), the z-component of the IMF (in GSM coordinates), and the daily averaged electron fluxes of different energies measured from four LANL spacecraft at geosynchronous orbit. The overall impression from Figure 1 is that fluxes of electrons of all energies increase in correlation with solar wind speed enhancements and larger solar wind speed enhancements correspond to larger electron enhancements. Figure 1 also reveals the following: (1) variations of the electron fluxes have different magnitudes for different energies, with 1.8-3.5 MeV electrons having the largest relative variations, (2) the enhancements of lower energy electrons ($<$200 keV) are also well correlated with the $-V$xB_Z, (3) electron enhancements start at different times, with longer delays for higher energy electrons. Low energy electrons, such as 50-75 keV, can even increase ahead of solar wind speed enhancements if the B_Z was negative earlier, e.g., around the first vertical dotted line (day 17), which suggests that lower energy electrons are especially sensitive to the polarity of the IMF.

Figure 2 shows the solar wind speed, solar wind speed fluctuations, the z-component of the IMF and electron fluxes same as in Figure 1 but for the second half year of 1998. Note scale changes for solar wind speed (top panel) and the Dst index (bottom panel).

The overall features are the same as in Figure 1: electrons of all energies enhance in correlation with the solar wind speed and larger solar wind speeds correspond to larger electron enhancements.

Solar wind speed fluctuations are usually well correlated with the solar wind speed itself, as shown Figures 2. There are, however, some exceptions, such as around day 245 of 1998, indicated by the first vertical dotted line in Figure 2, where there is an enhancement of fluctuations while the solar wind speed continues to decrease and there is an enhancement of MeV electrons. In Li et al. [2001a], the diffusion coefficient is a function of both solar wind speed and solar wind speed fluctuations, and they found that using either of the two terms can produce good results but using both terms gives better results.

Figure 3 shows the correlation of 1.1-1.5 MeV electrons with lower energy electrons:

50-75 keV, 105-150 keV, 225-315 keV, and 500-750 keV for the data in Figure 1 (these energy channels are from the same instrument, as opposed to the highest two energy channels on Figs. 1-2). Figure 3a shows the linear correlation (LC) coefficients without any time-shift by symbol squares and with the optimal time-shift which maximizes the LC coefficients by symbol asterisks. It is evident from the figure that, even without any time-shift, the correlation is higher if the electron's energy is closer to 1.1-1.5 MeV. The lowest correlation coefficient is 0.55 for the lowest energy channel: 50-75 keV electrons.

The correlation coefficients were significantly enhanced with proper time-shifts. The optimal delay times (for the enhancement of 1.1-1.5 MeV electrons) are 36, 32, 14, and 6 hours for 50-75 keV, 105-150 keV, 225-315 keV, and 500-750 keV, respectively. While the trend is still the same - better correlation for among the electrons that differ least in energy, the correlation is improved most for the lowest energy electrons, from 0.55 to 0.81, a 47% increase.

Figure 3b shows the actual curves of the correlation coefficients as a function of the delay time. This shows how sensitive the correlation coefficients are with respect to the delay time. This will be helpful if one is to contemplate using these results in a prediction mode. Overall, the peaks are rather broad but smooth and the trend is clear.

We have done the same analysis for a longer time period, 1995-1999, 5 years. The results are basically the same. The optimal time-shifts and correlation coefficients between the 1.1-1.5 MeV electrons and the four lower energy electrons are 36, 32, 13, 7 hours and 0.75, 0.77, 0.81, 0.92, respectively. Without any time-shift, the corresponding correlation coefficients are 0.55, 0.64, 0.74, 0.90.

To further analyze the correlation between solar wind velocity enhancement and the corresponding electron enhancement, for a wide energy range of electrons and under different IMF conditions, we choose to focus on the time intervals when solar wind speed is increasing and then we separate these solar wind enhancement events into three categories: those with an IMF $B_Z < 0$, B_Z near 0, and $B_Z > 0$.

Solar wind speed enhancement intervals are determined from the daily averaged V_X (for 1995-1999) based on the following procedure: To be accepted as a solar wind speed

enhancement event, the daily averaged speed must increase by a least 80 km/s within the interval. The intervals consist of whole days. The first day of an interval is the day before the daily averaged velocity increases by 70 km/s. The last day of an interval is the day before the daily averaged velocity drops from the maximum value within the interval by 20% of the difference between the maximum and the value of the first day. The polarity of a solar wind speed enhancement event is defined by the average B_Z over the first half of the event. If the average B_Z over the first half of the event is either >0.5nT or <-0.5nT, the event is classified as positive or negative, otherwise it is classified as B_Z near zero. We average the B_Z only over the first half of the event because we focus on how the electrons respond to the rising part of the solar wind speed enhancement.

Figure 4 shows an example of the classified events (overplotted with different color bars) for the first 90 days of 1995 of the solar wind speed and the normalized logarithm of electron fluxes, both are averaged over a day, plus the Z-component of IMF (every 3 hours). From visual inspection, one can see that the magnitude of the time-delay after a solar wind speed enhancement is different for different polarities of the IMF. The electron enhancement has a positive delay when $B_Z > 0$ for all electrons at all energies (and longer delay for higher energy electrons). For $B_Z < 0$ events, the electron enhancement has no delay or even a negative delay for lower energy electrons, such as 50-105 keV electrons, and a positive delay for higher energy electrons but the delays are shorter in comparison with the case of $B_Z > 0$. For the events of B_Z near 0, the time-delay of electron enhancements is in between.

For solar wind speed enhancement events during the five years, 1995-1999, we calculated the time-shift (with respect to solar wind speed enhancements) for the electron flux enhancements that maximized the linear correlation coefficients between solar wind speed enhancements and electron flux enhancements, for different energies and different polarities of IMF. Because the time-shifted electron flux measurements no longer coincide in time with the solar wind speed measurements, we calculated the linear correlation coefficients after interpolating the time-shifted electron fluxes at the time of the solar wind speed. Then we determined the optimum time-shift by finding the maximum linear correlation coefficient.

Figure 5 shows the quantitative results, (a) for all solar wind speed enhancement events

regardless of IMF polarity, total 476 days, (b) for B_Z near 0, total 135 days, (c) for $B_Z < 0$, total 211 days, and (d) for $B_Z > 0$, total 130 days. The error bars indicating the range of delay times if the best correlation coefficients are reduced by 1% of their values. The size of error bars indicates that the best correlation coefficients between the solar wind enhancements and the enhancements of electrons with different energies (under different IMF polarities) do not change significantly over a certain range of time-shift.

Several significant points can be drawn from above observations and analysis, which warrant more discussions.

Magnitudes of the variations

The >1 MeV electron fluxes have the largest relative variations. One explanation is that the enhancements of lower energy electrons are associated with substorm injections [e.g., Baker et al., 1986] and magnetospheric convection, which are associated with solar wind convective electric field (-VxB_Z), and occur more frequently, so their background levels remain high. Also note that the background count rate, mostly due to the cosmic ray particles, has not been removed. Therefore, the actual relative variation for the highest energy, 3.5-6.0 MeV, with lowest count rate, should be even greater than is shown in the figures.

Lower energy electron enhancements are clearly associated with the polarity of the IMF, e.g., around day 17 (the first vertical dotted line) of 1995 in Figure 1. However, if the solar wind speed is low, the lower energy electron flux is also low, as shown in Figure 2 for the last two months of 1998. Generally speaking, the polarity of the IMF controls the coupling efficiency between the solar wind and the magnetosphere, but the available solar wind energy depends on solar wind speed.

Comparison between 1995 and 1998

During 1995 the solar cycle was in a declining phase approaching sunspot minimum. At such times recurrent high speed solar wind streams emanating from persistent trans-equatorial coronal holes are prominent and long lasting. The year 1998 was during the ascending phase of the solar cycle approaching sunspot maximum, when the occurrence of coronal mass

ejections (CME) increases. While fast CME's can be very capable of driving magnetic storms and accelerating radiation belt electrons, such CME's do not occur as often or last as long as the recurrent high speed solar wind streams of the declining phase of the solar cycle.

The solar wind speed reached higher values in 1998, Figure 2, but periods of high speed solar wind did not last as long as in 1995, Figure 1. The Dst index, which measures the disturbance level of the Earth's magnetosphere, also reached more negative values in 1998. But, the electron fluxes for all energies were clearly higher in 1995, Figure 1. This further demonstrates that radiation belt electrons are most intense during the declining phase of the solar cycle [Baker et al., 1998b, Li et al., 2001b].

Geoeffectiveness: Dst index vs. MeV electrons

The term 'geoeffectiveness' has often been used in discussions of the Sun-Earth connection, usually referring to whether a specific kind of solar wind condition can cause significant geomagnetic disturbances. If we simply define geoeffectiveness in terms of the Dst index, $V_X B_Z$ is clearly the dominant controlling parameter [Burton et al., 1975; Temerin and Li, 2002].

On average, variations of radiation belt electrons are closely associated with geomagnetic storms, or the Dst index [e.g., Figure 1 of Li et al., 2001b]. A recent statistical study [Reeves et al., 2003] shows that about half of magnetic storms increased the fluxes of relativistic electrons, one quarter decreased the fluxes, and one quarter produced little or no change in the fluxes for 276 moderate and intense geomagnetic storms spanning the 11 years from 1989 through 2000.

On the other hand, Reeves et al. [2003] also found that high solar wind speeds increase the probability of a large electron flux increase, which is consistent with previous finding by O'Brien et al. [2001]. For electrons with energy greater than 1 MeV at geosynchronous orbit, this correlation is more evident. For example, after careful inspection of two years of data–1995 to 1996, we found that 1.8-3.5 MeV electron fluxes always enhanced after the passage of a high speed solar wind stream with a speed of $>$500 km/s lasting for more than a day. It is also evident that the $>$1 MeV electron fluxes are higher in Figure 1 even though

the Dst index in Figure 1 is not as negative as in Figure 2. On the other hand, statistically, the time-delay for these electron enhancements after solar wind speed enhancements is shorter when the average $B_Z < 0$ and longer when the averaged $B_Z > 0$, as shown in Figure 5, which is consistent with the finding of [Li et al., 2001a], where the diffusion coefficient is greater when B_Z is negative.

Acceleration mechanisms for different energy electrons

As mentioned earlier, there is a longer delay for the enhancement of higher energy electrons after the passage of a high speed solar wind than for lower energy electrons. Low energy electrons can even increase before the arrival of the high solar wind if B_Z has been continuously negative, such as around day 17 of 1995, as shown in Figure 1. It is also possible to observe an enhancement of low energy electrons without an enhancement of high energy electrons, such as around day 251 of 1998, indicated by the second vertical dotted line in Figure 2. Since low energy electrons are usually associated with substorm injections [e.g., Baker et al., 1986; 1998b] and since substorm injections usually do not directly produce >1 MeV electrons [e.g., Baker et al., 1986; Li, 2002], the question is where do the >1 MeV electrons come from and how are they energized?

There are two possible sources: less-energetic electrons at larger L-shells and less-energetic electrons at the same L-shell (L corresponds to the radial distance in units of R_E at the equator if Earth's magnetic field is approximated as a dipole). In both cases, lower energy electrons usually have a substantially larger phase space density and thus, either source is a feasible candidate. The observations shown here are consistent with either source and with either of two acceleration mechanisms. The radial transport theory (conserving the first and second adiabatic invariants) says that radial diffusion/transport energizes electrons by bringing electrons inward from larger L-shells. More-energetic electrons diffuse inward slower [Schulz and Lanzerotti, 1974; Li, 2004] so there is a longer delay for the enhancement of the more-energetic electrons, as shown in Figure 1 and 2. On the other hand, the time delay for all energies can also be explained by in-situ heating of electrons by VLF waves on the same L-shell (violating the first adiabatic invariant) [Temerin et al., 1994; Summers et al.,

1998; Meredith et al., 2001; Albert, 2002]. Because it would take longer to energize the more energetic electrons with VLF waves, this mechanism also explains the longer delay at high energies.

Radial diffusion vs local-heating

Given the observed enhancements of MeV electrons, distinguishing whether they are due to a local heating process or due to enhanced radial transport is a difficult problem. The good correlation of low energy electrons with higher energy electrons on the same L-shell together with the much higher phase space density of lower energy electrons suggests that these lower energy electrons may be the source of the higher energy electrons through heating. However, merely the presence of more lower energy electrons would not explain this correlation since the relative change in the higher energy electrons is greater rather than less than the relative change in the lower energy electrons. A change in the heating rate is required as well. Thus a possible explanation is that enhancements of lower energy electrons produce waves that heat electrons to produce the higher energy electrons. Another possible explanation is that these electrons come from larger L-shells with the higher energy electrons taking a longer time to reach geosynchronous orbit.

The shorter time-delay of >1 MeV electron enhancements for B_Z <0, shown in Figure 5, is also consistent with both possible energization processes, since we know the VLF waves (in particular, Chorus waves) are enhanced and long-lasting during sustained substorms [Meredith et al., 2001] and we also know that the radial diffusion coefficient is also enhanced during higher geomagnetic activity [Lanzerotti et al., 1978; Brautigam and Albert, 2000; Li et al., 2001a]

Summary

We have shown that the solar wind speed is the leading controlling parameter on the variations of daily averaged energetic electron fluxes at geosynchronous orbit over a wide energy range: 50 keV to 6.0 MeV. Lower energy electrons (<200 keV) are more sensitive to

the polarity of the IMF while higher energy electrons (>1 MeV) respond more to the solar wind speed but all the electrons in this energy range are well correlated with solar wind speed. Generally, electron enhancements occur with successively longer delays with higher energy after a passage of a high speed solar wind stream with a certain polarity of IMF. However, for a given high speed solar wind stream, the electron enhancements have different delays for different polarity of IMF, with shortest delay for $B_Z < 0$ and longest delay for $B_Z > 0$. These statistical results are of significance in terms of space weather application.

In addition, the variations of different energy electrons are well correlated among themselves. The correlation is greatly enhanced if a time-shift in proportion to their energy differences is included, which is consistent with two possible interpretations for the enhancements of higher energy (>1 MeV): inward radial diffusion or in situ heating by VLF waves. However, the relative importance of these two mechanisms is still unknown.

The enhancements of lower energy electrons (<200 keV) are associated with enhanced substorm activities and magnetospheric convection which are associated with solar wind convective electric field ($-V_X B_Z$).

Figure Captions

Figure 1. Relevant solar wind parameters (every 10 min) and daily averaged electron fluxes (particle/cm^2-s-MeV) from four LANL spacecraft with identical instruments at geosynchronous orbit at different longitudes. The three vertical dotted lines are guides for the eyes to see the timing better.

Figure 2. Similar to Figure 1, but for the second year of 1998 and panel 2 is for the solar wind speed fluctuation, which is directly calculated from the solar wind speed using data at a rate of one measurement every 10 minutes and window-averaged over about 1.5 hours. Please note scale changes for solar wind speed (top panel) and the Dst index (bottom panel).

Figure 3. (a) Correlation of 1.1-1.5 MeV electrons fluxes with lower energy electron fluxes shown in Figure 1. The square symbols represent the LC coefficients without any time-shift and the asterisks represent LC coefficients with an optimal time-shift. See text for details of

the time-shifts. (b) the actual curves of the correlation coefficients as a function of the delay time. The correlation coefficients at zero hour correspond to no time-shift and the asterisks indicate the LC coefficients at the optimal time-shift.

Figure 4. Daily averaged solar wind velocity (V_X, solid line) is plotted against normalized logarithm of daily averaged electron fluxes (dotted line) of different energies at geosynchronous orbit. The last panel is for B_Z at a cadence of 3 hours. The different colors of the shaded areas indicate whether the averaged B_Z for the first half of the shaded area is > 0 ($B_Z > 0.5$ nT, green), or < 0 ($B_Z < -0.5$ nT, red), or near 0 ($|B_Z| < 0.5$ nT, purple).

Figure 5. The best linear correlation (LC) coefficients and the optimal time-delay between solar wind velocity enhancement and electron flux enhancement for different energies for the five years, 1995-1999, which are determined by an optimal time-shift of the electron enhancements which maximizes the correlation coefficients; (a) for all velocity enhancement events regardless of IMF polarity, total 476 days, (b) for B_Z near 0, total 135 days, (c) for $B_Z < 0$, total 211 days, and (d) for $B_Z > 0$, total 130 days. The error bars in the Delayed Time panels shows the range of delay times if the best correlation coefficients are reduced by 1% of their values.

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