

# POLAR MAGNETIC FIELDS OF THE SUN: 1960–1971

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**Abstract.** Observations of the magnetic fields in the polar regions of the Sun are presented for the period 1960–1971. At the start of this interval the fields at the two poles were consistently of opposite sign and averaged around 1 G. Early in 1961 the field in the south decreased suddenly and the field in the north decreased in strength slowly over the next few years. By the mid-1960's the fields at both poles were quite weak and irregular. Throughout the period of these observations the fields at both poles often showed a remarkable tendency to vary in unison. About the middle of 1971 the north polar field became significantly positive, first at lower latitudes, then above  $70^\circ$ . An auto-correlation analysis of the polar fields in the north shows a weak rotation peak, indicating significant 'features' in these regions. A comparison of field strengths in the east and west quadrants in the north suggests that even at the extreme polar latitudes the following polarity fields are inclined slightly toward the rotation and the preceding polarity field lines are inclined slightly to trail the rotation.

## 1. Introduction

The magnetic fields in the polar regions of the Sun have interested solar physicists and others for many decades. Since the first development of the solar magnetograph (Babcock, 1953), these fields have been measured regularly by Mount Wilson astronomers. Earlier polar field observations have been published by H. W. and H. D. Babcock (1955) and by H. D. Babcock (1959), who noted a reversal of polarity of the fields near the solar poles around the time of the activity maximum of cycle 19 in 1957 and 1958. Some of the data presented in this paper have been published earlier by this author (Howard, 1965).

The early polar field data published by the Babcocks were obtained with the prototype solar magnetograph at the Hale Laboratory telescope in Pasadena. Starting in 1957, observations were made with the magnetograph at the 150-ft tower telescope at Mount Wilson. All the observations presented here were made with this instrument. This magnetograph has undergone a succession of improvements over the years. In general the quality of the data has improved steadily with time. Starting in the second half of 1966, the output of the magnetograph and scanning systems was digitized and recorded on magnetic tape for subsequent analysis. This improvement has enabled us to obtain more accurate integrated magnetic field strengths than before, and to examine more carefully than we could before the distribution of magnetic fields averaged over specific regions of the solar surface.

In this paper I shall examine the magnetic data in polar latitudes for the years 1960 to 1971. The fact that the quality of the data varies with time makes it hazardous to compare results from one part of this interval to another. In particular, a comparison between the analog and digital data may be uncertain. The years 1967 and 1968

are presented in both analog and digital forms as a check on the consistency of the data.

## 2. The Older Data

### 2.1. THE INSTRUMENT AND THE ANALYSIS

From 1960 until the end of 1962 the magnetograph signal was recorded on an oscilloscope screen with a technique that enabled us to see relatively easily the magnetic-field, strength and polarity and position on the solar disk (Howard and Babcock, 1960).

During the period 1963–1968 the polar field estimates were made from an analog magnetograph signal which was recorded on an X–Y servo plotter display (Howard 1963). The solar disk was scanned in a raster pattern with a square aperture, which until 1967 was 23" on a side. After this time the resolution was 17". An image slicer was used to spread the light along the spectrograph entrance slit. The X–Y servo plotter pen assembly moved over the plotting paper in the same pattern that the aperture effectively scanned the solar image. Two separately actuated colored pens were lowered to write in a coded sequence as the magnetic signal varied. In principle, a large number of magnetic levels of both polarities may be distinguished with such a scheme. In practice, the levels become difficult to distinguish in a big active region where magnetic gradients along the surface of the Sun are large, but in the polar regions it is easy to identify the magnetic levels without ambiguities.

The average magnetic fields in Figure 1 represent eye estimates of magnetic field strength poleward of about  $60^\circ$  latitude. Ten-day averages are presented. These field strengths represent the average longitudinal component of the magnetic fields with no

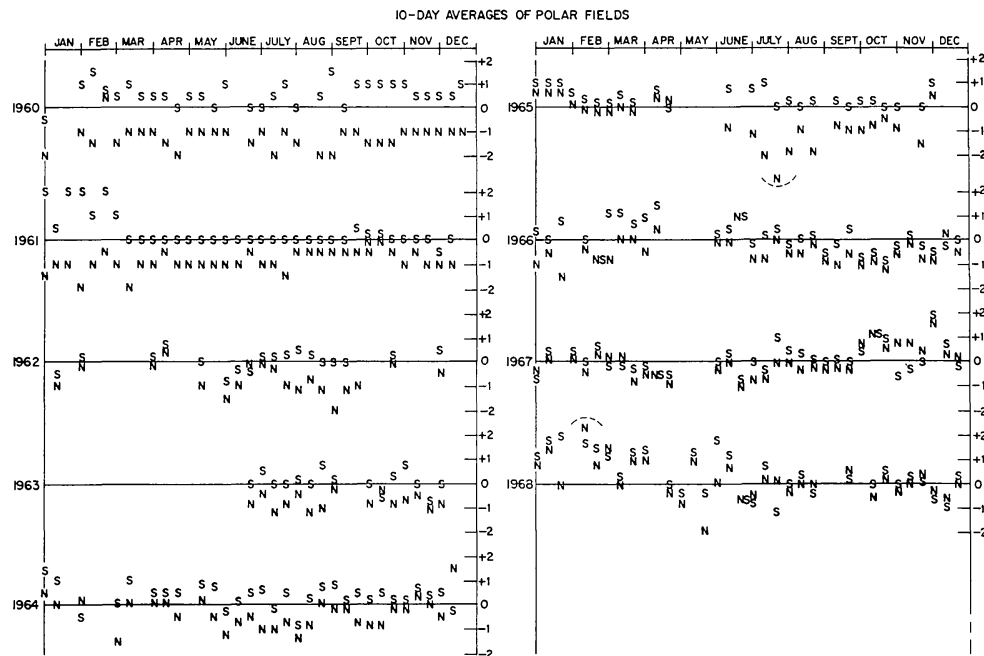


Fig. 1. Ten-day averages of polar magnetic fields from 1960 through 1968. 'S' indicates the field in the south, and 'N' indicates the field in the north. The scales are in gauss. There was a lengthy gap in the data in early 1963 due to a change in instrumentation.

correction for orientation of field lines, limb darkening, or temperature sensitivity effects of the  $\lambda 5250$  Fe I line that was used.

If daily values of the polar fields were represented they would show considerable variation not seen on the averages. Part of this ‘noise’ is undoubtedly due to zero shifts and other instrumental artifacts; however, some of this day to day variation is due to true rapid changes of the magnetic fields in the polar regions of the Sun, as was pointed out by H. W. and H. D. Babcock (1955). This effect has been studied more recently by Severny (1971), but it will not be considered in this analysis.

## 2.2. RESULTS

As can be seen in Figure 1, the two polar fields in 1960 were predominantly of opposite sign, and the situation was generally similar to that following the polarity reversals a few years before. (Negative fields were in the north.) The field strengths in the north were slightly greater than those in the south.

In about February or March 1961, the south polar fields dropped suddenly in strength, and, although they increased slightly later, they never again became consistently as strong as they were before early 1961. The north fields decreased somewhat through 1961.

In the years following 1961 the situation became less simple, and variations with time became greater. In general, although there were lengthy intervals of time when the polarity at one or the other pole was reversed, the polarity of the polar fields remained as it had been in 1960, but the field strengths were greatly reduced. This situation prevailed until early in 1967 when the field strengths in the polar regions reached their smallest values.

In the last few months of 1967 and throughout 1968 the polarities of the polar fields were mixed, although the amplitudes were at times high.

Throughout the interval shown in Figure 1 there is no indication of a distinct long-lasting polarity reversal at either pole. The inhomogeneities inherent in the data because of the rather frequent changes in instrumentation are a disadvantage in studying synoptic records of this type, nevertheless we may be confident that gradual long-term variations are or would be real. The sudden change in early 1961 does not coincide with any instrumental change and is certainly a real phenomenon.

## 3. The Recent Results

### 3.1. THE INSTRUMENT AND THE DATA

Starting in the last half of 1966, the magnetic signal and the position information, along with other data, were digitized and recorded on magnetic tape. A subsequent analysis has been made of all this data on a digital computer to obtain average magnetic field strengths over various latitude zones in each of the four quadrants of the solar disk. These data are not corrected for inclination of field lines or temperature sensitivity of the  $\lambda 5250$  line; however, the limb darkening is compensated because the brightness signal in the line is recorded and used in the analysis. This means that the

fields nearer the limb will be relatively more important in determining the average fields in these later data.

Most of the results published here for the later data are in the form of 31-day running means of the magnetic field strength. This smooths out many of the rapid fluctuations mentioned above.

For the data poleward of  $70^\circ$  latitude, the inclination of the solar rotation axis to the ecliptic becomes an important factor. In the winter months the north polar latitudes are partly obscured, and in the summer months the south polar region is partly obscured. On the figures in this paper these intervals are marked for each pole.

### 3.2. AVERAGE FIELDS OVER THE POLAR REGIONS

Figure 2 shows for each hemisphere average fields poleward of  $70^\circ$  and of  $60^\circ$  latitude.

The fields at both poles started out at the end of 1966 with negative polarity, with the north slightly more negative than the south. These fields weakened during 1967 and by the end of the year were slightly positive. These fields weakened again during 1968 and became very slightly negative by the end of 1969. Throughout 1970 and early in 1971 the fields remained extremely weak but slightly negative on the average. In the last part of 1971 the polarity of the polar fields became consistently positive, first in the north, then two months or so later in the south.

An interesting feature seen in Figure 2 is the tendency for the fields at both poles to show the same behavior at times. One must be careful with fields as weak as these that instrumental effects do not predominate; however, there are enough differences between different parts of the solar surface and enough cases of time lags between various parts of the Sun that we may feel confident that almost all the important features seen on these plots are solar in origin. For example, in the first few months of

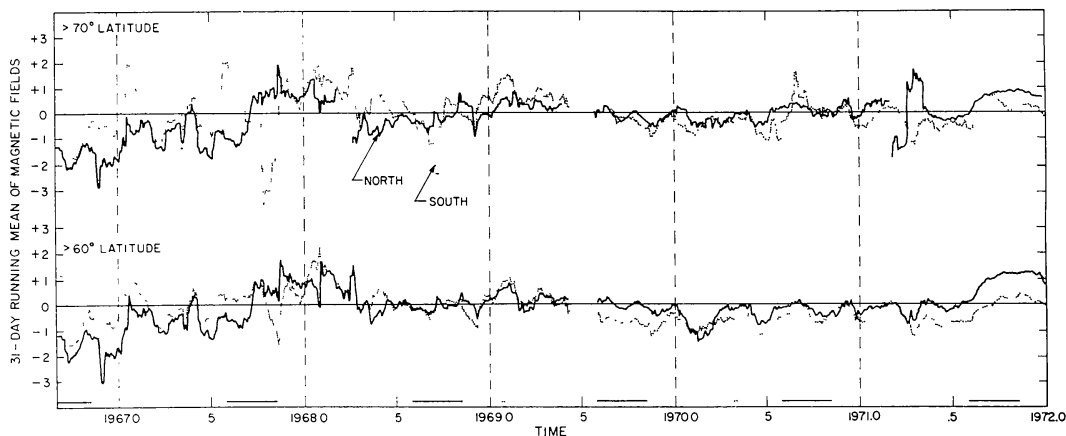


Fig. 2. Thirty-one-day running means of the magnetic fields of the Sun poleward of latitude  $70^\circ$  (top) and poleward of latitude  $60^\circ$  (bottom). The solid line represents the northern data, and the dotted line represents the southern data. The scales are in gauss. In this and the next two figures the straight dotted lines at the bottom of the figures represent an interval of time when the latitude of the center of the solar disk ( $B_0$ ) is less than  $-4\frac{1}{2}^\circ$ , therefore the polar fields in the north are poorly seen. The straight solid lines at the bottom of the figures represents a similar period when the south polar fields are poorly seen.

1970 there is a negative drift of the fields in the  $60^\circ$  plots both in the north and in the south. These features are not present – or only faintly so – on the  $70^\circ$  plots.

### 3.3. LATITUDE DRIFT

In Figure 3 are presented for each hemisphere the average fields in latitude zones  $51\text{--}60^\circ$ ,  $61\text{--}70^\circ$ , and poleward of  $70^\circ$ . Often the behavior of the fields in all three zones is quite similar, but at times there is evidence for a time lag in flux changes. This is especially evident in the north in the last half of 1971, where the rise to relatively high positive fields takes place first in the  $51\text{--}60^\circ$  latitude zone, then drifts poleward.

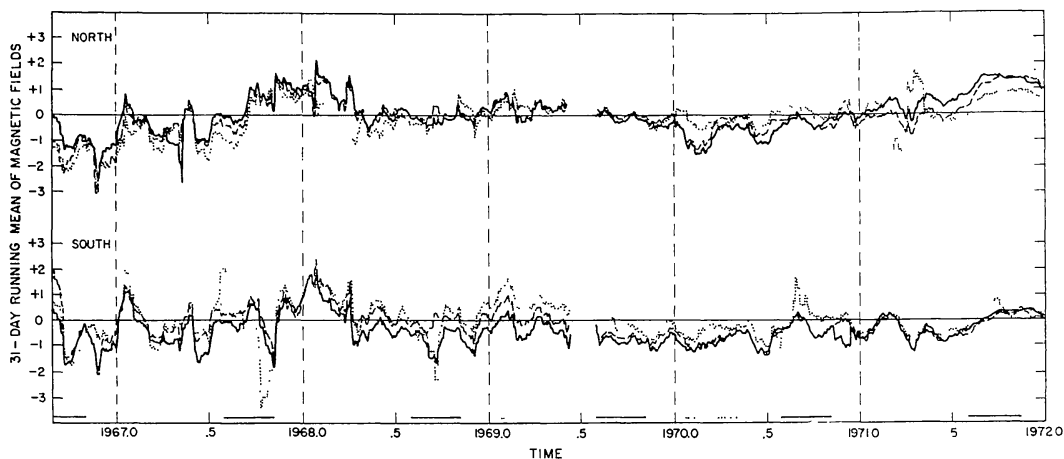


Fig. 3. Polar fields near the north pole (top) and the south pole (bottom). The solid lines represent the fields averaged over latitudes of  $51\text{--}60^\circ$ . The dashed lines represent fields averaged over latitudes of  $61\text{--}70^\circ$ . The dotted lines represent fields averaged over latitudes poleward of  $70^\circ$ . The scales are in gauss.

This seems to represent a real poleward drift of positive polarity magnetic flux. Later in the year fields in the  $51\text{--}60^\circ$  zone decreased in strength somewhat. This is the clearest indication of a polar field reversal in this cycle, and it may represent in the north the polarity reversal that has been anticipated for some years. The polar fields in the southern hemisphere also became somewhat positive in the last months of 1971, so we still cannot say that the Sun has reversed its polarity. In the last cycle the magnetic fields at the south pole reversed about one year before the reversal at the north pole (Babcock, 1959).

### 3.4. THE EAST AND WEST HEMISPHERE

In Figure 4 are plotted the average fields over the latitude range  $N61\text{--}N70^\circ$ , with each quadrant plotted separately. There is a definite tendency for the fields in the NW quadrant to be more negative than those in the fields in the NE quadrant. This is particularly true in the later period.

A similar comparison of east and west hemisphere data for latitudes poleward of  $70^\circ$  in the south shows little or no such effect. The fields at lower latitudes in the north show a much stronger effect in the same direction. The southern fields at lower lati-



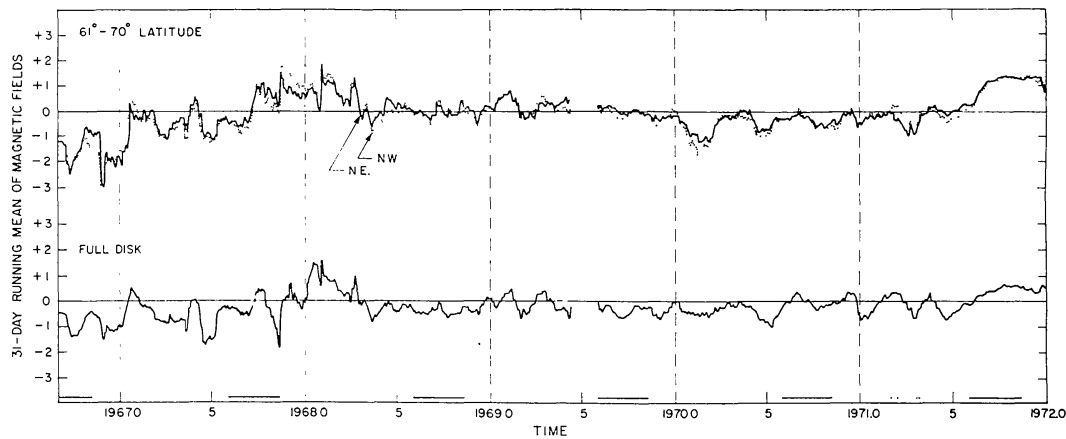


Fig. 4. Top: Thirty-one-day running means of average magnetic fields in latitude zone  $61\text{--}70^\circ$ . The solid line represents the average in the northeast, and the dotted line represents the average in the northwest. Bottom: Thirty-one-day running mean of the magnetic fields averaged over the whole solar disk. The scales are in gauss.

tudes show the opposite effect, i.e., the western quadrant is more positive than the eastern quadrant.

Since it seems unlikely that the fields on the Sun could be reacting to the position of the Earth in its orbit, the most probable explanation of this effect is that the lines of force of the two polarities show slightly different inclinations to the vertical at the depth in the photosphere where the  $\lambda 5250$  line is formed. The sense is that the preceding polarity fields are inclined slightly to the east (trailing the rotation), and the following polarity fields are inclined slightly to the west. This same effect has been found before in active regions (Howard, 1959). Table I lists the results in the various latitude zones for the whole period for which digital data are available and for each year. In the table are listed the average magnetic field in G for each quadrant and each latitude zone. Also the east-west differences are given. Curiously, in the south the differences are not always what one should expect for following polarity inclined toward the rotation and preceding polarity inclined away from the rotation. In 1970 the east-minus-west difference in the south was strongly positive. This effect was also noted in the lower northern latitudes (a positive shift of the difference), but the northern polar latitudes were unaffected.

It is difficult to estimate the inclination of field lines very accurately from these results because we see magnetic fields in each hemisphere that are inclined at various angles to the line of sight at any one time; moreover, the absence at this time of the magnetic-flux data for each sign of the field makes such estimates uncertain. Therefore, a calculation of the magnitude of the inclination of the field lines will be made in a later paper, when the flux data are available.

### 3.5. AUTOCORRELATION OF POLAR FIELD DATA

Figure 5 shows the autocorrelation of magnetic-field data poleward of  $N70^\circ$  done for the eastern quadrant, the western quadrant, and for data from both quadrants. This

TABLE I  
Average magnetic fields (G)

	All data			1966			1967					
	E	W	E-W	E	W	E-W	E	W	E-W			
North												
> 70°	-0.18	-0.25	+0.07	-1.74	-1.63	-0.11	-0.39	-0.52	+0.13			
61-70°	-0.01	-0.09	+0.08	-1.39	-1.59	-0.20	-0.11	-0.14	+0.03			
51-60°	+0.08	+0.01	+0.07	-1.11	-0.95	-0.16	+0.13	+0.08	+0.05			
South												
> 70°	-0.02	+0.03	-0.05	-1.01	-0.66	-0.35	-0.04	+0.03	-0.07			
61-70°	-0.22	-0.23	+0.01	-0.81	-0.49	-0.32	-0.06	+0.03	-0.09			
51-60°	-0.38	-0.43	+0.05	-0.86	-0.94	+0.08	-0.28	-0.27	+0.01			
	1968			1969			1970			1971		
	E	W	E-W	E	W	E-W	E	W	E-W	E	W	E-W
North												
-0.20	+0.11	-0.31	+0.11	-0.06	-0.16	+0.10	+0.07	+0.02	+0.05	+0.36	+0.30	+0.06
+0.15	+0.13	+0.02	+0.13	+0.04	-0.03	+0.07	-0.36	-0.44	+0.08	+0.51	+0.43	+0.08
+0.11	+0.07	+0.04	+0.07	-0.04	-0.08	+0.04	-0.49	-0.64	+0.15	+0.78	+0.68	+0.10
South												
+0.58	-0.06	+0.64	-0.06	+0.47	+0.49	-0.02	-0.26	-0.39	+0.13	-0.26	-0.19	-0.07
+0.26	-0.04	+0.30	-0.04	-0.16	-0.10	-0.06	-0.55	-0.75	+0.20	-0.30	-0.36	+0.06
-0.27	-0.09	-0.18	-0.09	-0.51	-0.53	+0.02	-0.59	-0.77	+0.18	-0.21	-0.29	+0.08

autocorrelation is made from all the available digital data. On all three autocorrelation curves there is a hint of a broad rotation peak from about 20 to 35 days. This indicates that there are features in the extreme polar latitudes that are statistically distinguishable and that return with a period around 25 to 30 days.

The determination of a synodic period by the method mentioned above can be used to determine the rotation rate of solar magnetic fields as a function of latitude (Wilcox and Howard, 1970), although it has never before been extended to such high latitudes. From this same data, similar autocorrelations made using data at lower latitudes in the north show much stronger autocorrelation peaks, and in general give rotation periods that are in agreement with the results of Wilcox and Howard. One would expect that the rotation period for the polar cap would be longer than that derived from Figure 5 – perhaps 35 days.

Similar autocorrelation curves for the southern hemisphere polar cap do not show any hint of a rotation return. The lower latitude southern autocorrelations show return peaks, but they are weaker correlations than are seen for the north. It seems that the lower level of solar activity in the south (Waldmeier, 1971) has provided a weaker pattern of magnetic fields there.

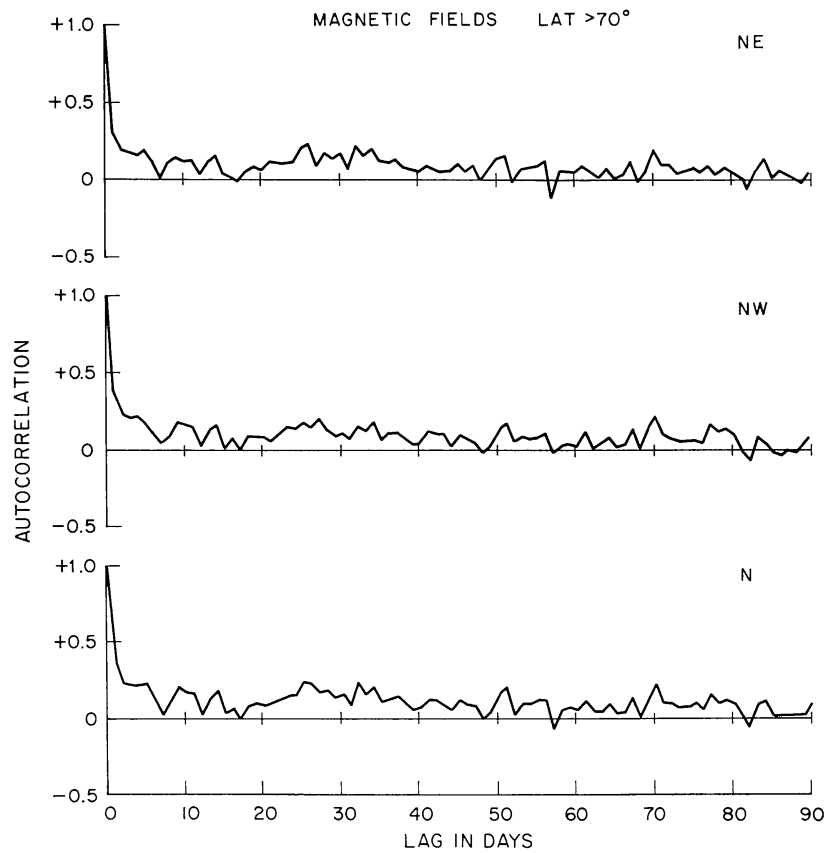


Fig. 5. Autocorrelation as a function of lag (in days) for magnetic fields averaged over latitudes poleward of  $N70^\circ$ . Top: in the northeast; center: in the northwest; bottom: for data from both the northeast and the northwest.



#### 4. Discussion

The ~~polar crown filaments, which had been observed for some years, disappeared near the end of 1970.~~ There appears to be no particularly striking behavior of the polar magnetic fields associated with the end of 1970. Thus, although it seems quite reasonable ~~that the polar crown filaments are associated with the polar magnetic fields,~~ the observations do not show any obvious connections.

The evidence for the drift of magnetic flux toward the north solar pole in mid-1971 is quite strong (see Figure 3), but the speed with which the fields appear to move is quite great. Since the time taken for the positive polarity fields to go from about  $60^\circ\text{N}$  to about  $80^\circ\text{N}$  latitude is approximately 4 months, this is about 25 m/s. This is much faster than the polar drift of magnetic flux required in the Babcock activity model (Babcock, 1961) or in the dynamo model of Krause and Rädler (1971).

The result seen in Table I concerning the inclination to the vertical of preceding and following polarity field lines, although somewhat preliminary at this time, is rather puzzling. One would not expect that inclinations which are certainly present in young active-region fields would persist many months until these fields are found at polar latitudes.

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