GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 9, PAGES 1371-1374, MAY 1, 2000

Lessons from the ring current injection during the September 24, 25, 1998 storm

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Abstract. Because the conditions in the solar wind that lead to the injection of energetic particles into the ring current simultaneously affect a variety of geomagnetic phenomena, it is often difficult to determine whether these magnetospheric processes are causally related or are simply contemporaneous. The sequence of interplanetary conditions leading up to the September 24-25, 1998 geomagnetic storm are particularly suited to illustrating what conditions lead to significant activity in the auroral zone as distinct from the injection into the ring current. This interval illustrates that the magnetosphere requires a period of strong, steady, not time-varying, convection for the buildup of the ring current, and that the AE index cannot be used to forecast the ring current buildup. Furthermore, when the ring current reached its peak strength, it contained 6 PJ and was dissipating energy at a rate of about 0.4 TW. The northern auroral regions and southern added another 1.2 TW of dissipation. This rate of dissipation could be maintained readily by the mechanical energy flux of the solar wind of about 40 TW but would require coupling to much of the incident solar-wind Poynting flux if that were the sole energy source.

Introduction

The existence of a magnetosphere and an embedded ring current was one of the earliest postulates to explain the geomagnetic storm [*Chapman and Ferraro*, 1930]. The basic tenets of this model have been confirmed by in situ observations of both the solar wind [e.g. *Burton et al.*, 1975] and the particle populations of the magnetosphere [*Hamilton et al., 1988*]. However, the conditions and the mechanisms that lead to the development of the ring current remain the subject of study. Some maintain that the same conditions that lead to auroral zone activity produce the ring current so that the AE index can be used to predict the Dst index [*Davis and Parthasarathy*, 1967; *Akasofu*, 1994]. Others maintain that a strong, steady, southward IMF is needed [*Russell et al.*, 1974] so that the AE index, that can be enhanced by a fluctuating, modest-amplitude, southward IMF, is not predictive of the Dst index. Examination of the Dst index at the onset of substorms, rather shows enhanced decay associated with the substorm, not enhanced injection [*Iyemori*, 1994]. Nevertheless there is still much belief in the storm as a sum of substorms [*Lui*, 2000].

Paper number 1999GL003718.
0094-8276/00/1999GL003718$05.00

Attempts have been made to predict ring current buildup with both quasi steady and intrinsically time varying models. The first formula that attempted to predict the Dst index from solar wind conditions [*Burton et al.*, 1975] filtered out rapid fluctuations in the IMF with periods less than 20 minutes because they were not effective in Dst injections. In contrast some modern paradigms of the ring current injection process invoke a recirculation of plasma through the plasma sheet [*Baker et al.*, 1996] that is then injected into the magnetosphere by a fluctuating convection pattern in the magnetosphere [*Chen et al.*, 1993].

In this paper we examine the solar wind conditions and magnetospheric response surrounding the geomagnetic storm of September 24-25, 1998 to illustrate what conditions lead to activity in the auroral zone, what conditions lead to the build up of the ring current, and what component of the solar wind is providing the energy for the storm.

Solar Wind and Magnetospheric Conditions

Some of the solar wind conditions and the magnetospheric response to these conditions have been reported by *Russell et al.* [1999] and *Moore et al.* [1999] who concentrated on the immediate response of the magnetosphere to the shock passage and the flows over the polar cap. Figure 1 shows the solar wind dynamic pressure, the By and Bz GSM components of the IMF, the dawn-dusk component of the interplanetary electric field, the AU and AL indices and the Dst index. The AU and AL indices are computed from the north-south component of the magnetic perturbations measured by 65 magnetometer stations located between 55 and 76 degrees magnetic latitude north and south. The Dst index is calculated from the standard 4 low-latitude stations. Also shown in the panel with the AU and AL indices is the AL index computed only in the local time sector from 21 to 01 hours MLT.

Figure 1 reveals three distinct types of solar wind conditions. Initially from 2000 UT to 2345 UT, the IMF is about 10 nT in the Y GSM direction with a generally weak southward component. The interplanetary dawn-dusk electric field is shown in the middle panel and averages about 3 mV/m during this period. The AU index is about 300 nT and the AL index about -700 nT corresponding to an AE index of about 1000 nT. The ring current was moderately disturbed averaging about -60 nT.

When the interplanetary shock arrives at 2345 UT, the dynamic pressure rises sharply from 3 to approximately 15 nPa and Dst jumps to a more positive value close to zero as the magnetosphere is compressed. The arrival of the shock marks what is classically known as the sudden storm commencement or SSC. The AE index shows some enhancement at this time but is

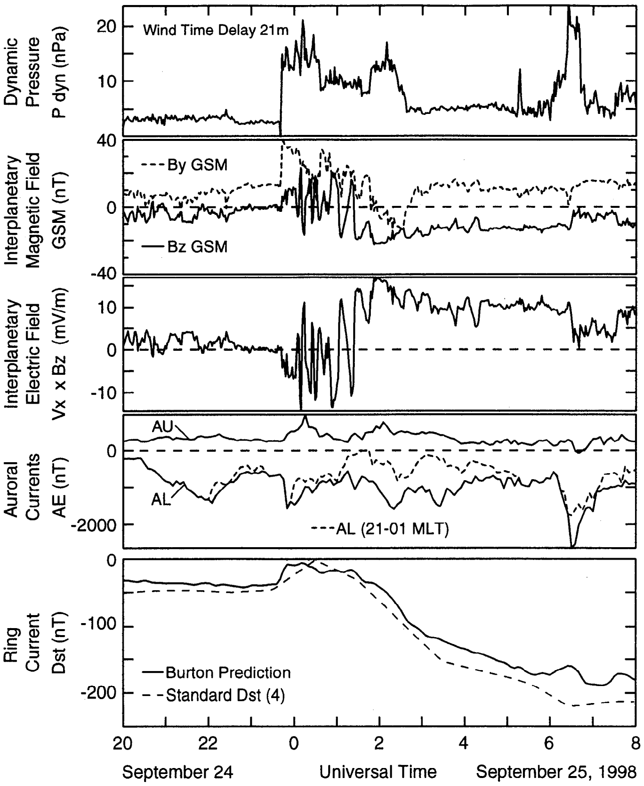

Figure 1. Solar wind input and magnetospheric response on September 24-25, 1999. (Top) Solar wind dynamic pressure measured by the WIND spacecraft with a 21 minute delay. (Second panel) The IMF By and Bz components in GSM coordinates as measured by WIND with a 21 minute delay. (Third panel) The electric field of the solar wind (Vx Bz) in the dawn-dusk direction calculated from the Wind measurements. (Fourth panel) AU and AL indices calculated from the AMIE stations. AE index is the distance between these two lines. The AL index for the sector from 2100 to 0100 MLT is also shown. (Bottom) The standard Dst index calculated from 4 low latitude stations with Burton et al. [1975] prediction for comparison.

no more disturbed than it was at 2200 UT for much more normal solar wind conditions. The magnetic field is greatly enhanced and oscillates north and south causing large dawn-dusk and dusk-dawn electric fields in the solar wind of over 10 mV/m, but there is no evidence for the development of the main phase injection until after 0100 UT when the oscillation period first lengthens and then ceases resulting in a steady dawn-dusk electric field (corresponding to a southward interplanetary magnetic field). During the build-up of the ring current there is no increase in the auroral zone currents as measured by AE. In fact during this time there was a decrease in AL measured at stations in the sector 2100 to 0100 MLT, where substorm onsets usually produce the largest currents in the auroral electrojets. This decrease indicates a cessation of the usual substorm activity during the buildup in the ring current. The nearly steady, strong IMF conditions from 0200 to 0600 UT produced a Dst index that reached a quasi-steady state value about -180 nT. The solid line in the bottom panel shows a strict application of the original formula of Burton et al. [1975] to this interval with all parameters smoothed over 20 min. There is a slight difference prior to the sudden impulse when the interplanetary magnetic field is nearly horizontal and the ring current injection is slightly slower than observed but the correct steady state level of activity is correctly predicted.

At about 0630 UT a 20 minute long "plug" of high density plasma caused a sudden increase in the dynamic pressure to values even higher than those that produced the SSC. The AE responds rapidly to this, but the Dst index becomes less negative rather than stronger. This change in Dst is caused by enhanced magnetopause currents in response to the enhanced dynamic pressure with no change in the ring current. When the plug of density passes, the Dst index returns to its earlier level, and the auroral electroject currents continue at roughly the values that they had maintained for the previous 12 hours.

AMIE Inversions

The measurements from the available ground based magnetometers have been inverted for this storm using the AMIE technique [*Richmond and Kamide*, 1988] to obtain not only Dst and AE as shown in Figure 1 but also the potential drop across the polar cap, the Joule dissipation and the auroral energy flux as shown in Figure 2. The Joule heating is sensitive to the interplanetary electric field (IEF) and when the IEF becomes strong at the beginning of the storm the Joule heating and auroral energy flux both increase. The potential drop across the polar cap also increases although the percent increase is smaller than that of the Joule heating. Most importantly in neither case is the increase linear with the IEF variation and the potential drop is particularly increasingly insensitive to the change in IEF during the main phase of the storm. This is in contrast to the ring current injection that is predicted by the same linear relationship to the IEF at quiet times, for weak storms, and powerful storms.

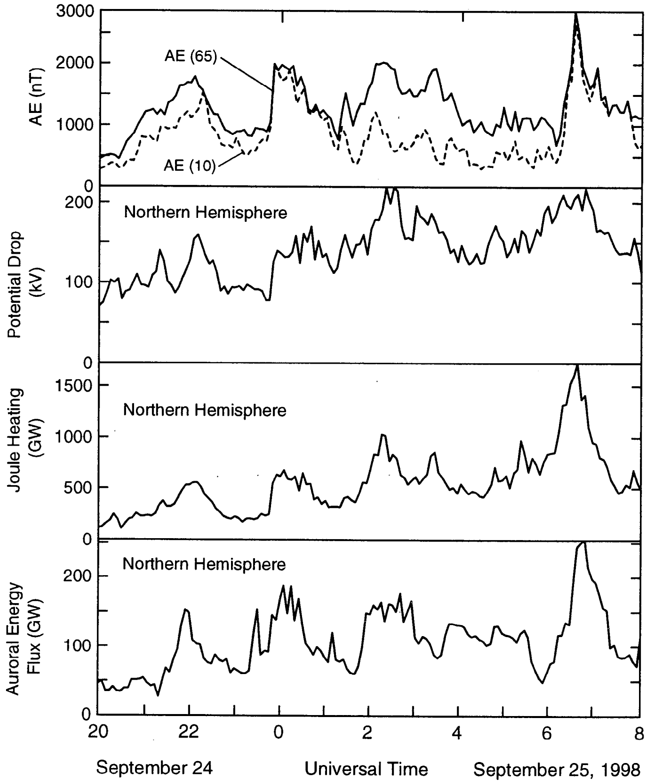

Figure 2. Output of the AMIE inversion of the ground based magnetic records for this storm. (Top) AE index for 65 auroral zone stations and the 10 standard stations. (Second panel) Potential drop across the polar cap in the northern hemisphere. (Third panel) Joule heating in the northern hemisphere. (Bottom) Auroral energy flux in the northern hemisphere.

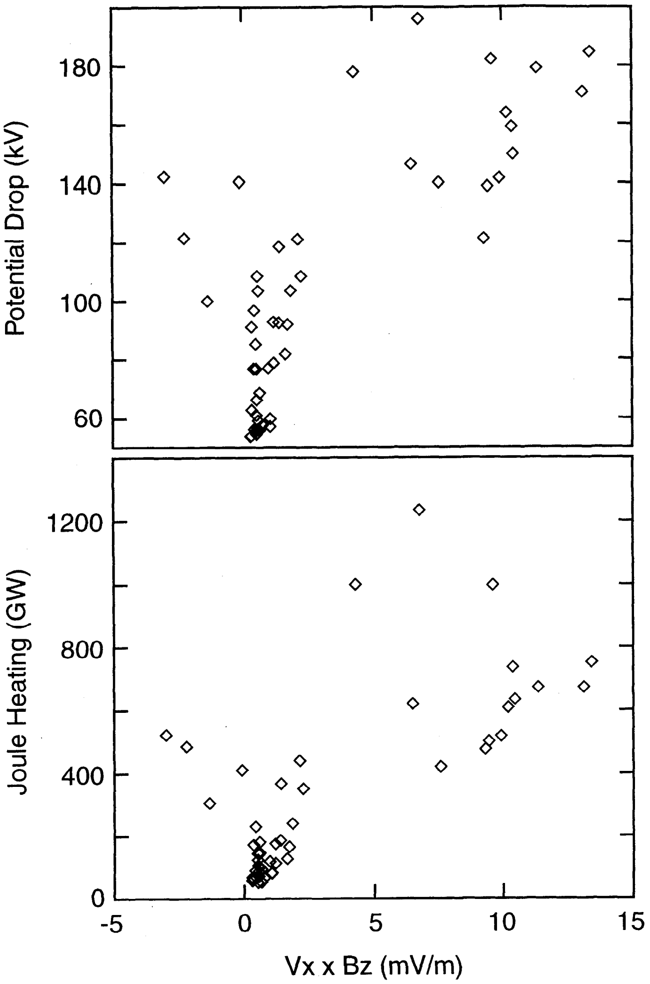

Figure 3. One hour averages of the polar-cap potential drop (top) and the Joule heating (bottom) versus the simultaneous interplanetary electric field obtained from 0800 UT on September 24 to 0800 UT on September 25, 1998 using the AMIE inversion.

The non-linearity of the response of the potential and the Joule heating is illustrated more clearly in Figure 3 that shows one hour averages plotted versus the IEF. There is much scatter due to the unsteady response of the magnetosphere to even steady input. There is also an apparent fly-wheel effect in which once a potential drop and Joule heating rate are established they are maintained for a while when the IEF drops to low values or goes negative (dusk to dawn). The fly-wheel effect causes the scatter on the left-hand side of the plot. In both upper and lower panels the polar cap responds rapidly to the IEF in the range 0 to 3 mV/m, reaching a potential drop and heating rate of about 120 kV and 500 GW at 3 mV/m. Then they increase only to about 180 kV and 700 GW at 10 mV/m and above with an occasional pulse of extra potential drop and Joule heating that appear to be temporal phenomena. It seems that above about 3 mV/m the response of the polar regions to the IEF undergoes a major change. In contrast at lower latitudes, the magnetospheric circulation pattern shows its expected sensitivity to the IEF on this day with erosion of the plasmasphere as low as L=2 [*Chi et al.*, 2000].

Discussion

The auroral electrojets are very sensitive indicators of the coupling of the solar wind with the magnetosphere. They are active when the north-south component of the IMF oscillates, producing transient southward fields; they are stimulated by steady southward IMF; and they become enhanced when the solar wind dynamic pressure is enhanced. The Dst index is also sensitive to several different solar wind inputs. Clearly, when the dynamic pressure is enhanced and the currents on the magnetopause increase, the Dst index becomes more positive. However, when the dynamic pressure drops, the Dst index immediately recovers to its previous value, indicating that only the magnetopause and not the ring current itself was affected. The Dst index is most sensitive to the strength of the ring current, whose time for build-up under steady-state conditions is much longer than other currents. Under the steady-state conditions operative early on September 25 the ring current took about 3 hours to reach its maximum strength. Other estimates based on the ring current decay time in the absence of input suggest even longer time scales [*Burton et al.*, 1975]. In either event the ring current is the slowest part of the magnetosphere to respond to solar wind input.

It is instructive to examine the energy flux convected to the Earth by the solar wind during this storm and compare it with the energy dissipated by the ring current, the auroral Joule dissipation and the particle precipitation. The mechanical energy flux intersecting a circular area whose radius is 15 R_E was 40 teraWatts during the steady state period from 0200 to 0400 UT. The Poynting flux $VB_s^2/2\mu_0$, that is the basis for the ε-function (*Perreault and Akasofu*, 1978), was 3 TW over the same cross-section. The steady state ring current, reached about 0400 UT, was about 200 nT or total energy of about 6 petaJoules. At this time the ring current dissipation and energization are in balance. If we take the decay time of Burton et al. of 7.7 hr., the ring current is dissipating at 0.2 teraWatts. If the decay rate were about twice this value, then the rate of dissipation would be doubled to 0.4 TW. Except when the high density pulse arrived at about 0630 UT, the Joule dissipation in each auroral zone was about 0.5 TW and the precipitation dissipation was about 0.1 TW in each hemisphere. Adding each of these sources we obtain a total dissipation of approximately 1.6 TW. This is about 4% of the available mechanical energy flux and over 50% of the Poynting flux incident on the entire dayside magnetospheric cross-section. The bow shock exists because the magnetosphere is an obstacle to the flow. Since it is found to be a permanent feature of the solar wind interaction, most of the solar wind incident on the magnetosphere must be deflected around it, and not reconnect with it. Thus, it is unlikely that the magnetosphere could tap into so large a fraction of the incident Poynting flux. We infer that the magnetosphere was powered instead by tapping into the mechanical energy flux through reconnection.

It is also evident from this example that the process that creates the ring current depends on steady-state solar-wind coupling, rather than on the presence of substorms or time-varying convective electric fields. Perhaps the depth to which convection reaches in the magnetosphere determines the asymptotic saturation limit of the ring-current intensity for a particular storm. The AE index showed very little difference during the periods that the ring current was weak, was undergoing strong injection, or was intense. Although both the electrojets and the ring current are sensitive to solar wind input, their response is so different to these inputs that it is not possible to predict one from the other. The AE index responds rapidly to changing IMF B_z but the ring current does not.

Finally, this interval shows that the polar cap potential drop appears to have a different relation to the interplanetary electric field for small and large potentials. This saturation is evident in previous case studies e.g. *Ahn et al.* [1992] and in statistical studies *Burke et al.* [1999]. It is not peculiar to this storm. Despite the large increase in the interplanetary electric field, the potential drop across the polar cap changed less than a factor of 2 and its temporal variation showed little correlation with the temporal variation of the IEF. Lest one attribute this saturation to the inability of the AMIE technique to sense large potential drops, we note that the same behavior can be seen in Figure 2 of the statistical study of *Burke et al.* [1999] who compare DE-2 measurements of the polar cap potential drop with the IEF. This potential drop is linear with the applied interplanetary electric field up to about 3 mV/m and very insensitive to it above this level. The IEF on September 25 during the storm main phase ranges from 10-15 mV, well into the saturation region.

One way to reduce the polar cap potential drop per unit of IEF is for the merging region on the nose of the magnetosphere to shrink for high values of the IEF. However, the ring current continues to build up during this storm as one would expect from a linear dependence of the magnetospheric circulation on the IEF. Moreover, the plasmasphere was depleted down to at least L=2 on this storm [*Chi et al.*, 2000]. This distance is close to the value expected for a 15 mV/m IEF if the efficiency of reconnection is of the order of 15-20%. We note that this efficiency has to be significantly greater than the efficiency by which the magnetosphere taps into the solar wind energy flux because a large fraction of the energization of the magnetotail is immediately returned to the "solar wind" through the anti-sunward acceleration of plasma. It appears that the low-altitude polar-cap ionosphere in which DE-2 is orbiting and to which AMIE is sensitive is not seeing the full potential drop in the high altitude magnetosphere.

Conclusions

The sudden storm commencement of September 24-25, 1998 is an ideal vehicle for demonstrating that the auroral electrojets and ring-current are only weakly correlated. While disturbed periods in the solar wind produce active electrojets and an energetic ring current, the types of solar-wind conditions that lead to substorm electrojet intensifications are not necessarily the same as those that lead to ring-current intensifications. The ring current can be produced by a strong, steady-state convection pattern and does not need time-varying convection to be produced. During the storm the polar-cap potential drop as measured by the AMIE inversion technique increases more slowly once the IEF increases above 3 mV/m in the dawn-dusk direction. We have ample evidence from the ring-current injection and the depletion of the plasmasphere down to low L values that the full expected electric field was applied to the magnetosphere. Thus the flows in the low-altitude polar-cap ionosphere at the peak of the storm appear to not be as responsive to the solar wind as the flows that are occurring in the magnetosphere at high altitudes. Finally, the mechanical kinetic energy flux provides a much larger power source for the magnetosphere than the solar-wind Poynting flux. To power this storm the majority of the Poynting flux incident on the magnetospheric cross-section would have had to have been used, whereas only 4% of the mechanical energy flux would have powered all the observed dissipation during the steady-state part of the main phase. While the energy that enters the tail as a result of reconnection does so as a Poynting flux, the interaction leaves the solar wind with a net reduced velocity over the region of interaction with the magnetosphere. It is the mechanical energy flux of the solar wind that is diminished and that is the principal source of the power for magnetic storms. Thus it is important to consider both the solar wind mechanical energy flux, as well as the Poynting flux, when studying space weather phenomena, especially storms.

Acknowledgments. We gratefully acknowledge K. W. Ogilvie who provided solar wind data from the Wind Spacecraft and R. P. Lepping who provided the IMF measurements from Wind. The work at UCLA was supported by the National Aeronautics and Space Administration under research grant NAG5-7721.

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(Received November 19, 1999; revised February 29, 2000; accepted March 2, 2000.)