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Correlation of Geomagnetic Activity Indices ap with the Solar Wind Speed and the Southward Interplanetary Magnetic Field

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Abstract. Correlation studies were carried out wit the geomagnetic activity index ap, the solar wind velocity v and the southward interplanetary magnetic field (IMF) component, using a comprehensive interplanetary data set for the years 1963–1975. The calculations show that ap is best represented by the sum of two terms, one proportional to the second (or higher) power of v and to the first (or higher) power of the IMF southward component. The second term is proportional to v^2 only and contains the main part of the semiannual ap variation. The two terms may be regarded as indicators of two different mechanisms of energy transfer from the solar wind to the magnetosphere.

Key words: Geomagnetic activity – Solar wind velocity – Interplanetary magnetic field – Semiannual wave of geomagnetic activity

Introduction

The three-hourly geomagnetic planetary indices Kp and ap were defined by Bartels (reviewed by Siebert 1971) to be a measure of the solar corpuscular radiation. When in situ observations of the solar wind became available it turned out that these indices were indeed a measure of the influence of the solar wind on the geomagnetic field. Snyder et al. (1963) calculated a correlation coefficient of 0.73 between the daily average solar wind velocity v and the daily sum of Kp. In later years this relation was confirmed with more spacecraft measurements (Wilcox et al. 1967; Olbert 1968; Ballif and Jones 1969). In these studies, however, it was found not only that the solar wind velocity influences geomagnetic activity, and that other parameters of the interplanetary medium such as the interplanetary magnetic field (IMF) and its directions and fluctuations are also related to geomagnetic indices, but also that geomagnetic activity correlates better with some of these parameters than with the solar wind velocity.

The relationship of the IMF fluctuations to geomagnetic activity was studied by Ballif and Jones (1969), among others, indicating high correlations between the standard deviation of the IMF components transverse to the sun-earth line and Kp. On the other hand Garret (1974) emphasized the importance of the variance of the IMF for the magnitude of geomagnetic activity.

In connection with theories of field line reconnection or merging of a southward interplanetary magnetic field with the geomagnetic field, the importance of the IMF north-south component for increasing geomagnetic activity was studied in several papers. Arnoldy (1971) correlated hourly solar wind data with the auroral electrojet index AE and found that the best correlation was between AE and the time-integral of the southward IMF component in solar magnetospheric coordinates. The product of the solar wind velocity v and the southward IMF component B_s, which is important in merging theories, is highly correlated with geomagnetic activity (Russell et al. 1974). Further, the product $B_s \cdot v^2$ was found to be correlated best with the daily activity index Ap (Crooker et al. 1977). The latter authors suggest that variations of long-term averages of geomagnetic activity relate more to variations of v^2 whereas hourly (or three-hourly) activity variations are controlled by variations of B_s.

In this paper a relation is developed for the ap indices using the solar wind velocity and the southward IMF component and taking into account, to a certain degree, the IMF fluctuations by computing an "effective southward IMF component" B_{ZE}, comparable to the quantity Arnoldy (1971) found to be best correlated to the activity indices AE. The calculations show that ap is best represented by the sum of two terms, one proportional to $v^{2.25} \cdot B_{ZE}^{1.25}$ and the other proportional to v^2 (v is in km/s and B_{ZE} in nT throughout this paper). The second term is related to the main part of the semiannual variation of ap.

Effective IMF Southward Component

The interplanetary data used in this study are those prepared and described by King (1977a, b). The data are available on tape at the World Data Center A. From the composite tape containing hourly averages of IMF and interplanetary plasma data of the years 1963–1975, only those time intervals with both IMF and solar wind data have been selected. To correlate the interplanetary data with ap indices, three-hourly averages were computed. Thus, 13,820 three-hour intervals (about 4.7 years) of data are available for our calculations. Though the data were provided by different spacecraft and the temporal coverage varies significantly over the time interval of about one solar cycle, the data are treated as one homogeneous set.

First we correlate ap with the solar wind speed v dividing

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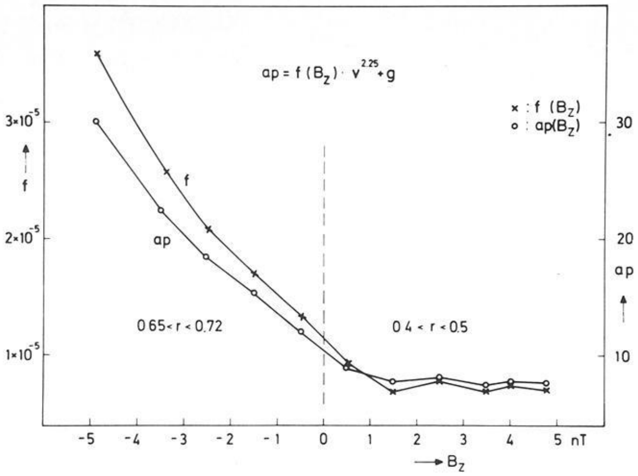

Fig. 1. The coefficient f in the relation $\mathrm{ap}=f(B_Z)\cdot v^{2.25}+g$ as a function of the IMF component B_Z in GSM coordinates. In addition the ap averages for the different B_Z intervals are shown

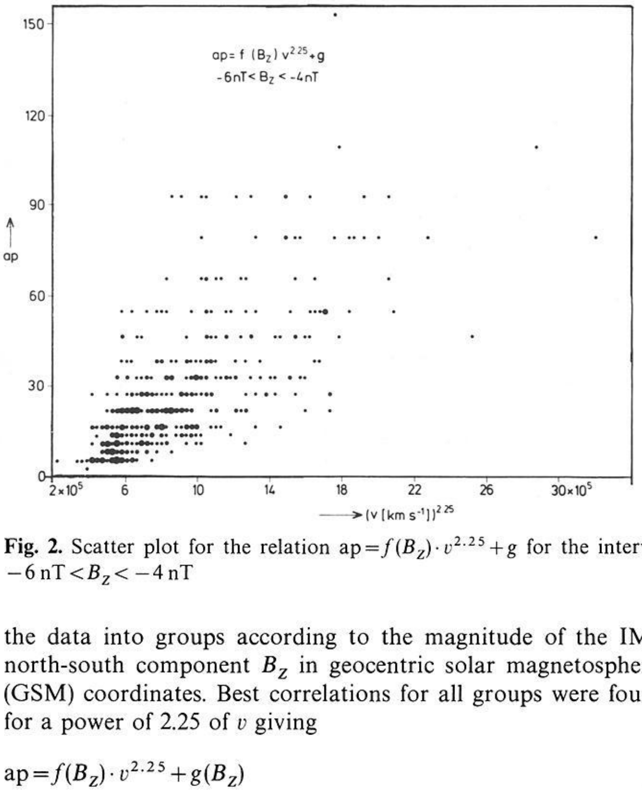

Fig. 2. Scatter plot for the relation $\mathrm{ap}=f(B_Z)\cdot v^{2.25}+g$ for the interval $-6\,\mathrm{nT}<B_Z<-4\,\mathrm{nT}$

the data into groups according to the magnitude of the IMF north-south component B_Z in geocentric solar magnetospheric (GSM) coordinates. Best correlations for all groups were found for a power of 2.25 of v giving

$$\mathrm{ap}=f(B_Z)\cdot v^{2.25}+g(B_Z) \tag{1}$$

where the coefficients $f(B_Z)$ and $g(B_Z)$ may vary with B_Z. The same relation of the am indices (Mayaud 1967) with $v^{2.25}$ was found by Svalgaard (1978). Figure 1 shows the coefficient f as a function of B_Z(B_Z being the average in the corresponding interval). For negative B_Z values f grows nearly linearly with decreasing B_Z; for $B_Z \geqq 1\,\mathrm{nT}$ however, f is nearly constant and small. The correlation is significantly greater for $B_Z<0$ than for $B_Z>0$. Two scatter plots of relation (1) for intervals of negative and positive B_Z are shown in Figures 2 and 3 to demonstrate the different relationship of ap with $v^{2.25}$ for positive and negative B_Z. There is significantly less scatter in Fig. 2 where 438 points in the relatively wide interval $-4\,\mathrm{nT}>B_Z>-6\,\mathrm{nT}$ are plotted (correlation coefficient $r=0.67$) than in Fig. 3 with 506 points in the interval $3\,\mathrm{nT}<B_Z<4\,\mathrm{nT}$ ($r=0.41$). Considering only those points of Figure 3 with $\mathrm{ap}>27$, no correlation of ap with $v^{2.25}$ is seen. Inspection of the interplanetary data for these three-hourly intervals showed that either (i) at least one hourly averaged B_Z of the corresponding three-hourly interval was negative, or (ii) the three-hourly averages of B_Z are positive but there are strong fluctuations of the IMF in at least one of the hourly intervals, or (iii) in the preceding three-hourly interval there was a negative B_Z value or strong fluctuations of the IMF.

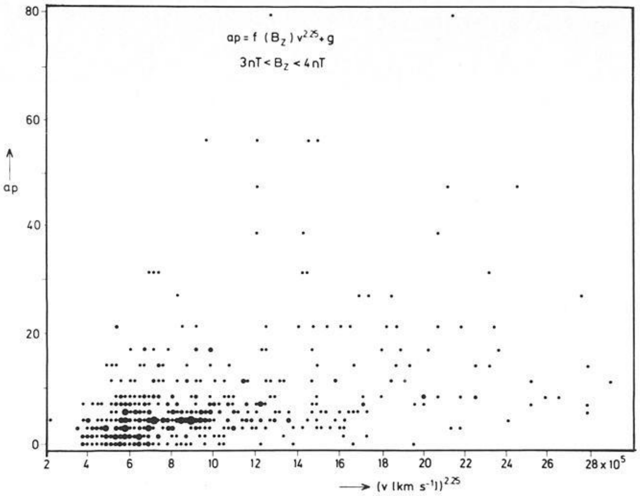

Fig. 3. Scatter plot for the relation $\mathrm{ap}=f(B_Z)\cdot v^{2.25}+g$ for a positive B_Z interval $3\,\mathrm{nT}<B_Z<4\,\mathrm{nT}$

No other remarkable features of the interplanetary data were found. From these examples, remembering that the ap indices are based on the greatest positive and negative geomagnetic disturbances (not an average disturbance) in a three-hourly interval at several observatories, we may conclude that the three-hourly average of B_Z is not the appropriate parameter to correlate with ap. A better parameter to describe the strong influence of the southward IMF component on geomagnetic activity is an "effective southward IMF component" that takes into account at least points *i)* and *ii)* of the foregoing discussion. It is defined as follows:

The individual IMF values, from which the hourly averages of the NSSCD interplanetary data set (King 1977a) are constructed, are assumed to be normally distributed. Thus for the GSM north-south component of the IMF the hourly mean M_{B_Z} may be written

$$M_{B_Z}=\int_{-\infty}^{+\infty} h(B_Z)\cdot B_Z\cdot dB_Z \tag{2}$$

with the frequency distribution

$$h(B_Z)=\frac{1}{\sigma_{B_Z}\cdot\sqrt{2\pi}}\exp\left\{-\frac{(B_Z-M_{B_Z})^2}{2\sigma_{B_Z}}\right\} \tag{3}$$

where σ_{B_Z} is the standard deviation of the B_Z values. The effective southward component B'_{ZE} is defined to be the average of the negative part of the frequency distribution

$$B'_{ZE}=\int_{-\infty}^{0} h(B_Z)\cdot B_Z\cdot dB_Z \simeq \int_{M_{B_Z}-3\sigma_{B_Z}}^{0} h(B_Z)\cdot B_Z\cdot dB_Z \tag{4}$$

From hourly averages M_{B_z} and standard deviations σ_{B_z} we may compute B'_{ZE} numerically. Some examples are $M_{B_z}=-4\,\mathrm{nT}$ and $\sigma_{B_z}=3\,\mathrm{nT}$ giving $B'_{ZE}=-4.2\,\mathrm{nT}$; $M_{B_z}=4\,\mathrm{nT}$ and $\sigma_{B_z}=3\,\mathrm{nT}$ giving $B'_{ZE}=-0.12\,\mathrm{nT}$; $M_{B_z}=4\,\mathrm{nT}$ and $\sigma_{B_z}=8\,\mathrm{nT}$ giving $B'_{ZE}=-1.6\,\mathrm{nT}$.

Unfortunately the available IMF data contain σ_{B_z} values only for a part of the time interval covered by the whole data set. The only consistent measure of IMF fluctuations is the vector standard deviation $(\sigma^2_{Bx}+\sigma^2_{By}+\sigma^2_{Bz})^{1/2}$ (King 1977a). Four our computations of B'_{ZE} we used this quantity as an approximation of σ_{B_z}.

Significantly better correlations were found by correlating ap with three-hourly averages of B'_{ZE} than by correlating ap with B_Z. A slight enhancement of the correlation coefficients was achieved using the minimum of the three one-hourly B'_{ZE} values instead of the three-hourly means. Therefore, and in order to have positive values for the effective southward IMF component, we redefined

$$B_{ZE}=|\min(B'_{ZE\,1},B'_{ZE\,2},B'_{ZE\,3})| \tag{5}$$

where B'_{ZEi} are the three one-hourly values in the respective three-hourly ap interval. The further correlations were carried out using B_{ZE} as defined in Eqs. (4) and (5). It should be added that B_{ZE} is, to a certain degree, comparable with the time-integral of the southward IMF component, which Arnodly (1971) found to be best correlated with AE indices.

Correlation of ap with v and B_{ZE}

The whole data set of 13,820 three-hourly intervals were divided into 10 groups according to the strength of the solar wind velocity. For all groups ap was correlated with B_{ZE}

$$\mathrm{ap}=C(v)\cdot B^q_{ZE}+D(v) \tag{6}$$

where the coefficients $C(v)$ and $D(v)$ may be functions of v. Best correlation was found for a power $q=1.25\pm0.1$; the error was estimated from the slightly varying best power for the different v intervals. In Fig. 4 the two functions $C(v)$ and $D(v)$ of Eq. (6) are shown for $q=1.25$. Both functions may be described by power laws

$$C(v)=c\cdot v^p+d \tag{7}$$

$$D(v)=e\cdot v^{p'}+f \tag{8}$$

Correlating $C(v)$ and $D(v)$ with v, the coefficients c, d, e, f, and the powers p and p' were calculated by maximizing the correlation coefficients. The numerical results were $p=2.25\pm0.10$, $p'=2.0\pm0.3$; $d=0.081\pm0.132$, $f=0.35\pm0.5$; $c=2.77\ 10^{-6}$, $e=2.30\cdot10^{-5}$. Since $c\ v^p \gg d$ and $e\cdot v^{p'}\gg f$, Eqs. (7) and (8) may be simplified with $d=f=0$. Inserting (7) and (8) into (6), one finds

$$\mathrm{ap}=c\ v^{2.25}\cdot B^{1.25}_{ZE}+e\cdot v^2 \tag{9}$$

The same relationship of ap to v and B_{ZE} and equivalent values for the powers and coefficients (in the limits of the error ranges) were obtained by a similar procedure. Dividing the data into groups of different B_{ZE} intensities, the appropriate power of v was calculated by a correlation of the form

$$\mathrm{ap}=A(B_{ZE})\cdot v^p+B(B_{ZE}) \tag{10}$$

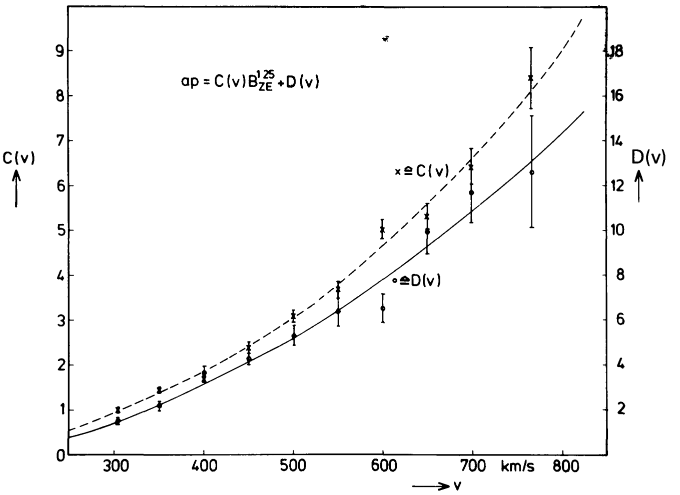

Fig. 4. The functions $C(v)$ and $D(v)$ in the relation $\mathrm{ap}=C(v)\cdot B^{1.25}_{ZE}+D(v)$. The crosses for $C(v)$ and circles for $D(v)$ with error bars were calculated from correlations in the different v intervals. The dashed and solid curves are the best power laws for $C(v)$ and $D(v)$ according to Eqs. (7) and (8)

Thus assuming simple power laws for the relation of ap to v and B_{ZE} the correlation calculations show that at least two terms should be taken into account, one with the second (or higher) power of v and the first (or higher) power of B_{ZE} and the other approximately proportional to v^2.

For a general form of Eq. (9)

$$\mathrm{ap}=h\ v^p\cdot B^q_{ZE}+k\cdot v^{p'}+j \tag{11}$$

with coefficients h, k and j, multiple correlation calculations of ap with v and B_{ZE} were carried out, varying the powers p, q, p'. The best multiple correlation coefficient $r_m=0.82$ was found as expected for $p=2.25$, $q=1.25$, and $p'=2.0$. For these values the coefficients h and k are (within the limits of errors) identical with c and e of Eq. (9) and $j=0.064\pm0.142\simeq0$.

Equations (9) and (11) therefore may be regarded as a reasonable approximation of the activity index ap in terms of solar wind parameters. In a very recent paper extending earlier results of Murayama and Hakamada (1975) and Aoki (1977), Murayama et al. (1980) found a relation similar to Eqs. (9) and (11) of the AL index as a measure of the westward auroral electrojet $\mathrm{AL}=K\cdot(0.5+B_s)\,v^2$ where B_s was defined and calculated as B_{ZE}; the factor K was found to be a function of the IMF B_y component and of the dipole tilt angle.

Our relations (9) and (11) do not explicitly contain the semiannual variation of ap, which is the most pronounced variation after the 11.5 year solar cycle. To investigate in which term or factor of Eq. (11) the semiannual wave is contained, data for individual months were lumped together and month by month calculation of the multiple correlation coefficients for Eq. (11) was made. Biases which might arise from varying amounts of data for individual months (maximum of 1510 for January and minimum of 840 for October) and uneven distribution for the individual months during the 13 year period were not taken into account.

The results of the calculations are presented in Fig. 5. The upper curve (crosses) shows the monthly averages of ap for the available data. The seminannual variation for these time intervals is not so marked as for longer time interval but is

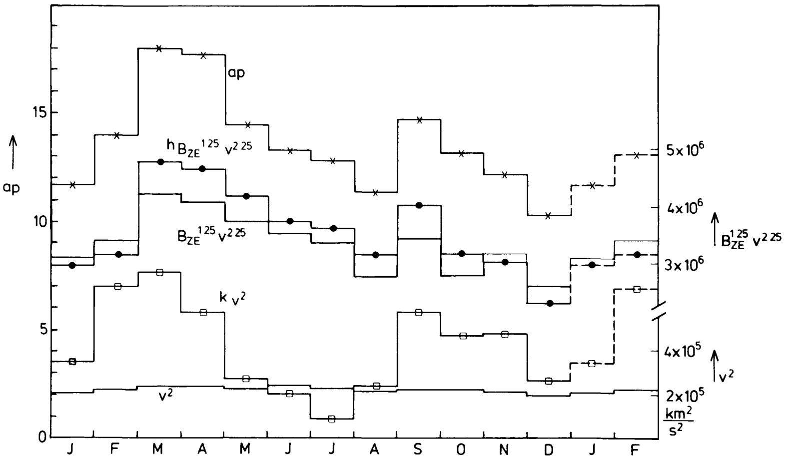

Fig. 5. Monthly averages of observed ap and the different quantities of Eq. (11) computed with multiple correlations for every month

clearly seen, and an annual wave with maximum near the vernal equinox may be superposed. The second curve (full circles) shows the yearly variation of the first term of the right hand side in Eq. (11). A slight semiannual wave is present, again superposed by an annual wave. Harmonic analysis of this curve yields amplitudes of 1.7 and 0.66 ap units for the annual and semiannual waves with maxima near 19 April (annual) and 25 April, 24 October (semiannual). The third curve (thin line) of Fig. 5 shows montly averages of the quantity $B_{ZE}^{1.25}\ v^{2.25}$ on a comparable scale. This curve is nearly parallel to the second curve and the coefficient h of Eq. (11) is seen to be nearly constant for all months. Since $v^{2.25}$ is also nearly constant (see the lower thin curve), the yearly variation of the first right hand term of relation (11) must be attributed to variations in B_{ZE}. These yearly B_{ZE} variations with maximum near spring and minimum near fall should be observed if, in the available interplanetary data, there were more IMF toward than away days, if the average IMF toward fields are stronger than the away fields, or if the IMF southward component is stronger in spring than in fall months. A heliographic latitude dependent variation of the relevant solar wind parameters, which was suggested by Murayama (1974) to cause one part of the semiannual variation of Kp, should also be attributed to the variation of B_{ZE}, since the averages of v^2 and also of $|B|$ (see the corresponding curve in Fig. 6) show no appreciable variation throughout the year. An analysis of the data to investigate the reasons for the B_{ZE} variations has not yet been carried out.

The fourth curve of Fig. 5 (open squares) represents the second right hand term of Eq. (11). This term shows a clear semi annual wave. Harmonic analysis yields an amplitude of 2.7 ap units and maxima at about 22 March and 21 September for this wave. This variation is not seen in v^2 and must be attributed to a semiannual variation in the coefficient k.

Thus it may be concluded that the main part of the semiannual variation of ap is contained in a variation of k in Eq. (11) and not in the variation of the solar wind speed v nor in the variation of the southward IMF component B_{ZE}.

The mechanism proposed by Boller and Stolov (1970, 1973) can account for such a semiannual modulation of the coefficient k in Eq. (11). According to Boller and Stolov the maxima of geomagnetic activity near the equinoxes are caused by an enhanced probability of occurrence of the Kelvin-Helmholtz instability along the flanks of the magnetosphere. The instability criterion they apply is

$$v^2 > \frac{\rho_I + \rho_M}{\mu_0 \cdot \rho_I \cdot \rho_M} (B_I^2 \cos^2 \psi_I + B_M^2 \cos^2 \psi_M) \tag{12}$$

where indices I and M stand for interplanetary and magnetospheric values respectively, ρ are plasma densities, B the magnetic field strengths and ψ the angles between the velocity v and the magnetic fields. The second term on the right hand side of Eq. (12) yields a semi annual variation since at the equinoxes $\psi_M = 90°$ maximizes the instability probability.

For our calculations we simplify the criterion of Eq. (12) by assuming: *(i)* the factor $(\rho_I + \rho_M)/\rho_I \rho_M = 1/\rho$ is constant, *(ii)* the part of the geomagnetic activity indices ap relating to the Kelvin-Helmholtz instability is proportional to the difference between the left and right hand sides of inequality (12), and *(iii)* the two terms $c_0 = B_I^2\ \cos^2 \psi_I/\mu_0 \rho v^2$ and $c_2 = B_M^2/\mu_0 \rho v^2$ are constant. With these simplications we may write

$$\mathrm{ap} = c_1\ v^2 \cdot (1 - c_0 - c_2 \cdot \cos^2 \psi_M) + \ldots \tag{13}$$

where the dots indicate the first term in Eq. (11) and c_0, c_1, and c_2 are constants.

The semiannual variation of ap is described in Eq. (13) only by the variation of $\cos^2 \psi_M$ which is a function of the time of year (Damaske 1977)

$$\cos \psi_M = \sin \delta_0 \cdot \cos \varepsilon_0 \cdot \cos \alpha \tag{14}$$

with the constant angles between the earth's rotation axis and the ecliptic plane $\delta_0 = 23.5°$ and between the rotation axis and the dipole axis $\varepsilon_0 = 11.5°$. The seasonal angle α begins with $\alpha = 0$ on 22 June.

Inserting the constant angles δ_0 and ε_0 and replacing $\cos \psi_M$ in Eq. (13) by $\cos \alpha$, and then comparing Eqs. (13) and (11), we finally have

$$\mathrm{ap} = h\ v^{2.25} \cdot B_{ZE}^{1.25} + c_1 \cdot (1 - c_0 - c_2 \cdot 0.153 \cos^2 \alpha)\ v^2 \tag{15}$$

Multiple correlation calculations of ap with $v^{2.25} \cdot B_{ZE}^{1.25}$ and $(1 - c_0 - c_2 \cdot 0.153\ \cos^2 \alpha) \cdot v^2$ were made for different values of the constants c_0 and c_2. The best multiple correlation coefficient is $r_m = 0.84$ for $c_0 = 0.5 \pm 0.25$ and $c_2 = 2.0 \pm 0.5$; for these values $h = (0.276 \pm 0.003) \cdot 10^{-5}$ and $c_1 = (0.591 \pm 0.015) \cdot 10^{-4}$.

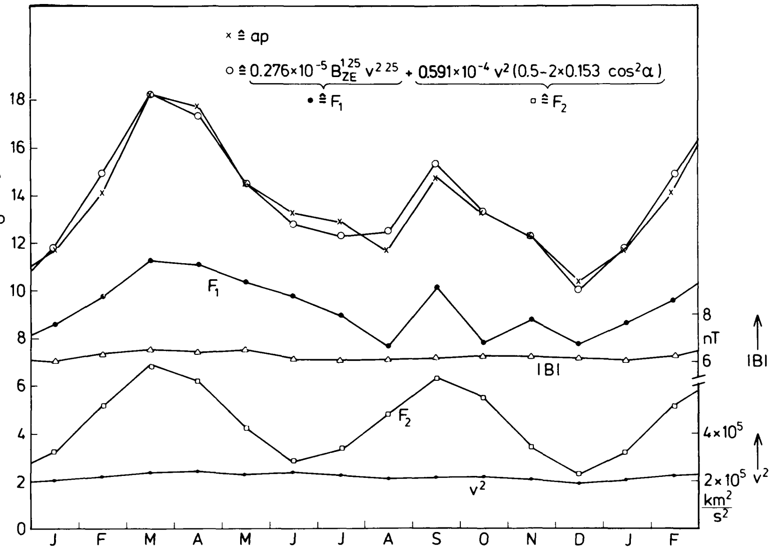

Fig. 6. Monthly averages of observed ap *(crosses)* and reconstructed ap *(circles)* according to Eq. (15), inserted above in explicit form. F_1 and F_2 are monthly averages of the two terms of relation (15), showing different contributions to ap during the year. The monthly averages of v^2 and IMF magnitude $|B|$ show no yearly variation

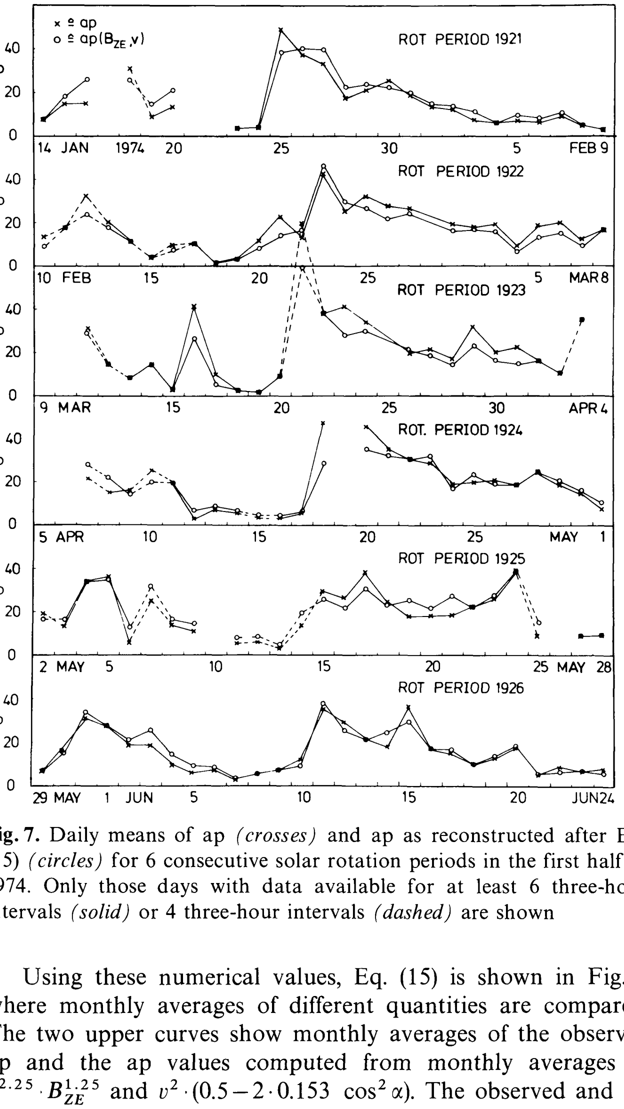

Fig. 7. Daily means of ap *(crosses)* and ap as reconstructed after Eq. (15) *(circles)* for 6 consecutive solar rotation periods in the first half of 1974. Only those days with data available for at least 6 three-hour intervals *(solid)* or 4 three-hour intervals *(dashed)* are shown

Using these numerical values, Eq. (15) is shown in Fig. 6 where monthly averages of different quantities are compared. The two upper curves show monthly averages of the observed ap and the ap values computed from monthly averages of $v^{2.25} \cdot B_{ZE}^{1.25}$ and $v^2 \cdot (0.5-2 \cdot 0.153 \cos^2 \alpha)$. The observed and reconstructed annual variations of ap are in good agreement. Comparing the two terms of Eq. (15) it is seen that the first term F_1, containing B_{ZE}, represents on the average about two thirds of ap, but the second term F_2 contains the main part of the semiannual wave. In addition monthly averages of v^2 and the IMF magnitude averages $|B|$ are shown, in comparable scales, indicating no yearly variation. The yearly variation in F_1 is mainly caused by variation of B_{ZE} as was seen in Fig. 5.

As well as the monthly averages, the daily ap means are approximated closely by Eq. (15). An example is shown in Fig. 7, where daily means of observed ap and reconstructed ap are shown for six consecutive solar rotations in 1974. For other periods the same good agreement between the two quantities were found, so Eq. (15) may be regarded as a reasonable representation of daily means of ap in terms of solar wind parameters.

Discussion

Before single three-hourly observed ap indices are compared with the ap values computed with Eq. (15) from solar wind parameters, it should be explained that, in principle, exact agreement between the two quantities is not possible.

The hypothesis proposed by Boller and Stolov (1970) and adopted in this study not only generates semiannual but also daily UT variations of geomagnetic activity. Also any other hypothetical mechanism relating variations of geomagnetic activity to the variations of the angle between the solar wind direction and the geomagnetic dipole axis produces such daily UT variations. This effect is neglected in Eq. (15), since in the procedure for generating ap indices these possible activity variations are eliminated (Siebert 1971). In fact the elimination is imperfect and UT variations remain in ap which are different for the two IMF polarities but are not real activity variations (Schreiber 1978). On the other hand ap is not a continuous measure and only 28 different values between 0 and 400 are possible whereas v and B_{ZE} are continuous.

In spite of these restrictions the observed and reconstructed ap values are compared in Fig. 8 for two solar rotations and give an impression of relatively good agreement, which generally was found for all the data. Although appreciable differences are sometimes evident especially during time intervals of high activity, no systematic behaviour of the differences throughout the solar cycle was discovered.

An improvement of the final relation (15) may be achieved

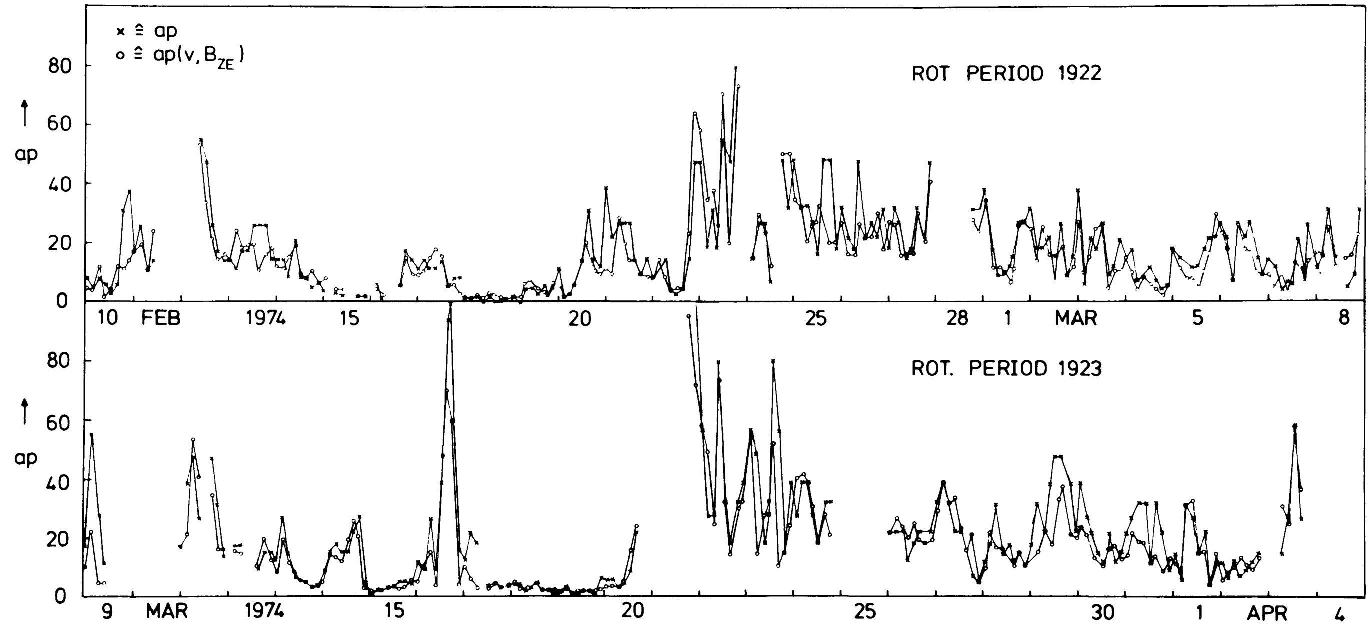

Fig. 8. Comparison of individual ap (observed) and ap (reconstructed) for two solar rotation periods. Gaps indicate missing interplanetary data

by including the above mentioned daily variations. These effects however should be studied using the am indices, introduced by Mayaud (1967), since these indices show the expected daily variations (Mayaud 1977). Taking into account other solar wind parameters, e.g., the plasma density n, for which Svalgaard (1978) observed that am is proportional to $n^{1/3}$ and Murayama et al. (1980) found AL to be proportional to $n^{0.13}$, may also refine the relation.

The main result of the present analysis is the finding of at least two terms of the relation between geomagnetic activity and solar wind parameters, one proportional to the southward IMF component B_{ZE} and the other independent of B_{ZE}. The definition of B_{ZE} includes the assumption that geomagnetic activity is generated, by, for example, a merging process of interplanetary and geomagnetic field lines, only if a southward IMF component is present. This process is sometimes named the half-wave rectifier response of the magnetosphere to the IMF orientation, meaning that energy transfer from the solar wind into the magnetosphere is possible only for a southward oriented IMF component, as first suggested by Arnoldy (1971) (see Crooker 1980, for a discussion of this problem). Russell and McPherron (1973) used this rectifier response in their hypothesis to explain the semiannual wave in geomagnetic activity. The results of the present correlative study (Figs. 5 and 6) indicate a slight semiannual variation due to the B_{ZE} term in Eqs. (11) and (15) in agreement with the Russell-McPherron hypothesis; the main part of the semi annual wave however was found in a second additional term which is essentially independent of a southward IMF component. This second term can be explained with the mechanism proposed by Boller and Stolov (1970) as one possible IMF-independent process of the interaction of the solar wind with the magnetosphere. A similar conclusion was reached by Berthelier (1976) investigating the influence of the IMF polarity on geomagnetic activity.

Thus the two terms of the relation between geomagnetic activity and solar wind parameters may suggest two different mechanisms of energy transfer from the solar wind to the magnetosphere and Eq. (15) and Fig. 6 may be regarded as a rough quantitative separation of the two parts.

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