JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. A6, PAGES 9541–9548, JUNE 1, 1991

PROXY STUDIES OF ENERGY TRANSFER TO THE MAGNETOSPHERE

L. Scurry and C. T. Russell

Institute of Geophysics and Planetary Physics

University of California, Los Angeles

Abstract. The transfer of energy into the magnetosphere is studied using as proxy the Am geomagnetic index and multilinear regressions and correlations with solar wind data. In particular, the response of Am to the reconnection mechanism is examined in relation to the orientation of the interplanetary magnetic field as well as the upstream plasma parameters. A functional dependence of Am on clock angle, the orientation of the IMF in the plane perpendicular to the flow, is derived after first correcting the index for nonreconnection effects due to dynamic pressure and velocity. An examination of the effect of upstream magnetosonic Mach number shows the reconnection mechanism to become less efficient at high Mach numbers. The reconnection mechanism is shown to be slightly enhanced by higher dynamic pressures.

Introduction

Long before in situ observations of magnetospheric phenomena were available, geomagnetic indices played an essential role in the study of the Earth's magnetosphere. The correlation of geomagnetic activity with solar phenomena, in fact, led to the postulate of the streams of solar plasma that we now call the solar wind [Chapman and Ferraro, 1930]. Early theories considered the Earth's magnetosphere to be either closed or open and connected to the solar wind. In these closed models, geomagnetic activity was caused by fluid interactions and instabilities of the solar wind flowing around the magnetospheric cavity [e.g., Axford and Hines, 1961]. These interactions along the flanks of the cavity provided a tangential stress or drag on the magnetosphere and caused a circulation of plasma within the magnetosphere.

In open models, geomagnetic activity was caused by the reconnection of the interplanetary and magnetospheric magnetic fields [e.g., Dungey, 1961]. This reconnection joined a southward interplanetary magnetic field with a previously closed magnetospheric field line, thus creating an open magnetic field line. This open line was then convected to the nightside magnetosphere where it reconnected with an oppositely directed line to become a closed field line once again. In this cycle, energy is first stored in the tail and then later released to produce substorms and other forms of geomagnetic activity.

Since the advent of satellite observations, many studies have been performed relating geomagnetic activity to conditions in the solar wind. Correlation studies between solar wind velocity and geomagnetic indices [Snyder et al., 1963] showed a positive correlation, as would be expected in the closed model of Axford and Hines. However, correlation studies also showed activity to be greater while the IMF was directed southward [Fairfield and Cahill, 1966; Rostoker and Falthammer, 1967]. Nonreconnection models could not readily explain this fact. Arnoldy [1971] found that the highest correlations of solar wind velocity and IMF magnitude with AE were attained when the index was delayed by one hour. This delay agrees with Dungey's hypothesis that flux is stored in the tail before its energy is released to produce geomagnetic signatures. Arnoldy [1971] and Burton et al. [1975] found that a half-wave rectifier function of the IMF, VB_s, best correlated with geomagnetic activity. In this model, geomagnetic activity is caused by the amount of southward interplanetary magnetic field carried to the magnetopause per unit time. A similar function was proposed by Perreault and Akasofu [1978] with two slight modifications. The energy input into the magnetosphere was proportional to the square of the interplanetary magnetic field strength carried to the magnetosphere per unit time, and the angular dependence of the IMF direction was chosen to be $\sin^4(\theta/2)$, where θ is the angle between the IMF and the z-GSM direction measured in the y-z plane. Several authors have attempted to provide a theoretical framework for this formula [e.g., Kan and Lee, 1979; Maezawa, 1979; Murayama, 1982]. In particular, dimensional analysis has been used to provide constraints on the functional form of the relationship, but no unique relationship can be found [Vasyliunas et al., 1982]. Empirical data are required to determine the functional form.

An increase in geomagnetic activity is generally taken as an indication of increased energy transfer (and consequent release) into the magnetosphere. Thus, the study of the influence of various solar wind parameters on geomagnetic activity has been used frequently as a proxy indicator of the factors controlling the energy transfer. These studies have been fraught with ambiguities for a variety of reasons. When multiple linear regression techniques are used, by definition one assumes that the correlation is linear. As noted above, the dependence on the north-south component of the IMF has been found to be quite nonlinear [e.g., Maezawa, 1979]. We will show another example of this nonlinearity below. Second, in these multiple regression studies the controlling factors should be independent variables. For example, when the magnetic field strength is large, one is more likely to encounter a strong southward magnetic field than when the IMF is small, since the angular distribution of IMF directions is independent of the field strength. Third, the controlling factors may not

Paper number 91JA00569.
0148-0227/91/91JA-00569$05.00

be additive but rather multiplicative; e.g., kVB_z might be the controlling factor rather than $aV + bB_z$, where a, b and k are constants to be determined. Finally, indices may respond to different factors in quite different ways. Response to solar wind dynamic pressure changes might be immediate while response to the connected southward IMF might be delayed by substorm growth times. Moreover, a similar change in the ground level field, and therefore the index, associated with two different processes might represent a quite different energy input into the magnetosphere. Thus any multiple linear regression study must be accompanied by some physical insight and caution.

In this paper we attempt to study the transfer of energy into the magnetosphere by examining the correlation of solar wind data and the Am index. Our aim is to determine those factors which control the energy transfer into the magnetosphere.

Database

The database used in the proxy studies consists of 3-hour averages of IMF plasma and field data combined with the Am geomagnetic index [Mayaud, 1980]. The Am index is similar to the Ap index in that it represents the worldwide 3-hour range in magnetic field about the quiet day value. The Am index is used because it provides a global measure of activity and has an improved distribution of stations over that used for the Ap index. The 3-hour IMF averages are derived from 1-hour averaged data covering over 25 years in the OMNI database at NSSDC. We will find it desirable to separate the data into times of northward and southward IMF. The direction of the IMF can fluctuate between north and south on time scales smaller than the 3-hour interval of the index. Therefore a 3-hour interval that averages to northward may still contain times of southward polarity. To minimize these effects we have required that, in order to be included in our analysis, all 3-hourly averages, taken from the OMNI database, within a given 3-hour interval be of one B_z-GSM polarity. This procedure reduces the size of our dataset but ensures a certain steadiness of the IMF. Nevertheless it does not completely eliminate short intervals of southward IMF in the northward dataset and vice versa.

Multiple Regression

The most straightforward means of examining how the different solar wind parameters affect the Am index is with a multiple linear regression assuming that the effects of different factors add. One can base the regression on the basic parameters measured by the satellite instruments such as the field components and the solar wind velocity and density, or these values can be combined to form more descriptive parameters. Using parameters such as dynamic pressure (solar wind momentum flux) and Mach number or other fluid quantities allows better comparisons to theory. For our linear regression studies we choose the following parameters: B_z(GSM), velocity, density, and dynamic pressure. For the multiple regression analysis we wish to include the minimum number of parameters needed to give a good overall correlation. Ideally we would like to choose an independent set of controlling factors, but clearly these parameters are correlated. Moreover, some parameters may affect geomagnetic activity in more than one way. For example, solar wind dynamic pressure has been found to contribute to geomagnetic activity when there is no dayside reconnection [Scurry and Russell, 1990] and apparently to modulate the rate of reconnection when the IMF is southward [Murayama, 1982; Gonzalez et al., 1989]. The second column in Table 1 lists the coefficients used in the overall equation to predict Am. The standard error column lists the estimated error for these coefficients which are used with the observed values of each parameter. By examining the standard coefficients listed in Table 1 we can determine which parameters affect Am the most. This standard coefficient is the regression coefficient for a given parameter adjusted according to the mean of that parameter. Using this standardized coefficient enables one to compare parameters with different scales. The t value measures how significantly different from zero is the coefficient. A larger t value indicates more confidence that the slope is not just a random fluctuation from zero. Similarly the quantity P(2 Tail) gives the probability that the effect of the parameter is due to random chance. In our tests, all correlations were significant to greater than 99.9% confidence or, equivalently, there was less than 0.1% chance that the correlation was random. This regression calculated with the complete dataset shows that the z component of the IMF and the dynamic pressure have the greatest effect on Am. This is indicated by the large standard coefficients of these parameters, -0.422 and 0.678, respectively. The negative value for the B_z coefficient implies that Am increases when B_z is increasingly negative. The B_z parameter has a larger t value than dynamic pressure even though its standard coefficient is smaller. This may indicate that the standardization of the coefficients may be skewed, since B_z can be both positive and negative and may have a nonlinear

TABLE 1. Multiple Linear Regression for all B_z

Variable	Coefficient	Std.Error	Std.Coef.	t	P(2 Tail)
Constant	-11.093	0.950	0.000	-11.677	<0.001
B_z	-2.787	0.033	-0.422	-84.185	<0.001
Velocity	0.045	0.002	0.190	21.637	<0.001
Density	-1.103	0.048	-0.289	-22.967	<0.001
ρV^2	9.049	0.161	0.678	56.341	<0.001

N - 17381, R - 0.751, R^2 - 0.564.

TABLE 2 . Multiple Linear Regression for B_z<0

Variable	Coefficient	Std.Error	Std.Coef.	t	P(2 Tail)
Constant	-33.430	1.333	0.000	-25.087	<0.001
B_z	-6.499	0.078	-0.519	-83.311	<0.001
Velocity	0.080	0.003	0.284	27.845	<0.001
Density	-1.142	0.066	-0.247	-17.347	<0.001
ρV^2	7.768	0.220	0.495	35.266	<0.001

N = 8544, R = 0.842, R^2 = 0.709.

effect on Am. The t values also show that the density and velocity parameters are effective predictors of Am.

A factor limiting the multilinear regression approach is that the relations may simply not be linear. The correlation with velocity is one example. Is the correlation linear with V or is it actually a correlation with the dynamic pressure ρV^2, which is clearly correlated with V, but nonlinearly. A somewhat different example of this is the z component of the IMF. If you consider only negative values, the relation between Am and B_z appears linear. When only positive B_z values are considered, the relation may still be linear but the slope is completely different. Thus a regression with just B_z will not fit as well to all the data as it would if separated into north and south. Table 2 shows the data obtained by a multiple regression with only the southward data used. Here 70.9% of the variance in Am is accounted for. This is greater than the previous all B_z regression. The standard coefficients reveal that, once again, the B_z and dynamic pressure parameters produce the greatest response in Am. The standard coefficients are -0.519 and 0.495, respectively. These two parameters also have the largest t values. The results of a regression with only northward data are in Table 3. Here we predict only 45.6% of the variance. B_z no longer has a great effect (std. coef. = -0.110), but rather dynamic pressure and velocity are the dominant parameters affecting Am (std. coef. = 0.611 and 0.277 respectively). These last two regressions illustrate the idea that not all parameters have a linear response. Thus it is important to try to single out the effects of a given parameter in order to understand how that parameter affects the processes that control Am.

As previously mentioned, intercorrelations of parameters can affect the results or the interpretation of the results of these regressions. The solar wind velocity and dynamic pressure correlation stated above is only one example. Other intercorrelations can affect the interpreted results as well. In Table 4 we show the correlation constants between each pair of variables in the regression. We include here some parameters that will be examined in more detail in the following section. It can be seen that there are significant correlations between variables. Velocity and density are anticorrelated, which has evidently reduced the correlation between dynamic pressure and velocity mentioned before. One way around this problem is to identify the principal factors, remove their effects, and then look at the factors which control the residuals.

IMF Clock Angle Effect

The correlation study above, as well as many previous studies indicate that the north-south component of the IMF as measured in solar magnetic coordinates is a significant factor in controlling geomagnetic activity, presumably through reconnection. However, a smaller correlation also present with B_y indicates that the relationship may not just be the simple half-wave rectifier model in which the amount of southward B_z carried to the magnetosphere by the solar wind per unit time is the important factor. Rather, we try to determine herein the function of clock angle (measured in the y-z plane) which best orders the Am index. The amount of flux available for reconnection is taken to be the solar wind velocity multiplied by the field magnitude perpendicular to the flow, VB_{Tan}. The efficiency of this flux in exciting the Am index as a function of clock angle will then be determined as a proxy measure of the reconnection clock angle dependence. To obtain the clock angle function the "reconnection efficiency" is calculated using the slope of Am versus VB_{Tan} through a linear regression for each clock angle bin.

Figure 1 examines how the reconnection efficiency changes with IMF clock angle, where the clock angle θ is given by $\mathrm{Tan}(\theta) = B_y/B_z$. The efficiency is greatest when the IMF is due south

TABLE 3. Multiple Linear Regression for B_z>0

Variable	Coefficient	Std.Error	Std. Coef.	t	P(2 Tail)
Constant	-14.718	0.993	0.000	-14.825	<0.001
B_z	0.755	0.059	0.110	2.879	<0.001
Velocity	0.043	0.002	0.277	19.766	<0.001
Density	-0.572	0.050	-0.236	-11.528	<0.001
ρV^2	5.323	0.174	0.611	30.647	<0.001

N = 8837, R = 0.675, R^2 = 0.456.

TABLE 4. Correlation Matrix

	B_y	B_z	Velocity	Density	ρV^2	Beta	M_{MS}	VB_{Tan}
B_y	1.000							
B_z	0.016	1.000						
Velocity	-0.026	0.013	1.000					
Density	0.014	0.019	-0.404	1.000				
ρV^2	0.002	0.034	0.200	0.738	1.000			
Beta	0.005	0.004	-0.223	0.363	0.173	1.000		
M_{MS}	-0.004	0.004	0.253	0.164	0.292	0.477	1.000	
VB_{Tan}	0.003	0.017	0.274	0.093	0.362	-0.331	-0.482	1.000

and then falls off to some constant value when the IMF is northward. For reference, the clock angle dependence $\sin^4(\theta/2)$ is included. This graph indicates that even while the IMF is northward the reconnection mechanism remains effective. The northward efficiency, almost half the peak value, is larger than one would expect from the reconnection of northward field lines. Reconnection of northward IMF lines is thought to occur with open magnetospheric lines. This process will not energize the tail as with the case of closed field lines. The clock angle curve also remains flat for angles below 80°. This constancy suggests that this implied "reconnection efficiency" is caused by a factor independent of clock angle but correlated with the IMF magnitude.

In our previous studies [Scurry and Russell, 1990] we examined several of these other mechanisms. We found that a correlation of the Am index with the northward field magnitude was in fact due to an intercorrelation of B_n with the solar wind dynamic pressure. Thus it was the dynamic pressure of the solar wind which produced most of the activity and not the northward directed IMF. This intercorrelation would produce an apparent positive "reconnection efficiency" since Am will increase with field magnitude. The results in Figure 1 will therefore be contaminated by this effect. We can account for this effect by creating an adjusted Am index. In Figure 2 we plot the relation between the Am index and solar wind dynamic pressure during times of northward IMF. A functional dependence of dynamic pressure on Am, also shown in the figure, was calculated by a least squares fit weighted by the probable error of the mean. Using this derived function, the effect of dynamic pressure can be subtracted from the Am index to produce an adjusted index. In Figure 3 we plot the "efficiency of reconnection" once again but now with the Am index adjusted for dynamic pressure. The efficiency during the northward clock angle is reduced as is the southward efficiency, since this dynamic pressure effect is independent of clock angle. Although the northward efficiency is reduced, there still appears a small positive value. This residual implies that there is yet another factor independent of clock angle that is correlated with VB_z that should be removed before finding the clock angle function.

Previous studies also indicate that the solar wind velocity is effective in energizing the magnetosphere by means other than through dynamic pressure fluctuations. Higher solar wind

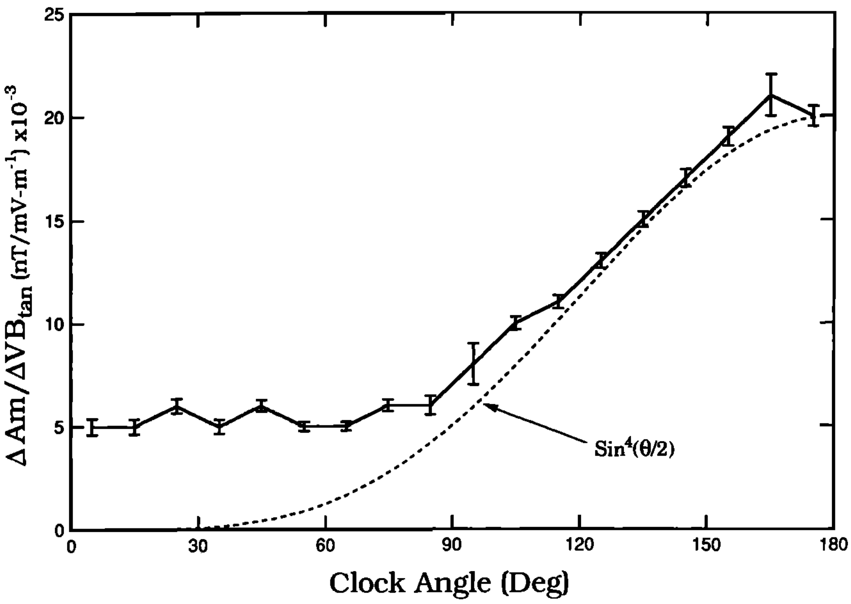

Fig. 1. Reconnection efficiency as a function of clock angle = $\tan^{-1}(B_y/B_z)$. The function $\sin^4(\theta/2)$ is plotted for reference.

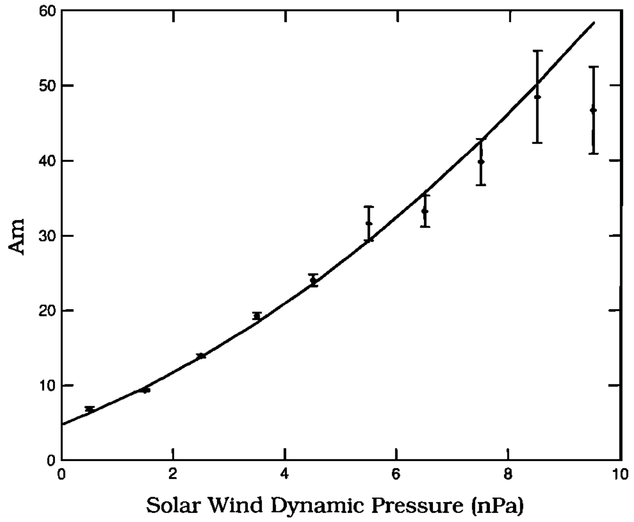

Fig. 2. The average Am index (dots) for each 1-nPa bin of solar wind dynamic pressure. The solid line is the functional form determined by a quadratic fit weighted by the error.

velocities are expected to increase the growth rates of instabilities, such as the Kelvin-Helmholtz, along the magnetospheric flanks. Using the Am index adjusted for dynamic pressure, we see in Figure 4 that the increasing solar wind velocities do produce higher levels of geomagnetic activity. Again this velocity effect can be accounted for in a similar manner as the dynamic pressure. Figure 4 shows the function used in the correction. This function is derived from a linear fit weighted by the probable error of the mean. After correcting the index for this mechanism, we can once again examine the clock angle relation (Figure 5). Now there is no evidence of reconnection being effective while the IMF is directed northward. However, there is a small but significant reconnection efficiency when the IMF is horizontal and slightly northward. The observed clock angle function is seen to be similar to but slightly below the $\sin^4(\theta/2)$ curve. This agreement may well be fortuitous. Some of the finite "reconnection efficiency" for slightly northward fields may be due to the influence of short intervals with negative B_z during hours of overall northward IMF. The use of higher-resolution solar wind data will be necessary to determine the significance of reconnection at zero clock angles.

Effects of Solar Wind Plasma Parameters

The IMF direction should not be the only mechanism affecting the rate of reconnection. Since reconnection is thought to involve the breakdown of frozen in magnetic flux in ideal MHD due to an increase in "resistivity", other plasma parameters could have some effect. Plasma beta is one obvious parameter since it measures the relative pressure of the plasma and the magnetic field. Moreover, the strength of accelerated flows at the magnetopause has been found to correlate with beta [Paschmann et al., 1986]. Two parameters which are thought to control the magnetosheath beta are the beta in the solar wind and solar wind Mach number. In Figure 6 the rate of reconnection is examined for three different values of solar beta and three values of Alfven Mach number. Alfven Mach number was assumed to be one of the nondimensional parameters that could govern the rate of reconnection [Vasyliunas et al., 1982]. These parameters appear to have little effect on the rate of reconnection. Figure 7 examines the efficiency of reconnection for different values of solar wind magnetosonic Mach number. Here the efficiency is constant until a value of about $M_{MS} \approx 7$, where it suddenly decreases. This indicates that reconnection may become less important for high Mach numbers. This has little practical importance for the Earth under typical

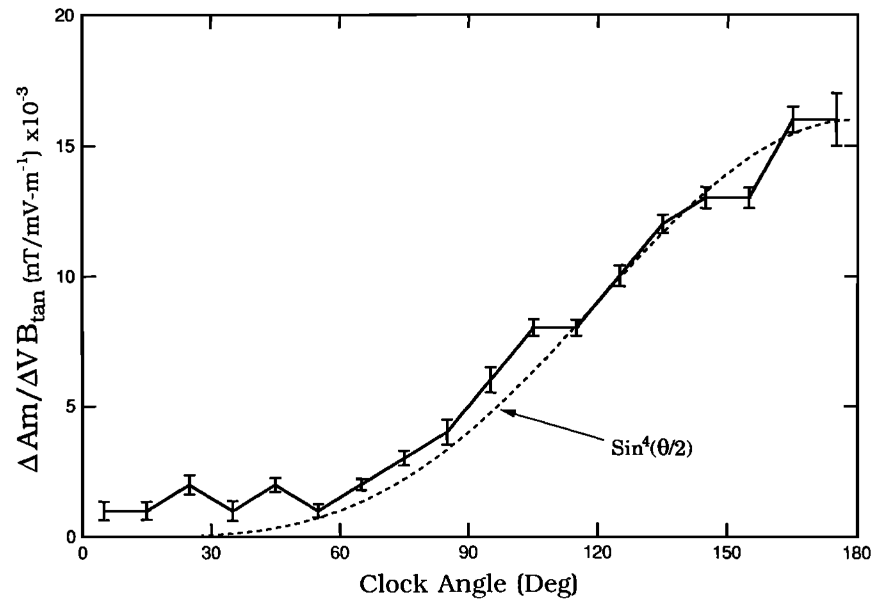

Fig. 3. The reconnection efficiency as a function of clock angle using the Am index adjusted for dynamic pressure effects.

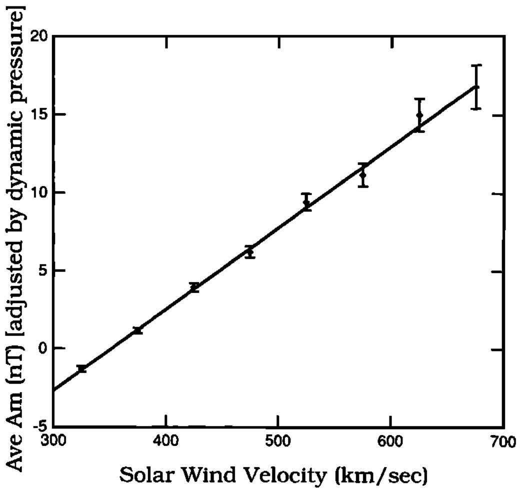

Fig. 4. The average value of the Am index adjusted for dynamic pressure effects for 50 km/s bins of solar wind velocity. The solid line is the functional form determined by a linear fit weighted by the error.

solar wind conditions, but could influence the reaction of the magnetosphere to extremely fast solar wind streams as well as the interaction of the magnetospheres of the outer planets with the solar wind where the Mach number is much higher than at 1 AU. We suggest that the reason for the apparent weakness of reconnection for high magnetosonic Mach numbers lies in the weakness of the magnetosheath magnetic field under such conditions.

Cone Angle and Dynamic Pressure Effects on Reconnection

Upstream waves, arising when the interplanetary magnetic field is nearly aligned with the solar wind flow, have been thought to cause pressure fluctuations. Fluctuations in pressure occur when these upstream waves are blown back against the magnetopause. The alignment of the magnetic field with the flow is measured by the cone angle, the angle between the IMF and solar directions. One might expect that the pressure fluctuations would increase reconnection or cause a disturbed magnetosphere for small cone angles. Figure 8 shows the effect of cone angle on the efficiency of reconnection for three separate ranges of clock angle. A slight increase in efficiency is seen for the southward clock angle case (150° - 180°). However, a horizontal line can be drawn through most of the error bars in this curve, and therefore the slope may not be significant. As evident in the previous clock angle figures, at clock angles close to 90° the efficiency is small such that any dependence on cone angle may not be detectable.

The functional dependence of Am on dynamic pressure described in the previous section was derived from the northward data only in order to remove all reconnection effects from our study. To test the hypothesis put forth in the cone angle study that dynamic pressure could affect reconnection, we plot in Figure 9 the reconnection efficiency for increasing dynamic pressure. The figure shows the reconnection efficiency to increase with increasing dynamic pressure. This increase is perhaps due to the increased pressure leading to greater pressure gradients in the magnetosheath and magnetospheric plasmas and stronger currents. These in turn might be expected to be more unstable, leading to greater resistivity and reconnection.

Several previous studies have included dynamic pressure in their solar wind coupling functions [Murayama, 1982; Vasyliunas et al., 1982]. However, in these models, dynamic pressure was a multiplicative factor such that energy transfer (reconnection) approached zero as dynamic pressure approached zero. Figure 9 clearly shows finite reconnection at low dynamic pressures.

Conclusion

Correlations of the Am index with the solar wind parameters have revealed a significant

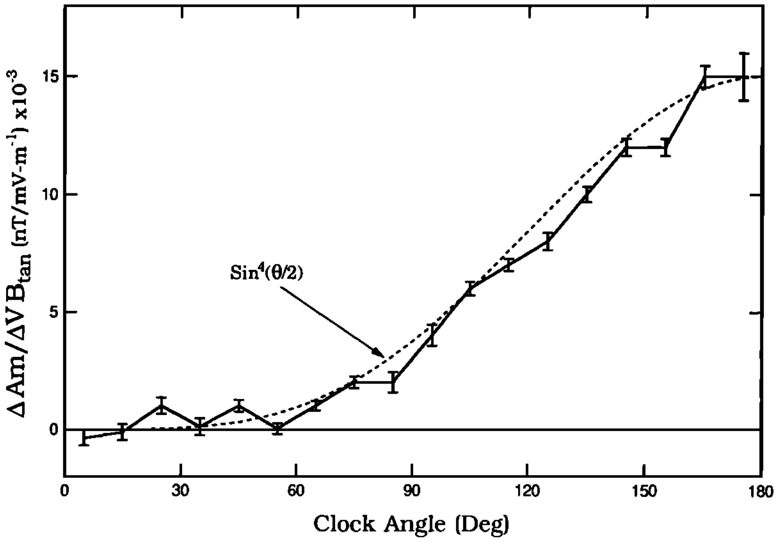

Fig. 5. The reconnection efficiency as a function of clock angle using the Am index which has been adjusted for effects due to both dynamic pressure and velocity.

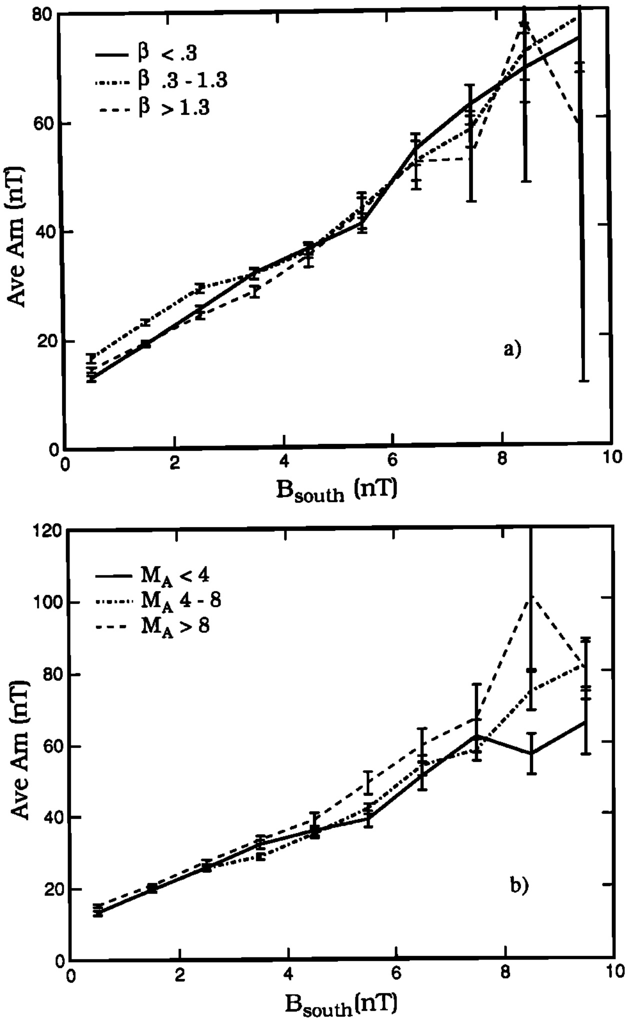

Fig. 6. (a) The average value of Am for 1-nT bins of the southward IMF (GSM) for three ranges of solar wind beta. (b) The average value of Am for 1 nT bins of the southward IMF for three ranges of solar wind Alfven Mach number.

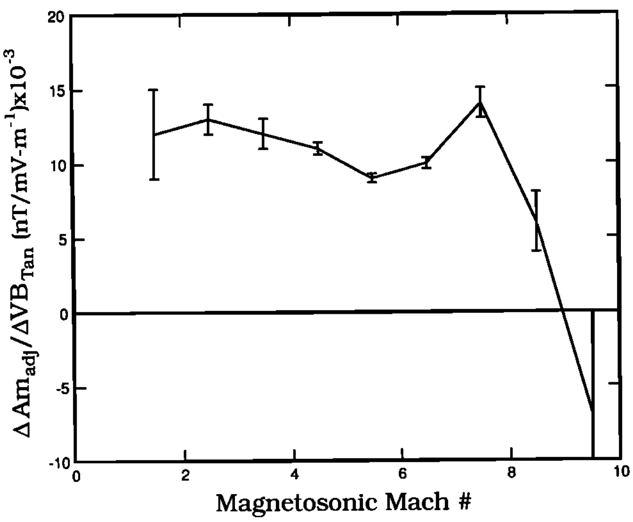

Fig. 7. The reconnection efficiency for one-unit-wide bins of magnetosonic Mach number using the Am index adjusted for the effects of dynamic pressure and velocity.

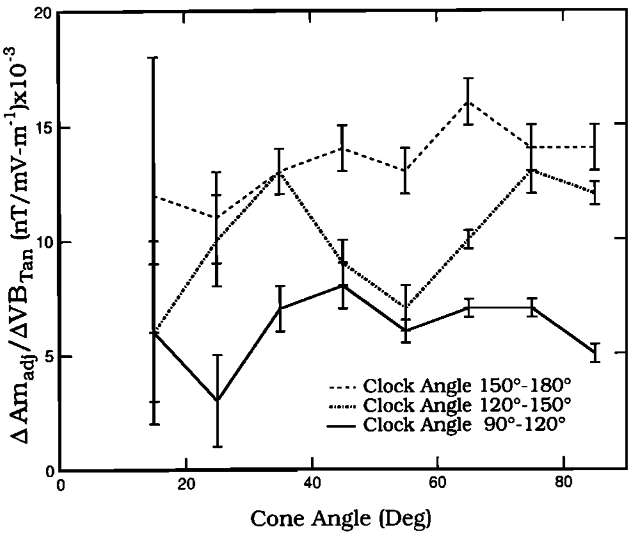

Fig. 8. Reconnection efficiency as a function of cone angle for three separate ranges of IMF clock angle.

dependence of geomagnetic activity on the solar wind dynamic pressure when the IMF is northward, when no reconnection is thought to be occurring. It may also affect geomagnetic activity by slightly enhancing the reconnection mechanism. The efficiency of reconnection as measured by the 3-hour Am index has a functional dependence on clock angle similar to $\sin^4(\theta/2)$, although the instantaneous functional dependence may be closer to a pure half wave rectifier. Even under steady horizontal IMF conditions, the fluctuations of the magnetosheath will cause periods of southward IMF. The reconnection efficiency decreases when the magnetosonic Mach number is larger than 7, possibly due to a dependence of the plasma beta in the sheath on the upstream Mach number. There seems to be little dependence of reconnection efficiency on cone angle.

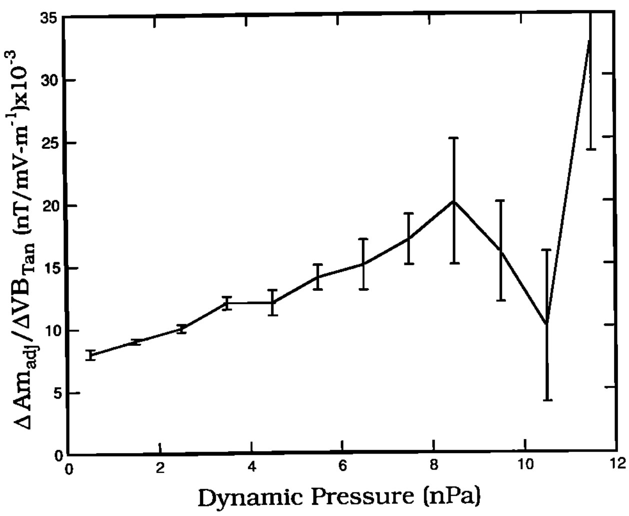

Fig. 9. The reconnection efficiency for 1-nPa bins of solar wind dynamic pressure using the Am index adjusted for nonreconnection dynamic pressure and velocity effects. The magnetosonic Mach number is restricted to below 7.

Acknowledgments. We are grateful to J. G. Luhmann for several useful suggestions in the course of this research. This work was supported by the National Science Foundation under research grant NSF ATM88-00670.

The Editor thanks B. Tsurutani and another referees for their assistance in evaluating this paper.

References

Arnoldy, R. L., Signature in the interplanetary medium for substorms, J. Geophys. Res., 76, 5189, 1971.

Axford, W. I., and C. O. Hines, A unifying theory of high-latitude geophysical phenomena and geomagnetic storms, Can. J. Phys., 39, 1433-1464, 1961.

Burton, R. K., R. L. McPherron, and C. T. Russell, An empirical relationship between interplanetary conditions and Dst, J. Geophys. Res., 80, 4204, 1975.

Chapman, S., and V. C. A. Ferraro, A new theory of magnetic storms, Nature, 126, 129, 1930.

Dungey, J. W., Interplanetary magnetic field and the auroral zone, Phys. Rev. Lett., 6, 47-48, 1961.

Fairfield, D. H., and L. J. Cahill, Jr., Transition region magnetic field and polar magnetic disturbances, J. Geophys. Res., 71, 155, 1966.

Gonzalez, W. D., B. T. Tsurutani, A. L. C. Gonzalez, E. J. Smith, F. Tang, and S. I. Akasofu, Solar wind-magnetosphere coupling during intense substorms (1978-1979), J. Geophys. Res., 94, 8835-8851, 1989.

Kan, J. R., and L. C. Lee, Energy coupling function and solar wind dynamo, Geophys. Res. Lett., 6, 577-560, 1979.

Maezawa, K., Statistical study of the dependence of geomagnetic activity on solar wind parameters, in Quantitative Modeling of Magnetospheric Processes, Geophys. Monogr. Ser., vol. 21, edited by W. P. Olson, pp. 436-447, AGU, Washington, DC, 1979.

Mayaud, P. N., Derivation, Meaning and use of Geomagnetic Indices, Geophys. Monogr. Ser., vol. 22, 154pp, AGU, Washington, DC, 1980.

Murayama, T., Coupling function between solar wind parameters and geomaagnetic indices, Rev. Geophys., 20, 623-629, 1982.

Paschmann, G., I. Papamastorakis, W. Baumjohann, N. Sckopke, C. W. Carlson, B. U. O. Sonnerup, and H. Luhr, The magnetopause for large magnetic shear: AMPTE/IRM observations, J. Geophys. Res., 91, 11,099-11,115, 1986

Perreault, P., and S.-I. Akasofu, A study of geomagnetic storms, Geophys. J. R. Astron. Soc., 54, 547, 1978.

Rostoker, G., and C.-G. Falthammar, Relationship between changes in the interplanetary magnetic field and variations in the magnetic field at the earth's surface, J. Geophys. Res., 72, 5853, 1967.

Scurry, L., and C. T. Russell, Geomagnetic activity for northward interplanetary magnetic fields: Am index response, Geophys. Res. Lett., 17(8), 1065-1068, 1990.

Snyder, C. W., M. Neugebauer, and U. R. Rao, The solar wind velocity and its correlation with cosmic-ray variations and with solar and geomagnetic activity, J. Geophys. Res., 68, 6381, 1963.

Vasyliunas, V. M., J. R. Kan, G. L. Siscoe, and S.-I. Akasofu, Scaling relations governing magnetospheric energy transfer, Planet. Space Sci., 30, 359-365, 1982.

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

(Received November 26, 1990;
revised February 7, 1991;
accepted February 8, 1991.)