GEOPHYSICAL RESEARCH LETTERS, VOL. 17, NO. 8, PAGES 1065-1068, JULY 1990

GEOMAGNETIC ACTIVITY FOR NORTHWARD INTERPLANETARY MAGNETIC FIELDS: AM INDEX RESPONSE

L. Scurry and C. T. Russell

Institute of Geophysics and Planetary Physics, University of California, Los Angeles

Abstract. The Am index is used to study the response of the magnetosphere to northward IMF. It is shown that most of the observed increase in activity can be explained by a correlation of the solar wind dynamic pressure with the IMF field strength such that the Am index varies only slightly with northward IMF strength when the solar wind dynamic pressure is held constant. There remains a smaller response of Am to solar wind velocity, which is usually attributed to a viscous interaction of the solar wind with the magnetosphere such as through the Kelvin-Helmholtz instability. The diurnal variation of Am during northward fields is also examined. A model invoking the Kelvin-Helmholtz instability on the flanks of the magnetopause have been used to predict the annual behavior of this diurnal variation. The predicted annual behavior is not found for northward IMF. The difference in diurnal variation from summer months to winter months, suggested to be caused solely by the Kelvin-Helmholtz instability, appears only for southward fields. Thus, while the Kelvin-Helmholtz instability may play some role in energy transfer into the magnetosphere and the resultant geomagnetic activity, this role is much less than that of dynamic pressure fluctuations and we find no evidence that it by itself plays any role in the annual variation of the diurnal variation of geomagnetic activity.

Introduction

When the interplanetary magnetic field (IMF) is directed southward, opposite to the Earth's equatorial magnetic field, the IMF becomes linked with the terrestrial field in a process that has become known as reconnection. The linkage of the IMF and terrestrial magnetic field leads to flux transport from the dayside to the tail. Eventually the stored energy in the tail is released in a substorm [Russell and McPherron, 1973]. Reconnection may occur between northward directed IMF and tail field lines but there is no transport of flux to the tail under these circumstances and no energization of the substorm process will take place as well.

The Kelvin-Helmholtz instability at the boundary between the solar wind and magnetosphere has been postulated as being another source of geomagnetic disturbance. The growth rate of the instability depends on the relative velocity of the two fluids and therefore depends on the solar wind velocity around the magnetosphere The instability grows with increasing solar wind velocity and should cause geomagnetic activity to increase as well. Apparently supporting evidence can be found in the dependence of geomagnetic activity on solar wind velocity and the dependence of the amplitude of magnetic pulsations [Crooker, 1977].

It has also been proposed that the relative orientation of the magnetic fields of the earth and the solar wind flow can have a destabilizing influence [Boller and Stolov, 1970]. The greatest instability would occur when the Earth's magnetic field and the magnetosheath magnetic field vectors are themselves parallel while both are perpendicular to the solar wind velocity. The relative polarity of the parallel fields has no effect and therefore maximum instability will occur when magnetosheath and magnetosphere magnetic fields are either parallel or anti-parallel. Because the growth rate of this instability depends on the angle between the fields and the solar wind velocity, geomagnetic activity should also be dependent on this angle. Boller and Stolov [1970] further proposed that the relative orientation of these fields and the flow at the dawn and dusk terminators was most effective in controlling this activity. The angle between the magnetospheric field and the flow, and hence the growth rate of the instability, depends both on the day of year and the time of day as the tilted magnetic dipole axis rotates around the Earth and as the Earth's rotation axis changes in orientation with respect to the direction to the sun in the course of the year. For a given solar wind velocity the instability growth rate during the summer solstice becomes a sinusoidal curve with a period of one day with a maximum at 0439 UT. During the winter solstice the minimum is at this time. It should be possible to see the effect on geomagnetic activity of this instability by subtracting the winter from the summer variation averaged over many years' data to remove any noncyclic effects. Boller and Stolov proposed that this mechanism explained the annual and diurnal variations of geomagnetic activity first described by McIntosh [1959].

Russell and McPherron [1973] postulated that the in-out component of the IMF translates into a north-south component in the earth's dipole frame and so the annual and diurnal variations of activity are due to changes in the amount of southward field and hence reconnected flux as the dipole rotates relative to the sun's dipole axis. Berthelier [1976] estimated the contribution of the mechanism proposed by Russell and McPherron and found that there remained some variation that was independent of the in-out component of the IMF. This remaining variation, dubbed the McIntosh affect, was attributed as evidence for Boller and Stolov's theory. Russell [1989] found no need to invoke additional cause for this variation. Further Russell showed the phase of

Paper number 90GL01810
0094-8276/90/90GL-01810$03.00

the summer minus winter diurnal variation to have a much greater delay than that expected for activity caused by Boller and Stolov's mechanism. This sparked further discussion of the magnitude of the McIntosh effect and the phase of this summer minus winter diurnal variation [Berthelier, 1990; Russell and Scurry, 1990].

It is possible to test these models by examining the variation of geomagnetic indices in response to changes in the IMF and solar wind velocity. The Am index [Mayaud, 1980] is useful in this regard because it covers the Earth fairly uniformly and appears to have little or no diurnal variation associated with the distribution of stations. The purpose of this paper is to perform such tests for northward IMF.

The Data Base

The database used consists of 3-hour averages of the interplanetary magnetic field, solar wind velocity, solar wind ion density, as well as the 3-hour Am index. The averages were made from one-hour data retrieved from the OMNI database at NSSDC and cover the years 1968 to 1987. Since effects of the northward field are to be studied, only times when the hourly average field has been northward for each of the three one-hour intervals have been used as to minimize the much greater southward field effects. When each of these hourly values were northward we averaged them to get a 3-hour value, B_n. We also kept track of the southward component for the other samples in a similar way. For each hourly data point B_s is set to the magnitude of B_z if it is southward or zero if B_z is northward. A 3-hour average, with a minimum three southward points, is then made for B_s. Although it is possible for an hourly average of B_z to be positive (northward) and still contain some southward field, by requiring that the average B_n be northward for three consecutive hours the southward field effects should be minimized. The total number of data points for northward IMF is 11965; southward 11632.

Dependence on North-South Field

Figure 1 shows Am as a function of $|B_z|$ for north and south fields in 1 nT intervals of B_z. Average values with their standard errors of the mean are plotted. A weak dependence of Am on northward field can be clearly seen. This could be interpreted as evidence that northward IMF reconnection, which should be proportional to field strength, does in fact cause some geomagnetic activity. However, it is possible that the effect on Am is not due to the magnitude of the field but rather some other mechanism that affects activity and is highly correlated with field magnitude. Fluctuations in the solar wind dynamic pressure also contribute to geomagnetic activity. It is reasonable to assume these fluctuations would increase as the solar wind dynamic pressure increases. We might expect that the IMF strength would correlate with the dynamic pressure because solar wind disturbances such as interplanetary shocks show an increase in both parameters. In Figure 2 we show how the Am index is affected by the solar wind dynamic pressure and how the northward field magnitude is correlated with dynamic pressure. We see that increased dynamic pressure does result in a larger Am and that a large northward field is associated with higher solar wind pressure. If we examine the dependence of Am on B_n for fixed dynamic pressure ranges, we see in Figure 3 that geomagnetic activity increases only slightly except in the range in which dynamic range is

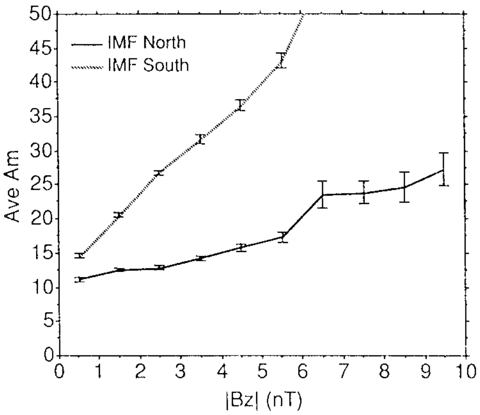

Fig. 1. Average values of the Am index with standard errors versus northward and southward B_z (GSM coordinates).

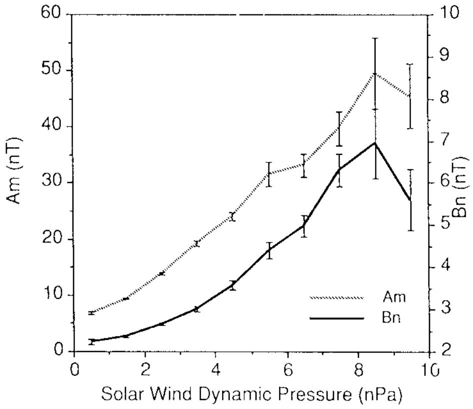

Fig. 2. Average values of the Am index and northward field versus the solar wind dynamic pressure.

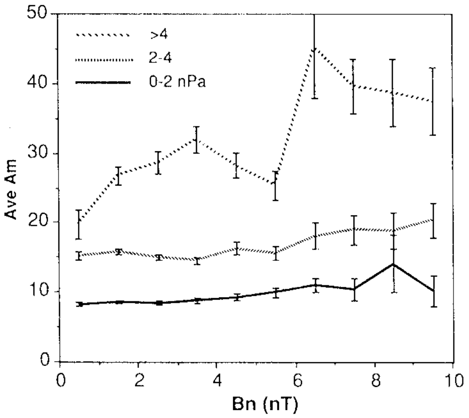

Fig. 3. Average values of Am with standard errors versus northward B_z for three ranges of solar wind dynamic pressure.

unbounded. Thus geomagnetic activity appears not to depend on the strength of the north-south component of the IMF when it is northward. This implies no significant flux transfer from the dayside to the nightside occurs when the IMF is northward.

Geomagnetic activity due to the Kelvin-Helmholtz instability, or other such viscous interactions, should increase as the solar wind velocity increases. If we examine the Am index for increasing velocity while holding the dynamic pressure constant we see in Figure 4 that Am does increase with velocity. When the dynamic pressure is larger Am is larger probably due to the greater effect of pressure fluctuations described above. There also appears to be a greater Am response to increasing velocity for the higher dynamic pressure ranges. Interestingly, if we extrapolate the curves linearly to zero Am index, the curves all intersect the abscissa near a solar wind velocity of 215 km/sec suggesting that below a solar wind velocity of 215 km/sec the Kelvin-Helmholtz instability is not active. We also note that for typical solar wind dynamic pressures of 2-4 nPa activity caused by high solar wind velocities (600 km/sec) is much smaller than that caused by reconnection of typical southward magnetic field amplitude (5 nT) as shown in Figure 1.

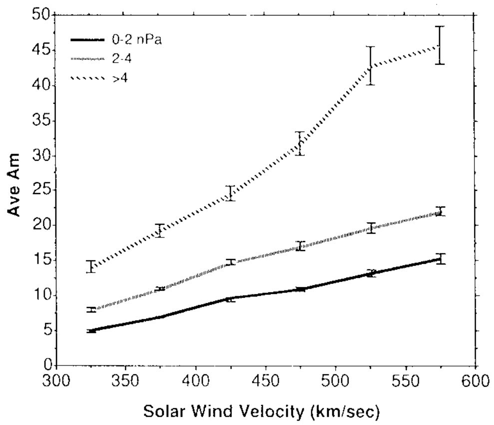

Fig. 4. Average values of Am versus solar wind velocity for three different ranges of solar wind dynamic pressure.

Diurnal Variation

As previously mentioned, the difference in the diurnal variation of the Am index in the summer and winter months has a form that has been claimed to be consistent with that expected if the flanks of the magnetopause are Kelvin-Helmholtz unstable [Boller and Stolov, 1970]. This summer minus winter variation, thought to be independent of the in-out component of the IMF and hence the Russell-McPherron mechanism, is shown for all values of B_z in Figure 5. This figure uses a database consisting of every available Am index from 1959 to 1987 regardless of IMF direction. The phase of this curve is 0524 UT ± 9 [Russell and Scurry, 1990]. We have shown previously that there is indeed evidence that the Kelvin-Helmholtz instability may play a role in energy transfer into the magnetosphere. It is interesting to determine whether the summer minus winter variation depends on the north-south polarity of the IMF. The variation due to the Kelvin-Helmholtz instability should be present for both northward and southward IMF. If it does depend on the polarity of the IMF, then this variation cannot simply be due to the Kelvin-Helmholtz instability.

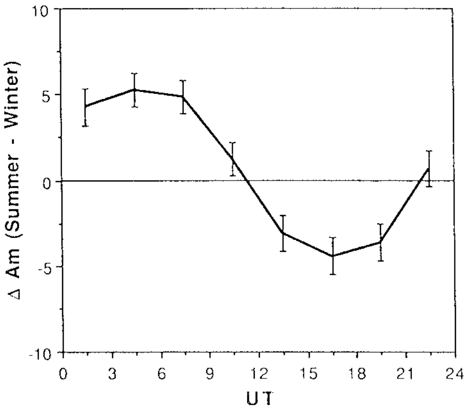

Fig. 5. Average Am (summer minus winter) with standard errors versus Universal Time for all values of B_z.

We measure this daily variation by taking the average Am values for each 3-hour interval of the day during the winter months December/January and subtracting these values from those found during the summer months June/July. Figure 6 shows the Am index versus Universal Time for northward IMF and 3 different magnitudes of southward IMF. For a southward field a diurnal variation is present and increases with southward field magnitude. When only a northward IMF is considered there is no significant variation. The variation that is remaining in this plot may either be due to just random fluctuations since its amplitude is smaller than the error bars or due to the imperfect separation into northward only fields in our hourly average data set.

Since the diurnal variation is sensitive to the southward component of the IMF and insignificant for northward fields, it must be associated with reconnection although apparently through a somewhat different mechanism than proposed by Russell and McPherron. Thus, although the Kelvin-Helmholtz instability may contribute in transferring energy to the magnetosphere while the IMF is northward, the daily variation of the magnetospheric field direction due to the tilt of the dipole does not appear to significantly affect this contribution. This may be because Boller and Stolov considered only the case where the instability produces a wave directed along the flow and is located at the equatorial region of the magnetopause. Although this case may be the most unstable, changes in the growth rates of waves in other directions and other locations in the magnetopause may offset any effects of instability in the equatorial plane. The appearance of a variation during a southward IMF may be due to an enhancement of the reconnection process by this instability [La Belle-Hamer et al., 1988].

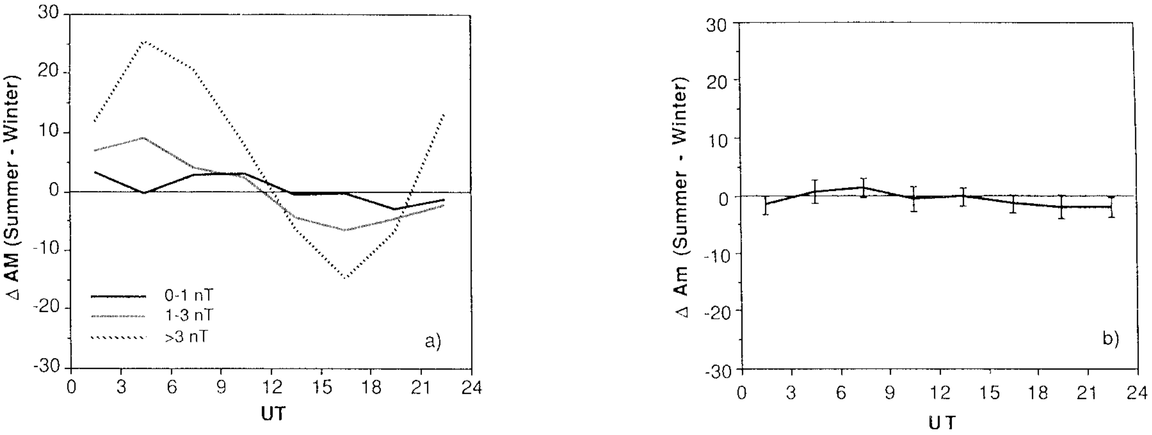

Fig. 6.a). Average values of Am (summer minus winter) versus Universal Time for three ranges of southward IMF and b) northward IMF for $B_z > 1$ nT.

A third mechanism has been proposed by Kivelson and Hughes [1990] in which the size of substorms is affected by dipole tilt. In this mechanism it is not the dayside reconnection rate that is affected by the dipole tilt but rather the release of the energy stored in the tail. In this model larger substorms occur when the tail is least bent. When the tail is strongly bent, or stressed, a larger number of smaller substorms is predicted. The phase of the diurnal variation shown in Figure 5 is found to be 0524 UT ± 9. This is 45 minutes later than the peak of the dipole tilt mechanism. This phase lag seems inconsistent with the current sheet bending hypothesis which should have near zero phase lag but it is consistent with time delays expected for tail storage of dayside reconnected flux [Bargatze et al., 1986]. Thus we favor Kelvin-Helmholtz enhanced dayside reconnection over the substorm size mechanism of Kivelson and Hughes.

Conclusions

The dependence of geomagnetic activity on the magnitude of northward IMF is found to be due to the correlation of field magnitude with the solar wind dynamic pressure. A correlation of geomagnetic activity with solar wind velocity indicates that the Kelvin-Helmholtz instability may make some contribution to the transfer of energy to the magnetosphere. However, the role of this instability in the summer-winter diurnal variation of geomagnetic activity is not confirmed when the IMF is northward. The diurnal variation is seen, however, when the IMF is southward and is found to depend on the magnitude of the southward component. Thus the Kelvin-Helmholtz instability and reconnection may act in concert in causing this variation.

Acknowledgments. This work was supported by the National Science Foundation under research grant NSF ATM88-00670.

References

Bargatze, L. F., D. N. Baker and R. L. McPherron, Magnetospheric response to solar wind variations, in Solar Wind-Magnetosphere Coupling, edited by Y. Kamide and J. A. Slavin, 93-100, Terra Scientific Publ. Co., Tokyo, 1986.

Berthelier, A., Influence of the polarity of the interplanetary magnetic field on the annual and diurnal variations of magnetic activity, J. Geophys. Res., 81, 4546-4552, 1976.

Berthelier, A., Comment on "The Universal Time variation of magnetic activity by C. T. Russell", Geophys. Res. Lett., 17(3), 307-308, 1990.

Boller, B. R. and H. L. Stolov, Kelvin-Helmholtz instability and the semiannual variation of geomagnetic activity, J. Geophys. Res., 75(31), 6073-6084, 1970.

Crooker, N. U., On the correlation between long-term averages of solar wind speed and geomagnetic activity, J. Geophys. Res., 82(13), 1933-1936, 1977.

Kivelson, M. G. and W. J. Hughes, On the threshold for triggering substorms, Planet. Space Sci., 38(2), 211-220, 1990.

LaBelle-Hamer, A. L., Z. F. Fu and L. C. Lee, A mechanism for patchy reconnection at the dayside magnetopause, Geophys. Res. Lett., 15, 152, 1988.

Mayaud, P. N., Derivation, Meaning and Use of Geomagnetic Indices, 154pp, American Geophysical Union.

McIntosh, D. H., On the annual variation of magnetic disturbance, Phil. Trans. Roy. Soc. London, Ser. A, 251, 525-552, 1959.

Russell, C. T. and R. L. McPherron, Semiannual variation of geomagnetic activity, J. Geophys. Res., 78(1), 92-108, 1973.

Russell, C. T., The Universal Time variation of geomagnetic activity, Geophys. Res. Lett., 6, 555-558, 1989.

Russell, C. T. and L. Scurry, Reply to Comment on "The Universal Time variation of magnetic activity by C. T. Russell", Geophys. Res. Lett., 17(3), 309-310, 1990.

L. Scurry and C. T. Russell, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024-1567

(Received: March 5, 1990;
revised: April 16, 1990;
accepted: May 11, 1990.)