

# Long Term Measurements of Radiation Belts by SAMPEX and Their Variations

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**Abstract.** The Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX), a low-altitude and polar-orbiting satellite, has provided a long-term global picture of the radiation belts since its launch on July 3, 1992. While the inner belt ( $L < 2$ ) protons appear to have only a solar cycle variation, the outer radiation belt ( $L > 2$ ) electrons vary on solar cycle, semiannual, and solar rotation time scales, and with geomagnetic storms. Recently developed models of predicting MeV electron at geostationary orbit [Li et al., 2001] and the Dst index [Temerin and Li, 2001] based on solar wind measurements are used to examine the cause of the prominent semiannual variations of outer belt electrons and the Dst index. The equinoctial effect (the angle between the Earth's dipole and the flow direction of the solar wind) contributes most to the semiannual variation of the Dst and MeV electrons deep in the inner magnetosphere ( $L < 5$ ). The semiannual variation of MeV electrons at geostationary orbit is attributed mostly to the semiannual variation of solar wind velocity.

## Introduction

The Earth's magnetosphere efficiently accelerates and subsequently traps energetic particles. The outer radiation belt consists of electrons with energies from hundreds of keV to several MeV. We show that MeV electrons in the outer belt deep inside geostationary orbit ( $L < 5$ , where  $L$  is the radial distance in  $R_E$  at the equator if the Earth's magnetic field is approximated as a dipole) are well correlated with the Dst index, a major indicator of magnetic storms with a more negative Dst indicating stronger magnetic storms and that electrons in geostationary orbit are well correlated with solar wind velocity. Since the Dst index and the outer belt electrons at geostationary orbit can be well predicted based on solar wind parameters only [Li et al., 2001; Temerin and Li, 2001], we argue that the solar wind is the controlling driver of the variations of the entire outer belt electrons.

## Observations and Discussion

SAMPEX has provided a picture of the radiation belts as a function of  $L$  near its altitude ( $\sim 550$  km) along the field line [Baker et al., 1993]. Figure 1 shows SAMPEX's measurements of radiation belt electrons and protons from launch to the end of 2000 together with the sunspot number and the Dst index. The inner proton belt is relatively stable

and varies over the time scale of the solar cycle or longer and is anti-correlated with sunspot numbers [e.g., Walt, 1996; Miyoshi et al., 2000]. The slow variation of the inner proton belt is in contrast to the outer electron belt, which varies on a range of time scales.

Several distinct features are notable in the long term electron measurements. The outer belt exhibits a strong seasonal and solar cycle variation. It was most intense, on average, during the descending phase of the sunspot cycle (1993-1995), weakest during sunspot minimum (1996-1997) and then became more intense again during the ascending phase of the solar cycle (1997-1999). Interestingly, the electrons are not most intense approaching or at sunspot maximum conditions. Seasonally, the outer belt is most intense [Baker et al., 1999] and also penetrates the deepest around the equinoxes. Equinox periods are marked by the vertical bars along the horizontal axis in Figure 1. Another remarkable feature of Figure 1 is the correlation of the inward extent of MeV electrons with the Dst index. For this interval of more than eight years, the two weakest electron periods corresponded to the only periods, summer of 1996 and 1999, when the averaged Dst was above zero.

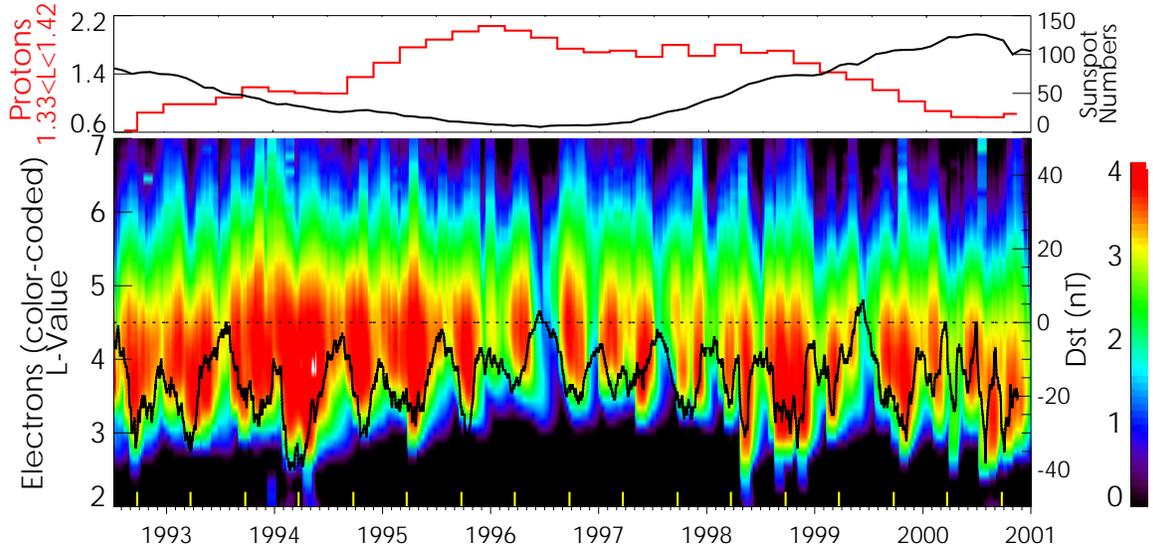
**Solar cycle dependence** It is known that during the declining phase of the solar cycle approaching sunspot minimum, recurrent high speed solar wind streams emanate from persistent trans-equatorial coronal holes. They are prominent and long lasting (weeks to months). These recurrent high speed solar wind streams are efficient in driving recurrent magnetic storms and enhancing radiation belt electrons [e.g., Baker et al., 2001]. During the ascending phase of the solar cycle approaching sunspot maximum, the occurrence of coronal mass ejections (CME) increases. While a fast CME is very capable of driving nonrecurrent magnetic storms and accelerating radiation belt electrons, geoeffective CME's do not occur as often, or last as long as the recurrent high speed solar wind streams.

**Seasonal dependence** It has long been recognized that geomagnetic activity exhibits a semiannual variation [e.g., Chapman and Bartels, 1940] with the greatest activity near the equinoxes. Its possible cause has been a point of debate and has recently been reviewed by Cliver et al. [2000], where three causes are cited: 1) the axial effect, that is the variation of the position of the Earth in heliographic latitude and the concurrent increase in solar wind speed at higher heliographic latitudes, 2) the equinoctial effect, that is the varying angle of the Earth's dipole with respect to the Earth-Sun line or rather the solar wind velocity and thus presumably a varying efficiency of coupling with the solar wind, and 3) the Russell-McPherron effect, an effect due to the larger z-component of the interplanetary magnetic field (IMF) near the equinoxes in GSM coordinates which in turn is due to the tilt of dipole axis with respect to the heliographic equatorial plane. Cliver et al. [2000] argue that the equinoctial effect is the dominant effect. Since it is clear

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**Figure 1.** Selected SAMPEX measurements of protons of 19-27.4 MeV ( $\#/\text{cm}^2\text{-s-r-MeV}$ ) and electrons of 2-6 MeV ( $\#/\text{cm}^2\text{-s-r}$  in logarithm, in bins of 0.1 L) since launch (July 3, 1992) and sunspot number and Dst index for the same period. The protons and sunspot numbers are window-averaged over a 9-month period and the electron and Dst index is window-averaged over a 30-day period in order to show the overall feature. The yellow vertical bars on the horizontal axis are marks of equinoxes.

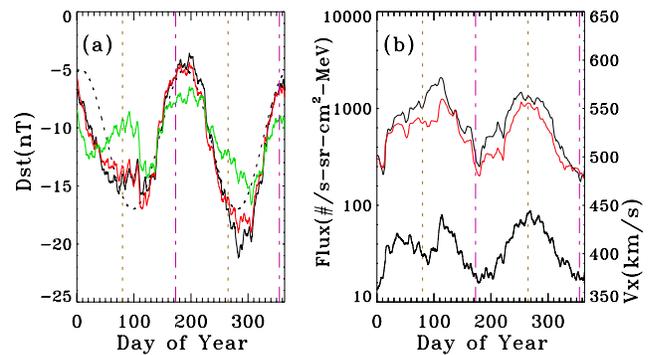
from Figure 1 that both Dst and the MeV electron flux have a strong semiannual variation we examine this variation in more detail here to help determine its cause.

The cause of the semiannual variation can be divided into two parts: a semiannual variation in the response of the magnetosphere to the solar wind, such as the equinoctial effect and a semiannual variation in the solar wind itself in GSM coordinates, such as the axial and Russell-McPherron effects. For Dst and the electron flux at geostationary orbit we can separate these two effects because we have good models that accurately predict these variations given the solar wind input. Recently, Temerin and Li [2001] produced a model that improved the predictability of the Dst by incorporating the equinoctial effect directly into the terms that drive changes in Dst. Figure 2a shows a superposed epoch analysis of five years of the Dst (1995-1999) index (black curve) and of the prediction (red curve) from this model window-averaged over 30 days. The agreement is very good which shows that the model predicts Dst well including its semiannual variation. In the model we can remove the equinoctial effect, then we get the green curve in Figure 2a. Thus the semiannual variation of the green curve must be due to the semiannual variation of the solar wind itself in the frame of Earth's magnetosphere: either the axial effect, the Russell-McPherron effect, or some random or unknown effect that changes the solar wind. The small peak near the vernal equinox and the overall phase of the green curve suggest that there is a significant contribution from random or unknown effects.

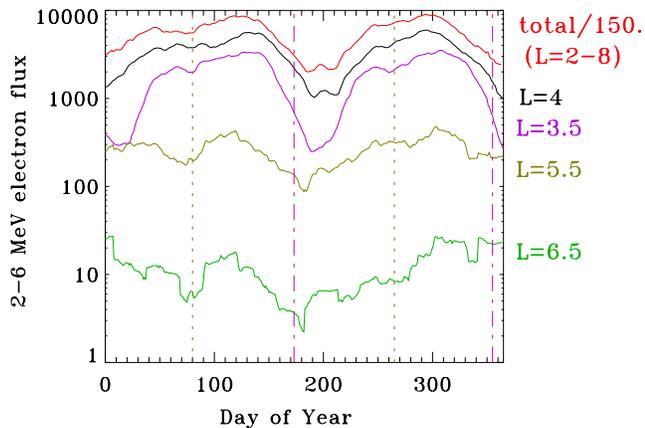
We can gain more insight into the semiannual variation of the Dst index by looking at its phase with respect to modeled Dst (red curve in Figure 2a). In the model [Temerin and Li, 2001] the equinoctial effect was not incorporated by using the known time of the equinox but rather the time of the equinox was treated as a free parameter. The best fit was found if the time of the equinox in the model was assumed to be shifted by 5 days (i.e., on March 27 rather than

March 22). This is physically reasonable since the important parameter in the equinoctial effect is not the angle of the dipole with respect to the Sun-Earth line but rather the angle with respect to the solar wind direction in the Earth's frame of reference which is aberrated by the motion of the Earth around the Sun. Based on this aberrated angle the 'solar wind equinox' is shifted by about 4 days ( $\text{atan}[\text{Earth's speed (30km/s)/averaged solar wind speed(425km/s)}] \approx 4^\circ$ ).

However, the Dst index has a phase shift from the equinox of 18 days rather than 4 days as shown by the smooth black dotted curve in Figure 2a, which is the best semiannual fit to the Dst. This additional phase shift must be due to a semiannual variation of the solar wind driver itself. The solar wind driver can have a semiannual variation from both random and systematic effects. The random effects occur because the solar wind has variations on various low frequency time scales and thus its frequency spectrum would have some Fourier components on a semiannual time scale



**Figure 2.** Five-year (1995-1999) superposed epoch plot for: (a) measured Dst (black), predicted Dst (red), and predicted Dst but without including the equinoctial effect; (b) measured MeV electrons (black), predicted (red), and the x-component of solar wind velocity (lower black curve).



**Figure 3.** Eight-year (1993-2000) superposed epoch plot of 2-6 MeV electron fluxes measured by SAMPEX at different L-value. The total flux is summarized from L=2 to L=8.

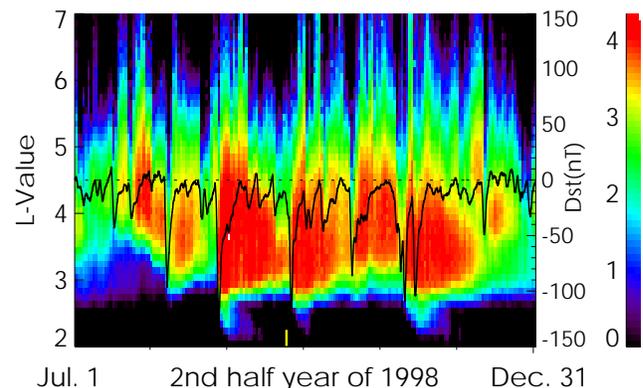
and other low frequency time scales. In addition there are also systematic effects. According to Cliver et al. [2000] the Russell-McPherron effect has a phase shift of about 16 days since it is on April 5 and October 8 that the ‘solar wind magnetic field lying entirely in the Sun’s equatorial plane has its maximum projection on the z-axis of the GSM coordinate system’. The axial effect has a phase shift of -15 days since the Earth reaches the minimum and maximum heliographic latitudes of 7.25 degrees on March 6 and September 8, respectively. The actual solar wind driver for Dst has a larger phase shift suggesting that there is some additional unknown or random component to its phase. Thus the semiannual variation of the Dst can be understood as an average of the equinoctial effect and the solar wind driver. The semiannual variation of the solar wind driver can be understood as due to the Russell-McPherron effect and the axial effect, which have almost exactly opposite phase lags, plus additional random and unknown effects.

We can do the same sort of analysis with the MeV electron flux at L=6.6 using our newly developed prediction model for MeV electrons at geosynchronous orbit [Li et al., 2001]. The model is based on the standard radial diffusion equation and the theory is that the variations in solar wind velocity, velocity fluctuation, and the orientation and magnitude of the IMF control the variations of the radial diffusion, which determines whether electrons starting from the outer boundary, chosen at L=11.5 [Li et al., 2001], can be transported to geostationary orbit and inward before being lost. Figure 2b shows superposed epoch analysis of five-years (1995-1999) of electron data (black curve) from the Los Alamos National Laboratory (LANL) sensors on geostationary satellites and our prediction (red curve). Both show a strong semiannual variation. A fit to the electron data and the model prediction show that both have a 4-day phase shift from the equinoxes. Here, however, the model does not include the equinoctial effect which means that the semiannual variation is almost all due to the solar wind driver. The responsible solar wind driver for MeV electron flux at L=6.6 is quite different from that of Dst. Dst is mostly driven by the southward component of the IMF, while the MeV electron flux at L=6.6 is driven mostly by high solar wind speeds. A superposed epoch analysis of the solar wind velocity (x-component in GSM coordinates) for 1995-1999 (lower black

curve in Figure 2b) shows a strong semiannual variation with about a 8-day shift from the equinoxes, in good agreement with the observed and modeled electron flux. We would expect a semiannual variation in solar wind speeds due to the axial effect since the solar wind speed should be larger at higher heliographic latitudes. The actual semiannual variation in solar wind speeds during this five-year period was much larger than what would be expected from this change in heliographic latitude. In addition the variation in solar wind speeds must be only partly due to the axial effect since its phase differs from that expected from the axial effect by 23 days (remember: the axial effect should give a phase shift of -15 days). Thus it appears that during this five-year period the random low-frequency variations in the solar wind speed mostly reinforced the semiannual variation expected from the axial effect. If part of the semiannual variation is fortuitous, it is likely to vary with time, which has been pointed earlier by Orlando et al. [1993]. Please note that there is some similarity between the green curve (black and red curves too) in Figure 2(a) and the inverted velocity curve in Figure 2(b), most pronounced near the vernal equinox, since the solar wind velocity is also a significant cause of the variation of the Dst index and the equinoctial effect determines the efficiency (the difference between the green and red curves).

Indeed Figure 3 shows that the semiannual variation is almost absent from 8 years of SAMPEX data at L=6.5. This absence is mostly due to the large enhancement in the electron flux at the end of 1993 and the beginning of 1994 as seen in Figure 1, while the semiannual variation would predict a minimum electron flux during solstices.

However, the semiannual variation is more pronounced at a lower L and there is also a larger phase shift of the electron flux peak from the equinoxes. At L=5.5, 4, and 3.5 the electron fluxes have a phase shift from the equinoxes of 26, 27, and 29 days respectively. At these smaller L values the correlation with Dst is also much better than near geostationary orbit. These phase shifts can be understood as the phase shift associated with Dst plus an additional shift associated with the inward diffusion and decay of the electron flux. The agreement between the electron fluxes at these smaller L values and the Dst is good even on smaller time scale.



**Figure 4.** Daily averaged SAMPEX electron measurements ( $\#/cm^2-s-sr$ ) and Dst index with 1-day window-average for the second half year of 1998.

**Correlation with solar rotations and magnetic storms** Figure 4 shows the daily-averaged electron fluxes and the Dst index for the second half of 1998. It is evident that outer belt electron enhancements vary over a solar rotation period (about 27 days) and are closely correlated with geomagnetic storms indicated by Dst. The correlation between Dst and enhancements of radiation belt electrons has long been recognized [Dessler and Karplus, 1961; McIlwain, 1966]. As shown in Figure 4, the outer belt electrons have the largest variations and also penetrate to lowest L-values when Dst is most negative. This relation has been explored by Tverskaya [1986], who has summarized the location of maximum MeV electron intensity following a magnetic storm as function of the minimum Dst index into an empirical formula. This correlation also implies that the ring current (a major factor for Dst) is closely coupled to MeV electron variations. The electron flux typically drops at the beginning of the main phase of a storm and starts to recover during the recovery phase of the storm and often exceeds pre-storm levels after one or two days [Dessler and Karplus, 1961; McIlwain, 1966; Li et al., 1997; Kim and Chan, 1997]. The re-formed electron belt outlasts the Dst variation and decays slowly until the next magnetic storm.

## Conclusion

Long-term and continuous measurements of the solar wind and magnetosphere are valuable and critically important for understanding physical processes during different parts of the solar cycle.

Long-term observations such as shown here demonstrate that the magnetosphere is strongly controlled by the solar wind. Large-scale magnetospheric features, such as currents, which determine the Dst index, and radiation belt particles respond systematically to variations in the solar wind. The semiannual variation of the Dst index and MeV electrons deep in the inner magnetosphere can be attributed mostly to the equinoctial effect (orientation of the Earth's dipole axis relative to solar wind flow) with the axial (heliographic latitude) and Russell-McPherron (IMF z-component in GSM coordinate) effects also contributing while the semiannual variation of MeV electrons at geostationary orbit is attributed mostly to the semiannual variation of solar wind velocity as seen by Earth.

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