Prediction of MeV Electrons at Geostationary Orbit on the Basis of Solar Wind Measurements

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Abstract.

Solar wind measurements can be 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 0.82 and a linear correlation of 0.84 were achieved for the two years 1995 and 1996 for the logarithm of average daily flux at geostationary orbit. Model parameters based on the years 1995-1996 gave a prediction efficiency and the linear correlation for the five year period 1995-1999 of 0.61 and 0.77, respectively. The radial diffusion equation is solved by setting the phase space density larger at the outer boundary than the inner boundary and by making the diffusion coefficient a function of the solar wind velocity and interplanetary magnetic field. The solar wind velocity is the most important parameter in the variation of relativistic electron fluxes at geostationary orbit. The model also explains the delay and amplitude of changes in the electron flux relative to changes in the solar wind.

Recent initiatives in space physics have emphasized the quantitative prediction of magnetospheric and ionospheric phenomena and the solar variability that is their cause. These initiatives go under the name of 'space weather' [1; 2]. Such quantitative predictions are of practical importance but also test our understanding of how the Sun influences the Earth. As part of the International Solar Terrestrial Program (ISTP) [3] the solar wind has been monitored almost continuously since Dec. 1994 by NASA's Wind spacecraft [4] and Advanced Composition Explorer (ACE) spacecraft [5]. Solar activity in the form of solar flares, coronal mass injections, and recurrent high speed streams influence Earth's space weather by increasing ionization in the ionosphere and by producing magnetic storms and their associated electrical currents, energetic charged particle injections, and aurora. These phenomena can have a deleterious impact on man-made systems. Currents flowing in the ionosphere during magnetic storms can induce large and fluctuating currents in power grids leading to transformer failure and blackouts [1]. Of increasing concern as mankind relies more on satellite systems are energetic particles, which can lead to satellite failure through radiation damage. 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 electron flux at geostationary orbit: (1) the approximate 1.5-2.0 day delay between the peak in the solar wind velocity and the peak in the MeV electron flux at geostationary orbit, (2) the seeming lack of any significant correlation between the southward component of the interplanetary magnetic field (IMF) and the MeV electron flux at geostationary orbit, and (3) the large relative variation in the MeV electron flux at geostationary orbit for relatively much smaller variations in the solar wind velocity.

We used solar wind data primarily from the Wind satellite. Solar wind velocity and density data were provided by the 3D/plasma and energetic particle instrument [6], and solar wind magnetic field data by the magnetometer [7]. Wind stayed in the solar wind almost continuously except during 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 [8; 9] to fill most of the gaps. ACE stayed near the L1 point (where the gravity from the Sun and the Earth result in an orbital equilibrium point). The ACE data are available from the ACE web page [5].

We compared our model results with the MeV electron data at geostationary orbit provided by 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. Data from all available LANL sensors is combined to form daily average flux levels. Data gaps are plotted as dotted lines in Figure 1.

Variations of the MeV electrons at geostationary orbit are controlled by the solar wind. It has been shown that there is a good correlation between the solar wind velocity and the MeV electron flux at geostationary orbit [10]. 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 at geostationary orbit with solar wind velocity has been a mystery [11].

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 of the electron [12]. Such violation can occur through large-scale fluctuations of the electric and magnetic fields, which result in a diffusion of electrons 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 the phase space density of electrons with the same value of the first and second adiabatic invariants (μ and J) [13]. 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 at a given energy, by radially diffusing electrons from larger distances while preserving their first two adiabatic invariants [14]. The effectiveness of radial diffusion depends on the radial profile of the phase space density of the electrons and the fluctuation level of magnetic and electric fields.

To be effective in producing radial diffusion the magnetospheric fluctuations in the electric and magnetic fields should be on the time scale of a drift period of the electron 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 changes in the electric and magnetic fields driven by substorms and magnetic storms [17]. Recently it has been argued that specific ULF waves are important in driving radial diffusion [15; 16]. Magnetohydrodynamic simulations and test-particle tracing have shown a direct response of radiation belt electrons to such magnetospheric changes [18]. ULF waves are known to be well correlated with solar wind velocity [19] which may provide an explanation for this solar wind correlation.

Previous predictive models have been based on correlations with solar wind parameters or magnetospheric activity measurements such as Kp using linear prediction filter [20] or neural network [21] 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 [22] of 52% [20].

Our model predicts the MeV electron flux at geostationary orbit by using solar wind measurements to change the radial diffusion rate. The model uses the standard radial diffusion equation [13]:

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

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

$$f = j/p^2, \tag{2}$$

where p is the momentum of the electron. If Earth's field is approximated as a dipole field, 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, 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 in our model are set at $L = 4.5$ and $L = 11$, respectively. The exact values of the inner and outer boundary do not significantly affect results at geostationary orbit.

Equation (1) is solved by setting f 10^4 times larger at the outer boundary than the inner boundary [23]) and by making D_0 a function of the solar wind parameters as

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

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 contributes only when b_z, the z-component of the IMF in GSM [24] coordinates, is negative since v_x is always negative; The third term is a function of solar wind velocity fluctuation. The term $\frac{\triangle v^2}{\triangle t}$ is directly calculated from the solar velocity using data at a rate of one measurement every 10 minutes and window-averaged over about 1.5 hours, β is the average of $(\frac{\triangle v^2}{\triangle t})^2$ in the time period of interest, which is five years for results in Figure 1. The velocity fluctuation is an approximation of 2v*dv/dt, a combination of solar wind velocity and velocity fluctuation. We also included two de-coupled processes: the D_{st} effect [25] and a dynamic pressure effect [26] to adjust f and then plotted the data and the simulated results

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

$$\chi^2 = \frac{1}{N}\sum_i^N [log_{10}(j_i) - log_{10}(j_i^l)]^2, \tag{4}$$

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 D_{st} and dynamic pressure effects for the years 1995 and 1996 but then plotted the data and the prediction for five years in Figure 1. The corre-

sponding parameters are $C = 0.036/day, v_0 = 425km/s, \alpha = 110km \cdot nT/s, \gamma_1 = 1.73, \gamma_2 = 0.105, \gamma_3 = 0.035, \tau_0 = 2.67$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 0.82 and the linear correlation was 0.84. For the whole five year period the prediction efficiency was 0.61 and the linear correlation was 0.77 using model parameters based on the years 1995 and 1996. In the model the most important source of variability in the electron flux is the variability in the diffusion coefficient which accounts for 0.76 of the prediction efficiency for 1995 and 1996 when excluding D_{st} and dynamic pressure effects. Including the D_{st} effect enhances the prediction efficiency to 0.79 while including the dynamic pressure effect without the D_{st} term enhances the prediction efficiency to 0.80.

The diffusion coefficient, D_0, in Eq. (3) is a product of three terms: the first term is a function only of the solar wind velocity; the second term also includes the solar wind velocity together with b_z; the third term is a function of fluctuations in the solar wind velocity which are highly correlated with the solar wind velocity. Thus variations of the diffusion coefficient are primarily due to variations in the solar wind velocity. D_0 has a total variability (maximum/minimum) of about 14 for 1995 and 1996 while the electron flux has a total variability of a factor of 400. A variation in the diffusion coefficient can produce a larger variation in the electron flux because of competition between diffusion and loss. 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.

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.

Our model also provides a physical explanation for some features of the correlation between the solar wind and the electron flux.

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 also some time for such changes to decay. We found that the best average life time of the electrons 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. Thus, 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 [27]. Substorms occur after the IMF points southward for some time. The ring current as measured by D_{st} 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 which should lead to more than a factor of seven increase in the electron flux, and yet including the IMF term to our diffusion equation improves the prediction efficiency by only 12% (from 0.73 to 0.82 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 that 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.

Our model can be use to predict the 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.

Figure Caption

Figure 1. A comparison of five years of daily averages of the MeV electron flux measured at geostationary orbit with the predicted results based solely on measurements of the solar wind. The red line shows electron flux measured at geostationary orbit, data gaps are connected by dotted lines. The green line shows predicted results. Horizontal axis shows the day of the year.

Figure 2. Most relevant solar wind parameters, model parameter, and the comparison of measurements and prediction of the electron fluxes for the first half year of 1995. From the top: solar wind velocity, velocity fluctuation, z-component of interplanetary magnetic field, D_0 from Eq. (3), and the observed and predicted electron fluxes.

References and Notes

1. Several U. S. government agencies have developed a program called the National Space Weather Program (NSWP). "Space weather" refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. Corresponding Person: Rich Behnke, Section Head, Upper Atmosphere Research Section, Division of Atmospheric Sciences, National Science Foundation, e-mail: rbehnke@nsf.gov, current web address: http://www.geo.nsf.gov/atm/nswp/nswp.htm. Examples of impacts of significant space weather events: (1) March 13-14, 1989. A severe geomagnetic storm caused a system-wide power failure in Quebec, Canada, resulting in the loss of over 20,000 megawatts. The blackout cut electric power to several million people. (2) April 29, 1991. A transformer at the Maine Yankee Nuclear Plant catastrophically failed within a few hours of a severe geomagnetic storm onset.
2. Living With a Star is a new NASA initiative to understand space weather and the effects of the Sun on the Earth's climate, Responsible NASA Official: Dr. George Withbroe NASA Headquarters, Code S, e-mail: gwithbro@hq.nasa.gov, current web address: http://sec.gsfc.nasa.gov/lws.html.
3. Since the 1980s, the collaborative efforts by NASA, the European Space Agency (ESA), and the Institute of Space and Astronautical Science (ISAS) of Japan have led to the conception of the International Solar-Terrestrial Physics Science Initiative. This program combines resources and scientific communities on an international scale using several spacecraft, along with complementary ground facilities and theoretical efforts, to obtain coordinated, simultaneous investigations of the Sun-Earth space environment over an extended period of time. Official NASA Contact: Mr. William Mish, e-mail, wmish@istp1.gsfc.nasa.gov, current web address: http://www-istp.gsfc.nasa.gov/istp/
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12. In a quasi-dipole magnetic field such as that of the Earth, trapped particles conduct three distinctive motions: gyration, bounce, and drift. There is an adiabatic invariant associated with each of these motions. The first invariant is proportional to the magnetic flux within a gyro orbit; the second invariant is proportional to the magnetic field integrated along the bounce orbit; and the third invariant is proportional to the magnetic flux within the drift orbit. As long as the magnetic field changes slowly over the respective time-scale, the corresponding invariant remains constant, Northrop, T. G., The adiabatic motion of charged particles. Interscience Publishers, New York, (1963).
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22. 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.
23. This is based on the examination of several orbits of Wind satellite data during several passes within the magnetosphere, which was presented by Li et al. at the International Association of Geomagnetism and Aeronomy (IAGA) Scientific Assembly, Uppsala, Sweden, (1997).
24. In the GSM coordinate system, the x-axis points from the earth to the sun, the y-axis is perpendicular to earth's magnetic dipole. The positive z-axis is chosen to be in the same sense as the northern magnetic pole.
25. The D_{st} effect is a measure of the adiabatic response of electrons to magnetic field changes. We implement this effect in an *ad hoc* way by adjusting f at all points,
$$f = f * exp[\frac{(Dst(t+\triangle t) - Dst(t))}{Dst_n}], \quad (5)$$
where Dst_n, equal to 72, is a parameter. This makes f at a given position decrease as D_{st} decreases and increase as D_{st} increases. D_{st} is directly calculated from the solar wind parameters by a modified Burton equation using solar wind velocity, density, and magnetic field, Burton, R. K., R. L. McPherron, and C. T. Russell, An empirical relationship between interplanetary conditions and Dst, *J. Geophys. Res.***80**, 4204, (1975).
26. The dynamic pressure effect is implemented by adjusting f in the following way
$$f = f * exp(-(p/p_n)^{0.6})$$
where $p = Nv^2$ in units of nPa. p_n, equal to 5.8, is a parameter. The above equation indicates that the MeV flux decreases when the solar wind dynamic pressure increases.
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28. We thank S. Monk for programming efforts and R. Selesnick for helpful discussions in solving the diffusion equation. We appreciate the effort by the science teams (Wind/3D, Wind/Mag, ACE/SWEPAM, ACE/Mag, LANL) to make the data available. This work was mainly supported by NASA grants (SAMPEX, NAG5-9421, and NAG5-4896) and NSF grants (ATM-9909357 and ATM-9901085).

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