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Quantitative Prediction of Radiation Belt Electrons at Geostationary Orbit Based on Solar Wind Measurements

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Abstract. Solar wind measurements are used to predict the MeV electron radiation belt flux at the position of geostationary orbit. Using a model based on the standard radial diffusion equation, a prediction efficiency of 0.81 and a linear correlation of 0.90 were achieved for the years 1995-1996 for the logarithm of average daily flux. Model parameters based on the years 1995-1996 gave a prediction efficiency and a linear correlation for the years 1995-1999 of 0.59 and 0.80, respectively. The radial diffusion equation is solved after making the diffusion coefficient a function of the solar wind velocity and interplanetary magnetic field. The solar wind velocity is the most important parameter governing relativistic electron fluxes at geostationary orbit. The model also provides a physical explanation to several long standing mysteries of the variation of the MeV electrons.

Introduction

As part of the International Solar Terrestrial Program, the solar wind has been monitored almost continuously since Dec. 1994 by spacecraft Wind [Acuna et al., 1995] and ACE [Stone et al., 1998]. Solar wind is the major driver of Earth's space weather. Energetic particles, which can lead to satellite failure through radiation damage, are of increasing concern as mankind relies more on satellite systems. Of special concern is the radiation environment at geostationary orbit where the largest number of satellites is located.

Figure 1 displays a comparison of five years of daily averages of the MeV electron flux measured at geostationary orbit with our prediction based solely on measurements of the solar wind. Both the shorter time scale and the longer seasonal effects, such as the overall reduction in the electron fluxes in the middle of 1996, are reproduced. Furthermore, the model provides a physical explanation for several features of the correlation between the solar wind and the MeV electrons at geostationary orbit: (1) the approximate 1-2 day delay between the peak in the solar wind velocity and the peak in the MeV electron flux, (2) the seeming lack of significant correlation between the southward component of the interplanetary magnetic field (IMF) and the MeV electron flux, and (3) the large relative variations in the MeV electron flux for relatively smaller variations in the solar wind velocity.

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We used solar wind data primarily from the Wind satellite. The solar wind velocity and density were provided by the 3D/plasma and energetic particle instrument [Lin et al., 1995], and solar wind magnetic field by the magnetometer [Lepping et al., 1995]. Wind was in the solar wind almost continuously except for a few passes through the magnetosphere. We interpolated the solar wind data during these gaps before ACE data were available in 1998 and then used ACE data from the SWEPAM and MAG instruments [McComas et al., 1998; Smith et al., 1999] to fill most of the gaps. ACE was near the L1 point, about 235 earth radii upstream in the solar wind from the Earth.

We compared our model results with the MeV electron data at geostationary orbit from the Los Alamos National Laboratory (LANL) sensors on geostationary satellites. These sensors are identically designed and record electron fluxes in the energy ranges of 0.7-1.8 MeV, 1.8-3.5 MeV, and 3.5-6.0 MeV. The long-term average of the LANL data gives an e-folding energy of 0.47 MeV if fitted by an exponential. Data from LANL sensors on all available satellites (max 5) were combined to form daily averaged fluxes.

It has been shown that there is a good correlation between the solar wind velocity and the MeV electron flux at geostationary orbit [Paulikas and Blake, 1979]. Since geomagnetic activity is known to be controlled more strongly by the polarity of the interplanetary magnetic field (geomagnetic activity is strongest when the interplanetary magnetic field points southward), the better correlation of MeV electrons with solar wind velocity has been a mystery [Li and Temerin, 2001].

To produce MeV electrons at geostationary orbit lesser energy electrons need be energized within the magnetosphere. This can be accomplished if electrons are transported radially inward to a region of stronger magnetic field. Radial transport violates the third adiabatic invariant [Schulz and Lanzerotti, 1974]. Such violation can occur through large-scale fluctuations of the electric and magnetic fields, which result in diffusion in radial distance. This 'radial diffusion' is thought to be the most important mechanism of electron energization. The tendency of radial diffusion is to equalize, across a range of radial distance, the phase space density of electrons with the same value of the first and second adiabatic invariants (μ and J) [Schulz and Lanzerotti, 1974]. Since the phase space density at a given μ and J usually increases with increasing radial distance, the usual effect of radial diffusion is to increase the flux at smaller radial distances, by radially diffusing electrons from larger distances while preserving their first two adiabatic invariants [Selesnick and Blake, 2000]. The effectiveness of radial diffusion depends on the radial profile of the phase space density of the electrons and the fluctuation level of the magnetic and electric fields.

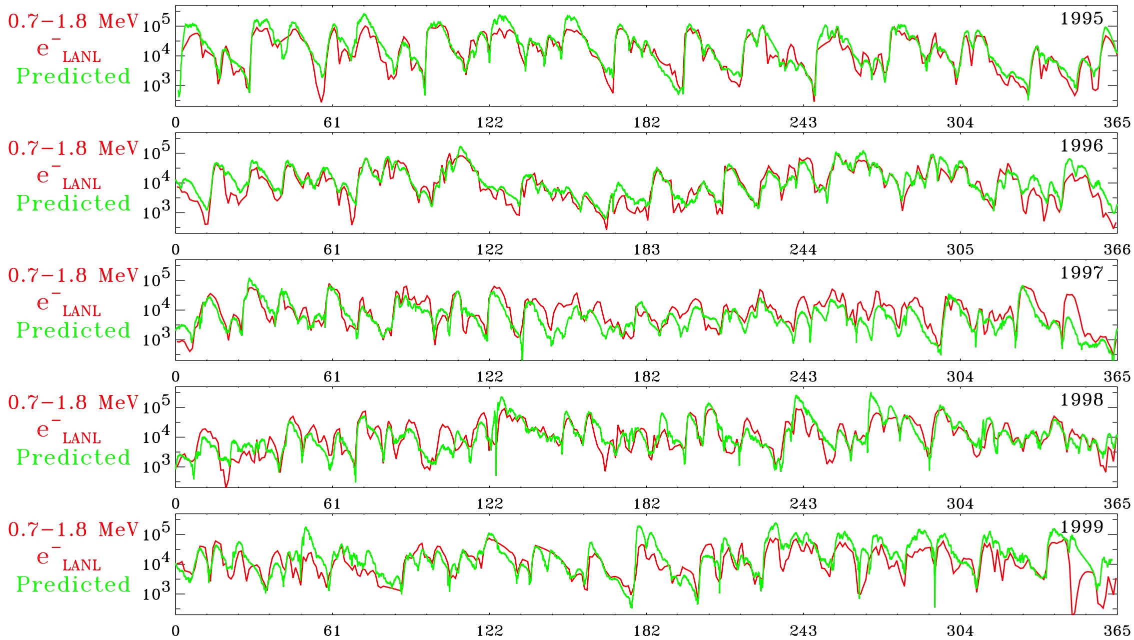

Figure 1. A comparison of five years of daily averages of the MeV electron flux measured at geostationary orbit with predicted results based solely on measurements of the solar wind. The red line shows the observed electron fluxes and green line shows predicted results. Horizontal axis shows the day of the year.

To be effective in producing radial diffusion fluctuations in the electric and magnetic fields should be on the time scale of drift period of electrons around the Earth. Such magnetospheric fluctuations can be due to fluctuations in the solar wind, to ultra low frequency (ULF) waves generated at the magnetopause or within the magnetosphere, or to the electric and magnetic fields driven by substorms and magnetic storms. It has been argued that specific ULF waves are important in driving radial diffusion [Rostoker et al., 1998; Baker et al., 1998]. Magnetohydrodynamic simulations and test-particle tracing have shown a direct response of radiation belt electrons to such magnetospheric fluctuations [Hudson et al., 1999; Elkington et al., 1999]. ULF waves are known to be well correlated with solar wind velocity [Engebretson et al., 1998] which may provide an explanation for this solar wind correlation.

Previous predictive models have been based on correlations with solar wind or magnetospheric parameters such as Kp using linear prediction filter [Baker et al., 1990] or neural network [Koons and Gorney, 1991] techniques. Such techniques are difficult to interpret physically and have only been applied to limited time intervals. The linear prediction filter method achieved a prediction efficiency [Baker et al., 1990] of 52%. Prediction efficiency is defined as [1-(variance of the residual)/(variance of data)] where the residual is the difference between the data and the prediction.

Model

Our model predicts the MeV electron flux at geostationary orbit by using the solar wind data to change the radial diffusion rate. The model uses the standard radial diffusion equation [Schulz and Lanzerotti, 1974]

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) - \frac{f}{\tau}, \qquad (1)$$

where f is the electron phase space density. It is related to the differential flux j by

$$f = j/p^2, \qquad (2)$$

where p is the momentum of the electron. If Earth's field is approximated by a dipole, L corresponds to the radial distance in units of earth radii at the equator. D_{LL} and τ are the diffusion coefficient and average life time of the electrons,

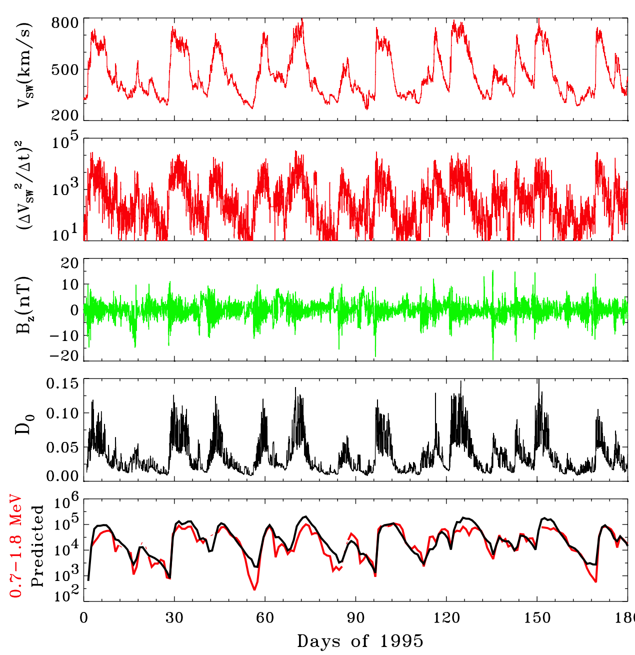

Figure 2. From the top: solar wind velocity, velocity fluctuation, z-component of IMF, D_0 from Eq. (3), and the measured and predicted electron fluxes.

and both are steep functions of L, $D_{LL} = D_0(L/6.6)^{10}, \tau = \tau_0(6.6/L)^{10}$. The inner and outer boundary are set at $L = 4.5$ and $L = 11$, respectively. The outer boundary is associated with the last closed drift orbit or the average magnetopause location.

Equation (1) is solved by setting f 10^4 times larger at the outer boundary than the inner boundary in approximate agreement with data [Li et al., 1997a] and by making D_0 a function of the solar wind parameters,

$$D_0 = C(\frac{v}{v_0})^{\gamma_1}[1+((v_x b_z+|v_x b_z|)/\alpha)^2]^{\gamma_2}[(\frac{\triangle v^2}{\triangle t})^2/\beta]^{\gamma_3}, \quad (3)$$

where the first term is a function of the solar wind velocity divided by its average; the second term is a function of the y-component of solar wind electric field, which varies only when b_z, the z-component of the IMF in GSM coordinates, is negative since v_x is always negative; the third term is a function of solar wind velocity fluctuations. The term $\frac{\triangle v^2}{\triangle t}$ is calculated from the solar wind velocity using data at a 10-minute resolution and window-averaged over about 1.5 hours. The β is the average of $(\frac{\triangle v^2}{\triangle t})^2$ over two years 1995-1996. We also included two de-coupled processes, the Dst effect and a dynamic pressure effect, to adjust f.

The Dst effect produces an adiabatic response of electrons to magnetic field changes [Li et al., 1997b; Kim and Chan, 1997]. We implement this effect in an *ad hoc* way by adjusting f at all points,

$$f(t+\triangle t) = f(t) * \exp[\frac{(Dst(t+\triangle t) - Dst(t))}{Dst_n}], \quad (4)$$

where Dst_n, equal to 56 nT, is a parameter. This makes f at a given position decrease as Dst decreases and increase as Dst increases. Dst is directly calculated from the solar wind parameters by a modified Burton equation using solar wind velocity, density, and magnetic field [Burton et al., 1975].

The dynamic pressure effect is implemented by adjusting f in the following way

$$f = f * \exp(-(p/p_n)^{0.6}), \quad (5)$$

where $p = Nv^2$ in units of nPa. p_n, equal to 4.0 nPa, is a parameter. The above equation indicates that the MeV electron flux decreases when the solar wind dynamic pressure increases. This may be because electrons with large pitch angles at equator starting on the night side will drift further out on the dayside. An enhancement in the solar wind dynamic pressure will push the magnetopause inward and enhance the magnetic field on the dayside such that more electrons will be lost by reaching the magnetopause.

Results and Discussions

We compared the predicted results with the MeV electron measurements by minimizing χ^2:

$$\chi^2 = \frac{1}{N}\sum_i^N [log_{10}(j_i) - log_{10}(j_i^l)]^2, \quad (6)$$

where the j_i is modeled result and j_i^l is from LANL MeV electron data. We adjusted the parameters $C, \alpha, \gamma_1, \gamma_2, \gamma_3, \tau_0$, and the parameters associated with Dst and dynamic pressure effects for the years 1995-1996 but then plotted the data and the prediction for five years in Figure 1. The corresponding parameters are $C = 0.036/day, v_0 = 425 km/s, \alpha = 70\ km \cdot nT/s, \gamma_1 = 1.86,\ \gamma_2 = 0.113, \gamma_3 = 0.03, \tau_0 = 2.67\ day$.

In 1995 the solar wind was dominated by recurrent high speed streams. In 1996 solar activity reached a minimum. Starting with 1997, the solar wind activity included coronal mass ejections as the new solar cycle began. For 1995 and 1996 the prediction efficiency for the logarithm of the electron flux was 0.81 and the linear correlation was 0.90. For the whole five year period the prediction efficiency was 0.59 and the linear correlation was 0.80 using model parameters based on the years 1995-1996. In the model the most important source of variability in the electron flux is the variability of the diffusion coefficient which accounts for 0.76 of the prediction efficiency for 1995 and 1996 when excluding Dst and dynamic pressure effects. Including the Dst effect without the dynamic pressure enhances the prediction efficiency to 0.80 while including the dynamic pressure effect without the Dst term enhances the prediction efficiency to 0.77.

Since the diffusion coefficient, D_0, in Eq. (3) is a product of three terms all of which include solar wind velocity and because solar wind velocity fluctuations are highly correlated with solar wind velocity, variations in the diffusion coefficient are primarily due to variations in the solar wind velocity. D_0 has a total variability (max/min) of about 14 for 1995-1996 while the electron flux has a total variability of a factor of 400. The three terms in Eq. (3) have an average variability (standard deviation/average) of 0.38, 0.25, and 0.06, respectively. Since the solar wind velocity fluctuation is highly correlated with the solar wind velocity itself, using either of the two terms can produce good results but using both terms gives the best results for 1995-1996.

The most relevant solar wind quantities, D_0 from Eq. (3), and the observed and predicted electron fluxes are shown in Figure 2 for the first half year of 1995.

The diffusion equation together with its loss term provides a delay for changes in the electron flux at geostationary orbit, since it takes some time for the electrons to diffuse inward to geostationary orbit in response to changes in the solar wind input and some time for electrons to decay. We found that the average electron life time is approximately 2.67 days at geostationary orbit, although it is much smaller at greater radial distances.

The MeV electron flux at geostationary orbit varies by two orders of magnitude whereas the solar wind velocity varies usually by at most a factor of three. The diffusion formulation with loss provides a natural explanation. In our formulation we have a boundary condition at L=11, where we assume a fairly constant phase space density of electrons. While this is probably unrealistic it does not matter much since most of the variation in the electron flux at geostationary orbit is due to changes in the diffusion coefficient. A variation in the diffusion coefficient can produce a larger variation in the electron flux because of competition between inward diffusion and loss. Most electrons starting from L=11 will be lost before reaching geostationary orbit unless there is a strong inward diffusion. In the model, increasing the diffusion rate by a factor of two increases the electron flux at geostationary orbit by about a factor of ten.

It is well established that the direction of the IMF controls much of the activity in the magnetosphere. Substorms occur after the IMF points southward for some time. The ring current as measured by Dst is enhanced when the IMF points strongly southward. Thus the very good correlation of the relativistic electron flux at geostationary orbit with solar wind velocity rather than with solar wind IMF has been a mystery. We find indeed that diffusion coefficient is about 44% greater when the IMF points southward than when the IMF points northward and yet including the IMF term in our diffusion equation improves the prediction efficiency by only 8% (from 0.75 to 0.81 for years 1995-1996). This is because the IMF fluctuates much more rapidly than the overall solar wind velocity (see Figure 2 as an example), and because diffusion takes on the order of two days. During a period of two days the solar wind usually has several intervals when the IMF has both southward and northward polarities and thus when averaged the b_z component of the IMF has little variation and thus little effect unless its polarity is constant for a long time.

We also investigated electron fluxes at a higher energy channel (1.8-3.5 MeV) using the same model. The best prediction efficiency, corresponding to a different set of model parameters, was 0.80 and the linear correlation was 0.90 for 1995-1996. For the whole five year period the prediction efficiency was 0.68 and the linear correlation was 0.83 using model parameters based on the years 1995-1996.

Our model can be used to predict the relativistic electron flux at geostationary orbit. Because the solar wind effects are delayed by diffusion to geostationary orbit, the MeV electron flux there can be quantitatively predicted 1-2 days in advance given knowledge of the solar wind. Such knowledge is now routinely available from the ACE spacecraft.

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