The Predictability of the Magnetosphere and Space Weather

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Yogi Berra once observed, apparently paraphrasing Niels Bohr: 'prediction is difficult, especially about the future.' Their backgrounds in baseball and quantum mechanics respectively probably prejudiced them since recent studies show that at least in geophysics not everything is as difficult to predict as the path of a knuckle ball or an electron through a double slit. Large-scale magnetospheric activity, we believe, is quite predictable given solar wind conditions. In Figure 1 we show the long-term variation of radiation belt electrons and the Dst index for approximately the last solar cycle. The long-term variation of radiation belt electrons and the Dst index provides evidence that radiation belt electrons and geomagnetic activity, on average, have a systematic response to the solar wind.

Radiation-belt electrons at geosynchronous orbit and the Dst index, which measures the disturbance level of the Earth's magnetosphere, are two important measures of large-scale magnetospheric activity that can be predicted well using only the solar wind as input. On a shorter time scale some examples of such predictions using only the solar wind as input are shown in Figures 2 and 3. Figure 2 shows a comparison of two years of the daily average of 0.7-1.8 MeV (million electron Volt) electron flux measured at geosynchronous orbit with a prediction while Figure 3 shows a comparison of the measured Dst index with a prediction. The accuracy of these predictions shows that global magnetospheric features are driven by the solar wind and are predictable in a rather deterministic sense. For such features, chaotic behavior within the magnetosphere has little influence on the global outcome.

Just how predictable is Earth's magnetosphere? With all the recent emphasis in the space physics community on 'space weather' [Baker, 2002], this has become an important practical question. The question is also fundamental to understanding the dynamics of the magnetosphere. For some years now there has been a mild controversy simmering between those who emphasize that the magnetosphere is mostly driven by the solar wind and thus its variability is due to the variability of the solar wind and those who emphasize that some of its variability is internally generated. The term 'space weather', though much broader than the magnetosphere (since it encompasses the solar wind and the Sun) appears to emphasize the internally-generated dynamics. The analogy commonly made is with our ordinary

tropospheric weather of rain, wind, heat, and cold. The variability of our day-to-day weather is not due to the variability of the Sun. The Sun is almost steady in those aspects that matter to the troposphere (highly variable UV and X-ray radiation does not affect the troposphere significantly) but the troposphere is nonetheless highly variable.

Here, we briefly review the history of our understanding of the Sun's influence on our space environment, discuss some magnetospheric responses to the solar wind, and show results that demonstrate our thesis that magnetospheric global features are driven by the solar wind and are predictable.

Understanding of Sun's Influence on Space Environment

That the Sun might influence Earth's magnetic field (the magnetosphere was not yet known) was first realized in 1859 when the largest magnetic storm ever recorded occurred 17 hours after a white light flare on the Sun [Carrington, 1859]. Amazingly, Tsurutani et al. [2002] have recently reanalyzed this storm and on the basis of a magnetometer in Coloba, India, have concluded that the Dst of this storm would have been -1760 nT (nanoTesla) or a negative deviation about three times bigger than any storm since 1957, the year the systematic official record of Dst begins. Dst is a measure of the average change in the magnetic field near the equator and is used as an index to determine the strength of magnetic storms. While there is no official boundary between different levels of magnetic storms, we usually consider that a moderate magnetic storm may have a Dst between -50 and -100 nT, while an extreme magnetic storm will have a Dst less than -300 nT. During magnetic storms, the equatorial magnetic field decreases due to currents flowing in the magnetosphere. Energetic charged particles in the dipole-like magnetic field of the Earth have a characteristic drift and thus a current, which produces a decrease in the magnetic field proportional to the total energy of the charged particles in the dipole-like magnetic field. The World Data Center at Kyoto University has compiled the Dst value every hour since year 1957. The largest magnetic storm in this record occurred on March 14, 1989 with a Dst of 'just' -589 nT (This particular geomagnetic storm caused a system-wide power failure in Quebec, Canada, resulting in the loss of over 20,000 megawatts of power production capacity. The blackout cut electric power to several million people for many hours). The largest magnetic storm of the current solar maximum occurred on March 31, 2001 with a Dst of -387 nT.

Dst is one of several indices used to summarize the state of the magnetosphere. Other common indices are AE and Kp, which are also based on ground magnetometers and measure the strength of ionospheric currents in the auroral and subauroral regions of the Earth, respectively. Other important features of the magnetosphere, such as the relativistic electron flux of the radiation belts, have no indices but are directly measured. Despite the coincidence in 1859 of a super magnetic storm occurring immediately after a super solar flare, it was not generally accepted, probably because of a lack of a known physical mechanism, that the Sun could directly influence the magnetic field of the Earth. Plasmas were not known, not even electrons and ions were known but it was known that the magnetic field of a dipole decreased as $1/r^3$ and so such a large magnetic field of the Sun could not extend through empty space to Earth as Lord Kelvin argued correctly.

A viable mechanism connecting activity on the Sun with magnetic storms on the Earth was not produced until late 1930's when it was realized [e.g., Chapman and Bartels, 1940] that if the Sun emitted charged particles in a solar flare (now we know it is the often-related CME's, coronal mass ejections, that are more important), those particles interacting with the magnetic field of the Earth would produce a current that would confine the magnetic field of the Earth and produce a magnetic disturbance on the ground. With the coming of the space era, it was discovered that charged particles from the Sun are emitted continuously, and that this solar wind carries with it its own magnetic field. It was noticed that magnetic storms were always preceded by disturbances in the solar wind. But since the density, velocity and magnetic field of the solar wind are all typically enhanced before a magnetic storm, it was not immediately clear which variables were the most important in controlling the magnitude of magnetic storms or in how much detail a magnetic storm was determined by the solar wind.

It was not until 1961 that James Dungey first proposed that the most important solar wind parameter influencing most aspects of the magnetosphere was the direction of the solar wind magnetic field, also called the interplanetary magnetic field or IMF. The direction of the IMF acts like a valve that controls energy input from the solar wind into the magnetosphere with the most favorable direction of the IMF being southward. This control is explained by the concept of magnetic reconnection under which the magnetic field of the IMF is connected well with the magnetic field of the Earth only when the IMF is not too far from the southward direction. The connection of the magnetic field of the Earth with the IMF allows solar wind

plasma and energy to enter, rather than to flow around, the magnetosphere. The solar wind energy is dominated by the kinetic energy of the solar wind flow. A faster and denser solar wind has more available energy and the magnetosphere will respond accordingly provided the valve is turned on.

Average Picture of Radiation Belt Electrons and the Dst Index

That the sun controls at least some aspects of the magnetosphere is clear from the solar cycle dependence of MeV electron fluxes in the magnetosphere. Figure 1 shows that MeV electron fluxes in the magnetosphere are weakest during sunspot minimum (1996-1997), more intense during the ascending phase and the maximum of the solar cycle (1997-1999), but, contrary to what one might expect, even more intense during the descending phase of the sunspot cycle (1993-1995) when recurrent high speed solar wind streams emanating from persistent trans-equatorial coronal holes become the characteristic feature of the solar wind. Energetic electrons are, on average, not as intense during sunspot maximum when the occurrence of coronal mass ejections (CME) is greatest. While fast CME's are very capable of producing magnetic storms and accelerating radiation belt electrons, CME's do not occur as often or last as long as the recurrent high speed solar wind streams of the descending phase of the solar cycle.

Even more apparent from Figure 1 are the seasonal variations. Radiation belt electron fluxes and geomagnetic activity, indicated by the larger negative magnitude of the Dst index, are most intense near the equinoxes, marked by the vertical bars along the horizontal axis, and least intense during the solstices. Also energetic electrons penetrate deeper into the magnetosphere near the equinoxes than they do near the solstices. The correlation of the inward extent of MeV electrons with the Dst index is remarkable, showing that electron enhancements are well correlated with magnetic storms. The seasonal dependence of the magnetic activity is due to the seasonally changing angle of the solar wind velocity and IMF with respect to the Earth's dipole. Thus, the seasonal dependence of magnetic activity can be thought of as another way that the varying solar wind (in the frame of the Earth's magnetic dipole) controls the magnetosphere.

Now we will discuss the control of the more rapid changes in the Dst index and of the radiation belt electrons at geosynchronous orbit by the intrinsic variations in the solar wind.

We will demonstrate this control by showing that the Dst index and radiation belt electrons can be predicted if the solar wind is known.

Prediction of the Dst Index

With the understanding of how the solar wind influences the magnetosphere, it became possible to make quantitative predictions of magnetic activity. However to compare predictions, we need a measure of the accuracy of the predictions. For a single temporally varying variable, a good measure of the relative accuracy of predictions is given by the 'prediction efficiency' which is defined as the fraction of the variance of that variable that is 'explained' by the prediction or as [1-(mean squared residual)/(variance of data)] where the residual is the difference between the data and the prediction.

Burton et al. [1975] was the first to show that the magnetosphere could be predicted well by actually making a good quantitative prediction of the Dst index using only the solar wind as input. The Burton method specifies the change in Dst due to a driver term and a decay term plus a correction term proportional to the ram pressure of the solar wind that represents the magnetopause currents. The driver term is a function of only the z-component (the north-south component) of the IMF and the solar wind velocity or equivalently the y-component of the electric field (since $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$ in the solar wind) and gives a negative contribution to the change in Dst if the solar wind E_y electric field exceeds 0.5 mV/m, equivalent to a z-component IMF of less than -1.0 nT for a solar wind velocity of 500 km/s. The decay term gives a constant decay rate of about 7 hours. Applied to the solar wind data during 1995-1999, the Burton formula with coefficients optimized for this period gives a prediction efficiency of 0.68. The main virtue of the Burton formulation is simplicity. It shows that magnetic storms are mostly determined by only one parameter (E_y) in the solar wind–a remarkable result. Still that left about 30% of the variance in the Dst index unexplained. What is it due to? Is it some unpredictable chaotic behavior of the magnetosphere? The simplicity of the Burton model suggests that a more complicated model should do better and this is indeed the case.

Others have improved the prediction by either modifying the driver and decay terms, or by using other methods such as neural networks or other innovative techniques and now several operational models are making real-time forecasts of the Dst index based on near real-time data from the ACE satellite, a spacecraft situated in a parking orbit near the L1 point,

about 240 Earth radii upstream of Earth (see references in http://lasp.colorado.edu/∼lix). We believe ours is the best of these models in terms of prediction efficiency [Temerin and Li, 2002]. An example of our model results applied to the first half of the year 2000 is shown in Figure 3. The prediction efficiency for this nearly half a year interval is 0.91. The model parameters were optimized based on data from 1995-1999. For this five-year interval the prediction efficiency was 0.87. The model is similar to the Burton model but more complicated. The main innovation is that instead of a single internal current system (ring current) with a single decay rate, there are three internal current systems (ring current, partial ring current, and magnetotail current) with different nonlinear decay rates. The decay terms have different time constants ranging approximately from five days to one hour. In addition the driver terms are more complicated functions of the solar wind and also depend on the angle of the Earth's dipole with respect to the solar wind velocity thus correctly modeling the seasonal dependence of magnetic activity. This model has been running in real-time using the real-time solar wind measurements from the ACE satellite. The forecast results are available on the web (http://lasp.colorado.edu/∼lix). It should be noted that a comparison of the real-time results of the model with the near real-time Dst is not yet very good. This is mostly a problem with data since the solar wind data are not always correctly calibrated in real time. We have run the model with the ACE science level 2 data the results are much better. These comparisons show the importance of accurate upstream solar wind measurements.

Prediction of MeV Electron at Geosynchronous Orbit

Another predictable feature of the magnetosphere is the outer electron radiation belt flux. Outer radiation belt electrons with energies of the order of a MeV, also known as 'killer electrons', can harm satellites through deep dielectric charging. More importantly astronauts can be exposed to excessive radiation, especially during space walks, when radiation belt levels are high.

It has been known since 1979 [Paulikas and Blake, 1979] that the MeV electron flux at geosynchronous orbit is well correlated with the solar wind velocity. This correlation was used by Baker et al. [1990] to develop a linear filter model to predict MeV electrons at geosynchronous orbit. The linear filter model was developed from limited intervals of continuous solar wind and MeV electron flux measurements. The linear prediction filter

method achieved a prediction efficiency [Baker et al., 1990] of 0.52 This model has been revised and is now making real-time forecasts of MeV electrons at geosynchronous orbit (http://www.sel.noaa.gov/refm/).

The availability of almost continuous solar wind data since the launch of the Wind satellite as part of the International Solar-Terrestrial Physics Program in late 1994 and of the ACE satellite in 1998 has enabled us to develop a radial diffusion model that is able to reproduce MeV electron flux variations at geostationary orbit even better. Figure 2 is an example, where a prediction efficiency of 0.81 and a linear correlation coefficient of 0.90 were achieved. This is also the best prediction efficiency ever achieved for radiation belt electrons for such a long period (2-year) under the same set of model parameters. The model is based on a radial diffusion equation with the diffusion coefficient determined by the solar wind velocity and IMF. The solar wind velocity has the most significant influence. The theory is that these solar wind variations perturb the magnetosphere and enhance the radial diffusion. This model [Li et al., 2001] has been updated and making real-time forecast of daily averaged >2 MeV electron fluxes at geosynchronous orbit. In this real-time forecast we predict the next two day's electron flux based on today's solar wind conditions and electron data. To do this, we extrapolate today's solar wind velocity into the future by assuming it will be the same. This is possible because the solar wind speed typically changes slowly and the electrons typically take one or two days to respond to changes in the solar wind velocity. Since it changes rapidly and cannot be extrapolated, the z-component of the IMF is simply taken as the average of the negative z-component (since positive z-components do not make a contribution in our model) or -2 nT. Such assumptions introduce some errors into our forecast results. On the other hand, we can make use of today's electron measurement to normalize our forecast for tomorrow and beyond, which is an advantage. The results are available on the web (http://lasp.colorado.edu/∼lix).

It should be noted that the prediction of MeV electrons described above are for daily averaged fluxes at geosynchronous orbit. Electron fluxes can vary on a much shorter time scale and variations of the electron fluxes inside geosynchronous orbit can be quite different and the physical mechanism driving the variations may be more complicated. Nonetheless, their variations are still strongly correlated with solar wind thus, we believe that their variations should be predictable given the solar wind.

Discussions of the Remaining Errors

While our models have high prediction efficiencies for both the Dst index, $\sim$0.9, and MeV electron fluxes at geosynchronous orbit, $\sim$0.8, there still exist unaccounted variances of about 9% for the Dst index and 20% for the electrons. The possible contributions to the unaccounted variances can be divided into four factors:

1) Inaccurate or inappropriate solar wind measurements. The solar wind measurements are made at distances upstream. It is known that such measurements do not correspond exactly to the solar wind as it strikes the magnetosphere. This is especially true for smaller scale features.

2) Inaccuracies in the measurements of the Dst index and the MeV electrons. The 'official Kyoto Dst' is derived from only four stations near but not at the magnetic equator. The secular variation and diurnal variations from the ionospheric currents are removed but this removal is not perfect and may also remove actual magnetospheric currents. The MeV electron measurements (shown in Figure 2) are also derived from four geosynchronous spacecraft spaced in longitude. The measurements may not be completely accurate. For example, the cosmic ray background was not removed. A strong solar proton event may introduce additional contamination.

3) Inaccuracies in our models. Our Dst model is far more complicated than some other models, (e.g., the Burton model) but it is far simpler than the magnetosphere. Some effects, such as the effect of solar cycle variations on the ionosphere are not included. Our electron prediction model makes predictions of daily averaged electron fluxes. However, it is known that the electron flux is higher on the dayside, usually peaking around local noon (except in cases when the day side magnetopause is compressed inside geosynchronous orbit) because of the solar wind compression of the Earth's magnetic field. So some compromises are made when the daily averaged fluxes are compared. To overcome this, we need to make prediction at different local times.

4) Inherent chaotic or complex behavior of the magnetosphere. On small scales the magnetosphere exhibits substantial turbulence as is evident from the beautiful motions of the aurora. The degree to which the magnetotail may exhibit turbulent behavior independent of the solar wind and thus influence the exact timing of substorms, recurrent smaller-scale enhancements in magnetic and auroral activity, is not yet known and highly controversial.

However, because of the accuracy of our models despite factors 1, 2, and 3 above, we believe there is very little room for 'chaotic or complex behavior of the magnetosphere' to play a major role in the large scale currents that affect the Dst index and the daily averaged MeV electrons at geosynchronous orbit.

Figure Caption

Figure 1. Upper panel shows yearly window-averaged sunspot numbers and weekly window-averaged solar wind velocity (km/s). The lower panel shows selected measurements of electrons of 2-6 MeV (#/cm^2-s-sr) by SAMPEX, the Solar, Anomalous, and Magnetospheric Particle Explorer, since its launch (July 3, 1992) into a low-altitude and highly inclined orbit. If Earth's magnetic field is approximated as a dipole, the L parameter describes a dipole field line that has a radial distance of L in units of Earth radii at the equator and intersects with the Earth's surface at a higher latitude. The Dst index for the same period is superimposed as a black curve on the lower panel. The electron and Dst index are 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.

Figure 2. A comparison of two years of daily averages of 0.7-1.8 MeV electron flux measured at geosynchronous orbit (averaged from four spacecraft spaced in longitude) with prediction, based solely on solar wind measurements.

Figure 3. A comparison of measured Dst index with prediction for the first half year of 2000 [Temerin and Li, 2002].

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