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On the Variation of Kp at Sector Boundaries

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Abstract. A superposed epoch analysis of Kp at well established sector boundaries of the interplanetary magnetic field (IMF) has been carried out for 4 classes of sector boundaries with the following results: The Kp increase at (+/−) sector boundaries near vernal equinoxes and at (−/+) boundaries near autumnal equinoxes is significantly greater than at sector boundaries with the opposite polarity change. For a smaller number of sector boundaries observed in the years 1966 1968, showing the same polarity- and season-dependent Kp variation, the influence of different components of the interplanetary magnetic field B and the solar wind velocity v on Kp is examined. From the results it is suggested that the observed Kp variations are controlled by the variation of the IMF southward component B_{SM}, which however, is not the only interplanetary parameter being responsible for the observed variations. A linear relation between Kp, B_{SM} and the solar wind velocity v gives a reasonable presentation of the Kp variations at sector boundaries.

Key words: Geomagnetic activity – Interplanetary magnetic field IMF – Sector structure – Solar wind velocity – Southward component of IMF.

Introduction

Since the discovery of the sector structure of the interplanetary magnetic field (IMF) many studies analysed the variation of interplanetary parameters and various geomagnetic indices within the sectors and at the boundaries (e.g. Wilcox, 1968, for a first review). On the average the solar wind velocity v as well as the IMF magnitude B vary systematically within the sectors with a relatively sharp increase near the boundaries, a maximum one or two days after the boundary, and a slow decrease to a pronounced minimum one day before the next boundary passage. The average slope is the same for (+) sectors when the IMF vector is pointing away from the sun and (−) sectors when the IMF vector is pointing towards the sun.

Geomagnetic indices as a measure of the interaction of the interplanetary medium with the magnetosphere show a similar variation during the passage of sectors and particularly in the vicinity of the boundaries (e.g. Wilcox and Ness, 1965; Ness and Wilcox, 1967; Wilcox and Colburn, 1972; Hirshberg and Colburn, 1973; Wilcox et al., 1975). The minimum of geomagnetic activity before sector boundaries seems to be more significant than the post boundary maximum which possibly is dependent on the sector polarity (Shapiro, 1974).

Correlations of geomagnetic indices have been found both with solar wind velocity v (Neugebauer and Snyder, 1966; 1967) and with B (Wilcox et al., 1967). Further studies gave evidence for a better correlation between geomagnetic activity and the fluctuations of the IMF (Ballif et al., 1969; Garrett, 1974), and with the IMF southward magnetospheric component B_{SM} (Hirshberg and Colburn, 1969; Arnoldy, 1971). It was also indicated that magnetic variations especially in the polar caps are related to the east-west component of the IMF perpendicular to the sun-earth line (Friis-Christensen et al., 1972; Berthelier et al., 1974). Since the parameters of the interplanetary medium are intercorrelated to a certain degree (e.g. an increased B implies increased values of the components of B and frequently enhanced fluctuations) it is often difficult to separate the influence of individual parameters on geomagnetic activity. This investigation analyses the average Kp variation at sector boundaries for the different geometrical configurations between the IMF and the magnetosphere in vernal and autumnal months. Comparing the variations of some interplanetary parameters with the observed polarity-dependent Kp variations the effect of the southward component of the IMF will be pointed out.

Analysis and Results

In a series of papers, lists of "well established" IMF sector boundaries have been published, giving the polarity, the dates and (generally) 3 h intervals of boundary observations at the earth (Wilcox and Colburn, 1969, 1970, 1972; Wilcox et al., 1975; Fairfield and Ness, 1974). "Well established" sector boundaries are defined in the way that at least for 4 days the IMF has one polarity followed by at least 4 days with the opposite polarity. From the above mentioned lists covering the years 1962–1972 four classes of sector boundaries have been selected: 50 boundaries near vernal equinoxes (26 (+/−) and 24 (−/+) polarity-changes) and 48 sector boundaries near autumnal equinoxes (22 (+/−) and 26 (−/+) polarity changes). The dates of the boundary observations are Feb 4–May 17 for the vernal and Aug 13–Nov 23 for the autumnal classes. To have nearly equal numbers in the 4 classes 3 sector boundaries of the last class tabulated in the list for 1964 have been omitted. A superposed epoch analysis was applied to calculate the average Kp indices from 3 days before until 3 days after the sector boundary passage. The Kp variation for the 4 classes are shown in Figures 1 and 2. It is seen from the figures that Kp has a minimum before the boundaries and increases near the boundaries, but the increase is strong for the (+/−) polarity change near vernal equinoxes and for (−/+) changes near autumnal equinoxes and weak for the respective opposite polarity changes.

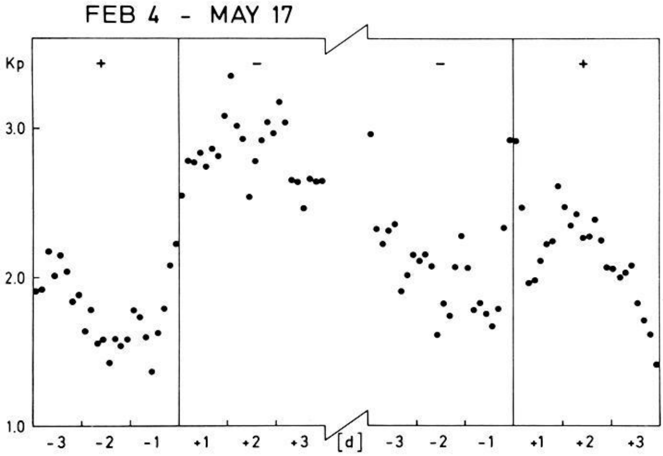

Fig. 1. The average Kp variation at (+/−) and (−/+) sector boundaries near vernal months from 3 days before until 3 days after the boundaries

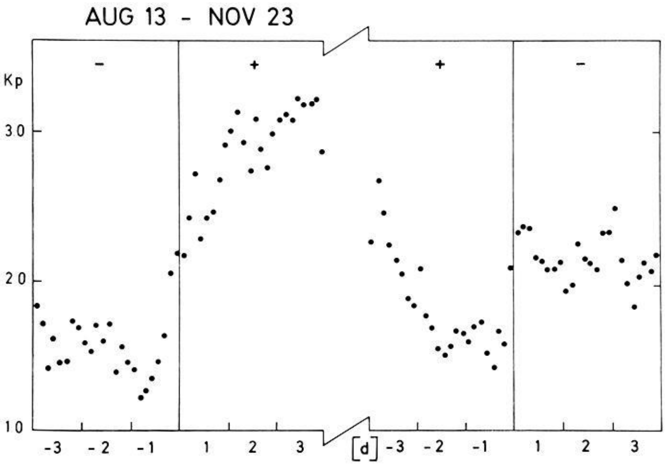

Fig. 2. The average Kp variation at (−/+) and (+/−) sector boundaries near autumnal months from 3 days before until 3 days after the boundaries

Daily averages of Kp for the intervals 36–12 h before and 12–36 h after the IMF polarity change have been calculated. From these values the average Kp increases were found to be:

1.38, vernal (+/−) change; 0.41, vernal (−/+) change;

1.36, autumnal (−/+) change; 0.48, autumnal (+/−) change.

Applying the *t*-test the significance of the polarity-dependent Kp increases can be proven: For the vernal as well as for the autumnal sector boundaries, the probability P for the null hypothesis (i.e. that the Kp increase is the same at the 2 sector boundaries) was found to be $P < 10^{-2}$.

Table 1. Dates and 3 h intervals of observed sector boundaries for which IMF measurements are available; (v) indicates that also measurements of the solar wind velocity are available

Vernal months		Autumnal months	
+/−	−/+	+/−	−/+
Feb 7, 67, 3–4 (v)	Mch 22, 67, 7–8	Sep 6, 67, 6–7	Oct 30, 66, 5–6
Feb 26, 68, 6–7 (v)	Feb 11, 68, 3–4 (v)	Oct 3, 67, 1–2	Aug 30, 67, 6–7
Mch 23, 68, 5–6 (v)	Mch 10, 68, 4–5 (v)	Aug 21, 68, 2–3	Sep 27, 67, 3–4
Apr 21, 68, 3–4	Apr 5, 68, 6–7 (v)	Sep 19, 68, 2–3	Oct 24, 67, 2–3
May 17, 68, 5–6	May 2, 68, 1–2	Oct 16, 68, 5–6	Aug 13, 68, 7–8

To compare the Kp variations with parameters of the interplanetary medium 5 sector boundaries for every class have been selected for which IMF measurements are available as "Multispacecraft hourly averaged interplanetary magnetic field vectors" on a tape prepared by the National Space Science Data Center (NSSDC), Greenbelt, Maryland, USA. For six of these sector boundaries listed in Table 1 also measurements of the solar wind velocity v are available on a NSSDC tape "Hourly averaged interplanetary plasma data".

The Kp variations at these sector boundaries indicate the same features as shown in Figures 1 and 2; therefore we averaged the Kp values of vernal (+/−) boundaries and autumnal (−/+) boundaries and also those of the respective opposite polarity changes. The result is shown in Figure 3 (closed circles) together with averaged threehourly values of IMF magnitude B (open circles). The variation of B is similar at both sector boundaries whereas Kp shows the different variation as it was seen in Figures 1 and 2.

A corresponding comparison of the average variation of Kp and v at sector boundaries was not possible because only 6 vernal sector boundaries with measurements of v (one of them with some gaps) have been available. Three hourly averages of v (omitting the gaps in the averaging procedure) at these sector boundaries are shown in Figure 4 together with the daily averaged Kp values of the day before and after the IMF polarity changes. The Kp increases at the boundaries resemble the increases shown in Figures 1–3 whereas the variation of v is quite different with less v increase at the (+/−) boundary where the Kp increase is greater. Though Figure 4 does not represent the average behaviour of v at vernal sector boundaries it is an example to show that the observed Kp variations are not caused by variations of v alone.

Rosenberg and Coleman (1969) found a heliographic latitude dependence of the dominant polarity of the IMF with more days of negative polarity at northern and more days of positive polarity at southern heliographic latitudes in the years 1964–1967. This dominant polarity effect changes sign after sunspot maximum (e.g. Rosenberg, 1975). Supposing that the solar wind velocity v is connected with the dominant polarity of the IMF in a way to cause the observed Kp variation of Figures 1–3, the Kp variations also should change after 1970. However, an analysis of Kp at sector boundaries of the years 1970–1972 gave the same results as they are shown in Figures 1–3.

Therefore we suggest that on the average the IMF magnitude B and the

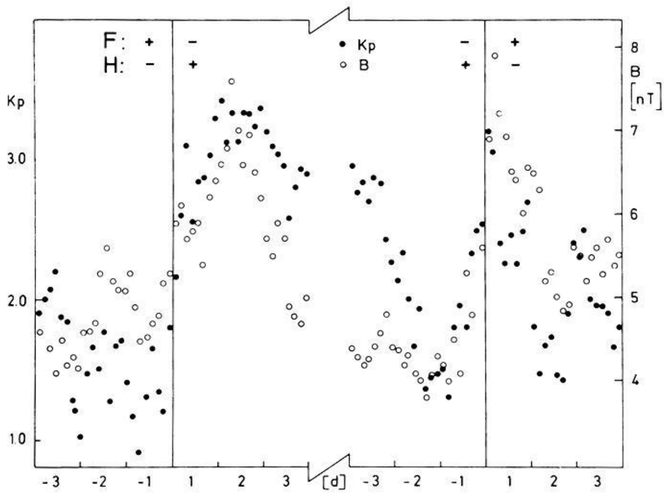

Fig. 3. Average Kp variation (full circles) for vernal $F(+/-\cdots-/+)$ and autumnal $H(-/+\cdots+/-)$ boundaries and the respective 3 hourly values of IMF magnitude B (open circles)

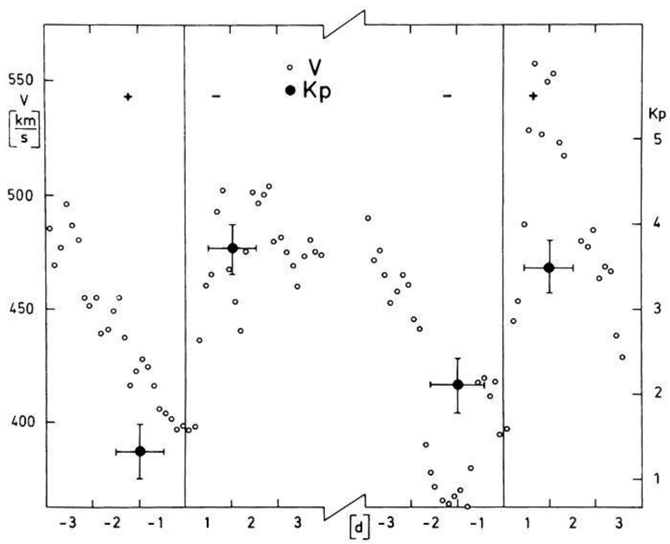

Fig. 4. Variation of 3 hourly values of the solar wind velocity v averaged for 6 vernal sector boundaries with available v data and daily averages of Kp 36–12 h before and 12–36 h after the boundaries

solar wind velocity v vary similarly at the four classes of sector boundaries and that the variations of these parameters alone do not cause the observed Kp variations.

In the following the influence of individual IMF vector components will be analysed in a somewhat more quantitative manner. The hourly IMF vector components three days before to three days after the 20 sector boundaries listed

Table 2. Changes Δ of 24 h average IMF magnetospheric components, Kp and solar wind velocity v at different sector boundaries (see text)

Season	Vernal months		Autumnal months	
Pol. change	+/− (I)	−/+ (II)	−/+ (I)	+/− (II)
ΔKp	1.92	0.63	1.53	0.37
ΔB [nT]	1.64	0.60	1.24	3.38
ΔB_{XM} [nT]	3.53	−3.67	−6.67	6.15
$\Delta \lvert B_{XM}\rvert$ [nT]	0.67	1.91	1.79	1.83
ΔB_{YM} [nT]	−5.07	4.20	5.64	−4.72
$\Delta \lvert B_{YM}\rvert$ [nT]	0.11	−1.18	0.58	2.60
$-\Delta B_{ZM}$ [nT]	1.59	−1.90	1.71	−1.92
ΔB_{SM} [nT]	1.44	−1.04	1.03	−0.14
Δv [km/s]	$1.10 \cdot 10^2$	$1.10 \cdot 10^2$	$1.10 \cdot 10^2$	$1.10 \cdot 10^2$

in Table 1 have been transformed from the given ecliptic into magnetospheric coordinates (e.g. Russel, 1971). This coordinate system should be used for interaction between the IMF components and the magnetosphere (Hirshberg and Colburn, 1969; Arnoldy, 1971), because here the Z-axis Z_M is connected with the actual direction of the earth's magnetic dipole axis.

From the hourly values daily averages were calculated taking into account 36–12 h before and 12–36 h after the sector boundaries. The differences Δ between these 2 daily means before and after the IMF polarity changes are listed in Table 2 together with the respective average ΔKp-values. The Δv value of 110 km/s listed in Table 2 was assumed to be equal at the four classes of sector boundaries. It was calculated from the averages of the 6 boundaries listed in Table 1 and agrees with the average v increase reported in previous studies (e.g. Wilcox, 1968). In Table 2 B_{XM} and B_{YM} are the average magnetospheric X and Y components of B and B_{ZM} is the average IMF magnetospheric Z component including northward directed hourly values, whereas the southward component B_{SM} is defined as $B_{SM} = -B_{ZM}$ for $B_{ZM} < 0$ and $B_{SM} = 0$ for $B_{ZM} > 0$. This definition implies, when B_{SM} is compared with Kp, that northward directed IMF fields are unimportant for generating geomagnetic activity as Arnoldy's (1971) results indicate.

From the individual lines of Table 2 it can be seen that at the four classes of sector boundaries no parameter shows similar variations as Kp. If for example the Kp variations were influenced only by the B_{ZM} (or B_{SM}) component of the interplanetary magnetic field the ΔKp values at sector boundaries (II) should be negative. Thus at least two parameters must be taken to account for the ΔKp values.

We assume as a first simplified approximation a linear relation between Kp, v and one component B_{KM} (K indicating either one of X, Y, Z or S) of the interplanetary field to describe the variation of Kp at the sector boundaries:

$$\mathrm{Kp} = a + b\,v + c\,B_{KM}$$

$$\Delta \mathrm{Kp} = b\,\Delta v + c\,\Delta B_{KM}. \tag{1}$$

At the boundaries (I) and (II) (in Table 2) we have two equations to calculate b and c from ΔKp, Δv and ΔB_{KM}. The coefficients b and c for sector boundaries near vernal months should approximately equal those for autumnal months. The calculations show that this condition is only satisfied, if we choose the Z-component $\Delta B_{KM} \equiv -\Delta B_{ZM}$ or $\Delta B_{KM} \equiv \Delta B_{SM}$.

In the first case we get $b_F = 1.2$ (vernal), $b_H = 0.90$ (autumnal), $b_M = 1.1$ (average) and $c_F = 0.37$, $c_H = 0.32$, $c_M = 0.34$ respectively. Assuming $\Delta B_{KM} \equiv \Delta B_{SM}$ we get $b_F = 1.1$, $b_H = 0.60$, $b_M = 0.82$ and $c_F = 0.52$, $c_H = 0.85$, $c_M = 0.67$, where in Equation (1) v is measured in units of 10^2 km/s and the IMF component in Nanotesla, $1\,nT = 1\,\gamma$. Though the vernal and autumnal coefficients seem to agree better for $\Delta B_{KM} \equiv -\Delta B_{ZM}$ this simple analysis cannot decide whether the average magnetospheric Z component B_{ZM} or the average southward directed component B_{SM} (ignoring northward directed fields) is the appropriate IMF parameter.

Using the absolute daily averages of Kp, v and B_{SM} and after the sector boundaries the coeffihcient a of Equation (1) may be calculated and we get with the data of 20 sectors listed in Table 1 an average relation

$$\mathrm{Kp} = -2.38 + 0.82\,v + 0.67\,B_{SM}; \qquad v[10^2\,\mathrm{km/s}], \qquad B_{SM}[nT]. \tag{2}$$

Independently a linear regression was calculated with daily averages of 120 days for which hourly IMF and solar wind velocity data have been available. The result

$$\mathrm{Kp} = -1.89 + 0.81\,v + 0.50\,B_{SM} \tag{3}$$

is similar to relation (2) indicating that at least the coefficients for v and B_{SM} of the relation between Kp, v and B_{SM} are similar on days near sector boundaries and on all days.

Discussion

The polarity- and season-dependent Kp increase at sector boundaries shown in Figures 1 and 2 is explained by the influence of the southward IMF component in magnetospheric coordinates and it is shown that some other IMF parameters as the magnetospheric X- and Y-components are less important to account for the observed Kp variations. The variation of the average three hourly B_{SM} component near sector boundaries is illustrated in Figure 5: At the left boundaries we see a sharp increase of B_{SM} and this in addition to an increasing v results in the great Kp-increase at the corresponding boundaries. At the right boundaries B_{SM} is slightly decreasing, and this in addition to an increasing v (assumed to equal the v increase at the left boundaries) results in a slight Kp increase. The simple linear relation (2) describing our interpretation should not be overestimated because it only includes the influence of v and one IMF component. Equation (2) is regarded only as an average relation of Kp, v and B_{SM} for daily means; errors of the constants may be estimated by a comparison of the coefficients in (2) and (3). Calculating in an analogous manner the coefficients b and c in Equation (1) for the 6 vernal (+/−) and (−/+) boundaries with available IMF and v data we obtained coefficients differing to a

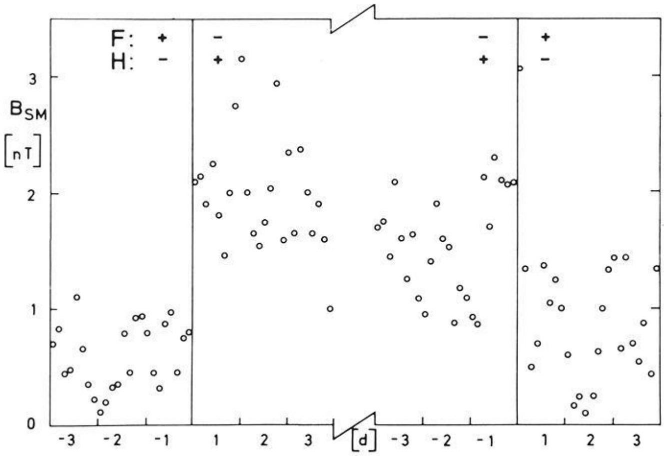

Fig. 5. Three hourly values of the southward magnetospheric IMF component B_{SM}; averages of vernal $F(+/-\cdots-/+)$ and autumnal $H(-/+\cdots+/-)$ boundaries

certain degree from those in (2). Assuming $B_{KM} \equiv B_{SM}$, we obtained $b_F = 1.4$ and $c_F = 0.82$, indicating that the assumed linear relation is not valid for all activity ranges, or that other parameters have to be included for a better description. However, these calculations also showed that the southward component should be included in the explanation of Kp. An exact error calculation for the coefficients in (2) is not possible with the few v data of only 6 sector boundaries.

The variation of IMF fluctuations and their possibly additional effects on geomagnetic activity as it was shown by Garrett (1974) is not examined and discussed here, and it is not excluded that IMF fluctuations may also be important for an explanation of the observed Kp variation. In the vicinity of the right sector boundaries of Figure 5 for example we find very high B_{SM} values which might be related to enhanced fluctuations at the boundaries, and corresponding high Kp values are seen in Figures 2 and 3 at the right boundaries.

The observed Kp variations at sector boundaries are in agreement with the hypothesis of Russel and McPherron (1973) to explain the different annual variation of geomagnetic activity for the two IMF polarities: Figures 1 and 2 show the predicted enhanced activity during vernal (−) sectors and autumnal (+) sectors. This should lead to an annual variation with vernal maximum for (−) and autumnal maximum for (+) sectors.

In a recent study Burton et al. (1975) relate the D_{st} index as a measure of the magnetospheric ring current to v and the product $v \cdot B_{SM}$. A corresponding relation of Kp being a linear function of v and $v \cdot B_{SM}$ also may explain the Kp variation of Figures 1 and 2 as it was examined by similar calculations as in the previous section. Thus we conclude that a relation of geomagnetic activity and parameters of the interplanetary medium should include the influence of the IMF southward component; however, it is also seen that the southward component is not the only parameter controlling geomagnetic activity. Theoretically the influence of the IMF southward component is described with merging models of interplanetary and geomagnetic field lines (e.g. Vasyliunas, 1975, for a review).

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