

THE UNIVERSAL TIME VARIATION OF GEOMAGNETIC ACTIVITY

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Abstract. Geomagnetic activity exhibits both annual and daily variations. We examine these variations in the Am index which was designed to provide an accurate measure of the Universal Time variation of geomagnetic activity. The dayside reconnection process can quantitatively account for the observed variation in both indices. Control of these variations by the angle of the flow relative to the dipole axis is weaker than control by reconnection.

Introduction

Many studies have shown that geomagnetic activity is controlled by the southward component of the interplanetary magnetic field as measured in solar magnetospheric coordinates (cf. Hirshberg and Colburn, 1969; Arnoldy, 1971) through the reconnection process (Dungey, 1961). Geomagnetic activity maximizes near the equinoxes (Cortie, 1912; Chapman and Bartels, 1940). This variation has been postulated to be due to variations in the reconnection rate caused by the varying angle between the magnetospheric magnetic field and the direction of the interplanetary field (Russell and McPherron, 1973). This angle varies as the Earth moves around the Sun keeping its rotation axis fixed in inertial space. Magnetic fields pointing outward from the Sun along the Parker spiral and therefore opposite planetary motion will be more southward than northward during six months of the year and vice versa the other six months centered roughly on the equinoxes. This postulate predicts that the semiannual variation can be split into two annual variations if geomagnetic activity is ordered by the IMF. This splitting is observed (Russell and McPherron, 1973).

Since geomagnetic activity is also responsive to variations in the velocity of the solar wind, it has been hypothesized that the Kelvin-Helmholtz instability is also effective in causing geomagnetic activity. However, recent results suggest that little convection is driven by this process (Mozer, 1984) and little of the boundary motion expected to be caused by this instability (Song et al., 1988). Although to explain the observed annual variation it seems necessary to include effects associated with the heliographic latitude dependence of the solar wind velocity, it is possible that this velocity effect enters through its influence on the rate of reconnection and not through the Kelvin-Helmholtz instability.

If there is an annual variation of geomagnetic activity, there should also be a diurnal Universal

Time variation since the dipole axis varies in direction with respect to the average IMF direction diurnally due to the Earth's rotation around its axis. This variation is $\pm 11.3^\circ$ compared with the annual variation of $\pm 23.5^\circ$. Thus, the UT motion of the dipole should produce only about one-half the effect of the annual motion. The reconnection mechanism should produce a maximum in geomagnetic activity somewhat after 1039 UT or somewhat after 2239 UT each day depending on whether the IMF has a component parallel or antiparallel to planetary motion. The delay in response to the IMF input varies from 20 to 80 minutes depending on the nature of the response and the strength of the input (Bargatze et al., 1986), the delay being longer for weaker activity.

An attempt has been made to construct an index which accurately reflects the UT variation of geomagnetic activity (Mayaud, 1980). This index, Am, is derived from 15 stations distributed around the world at subauroral latitudes in both the southern and northern hemispheres. Since the stations are not ideally located, an attempt has been made to correct for the effects of this non-ideal positioning of the observatories. It is the purpose of this paper to examine the Universal Time variation in this index. In order to understand the cause of these variations we will also examine the annual variation and the dependence of these variations on the direction of the IMF.

The Data Base

Since we are concerned with not only the Universal Time variation of geomagnetic activity but also how it is controlled by the solar wind, we take as our data base all values of the Am index while there was simultaneous, nearly complete coverage of the interplanetary magnetic field and solar wind parameters by IMP-8. By nearly complete we mean that over the 3-hour interval covered by the index that there were 5-minute averages of the solar wind and IMF for at least 160 of the 180 minutes. The IMP-8 data used were obtained from the National Space Science Data Center and cover the period 11/21/73 to 2/6/86. There were 5692 three-hour averages and corresponding Am indices in our study period. This procedure is quite different from that of Bertheliet (1976) who used daily dominant polarity tables to classify entire days as either positive or negative polarity.

The value of the Am index is strongly correlated with IMF conditions. Figure 1 shows from bottom to top the dependence on the average southward component of the IMF, on the average product of the solar wind velocity and the southward component and on the average product of the velocity squared and the southward component. In this analysis the component of the IMF in the north-south direction in solar-magnetospheric coordinates is taken to be

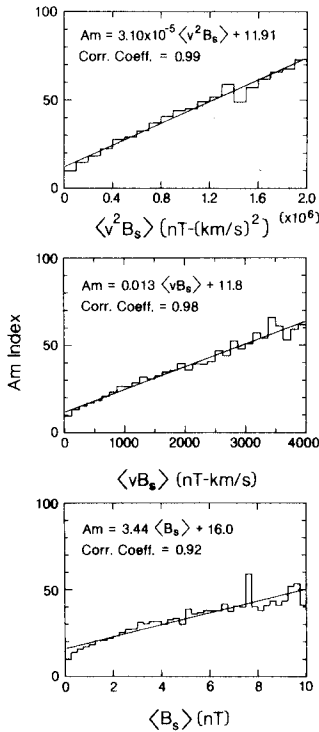


Fig. 1. Dependence of the Am index on the southward component of the IMF in GSM coordinates (bottom), on the product of the solar wind velocity and the southward component of the IMF (middle) and of the product of the square of the solar wind velocity and the southward component (top). The values shown are medians in their respective intervals.

zero in each 5-minute interval when it is northward and is assigned its average value otherwise. If there are less than 32 5-minute averages for any 3-hour period, the data are not used in this study. In constructing Figure 1 we sorted the Am indices into bins according to the average value of B_s , $v B_s$, and $v^2 B_s$, and then found the median Am index in each bin. On each panel of this figure we show the best least square fit to the variation and the correlation coefficient. The $v B_s$ and $v^2 B_s$ correlations are nearly identical at 0.98 and .99, respectively, and are somewhat higher than that of B_s with Am, 0.92. We note that the median Am index of 17 can be produced with a southward field of only 0.5 nT according to the bottom panel of Figure 1. The dependence of Am on B_s is clearly non-linear. If we are interested solely in southward fields less than 2 nT in strength, then we obtain the relation $Am = 5.9 B_s + 11.25$ which has a correlation coefficient of 0.97 over the interval of B_s from 0 to 2.

The Annual Variation of Geomagnetic Activity

As mentioned above the semiannual variation of geomagnetic activity is expected to be divisible into two annual variations out of phase by 180° when separated according to the east-west component of the IMF, the directions roughly parallel and antiparallel to planetary motion. To check if the Am index has the expected behavior we calculated and show in Figure 2 the annual variation of Am

when the B_y solar magnetospheric component of the IMF is positive and negative, and also the difference between these two variations. The amplitude of the annual variation of the difference in the two Am time series is 8.1. The maximum difference is on October 17. If the only effect influencing the semiannual variation is the ordering of the field in solar coordinates, the difference between the two curves is predicted to peak on October 5 (Russell, 1975). However, if one takes account of the observation that the number of toward and away intervals varies as the earth changes its heliographic latitude in the course of a year (Rosenberg and Coleman, 1969), then the predicted date of the maximum difference between the two curves will be changed. Depending on the polarity of the overall dipole moment of the Sun which varies every 11 years the predicted maximum difference could be as early as October 1 or as late as October 27. The observed date falls right in the middle of these predicted dates. We note that any modulation of activity by a latitudinal gradient of the solar wind velocity which is symmetric about the equator will affect the semiannual variation but will be removed in our annual curve by the differencing process.

As mentioned above the amplitude of the annual variation in the differences is 8.1. In our model this amplitude constrains the IMF field strength. Using our low B_s formula since Am is more frequently low than high, we find that this corresponds to a southward magnetic field of 1.4 nT. During the month surrounding the equinoxes the average angle between the GSM coordinate system and the GSEQ system in which the IMF is ordered is about 26° . Hence the 1.4 nT southward field implies a field component of 3.2 nT in the GSEQ Y direction which would correspond to a total field of 4.5 nT if the IMF were only along the ideal spiral angle and would correspond to 5.5 nT if the IMF had a (random) component in the north-south direction equal in strength to the X and Y components.

In deriving the IMF strength needed to cause the observed Am variation we used the dependence of Am

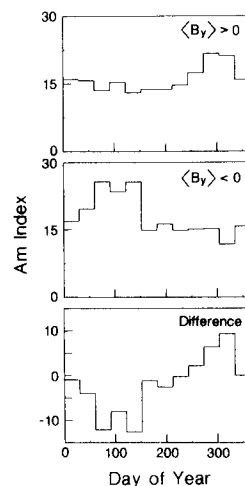


Fig. 2. The annual variation of the Am index when the B_y GSM component of the field is positive (top) and negative (middle). The bottom trace is the difference between the top two traces.

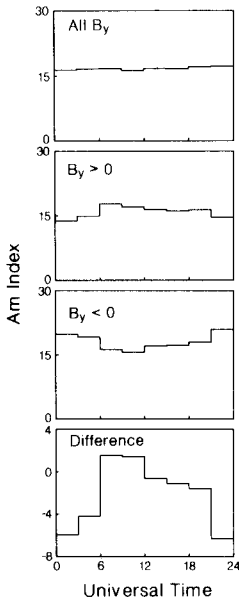


Fig. 3. The Universal Time variation of the Am index. The top trace shows the diurnal variation for all B_y polarities. The middle 2 traces show the diurnal variation for positive and negative B_y and the bottom trace shows the diurnal variation of the difference vector.

on B_s at low Am values which is steeper than for larger B_s values. If we were to use a less steep dependence to account for the fact that some of the annual variation is caused by larger southward fields, then the implied magnitude of the IMF would be somewhat greater than 5 nT as in fact it is observed to be (Slavin et al., 1986), varying from about 5.5 nT to 8 nT over the course of a solar cycle. In our data set the median magnetic field strength as calculated from the 3-hour averages of the components was 6 nT. (The average of the instantaneous values of the field would be larger). Thus the observed IMF strength is strong enough to cause the observed annual variation of Am.

The Universal Time Variation

Figure 3 shows the variation of the Am index as a function of Universal Time. The top panel shows all the data combined. The middle two panels show the variation when the variation is separated according to whether the y-component of the IMF is positive or negative. The bottom panel on an expanded scale shows the difference between these two variations. The top panel illustrates that on average there is essentially no Universal Time variation of the Am index. However, when ordered by the y-component a Universal Time component is evident. Our simple model would predict that the maximum difference would occur 20 to 80 minutes after 1039 UT using the delays found by Bargatze et al. (1986). Fourier analysis of the bottom panel of Figure 3 gives the phase of the maximum to be at 1146 UT which corresponds to a storage time of 61 minutes. The amplitude of 3.6 is only 44% of the annual variation. The Universal Time variation is associated with the tilt of the Earth's dipole axis from the rotation axis which is 11.3° and the

annual variation is associated with the 23.5° inclination of the Earth's rotation axis to the ecliptic pole together with a small effect due to the orientation of the solar rotation axes. The combined effect of the inclinations of the Earth and solar rotation axis is a 26.3° annual variation. To first order we might expect the size of the effect to be proportional to these two angles. Thus we would expect the UT variation to be about 44% of the annual variation, and it is.

We would also expect that the phase of the difference curve would remain the same through the year while the amplitude would vary. Table 1 shows the amplitude of the diurnal variation and the time of the maximum obtained from the difference curve for pairs of months around the equinoxes and solstices. Within the statistical accuracy of the smaller datasets the phase of the variation is stable. The amplitude does vary being largest in Spring and Fall and least in the Summer and Winter months.

A B_y -independent variation has been reported by Berthelier (1976) and attributed to the MacIntosh effect which hypothesizes that geomagnetic activity is greatest when the dipole is perpendicular to the solar wind (MacIntosh, 1959). The time at which this configuration most nearly occurs at the Summer solstice is 0439 UT and at the Winter solstice, 1639 UT. To maximize this effect we subtract the two diurnal variations using all Am values independent of solar wind conditions. This result is shown in Figure 4. Its amplitude (3.3 nT) is less than that due to the B_y -dependent process but it is present only in the Summer-Winter difference, whereas the B_y effect is present every month. On the other hand, this variation is unlikely to be due to the MacIntosh effect because the observed phase (0623 UT) is almost two hours later than predicted, assuming there is no energy storage time in the magnetosphere for this process. It is appropriate to assume no energy storage time because energy coupling is thought to occur directly to the ionosphere via waves or field-aligned currents generated by the Kelvin-Helmholtz mechanism in the MacIntosh effect. We cannot comment on the observed versus expected amplitude because there is no quantitative prediction for the size of the MacIntosh effect.

Another prediction of the MacIntosh effect is that there would be a semi-diurnal variation in geomagnetic activity at both equinoxes with maxima at 1040 and 2240 UT. Figure 4 shows the observed variations at the equinoxes. The observed semi-diurnal variation is weak, 0.5 nT, maximizes at 0814 and 2014 UT and not in phase with predictions, this time being early by over 2 hours. We

Table 1. Amplitude of Universal Time Variation in Am Index Curves Differenced According to Polarity of IMF

Month	Amplitude	Time of Maximum
Mar/Apr	6.9 nT	1226 UT
Jun/Jul	2.3	1038
Sep/Oct	4.2	1323
Dec/Jan	2.5	1328
All months	3.6	1146

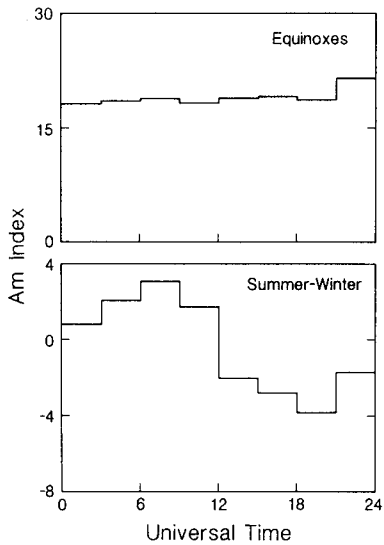


Fig. 4. (Top panel). Diurnal variation of the Am index for the four equinoctial months March, April, September and October. (Bottom panel). The diurnal variation for Summer and Winter months differenced.

note that this same amplitude was found by Mayaud (1980) in his study of the Am index for 20 days each year centered on the equinoxes. He also found that the last Am index value of the day was anomalously high as we see here in the top panel of Figure 4.

Conclusions

The model proposed by Russell and McPherron (1973) predicts both semiannual and diurnal variations of magnetic activity. Examination of the Am index, which was designed to provide a measure of the Universal Time variation of geomagnetic activity, reveals both variations. By comparing the Am index to the southward component of the interplanetary magnetic field we were able to calibrate the response of the Am index to the IMF and then predict the size of the semiannual variations. Both the observed magnitude and phase of the semiannual and diurnal variations are found to be close to those predicted.

The Am index has little or no Universal Time variation if averaged over an entire year. Diurnal variations arise only in monthly averages and when the index is studied according to IMF polarity. The semiannual variation can be broken into two annual waves upon separation by the IMF By component. The daily variation can similarly be divided. The difference between these two daily variations varies in amplitude but not in phase over the solar cycle again as expected.

The greatest daily variation due to the MacIntosh effect should be at the solstices and indeed a measurable diurnal variation is seen at this time. The amplitude however is much smaller than that caused by the By-effect when averaged over the year and its phase is incorrect by 2 hours which is much longer than any direct coupling model would predict and long even if storage in the tail were involved.

In short, both the semiannual and daily variations are consistent with a dayside reconnection source. Effects due to other sources may also be

present but they are weak compared to that caused by the By-effect. In particular, there is no evidence for the MacIntosh effect as originally stated, i.e., maximum activity when the dipole is most perpendicular to the flow.

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