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

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Recent initiatives in space physics have emphasized understanding of solar disturbances and the quantitative prediction of resultant magnetospheric and ionospheric phenomena. These initiatives go under the name of 'space weather' [1; 2]. Such quantitative predictions are of practical importance but also test of our understanding of the mechanisms by which 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 (CME), and recurrent high speed streams from solar coronal holes 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. Such magnetic phenomena on the Earth 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. Here we report on a method of predicting the MeV electron flux at geostationary orbit on the basis of solar wind measurements. Figure 1 displays the comparison of five years of daily averages of the MeV electron flux measured at geosynchronous orbit with predicted fluxes based solely on measured solar wind parameters. Not only most of the individual peaks but also the seasonal effects were reproduced. Furthermore, our model provides a physical explanation for observed features of the correlation between the solar wind and the MeV electron flux at geosynchronous 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 geosynchronous 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 geosynchronous orbit, and (3) the large relative variation in the MeV electron flux at geosynchronous orbit for relatively much smaller variations in the solar wind velocity.

Data Sources

The data base of MeV electrons at geosynchronous orbit in our study is from the Los Alamos National Laboratory (LANL) sensors on geosynchronous satellites. These sensors (identically designed) record electron flux data in the energy ranges of 0.7-1.8 MeV, 1.8-3.5 MeV, and 3.5-6.0 MeV. We combine the hourly data from LANL senors and then determine daily averages. However, there are still some data gaps, which are plotted as dotted line in Figure 1.

The solar wind data are mainly from Wind, which was launched at the end of 1994. Solar wind velocity and density data are from the 3D/plasma and energetic particle instrument [6], and solar wind magnetic field data are from the magnetometer instrument [7]. Wind in a series of large elliptical orbits stayed in the solar wind almost continuously except during its perigee passes. We interpolated the solar wind data during the Wind perigee passes before data from ACE were available in 1998. From then on we used ACE data, from SWEPAM and MAG instruments [8; 9], to fill in the data gaps during Wind perigee passes with time shifts given by the propagation velocity of the solar wind. ACE stayed near the L1 point (where the gravity from the Sun and the Earth are canceled) and ACE itself also has some data gaps. The ACE data are directly available from ACE home web page [5].

Background

The electron flux in the outer radiation belt typically drops at the beginning of the main phase of magnetic storms and starts to increase again during the recovery phase of the storm and often exceeds pre-storm levels after one or two days [10; 11; 12]. Some of this electron flux variation is adiabatic due to changes in the magnetic field associated with magnetic storms.

A more important cause of electron flux variations is thought to be radial diffusion. The tendency of radial diffusion is to equalize the phase space density of the 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 (but certainly not always) increases with increasing radial distance, the usual effect of radial diffusion is to increase the flux at smaller radial distances at given energy, by radially diffusing electrons from larger distances [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 transport, radial diffusion requires that there be variations in the electric and magnetic fields within the magnetosphere on the time scale of a drift period. Such variations can be directly due to the variations 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. Recently it has been argued that specific ULF waves are important in driving radial diffusion [15; 16]. MHD simulations and test-particle tracing have shown a direct response of radiation belt electrons to such magnetospheric changes [17; 18].

However, the variations of the MeV electrons at geosynchronous orbit is ultimately 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 geosynchronous orbit [19]. Since geomagnetic activity and substorms are known to be controlled more strongly by the polarity of the interplanetary magnetic field, the better correlation of the radiation belt electrons with solar wind velocity has been mysterious [20].

Other predictions of MeV electrons have been based on correlations with solar wind parameters or magnetospheric activity measurements such as Kp using linear prediction filter [21] or neural networks [22] techniques. Such techniques have only been applied to limited time intervals and have achieved prediction efficiency [23] of 52% [21]. In addition such techniques are difficult to interpret physically.

Model

The unique feature of our model is that the radial diffusion coefficient is directly linked to solar wind parameters. These parameters are in the geocentric solar magnetospheric (GSM) coordinate system [24]. The model is based on the standard radial diffusion equation [13]:

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

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 R_E 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. $D_{LL} = D_0(L/6.6)^{10}, \tau = \tau_0(6.6/L)^m$. The inner and outer boundary in our model are set at $L = 4.5$ and $L = 12.5$, respectively. The exact values of the inner and outer boundary do not significantly affect results at geosynchronous orbit.

Equation (1) is solved by setting f much larger (10^5 times larger, which is consistent with most observations) at the outer boundary than the inner boundary and by making D_0 a function of the solar wind parameters as

$$D_0 = C \times v^{\gamma_1} \times [(1.0 + ((-v_x b_z + \mathrm{abs}(v_x b_z))/E_0)^2.)]^{\gamma_2} \times [(\frac{\triangle v^2}{\triangle t})^2]^{\gamma_1}, \tag{3}$$

where v is the solar wind velocity, t is time, and b_z is the z-component of the IMF in GSM coordinates. 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 averaged over about 1.5 hours. It is an approximation of 2v*dv/dt, a combination of solar wind velocity and velocity fluctuation. We also include two de-coupled processes: the $\mathrm{D_{st}}$ effect [25] and dynamic pressure effect [26] to adjust the f.

We measure the difference between the predicted results and the MeV electron measurements by least square fitting χ^2 defined as:

$$\chi^2 = \frac{1}{N}\sum_i^N [log10(f_i) - log10(f_i^{lanl})]^2, \tag{4}$$

where the f_i is modeled result and f_i^{lanl} is from LANL MeV electron data. We adjust the parameters $C, m, E_0, \gamma_1, \gamma_2, \gamma_3, \tau_0$, $\mathrm{D_{st}}$ and dynamic pressure effects to minimize χ^2 for the years 1995 and 1996 but then plot the data and the prediction for five years in Figure 1. The parameters are $C = 2.95 \times 10^{-5}, m = 9.7, E_0 = 145, \gamma_1 = 1.23, \gamma_2 = 0.095, \gamma_3 = 0.08, \tau_0 = 2.7$.

Discussions

In 1995 the solar wind was dominated by recurrent high speed streams. In 1996 solar activity was approaching a minimum. Starting with 1997, the solar wind activity included more coronal mass ejections as the new solar cycle began. For 1995 and 1996 the prediction efficiency for the logarithm of the electron flux was 81.3% and the linear correlation was 0.83. For the whole five year period the prediction efficiency was 60% and the linear correlation was 0.75 using model parameters based on the years 1995 and 1996. The most important source of variance in the electron flux in the model is variance in the diffusion coefficient which accounts for 78.8% of the prediction efficiency for 1995 and 1996 when excluding the D_{st} and dynamic pressure effects. Including the D_{st} effect improves the prediction efficiency by approximately 2% and including the dynamic pressure improves the prediction efficiency only by approximately 1%

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 is a function of the y-component of solar wind electric field, which also implicitly includes solar wind velocity since it is essentially proportional to $v_x b_z$; the third term is a function of fluctuations in the solar wind velocity which are highly correlated with the solar wind velocity. Thus the variation of the diffusion coefficient is highly correlated to variations in the solar wind velocity. D_0 has a total variability (maximum/minimum) of about 14 for 1995 and 1996 but an average variability (standard deviation/average) of only 53% while the electron flux has a total variability of a factor of 400 and an average variability of 113%. A variation in the diffusion coefficient can produce a larger variation in the electron flux because of competition between diffusion and loss. The velocity term, the $v_x b_z$ term, and the velocity fluctuation term in Eq. (3) have an average variability of 28%, 23%, and 14%, respectively. Because of the rapid variation of E_y its variability becomes relatively less important in day long averages. Nevertheless the dependence of the diffusion term on $v_x b_z$ implies that diffusion is 1.44 times stronger on the average when b_z is negative than when b_z is positive.

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

Our model not only reproduced the observations but also provides a physical explanation for some features of the correlation between the solar wind and the electron flux.

Time delay between solar wind velocity enhancements and the electron enhancements

The diffusion equation together with its loss term provides a natural delay between changes in the diffusion and changes in the electron flux at geosynchronous orbit, since it takes some time for the electrons to diffuse inward to geosynchronous orbit in response to changes in the solar wind input and also some time for such changes to decay. We find that the best average life time is approximately 2.7 days at geosynchronous orbit, although it is much smaller at greater radial distances.

The seeming lack of IMF effects on the electron enhancements

The seeming lack of any significant correlation between the southward component of the IMF and the MeV electron flux at geosynchronous orbit has been a mystery. It is well established that the southward component of the IMF controls much of the activity in the magnetosphere [27]. In general it is assumed and well supported by many studies that the energy input from the solar wind into the magnetosphere is stronger when the IMF has a southward component. Our study suggests a resolution to this enigma. We find that a better fit to the data occurs if diffusion is about 44% stronger when the IMF has a southward component, and yet adding the IMF term to our diffusion equation, which was originally based solely on the velocity of the solar wind, improves the prediction efficiency by only a small amount: about 10%. The explanation for this seeming contradiction is based on the observation that the southward component of the IMF fluctuates much more rapidly than the overall solar wind velocity (see Figure 2 as an example), and that diffusion, as already mentioned, 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 components and thus when averaged the b_z component of the IMF has very little variation.

Large variations in the electron flux vs. much smaller variations in the solar wind velocity

The MeV electron flux at geosynchronous orbit varies by two orders of magnitude whereas the solar wind velocity varies usually by at most a factor of three. Our diffusion formulation with loss provides a natural explanation for this seeming discrepancy. In our formulation we have a boundary condition at L=12.5, where we assume a fairly constant phase space density of electrons. While this is probably unrealistic it will turn out that most of the variation in the electron flux at geosynchronous 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. In our model increasing the diffusion rate by a factor of two increases the electron flux at geosynchronous orbit by about a factor of ten.

Conclusions

The MeV electron variations at geosynchronous orbit can be quantitatively predicted 1-2 days in advance given knowledge of the solar wind condition. Our model is based on radial diffusion where the diffusion coefficient is directly tied to solar wind parameters. The decoupled processes: solar wind dynamic pressure effect and D_{st} effect have been incorporated in the model and both effects improve the prediction efficiency.

The significance of the correlation that we have found between the solar wind and the MeV electrons becomes more evident when interpreted physically. Even without any such interpretation it is clear from the correlation that the solar wind controls most of the variation in the MeV electron flux and that this correlation can be used to predict the MeV electron flux at geosynchronous orbit. This is a significant result. Our working hypothesis is that solar wind fluctuations drive fluctuations in the magnetosphere, which in turn drive radial diffusion which lead to enhancements in the flux at geosynchronous orbit. Our model with this interpretation has allowed us to provide a physical explanation for many features of the correlation between the solar wind and the electron flux that were previously somewhat mysterious.

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References

[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 consisting of a set of solar-terrestrial missions to be carred out during the 1990s and into the next century. This program combines resources and scientific communities on an international scale using a complement of several missions, 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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[23] 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.

[24] In GSM coordinate system, the x-axis is pointing from the earth to the sun, the y-axis is defined to be perpendicular to the earth's magnetic dipole, so that the x-z plane contains the dipole axis. 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 adiabatic response of electrons to magnetic field changes. We implement this effect in a somewhat *ad hoc* way by adjusting f at all points,

$$f = f * exp[\frac{(Dst(t + \triangle t) - Dst(t))}{Dst_n}], \tag{5}$$

where Dst_n, equal to 85 for Figure 1, is a parameter. This equation basically makes f at a given position decrease as D_{st} decreases and increase as D_{st} increases. The D_{st} is also directly calculated from the solar wind parameters using 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 effects is implemented by adjusting f in the following way

$$f = f * exp(-(p/p_n)^{0.6})$$

where $p = Nv^2$ in unit of nPa. p_n, equal to 4.3 for Figure 1, is a parameter. The above equation basically says that the MeV flux should decrease when the solar wind dynamic pressure increases. We use daily averaged values at r=6.6R_E. Electrons with large pitch angles starting on the night side will drift further out on the dayside along the contour of constant magnetic field at their mirror points. An enhancement in the solar wind dynamic pressure will push the magnetopause inward and enhance the magnetic field on the dayside such that electrons may be lost by reach the magnetopause.

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