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Recalibration of Bartels' Geomagnetic Activity Indices *Kp* and *ap* to Include Universal Time Variations

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The *ap* index (and derived indices) can be recalibrated by using Mayaud's *am* index to recover the correct universal time variations. Such variations were artificially removed in the original *ap* index. A number of tests are performed to show that the corrected index is capable of revealing the desired variations. These tests include comparisons of the universal time variations on days of opposite interplanetary magnetic sector polarity. The finding that geomagnetic activity was considerably higher during intervals of toward polarity prior to 1963 is strongly confirmed.

When Bartels designed the geomagnetic activity index *Kp* [*Bartels et al.*, 1939], he had hoped that the universal time variation of geomagnetic activity could be investigated by using the new index. It turned out that the *K* indices for each individual station had such a strong dependence on local time that the very nonuniform longitudinal distribution of the *Kp* stations made such investigations hopeless. Thus it was necessary to remove the local time variation as well as a seasonal variation by applying normalization factors for each station. The factors were determined for each season, 3-hour universal time interval, and *K* index value by using *K* indices derived for 1943–1948. *Siebert* [1971] has described the detailed and quite elaborate standardization procedure used in the computation of *Kp*. The resulting *Kp* index should then have no universal time variation at all. As *Michel* [1964] points out, this goal was not quite achieved, and a very small residual universal time variation is still present. Except for the lowest values the *Kp* index for the first and second 3-hour interval of the universal time day is systematically too high, while it is too low for the fourth and fifth interval. These differences are due to imperfections in the standardization tables but are of no practical significance except for investigations of the universal time variations themselves.

Mayaud [1967, 1968] has utilized the much better present-day distribution of geomagnetic observatories to construct a true planetary activity index *Km*. Had the present network of observatories been available 30 or 40 years ago, the intricate standardization procedures could have been avoided, and the present paper would never have been written. It is, however, our purpose here to point out the possibility of recalibrating the *Kp* index by using the *Km* index. It does not matter that the *Kp* index has errors; the important thing is that these are systematic and therefore can be corrected for. We will present a correction table that for each *Kp* value (actually the corresponding *ap* amplitude) and for each 3-hour interval gives the corresponding average *am* value. In addition, an empirical formula will be shown to account for the remaining errors depending on time of year (the *Kp* index is basically a northern hemisphere index) and on universal time (most of the *Kp* stations are in Europe). Besides systematic errors there are inhomogeneities in the *Kp* index caused by changes in the way the individual *K* values are scaled. Any use of the *Kp* index or the recalibrated index must be exercised with care and must take the possibility of inhomogeneities into account. For long-term studies the *aa* index derived by *Mayaud* [1972] is recommended.

The 10-year interval 1959–1968 was chosen as the basis for the calibration. The procedure is now to compute the average observed *am* index for every *ap* value for each 3-hour universal time interval. There are 28 different *ap* values, i.e., 0, 2, 3, 4, $\cdots$, 236, 300, 400, corresponding to the *Kp* values 0o, 0+, 1−, 1, $\cdots$, 8+, 9−, 9. For each 3-hour interval of the day the observed average *am* index is plotted against *ap*. A smooth curve is drawn through the points, and smoothed values of *am* are read off and tabulated. Table 1 shows the resulting conversion table. There is little point in discussing this table in any detail except to note that for average values of *ap* (i.e., $ap \sim 10$) the *am* index is about twice as large as *ap*. The reason is of course that *am* is expressed in units of 1 γ (=1 nT), while *ap* is expressed in units of 2 γ. There has been a tendency to treat *ap* as a dimensionless number; it seems appropriate, however, to remember the physical significance of *ap* as a disturbance measured in gammas, thus relating it quantitatively to physical processes in the magnetosphere.

Using Table 1, we convert *ap* to *am* for 1959–1968 and calculate the average values of the computed *am* index for each calendar month. The ratio between the observed and the computed monthly means of *am* gives a seasonal correction factor for each month. Table 2 shows the smoothed seasonal correction factors. The computation of *am* thus involves the following procedure:

$$am^* = \text{Table 1 } (ap, h) * \text{Table 2 (month)} \qquad (1)$$

where we denote the computed value by *am**. The notation 'Table 1 (*ap*, *h*)' stands for the value obtained by using the value of *ap* and the number *h* of the 3-hour interval as indices in Table 1.

Up to now we have little assurance that the conversion procedure is not just a formal exercise with meager physical contents. Given any two sets of numbers, a mapping from one set to the other can always be performed formally as described above. For the procedure to have meaning will require the ratio *am*/*am** between the observed and the computed values to be either constant (ideally equal to 1) or at least systematically organized in terms of parameters related to the physical situation. It is remarkable that the ratio *am*/*am** depends on time of year and on universal time in a simple way:

$$am/am^* = 1 + 0.16 \sin \lambda \sin (t + 1.5 \text{ hours}) \equiv g(\lambda, t) \qquad (2)$$

where λ is the longitude of the earth in its orbit and t is universal time. Figure 1 shows how close the relationship actually is. If d is day of year (January 1 $\equiv$ 1) and h is the

TABLE 1. Conversion Table Giving *am** for Each *ap* Value and Each 3-Hour Universal Time Interval

	Three-Hour Universal Time Interval								
ap	1	2	3	4	5	6	7	8	*Kp*
0	2.3	2.2	2.0	1.9	1.4	1.5	1.6	1.7	0o
2	3.6	3.7	3.4	3.1	2.9	2.8	2.9	3.4	0+
3	5.3	5.5	5.3	5.2	5.0	4.9	5.2	5.2	1−
4	6.9	7.1	7.3	7.3	7.1	7.1	7.1	7.1	1o
5	8.6	9.0	9.4	9.6	9.3	9.2	9.1	9.1	1+
6	10.6	11.1	11.7	12.1	11.7	11.6	11.4	11.4	2−
7	13.1	13.6	14.5	15.2	14.6	14.4	14.1	14.1	2o
9	15.7	16.2	17.4	18.4	17.7	17.2	17.0	17.0	2+
12	19.0	19.5	20.9	22.3	21.5	20.8	20.5	20.5	3−
15	23.0	23.3	25.1	27.0	26.0	25.0	24.8	24.7	3o
18	26.9	27.1	29.3	31.7	30.6	29.3	29.0	28.9	3+
22	32.2	32.1	34.9	37.8	36.6	34.8	34.6	34.5	4−
27	38.2	37.7	41.1	44.7	43.3	41.1	40.8	40.7	4o
32	44.0	42.9	47.0	51.4	49.7	47.0	46.8	46.7	4+
39	51	49	54	60	58	55	54	54	5−
48	60	57	64	70	68	64	64	63	5o
56	67	63	71	78	75	71	71	71	5+
67	76	72	81	89	86	81	81	80	6−
80	87	82	92	102	98	92	92	92	6o
94	98	92	103	115	111	104	104	104	6+
111	111	103	117	129	125	117	117	117	7−
132	127	117	133	148	143	133	134	134	7o
154	143	131	151	168	162	151	152	151	7+
179	172	156	181	201	194	180	182	181	8−
207	206	187	217	241	233	216	218	218	8o
236	244	219	256	286	275	255	258	258	8+
300	327	292	344	383	369	341	346	345	9−
400	462	410	486	541	522	482	490	488	9o

The conversion is different for each 3-hour interval of the universal time day. Note that further corrections must be applied as described in the text.

number (1–8) indicating the 3-hour interval, we have approximately

$$\lambda = 279.7° + 0.98565° \text{ d}$$
$$t = 3 \times (h - 0.5) \text{ hours} \tag{3}$$

In calculating the sine functions, 24 hours is taken as being equivalent to 360°. The existence of the close relation (2) indicates that the concept of systematic errors in *ap* is indeed viable. The function $g(\lambda, t)$ as defined by (2) can be thought of as a further correction factor, allowing us to write

$$am^* = \text{Table 1 } (ap, h) * \text{Table 2 (month)} * g(\lambda, t) \tag{4}$$

It is appropriate to investigate how well the computed values, *am**, compare with the observed values, *am*. Because of the inherent quantization of the *ap* index the comparison will be carried out in terms of *K* indices. The *am** index is converted to *Km** indices by using Table 3, given by *Mayaud* [1968]. The same procedure is applied to the *am* index, and the *Km* index results. The *Km* index is given on a scale of thirds, so that the quantity 3*Km* is an integral number. The choice of a finer graduation of *Km* than that of individual *K* indices is justified on the ground that the index is averaged over several stations. If the random errors in individual *K* indices are about 1 unit, then about 10 stations are necessary to justify reporting *Km* in thirds of a *K* unit. With the current number of stations used for *Km* the resolution chosen for *Km* (and for *Kp*) is just about right. This also means that as long as the difference between *Km** and *Km* is not more than one third of a *K* unit it is hardly significant. Table 4 shows the distribution of the difference *Km** − *Km* for the 10-year calibration period 1959–1968. More than 91% of the single values agree within one third of a *K* unit, and 99.35% agree with two thirds of a *K* unit. We conclude that there is no significant difference between the observed *Km* and the *Km** computed from *ap* as far as individual 3-hour intervals are concerned. The interesting question, however, is to what degree the computed index *Km** (or alternatively *am**) shows the same, and much more subtle, variations with season, universal time, and interplanetary magnetic field polarity as the observed *Km* (or *am*) index. Such variations are of the order of a few thirds of a *K* unit and are much more susceptible to systematic errors that may be small but always work in the same direction.

TABLE 2. Monthly Correction Factors to *am**

Month	Correction Factor
January	1.05
February	1.02
March	0.99
April	0.98
May	0.98
June	0.98
July	0.98
August	0.98
September	0.98
October	0.99
November	1.02
December	1.05

Using the *am* index, *Mayaud* [1970] was able to confirm the existence of a universal time variation of geomagnetic activity. The phase of this variation changes with season, as can be seen from Figure 2 (right-hand panel), which shows the universal

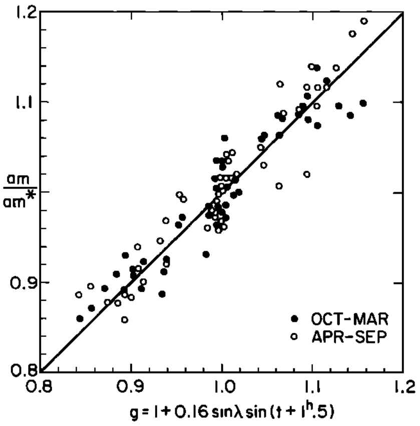

Fig. 1. Dependence of the ratio between observed *am* index and corrected *ap* (denoted *am**) on time of year and time of universal time day. The time of year is given as the ecliptic longitude λ of the sun, and the time of day as hours t of universal time. The function $g(\lambda, t)$ as defined in the figure strongly controls the value of the ratio *am*/*am**. Data points for two different parts of the year are plotted with different symbols. Monthly means of the ratio are plotted for each 3-hour interval of the universal time day.

time variation of the observed *am* index for the time interval 1965–1970. The left-hand panel shows the universal time variation obtained by using the computed *am** indices for 1969–1973. A different time interval was chosen deliberately; otherwise it would not be a real test of the ability of the *am** index to display those universal time variations. As is evident from the figure, it appears that the *am** index does indeed have the proper universal time variations, and thus it is suggested that we have succeeded in converting *ap* to an index that is useful in studying such variations. A critical examination of the conversion procedure could lead to the suspicion that it is precisely the correction factor $g(\lambda, t)$ that guarantees these universal time variations. It must be remembered that the *ap* index has a small residual universal time variation which has constant phase throughout the year. Applying the Table 1 conversion removes this variation. Multiplying by the $g(\lambda, t)$ factor then reintroduces whatever universal time variation might be present in the g function. On the other hand, the *am* index does have a universal time variation, and if it takes the g function to make *am** have the same universal time variation, then this can hardly be considered a deficiency in the conversion procedure.

An unambiguous test of the ability of the *am** index to exhibit real universal time variations can, however, be made by using the fact that geomagnetic activity has different universal time variations on days of opposite polarity of the interplanetary magnetic field [*Berthelier*, 1975; *Svalgaard*, 1976*a*]. Figure 3 shows the variations of the *am* index and its two components, the *an* index for the northern hemisphere and the *as* index for the southern hemisphere. The data have been divided into two groups on the basis of the interplanetary field polarity for each individual 3-hour interval. The activity during away polarity maximizes at 1040 UT, while the activity during toward polarity maximizes at 2240 UT. The difference between the diurnal variations for the two polarities is shown in the right-hand panel of the figure and is remarkably identical for both the northern and the southern hemispheres, the global or 'planetary' nature of this phenomenon thus being indicated. A quantitative theory explaining these variations has been presented by *Svalgaard* [1976*a*].

TABLE 3. Conversion Table Between *am* and *Km*

Km	*am* Interval
0o	0.0–1.4
0+	1.5–3.4
1−	3.5–5.4
1o	5.5–7.4
1+	7.5–10.4
2−	10.5–13.4
2o	13.5–16.4
2+	16.5–20.4
3−	20.5–26.4
3o	26.5–33.4
3+	33.5–40.4
4−	40.5–50.4
4o	50.5–60.4
4+	60.5–70.4
5−	70.5–86.4
5o	86.5–103.4
5+	103.5–120.4
6−	120.5–146.4
6o	146.5–173.4
6+	173.5–200.4
7−	200.5–243.4
7o	243.5–286.4
7+	286.5–330.4
8−	330.5–386.4
8o	386.5–443.4
8+	443.5–500.4
9−	500.5–611.4
9o	611.5–∞

The test is now simple in principle. Divide the days of a certain time interval into two groups according to the polarity of the interplanetary magnetic field. Compute the diurnal variation of geomagnetic activity measured by the index under test for each group. Compare the resulting variations with the variations shown in Figure 3. If the variations found have the same phases and amplitudes as the 'standard' variations of Figure 3, we may conclude that both the division of the days into groups according to polarity and the ability of the geomagnetic index to show real universal time variations have met with success. We shall now perform such a test.

The interplanetary magnetic field is organized into a large-scale sector structure where the polarity largely stays constant for several days (≈7) and then abruptly changes to the opposite polarity, which then is observed to be predominant for the next several days [e.g., *Wilcox*, 1968]. Regions of opposite polarity are separated by a narrow current sheet, the sector boundary. The sector boundary thus may serve as a marker

TABLE 4. Distribution of the Difference Between *Km** and *Km* for the 10-year Interval 1959–1968

K Unit	Number of 3-hour Intervals	Difference, %
<−1	10	0.03 (0.08)
−1	110	0.38 (1.03)
−⅔	1179	4.03 (6.95)
−⅓	6292	21.53 (23.31)
0	12803	43.81 (36.07)
+⅓	7567	25.89 (23.58)
+⅔	1192	4.08 (6.98)
+1	67	0.23 (1.75)
>+1	4	0.01 (0.25)

The numbers in parentheses give the distribution of differences between actual *Km* and average *Km* computed separately for each *Kp* bin [after *Mayaud*, 1967, Figure 3].

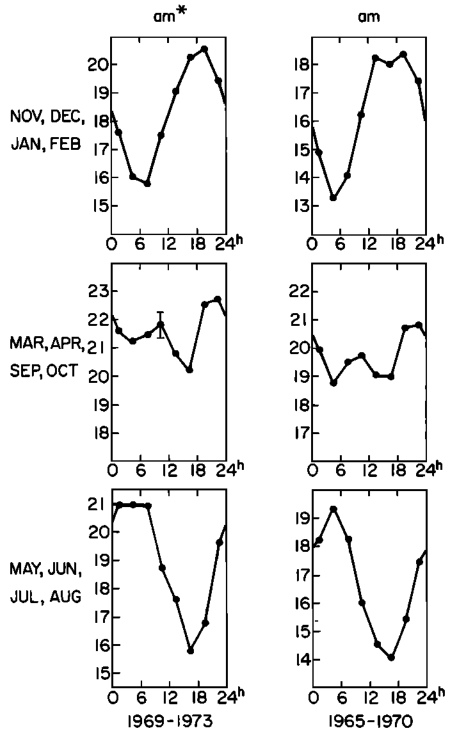

Fig. 2. Seasonal variation of the universal time variation of the *am* and the corrected *ap* index (denoted as am^*). The solstices have variations that are in antiphase, while at the equinoxes two maxima and two minima are apparent.

dividing days before the boundary from days following the boundary. This division will then also divide the days into two groups according to sector polarity. If the sector boundary is 'well-defined,' the polarity is the same for several days on both sides of the boundary. Most sector boundaries are well defined in the sense defined above. There are of course short-term fluctuations of the polarity, but within a given sector the predominance of a certain polarity is a persistent and well-documented property of the interplanetary medium. A list of well-defined sector boundaries during the years 1957–1974 has been compiled by *Svalgaard* [1975] and extended back through the time interval 1947–1956 [*Svalgaard,* 1976*b*]; the sector polarity was either measured by spacecraft (mostly after 1964) or inferred from geomagnetic records using very high latitude stations (Thule, Resolute Bay) only occasionally supplemented with polar cap boundary stations (Godhavn and Dumont D'Urville). An advantage in using a sector boundary list rather than a list of dominant polarity on each day is that the large-scale regularity and recurrence tendency of the sector structure makes identification of the boundaries more reliable than inferred polarities on individual days. Seasonal biases are also minimized.

The first step is to provide a 'standard' of the difference between the universal time variations for the two polarities by using the *am* index and sector boundaries for an interval where the identification of the latter is well supported by in situ spacecraft measurements. The time interval 1965–1970 contains 89 boundaries where the polarity changes from away to toward ((+, −) boundaries) and 92 boundaries where the polarity changes from toward to away ((−, +) boundaries). For the (+, −) boundaries the diurnal (i.e., the universal time) variation was computed for away polarity by using the four days from 5 to 1 day before the boundary for all the (+, −) boundaries. Similarly, the diurnal variation for toward days was computed by using the 4 days from 1 to 5 days after the boundary passage. Finally, the same procedure is applied to the (−, +) boundaries. The resulting universal time variations are shown in Figure 4, open and solid circles indicating away and toward polarity, respectively. The same general variations are present as those shown in Figure 3. The amplitude is a little less because the time resolution of the polarity division was 1 day rather than the 3 hours used in preparing Figure 3.

The next step is to repeat the above analysis by using the am^* index computed from *ap*. The result is also shown in Figure 4 (open and solid triangles). We note that the result is very similar to what we obtained when we used the original *am* index as regards both phase and amplitude. In fact, there is no significant difference between the two indices, and thus our contention is supported that we have succeeded in converting the *ap* index to an index (which we have termed am^*) capable of revealing the same universal time variations as the *am* index. This concludes the test of the similarity between the two indices even as regards very subtle statistical effects such as the elusive universal time variations.

A further comparison may be carried out by using the difference between the diurnal variations on away days and on toward days. Because the universal time variations increase in amplitude with increasing activity level [*Svalgaard,* 1976*a*], the 3-hour values for each day are now normalized by dividing each of them by the average value of the activity $(\overline{am})$ for that

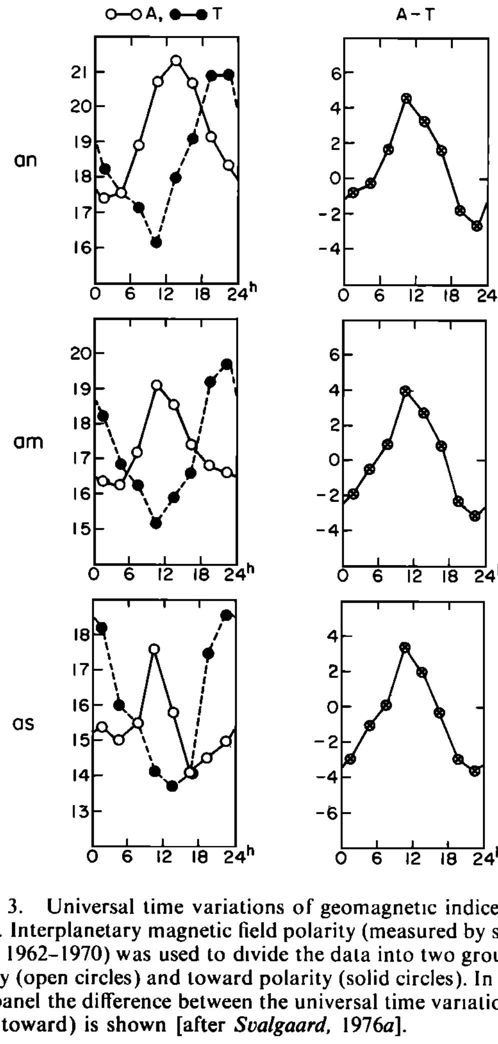

Fig. 3. Universal time variations of geomagnetic indices *an*, *am*, and *as*. Interplanetary magnetic field polarity (measured by spacecraft during 1962–1970) was used to divide the data into two groups: away polarity (open circles) and toward polarity (solid circles). In the right-hand panel the difference between the universal time variations (away minus toward) is shown [after *Svalgaard,* 1976*a*].

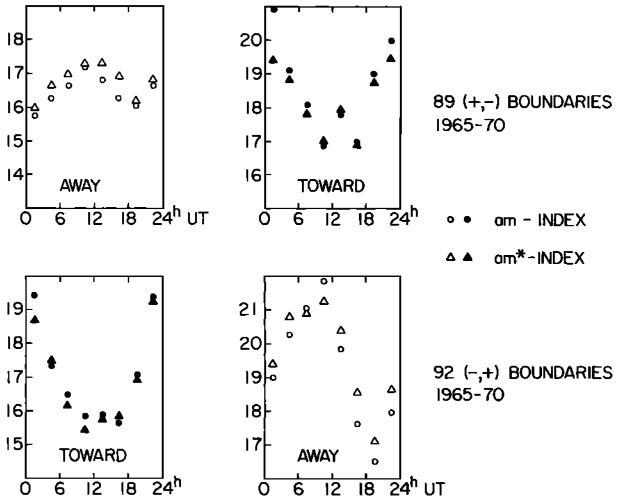

Fig. 4. Universal time variations of *am* (circles) and *am** (triangles) on 4 days before and after passage of sector boundaries during the interval 1965-1970. The two kinds of boundaries away to toward, or (+, −), and toward to away, or (−, +), are treated separately. Note that a trace of the doubled-peaked universal time variation shown in the center part of Figure 2 is superposed on the variations taken separately for the two polarities. This is particularly evident for the (+, −) boundaries.

day. As was described in the previous section, we again compute the average diurnal variations for away and toward days, but this time we further compute the difference between the two average variations:

$$\delta_{AT} = 100(am_A/\overline{am}_A - am_T/\overline{am}_T)\% \qquad (5)$$

By doing so we isolate universal time variation related only to the sector polarity. In Table 5 we report these percentage differences for both the *am* and the *am** indices for the years 1965-1970. As the two indices are plotted in Figure 5, we again note the close similarity between them. Both in Table 5 and in Figure 5 the variations are shown separately for each kind of sector boundary polarity change to indicate the noise level of the analysis. It seems almost superfluous to point out again the ability of both indices to reveal the universal time variation related to the sector polarity.

For the years 1947-1956, only the *am** index is available

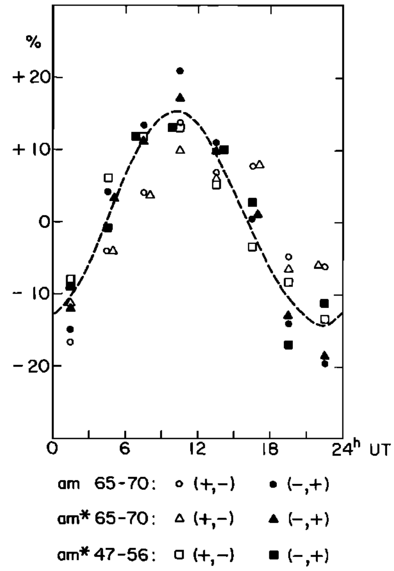

Fig. 5. Universal time variation of the difference between the normalized activity for the two opposite polarities (away minus toward). Various indices and time intervals are analyzed separately and indicated with different symbols as shown. The polarity division was performed by using well-defined sector boundary passages where the polarity is observed to be constant for several days on both sides of the boundary. The dashed line is drawn by hand to emphasize the overall structure of the difference curve.

(computed from *ap*, which goes back to 1932). By means of the sector boundary list prepared by *Svalgaard* [1976*b*] using polarities inferred from polar cap magnetograms we repeat the analysis described above and enter the results in Table 5 and on Figure 5 (squares). There is no significant difference in amplitude and phase of the universal time variation obtained by using these early data and the variation obtained by using the *am* index and the modern sector boundary data. We can only conclude the the sector boundary list for 1947-1956 represents apparently quite well true polarity reversals. At first sight there is nothing startling about this conclusion. If we assume that the response of the magnetosphere to the interplanetary magnetic field was the same in 1947-1956 as it is now, then we would expect that sector polarities inferred from magnetograms taken then should have about the same accuracy as the polarities inferred from modern magnetograms. The modern inferences are quite accurate, as is shown by

TABLE 5. Percentage Differences $\delta_{AT} = (a_A/\bar{a}_A - a_T/\bar{a}_T)$ Between the Universal Time Variations on Days With Opposite Sector Polarity

	am 1965-1970		*am** 1965-1970		*am** 1947-1956	
	(+, −)	(−, +)	(+, −)	(−, +)	(+, −)	(−, +)
Number of 3-hour interval						
1	−16.8	−15.0	−11.2	−11.5	−7.8	−8.9
2	−4.1	4.0	−3.8	3.4	6.2	−0.7
3	4.0	13.4	3.8	11.3	11.7	11.7
4	13.7	21.0	9.7	17.2	13.5	12.9
5	6.7	11.0	5.9	9.7	5.2	10.1
6	7.6	0.4	8.0	1.2	−3.4	2.7
7	−4.7	−14.1	−6.6	−12.9	−8.3	−17.1
8	−6.2	−19.7	−6.0	−18.5	−13.5	−10.8
Number of sector boundaries used	89	92	89	92	140	143

Here various time intervals and indices are compared as discussed in the test.

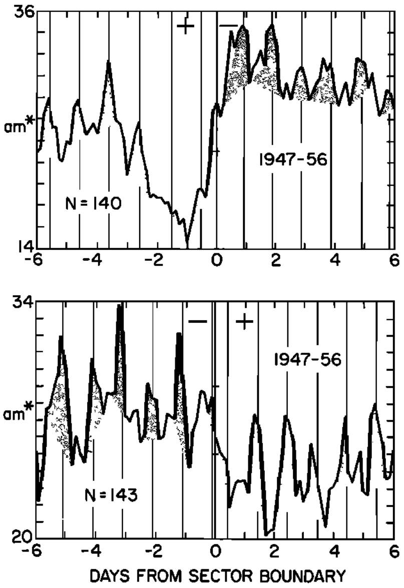

Fig. 6. Response of the *am** index to the passage of sector boundaries during 1947–1956, shown separately for the two kinds of polarity change. The numbers (*N*) of boundaries superposed are also shown. (Top) Response to (+, −) boundaries. (Bottom) Response to (−, +) boundaries. Light vertical lines are drawn at 24-hour intervals to indicate the expected position of the maxima in the universal time variations. The observed maxima (shaded) fall near the expected positions, the accuracy of the sector boundaries thus being validated. Much smaller secondary maxima are often seen, being residual traces of the double-peaked universal time variation discussed in the legend for Figure 4.

Russell et al. [1975*a*], *Wilcox et al.* [1975], and *Fairfield and Ness* [1974].

While the modern data (1965–1970) show no difference between the two polarities, the earlier data (1947–1956) reveal a marked difference in the sense that toward polarity was considerably more active than away polarity. This tendency has been noted by several workers, including *Chernosky* [1973], *Fougere* [1974], *Russell et al.* [1975*b*], *Mishin and Shelomentsev* [1975], *Bhargava and Rangarajan* [1975], and *Berthelier and Guérin* [1975], and is somewhat unexpected. This imbalance has been interpreted as a systematic error or 'bias' in the inferred polarity, as we would expect no such difference. Since geomagnetic activity depends on the field strength of the interplanetary magnetic field, the imbalance could also be explained by assuming that toward polarity was more concentrated into narrower sectors with stronger fields than away polarity was. Such a situtation is not likely to persist for extremely long periods, but there is no fundamental reason why it should not be able to exist for, say, some tens of years.

A striking illustration of the different activity level for the two sector polarities during 1947–1956 is given in Figure 6. The result of superposing *am** around the two kinds of sector boundaries is shown. All boundaries are nominally recorded to the nearest beginning of a universal time day; i.e., all passages are considered to occur at 0000 UT. Thus Figure 6 shows both the response of geomagnetic activity to the passage of a sector boundary and the universal time variation of the activity for each polarity. Away polarity should result in a maximum of activity at 1040 UT, while toward polarity should result in a maximum at 2240 UT [e.g., *Svalgaard,* 1976*a*]. On Figure 6, light lines are drawn for each day at the time of the expected maxima. Such maxima do indeed occur at the correct phases, and thus the reality of the inferred boundaries is strongly supported. Also the tendency for toward polarity to be more active is clearly seen. The 'standard' response of geomagnetic activity to passage of a sector boundary, i.e., an increase 1–2 days after the boundary, is not seen at all for the (−, +) boundaries but is on the other hand very pronounced for (+, −) boundaries. It is of interest to note that a similar but less pronounced difference between the two kinds of boundaries even exists during the time of spacecraft measurements [*Shapiro,* 1974].

We have investigated the possibility of correcting the *ap* index so that it becomes a close approximation of the real planetary index *am*. Various tests performed on the computed index *am** suggest that such conversion is meaningful. We propose that *ap* (and derived indices) be replaced by *am* from 1959 and by *am** before 1959. Preliminary indices may be computed by first computing *ap* in the standard way and then converting to *am**. In this way the rapid publication of the index is ensured. *K* indices are easily derived from *am**, and the vast majority of users of the indices will not have to worry about the distinction between the preliminary and the final values of the index. The scientific community will benefit from the simplification of using only one 'planetary' 3-hour index while at the same time the valuable long time series extending back to 1932 is preserved.

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