STUDIES OF SOLAR MAGNETIC FIELDS

III: *The East-West Orientation of Field Lines*

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(Received 2 September, 1974)

Abstract. Solar magnetic flux data accumulated from the magnetograph of the Mount Wilson Observatory are used to infer average east-west field inclination angles for the interval 1967–1973. In all latitude zones the total flux ($|F^+| + |F^-|$) measurements indicate that the field is inclined so as to trail the rotation by a small amount. Averaged over the whole disk, this angle is 0°8. No clear pattern may be seen in the variations of this quantity with time in any latitude zone. The individual polarities show some systematic behavior. In the north, the negative (preceding) fields are inclined so as to trail the rotation at all latitudes. The positive fields are inclined toward the rotation by a smaller amount. In the south, a similar situation exists for the fields below 40° latitude, but poleward of 40° the following polarity fields are strongly inclined to trail the rotation. In the north, there has been a gradual decrease of the inclination angles of both polarities during the seven-year interval. At the higher latitudes the sign of the east-west inclinations actually changed during the interval. From an examination of magnetograms it is clear that there are no systematic east-west inclinations of field lines outside sunspots greater than about 30° from the vertical. Cross correlations of the east-west inclination data indicate that equatorward of 40° variations in time of the orientation of fields of the two polarities tend to be parallel, and poleward of 40° these variations are such that the two polarities incline toward or away from each other.

1. Introduction

In the two earlier papers of this series (Howard, 1974a, 1974b), the Mount Wilson magnetograph observations and the accumulated magnetic field and flux data were discussed. In this paper the same flux data will be analyzed to infer the east-west orientation of magnetic field lines. These data were all obtained at the 150-ft Tower Telescope of the Mount Wilson Observatory, using the line Fe I λ5250.2.

The principle of the technique to obtain the orientation angles is simple: We divide the visible solar disk into the east and west halves, and average the magnetic fluxes for each half over whole rotations. It is not unreasonable to assume that the solar magnetic fields do not react to the relative position of the Earth, thus a comparison of the east and west fluxes can give an approximate east-west orientation of field lines for each solar rotation.

Some observational errors inevitably enter into such an analysis. The obvious random zero drifts discussed in Paper I are not so important for this analysis, because errors of that nature will tend to average out when integrated over a rotation. Systematic zero drifts, of course, may be a problem, but not a serious one because most of the results to be presented in this paper are derived from observations of fields of the same polarity measured at different points on the solar disk. More serious problems arise from errors introduced by selection effects. If gaps due to bad weather or

Solar Physics **39** (1974) 275–287. *All Rights Reserved*
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instrumental problems extend for more than two or three days, then some parts of the solar surface will be covered poorly, and this may lead to faulty rotation averages. A second potential problem is that of 'edge effects.' If a developing region lies near Carrington longitude 0°, it is possible that an imbalance in fluxes of the two polarities may occur, or some flux may be included for one half of the disk and not for the other. Both these effects should only introduce 'noise', not a long-term systematic bias.

2. The Orientation Angles

The observed east-minus-west flux ratio may be defined

$$\beta = \frac{|F_E| - |F_W|}{|F_E| + |F_W|}. \tag{1}$$

Referring to Figure 1, if a is the angle at which the flux is observed on either side of the central meridian, and α is the inclination of the field lines to the radial direction, then

$$|F_E| = |F| \cos(a - \alpha), \tag{2}$$

and

$$|F_W| = |F| \cos(a + \alpha) \tag{3}$$

for each polarity. Therefore

$$\beta = \frac{\cos(a - \alpha) - \cos(a + \alpha)}{\cos(a - \alpha) + \cos(a + \alpha)} = \tan a \tan \alpha, \tag{4}$$

or

$$\alpha = \arctan(\beta/\tan a). \tag{5}$$

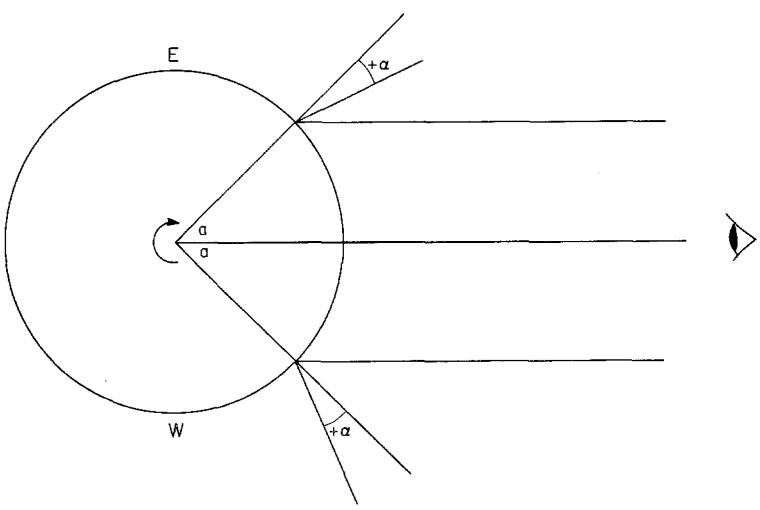

Fig. 1. A schematic diagram to illustrate the derivation of the inclination angle. The Sun is viewed here from above the north pole, and the observer is at the right.

Thus α may be determined as a function of β. It is not practical to pick out the flux at a particular angle, a, on either side of the central meridian. Instead we shall select an average a of 30° for all the flux east and west of the CM. The data within a few degrees of the solar limb are omitted.

Assuming $a=30°$, a value of 0.05 for β gives $\alpha=4\overset{\circ}{.}9$, according to Equation (5). The dependence of α on β is nearly linear for all the values of β discussed in this paper. The results, however, will in general be presented in terms of β. An analysis of an inclined uniform field across the disk gives a value of α within a few percent of that derived from the simple formula above, using $a=30°$.

3. The Results

3.1. The seven year interval

Table I gives average daily values of the total flux ($F^T=|F^+|+|F^-|$) for each latitude zone and the corresponding values of β. Note that at all latitudes β is negative, indicating that on the average the field lines are inclined toward the east so as to trail the rotation. The largest average inclination is in the north poleward of 70°, where the angle is a little less than 3°. The smallest angle of inclination is in the north below 40°, where the angle is about $0\overset{\circ}{.}4$. The average angle of inclination is about $0\overset{\circ}{.}8$. These angles

TABLE I

Average daily total magnetic flux by quadrants January 1967–December 1973

$|F^+|+|F^-|$

Latitude	N (Mx × 10^{20})			S (Mx × 10^{20})		
	E	W	β	E	W	β
> 70°	0.57	0.62	−0.042	0.41	0.42	−0.012
61°–70°	1.86	1.90	−0.011	1.55	1.60	−0.016
51°–60°	3.68	3.73	−0.007	3.34	3.51	−0.025
41°–50°	6.04	6.21	−0.014	5.88	6.00	−0.010
⩽ 40°	118	119	−0.005	109	112	−0.011
Total	130	132	−0.006	121	123	−0.011

are all rather low; however, the uniformity of the direction of the inclination for all latitudes is impressive evidence that we have here a physically significant result. The errors are smaller than the difference between the quadrants for almost all the latitude zones and will be discussed in more detail below in the discussion of the time variations of the data.

Average daily values of β for each polarity and each latitude zone are given in Table II. In the northern hemisphere, at all latitudes the preceding and following polarity field lines are inclined toward each other. The positive (following) polarity fields lead the rotation slightly, and the negative fields trail the roation by as much as about 10° poleward of 70°. In general, the largest inclination angles are below 40° in both hemispheres. In the south, the two polarities are inclined toward each other below

TABLE II

Average daily magnetic flux January 1967–December 1973

Latitude	Positive flux) (Mx × 10^{20}			Negative flux (Mx × 10^{20})		
	E	W	β	E	W	β
Northern hemisphere						
> 70°	0.34	0.33	0.010	0.24	0.29	−0.105
61°–70°	1.12	1.09	0.011	0.75	0.80	−0.035
51°–60°	2.12	2.07	0.012	1.56	1.66	−0.030
41°–50°	3.32	3.27	0.008	2.73	2.95	−0.039
⩽ 40°	59.1	54.1	0.045	59.2	65.6	−0.051
Total	66.0	60.9	0.040	64.5	71.3	−0.050
Southern hemisphere						
> 70°	0.19	0.20	−0.023	0.22	0.22	−0.008
61°–70°	0.62	0.63	−0.011	0.93	0.97	−0.022
51°–60°	1.24	1.29	−0.019	2.10	2.22	−0.028
41°–50°	2.38	2.41	−0.005	3.50	3.59	−0.014
⩽ 40°	52.7	59.5	−0.061	57.2	52.9	0.040
Total	57.1	64.0	−0.057	64.0	59.9	0.033

40° latitude, but poleward of 40° both polarities are inclined so as to trail the rotation, and, except poleward of 70°, the following polarity fields are more steeply inclined than are the preceding polarity fields.

3.2. The smaller scale fields

The results shown in Tables I and II represent averages over large areas of the solar surface and over a long time interval. However, from examination of the daily magnetogram plots it is possible to make some qualitative statements concerning the east-west orientation of magnetic field lines in active and quiet regions.

The line λ5250.2 of Fe I has the peculiar property that it measures magnetic fields to be too weak by nearly a factor 2 near the center of the disk, while near the limb the results are approximately correct (Howard and Stenflo, 1972). This effect is not corrected for in the results presented in this paper. This means that in the case of radial magnetic fields the field strengths will appear to change very little when compared at the disk center and near the limb. If fields are systematically inclined to the radial direction by more than about 30° toward the east or west, this should show up as a clear variation of apparent field strength with central meridian distance. In the case of sunspot magnetic fields, such effects are quite apparent, and it is not unusual even for sunspot magnetic fields to appear to reverse polarity near the limb because of the steep inclination of field lines within some portion of the spot. Such an effect has not been observed in either active or quiet regions in the nonspot fields seen in the 3000 or so Mount Wilson magnetograms obtained since 1963. There is not even a clear case of a substantial variation in field strength from center to limb except in instances of intrinsic growth of the regions.

Figure 2 shows an example of two magnetograms separated in time by 4 days, illustrating this effect. The effect may be verified by an examination of the many years of published Mount Wilson magnetograms.

It seems unlikely that magnetic features of a size comparable to, or perhaps slightly larger than, the 17″ aperture in active or quiet regions can in general be inclined to the vertical in the east-west direction by more than about 30°. It is quite likely that chromospheric magnetic fields display extreme inclinations – this seems to be true from the appearance of the chromospheric filamentary pattern which is believed to be closely associated with the fields. But in the upper photosphere, where the $\lambda 5250$ line is formed, no such extreme inclinations seem to exist. This is, of course, a qualitative judgment made with low-resolution observations and complicated by the existence of evolutionary changes within regions. A systematic study of the small-scale inclination of field lines in the photosphere is planned.

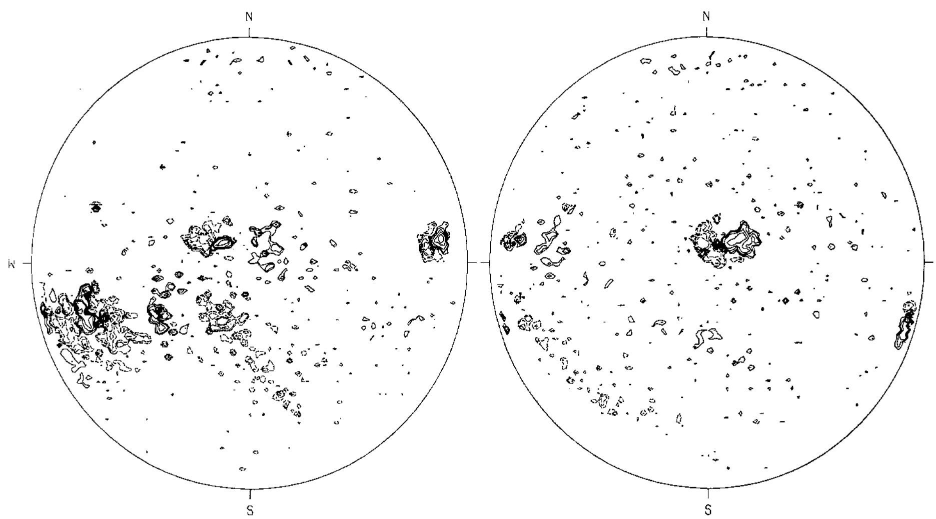

Fig. 2. Two regular Mount Wilson isogauss magnetograms. On the left is the magnetogram for 1974, June 9, and on the right for 1974, June 13. Solid contour lines represent positive fields, and dashed lines represent negative fields. The contour lines for each polarity are 5, 10, 20, 40, and 80 g. The pole markers represent the rotation axis of the Sun. Note the large region which is near the east limb on June 9 and near the disk center on June 13. Similarly, note the region just east of the disk center on June 9 and near the west limb on June 13. Although some evolutionary changes have taken place in these regions, the basic balance between polarities stays quite constant. Two large quiet regions behave in a similar fashion in the south

3.3. The variation of the inclination angle with time

Figure 3 shows the variation with time of the values of β obtained for the total flux (F^T) for most latitude zones. Each point represents a 13-rotation average – approximately one year. This is clearly a rather noisy signal; nevertheless, the negative average for the whole period is meaningful in all cases. The probable errors for the average

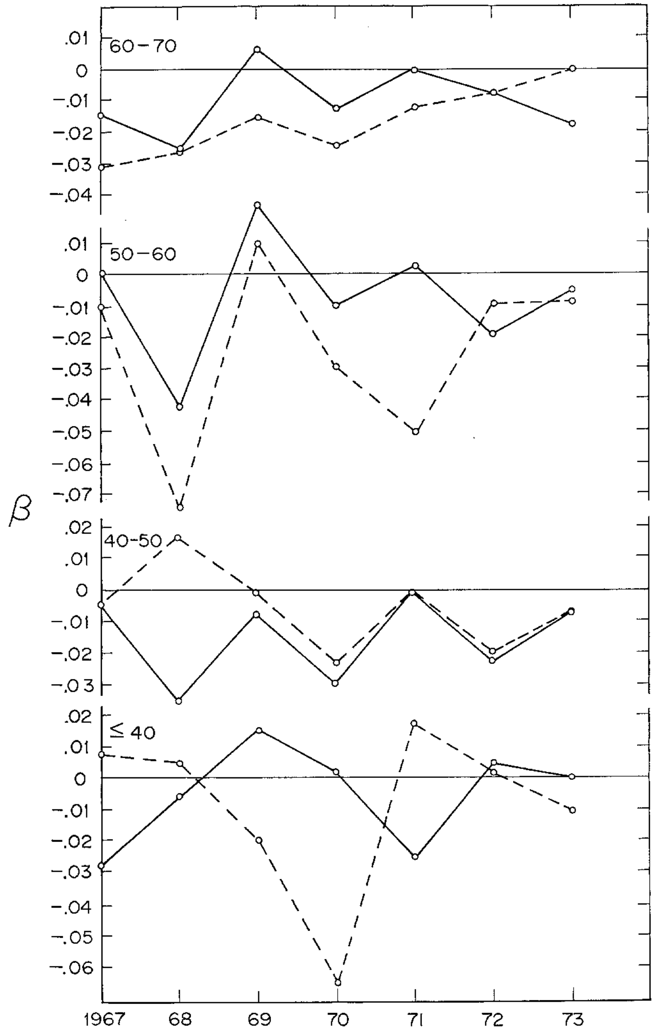

Fig. 3. The variation of β for the total flux (F^T) as a function of time in various latitude zones. These are 13-rotation averages starting with Carrington rotation 1517, and thus the averages correspond approximately to the years listed on the ower axis. The northern hemisphere latitude zones are indicated with solid lines and the southern hemisphere zones are indicated with dashed lines.

fluxes for the whole period are about 1% of the fluxes, except poleward of 70° where they are comparable with the flux values themselves.

There is no clear cycle-related variation of the total flux to be seen in Figure 3. Correlations of β with total flux have given no positive results; there is no correlation of the east-west orientation of the total flux with the total flux.

Figures 4 and 5 show the values of β separately for each latitude zone and for each polarity as a function of time. Each point of the thin lines represents one solar rotation. The thick lines represent 13 rotation (one year) running means. The data poleward of

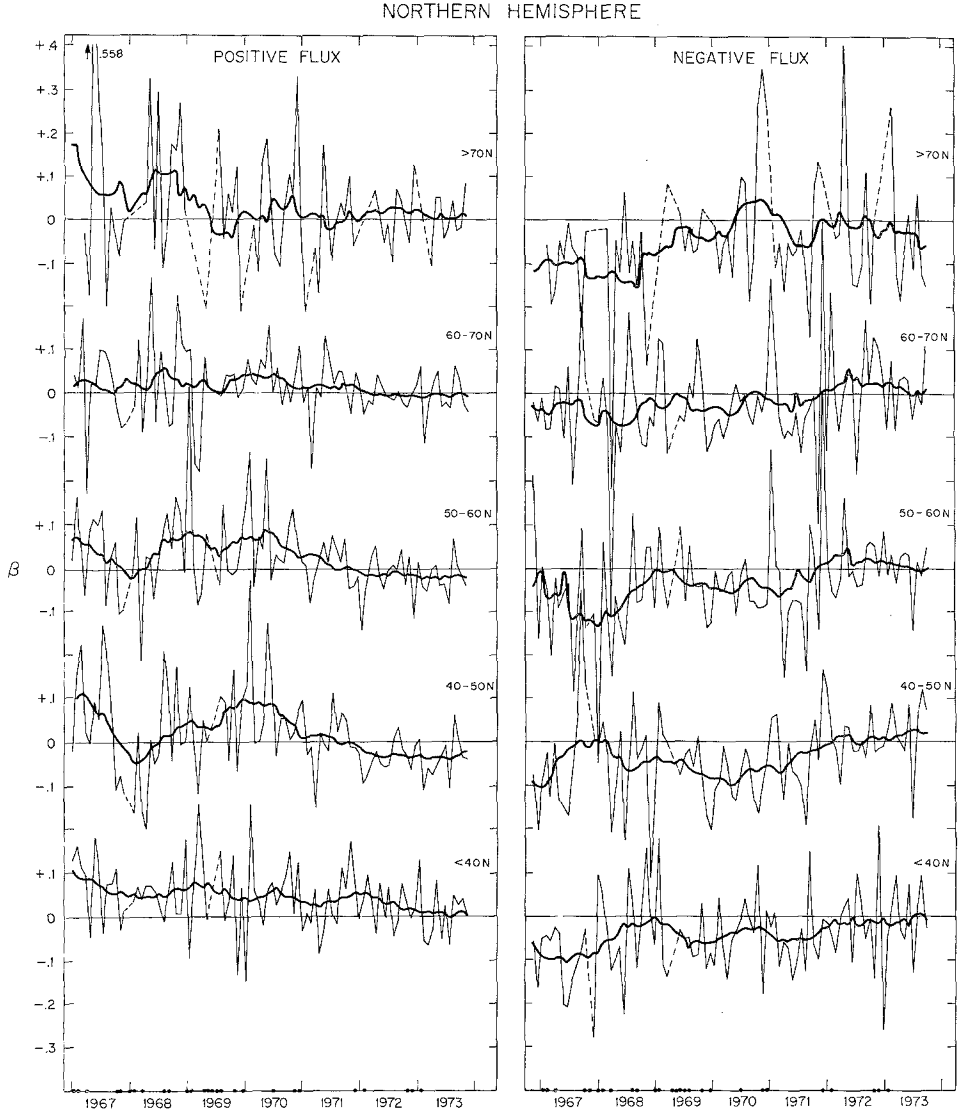

Fig. 4. Values of β for the various latitude zones for each polarity separately in the northern hemisphere. Each point connected by the thin lines represents the value of β derived from one Carrington rotation. The thick line is a 13-rotation running mean of the data. The dots on the time axis represent rotations within which two observations were separated by more than 100° in longitude. The dashed lines represent data missing.

70° are clearly more uncertain, with frequent gaps due mostly to the fact that each pole is tipped away from the Earth during some portion of the year.

The rotation averages of β are quite 'noisy.' As mentioned above, this is due in part to gaps in the data. Of the 92 rotations represented here, 27 of them had gaps of more than 100° in longitude between the central meridians of adjacent day's observations,

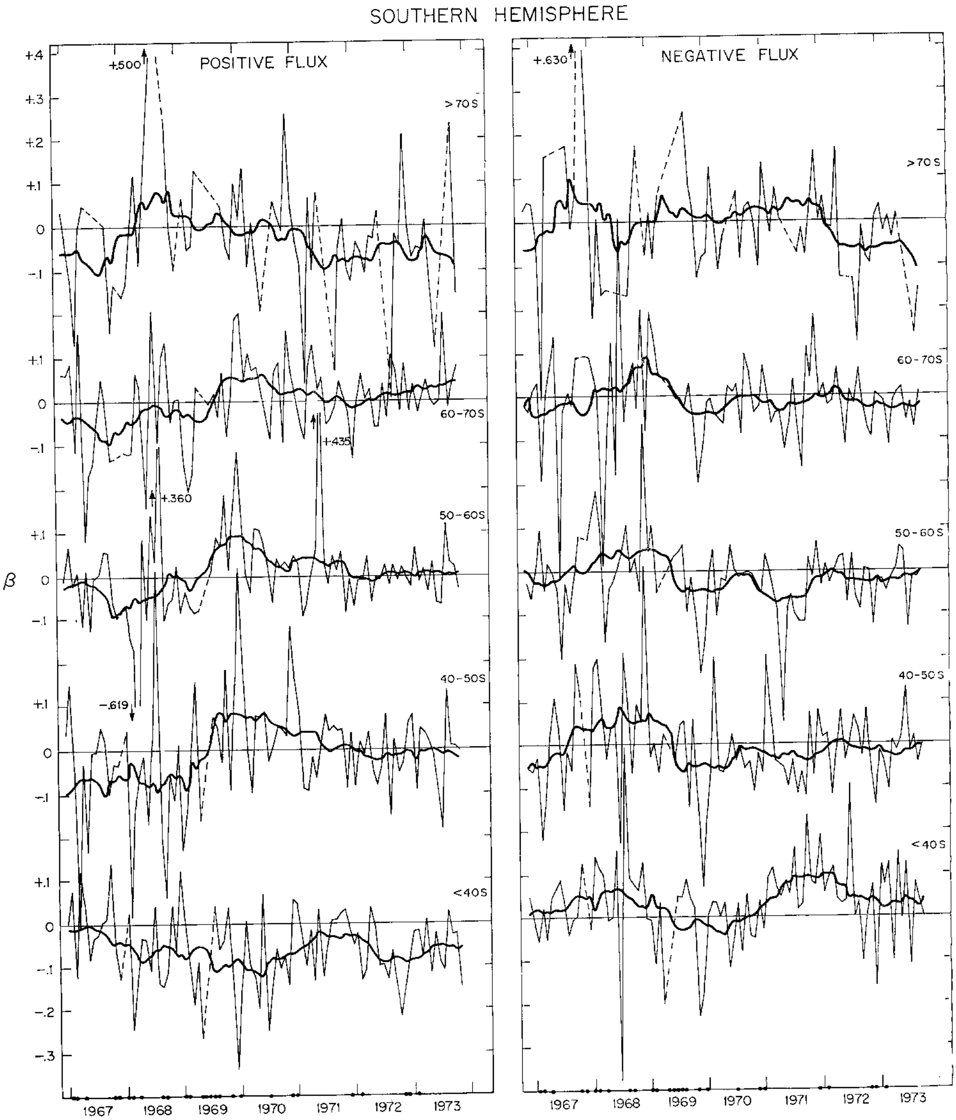

Fig. 5. Same as Figure 4 but for the southern hemisphere.

due mostly to poor weather. That is, some of the fields on the Sun were represented only at distances of more than 50° from the central meridian. These rotations are marked on Figures 4 and 5. Some portions of the sun, of course, were not represented at all. The 13-rotation running mean is probably a fairly reliable indicator of the long-term behavior of β, but the rotation-to-rotation values are obviously of poor quality.

Obvious variations with time are seen in the values of β. In the northern hemisphere below 40° latitude, the two polarities were consistently inclined toward each other during the interval, but for each polarity the angle of inclination of the lines of force has generally decreased throughout the interval. Early in 1967 the angle of the fields of each polarity was around 6°, and by the end of 1973 the angle in each case was near 0°. In the southern hemisphere, the fields equatorward of 40° do not behave in such a simple manner. The positive (preceding) fields undergo considerable variation, but they represent a greater angle at the end of the interval than they do at the start. The negative fields seem to oscillate sinusoidally with a period of around 4 yr.

The higher-latitude fields appear to behave in a less regular fashion. In the north, their behavior for each polarity roughly parallels that of the fields below 40°, except that β changes sign in early 1972, indicating a systematic shift of orientation from being inclined toward the opposite polarity fields to being inclined away from the opposite polarity fields. In the south, the behavior of the high-latitude fields is more chaotic, but it appears that for the positive fields the high-latitude values of β tend to increase with time, while the low-latitude values decrease. The negative fields in the south behave so irregularly that they defy description.

3.4. The correlation of the polarities

From an inspection of Figures 4 and 5 it is apparent that at many latitudes there is a correlation between field directions of the two polarities within the same latitude zone. A cross-correlation analysis confirms that this is so. The results from this analysis are given in Table III.

TABLE III

Cross correlation coefficients for magnetic flux of opposite polarities

Latitude	N	S
$>70°$	−0.32	−0.18
61°–70°	−0.44	−0.40
51°–60°	−0.40	−0.56
41°–50°	−0.60	−0.55
$\leqslant 40°$	0.31	0.26

The correlations are significant with the exception of the south polar latitudes, and they indicate a negative correlation between the orientation angles of fields of opposite polarity poleward of 40° and a positive correlation below that latitude in each hemisphere. Thus poleward of 40° there is a tendency for the two polarities to incline toward or away from each other – as one polarity bends eastward the other bends westward. Below 40° the two polarities tend to keep their relative orientations as they vary toward or away from the rotation.

4. Discussion

4.1. The total flux

The total flux is clearly inclined slightly at all latitudes to trail the solar rotation. The

λ5250.2 line of Fe I is formed in the photosphere; according to Lites (1973), the wings of the line are formed approximately at 150 km below $\tau_{5000}=0$; however, the contribution function is about 200 km thick. The field is probably nearly all confined to bundles of lines of force wherein the field strengths are at least several hundred gauss (Howard and Stenflo, 1972).

The reason for the eastward inclination of field lines poses interesting problems. It seems unlikely that the braking torque of the solar wind could be sufficient to alter the orientation of the strong fields in the dense photosphere. Theoretical models of the solar wind (e.g., Schatten *et al.*, 1969) assume an inner region where the magnetic energy density is greater than the plasma energy density, and thus where the magnetic fields are unaffected by the solar wind. A more likely explanation for the inclination is the effects of subsurface fields. The magnetic features at the solar surface rotate more rapidly than does the bulk of the photospheric gas, and it has been suggested (Foukal, 1972) that this rapid rotation results from a linkage to subsurface layers that rotate more rapidly than the surface. Perhaps the effect of the slow-moving photospheric gas is to exert enough force on the bundles of field lines to affect their inclinations at the surface.

It has been suggested that the reason preceding spots are larger on the average than following spots is that the magnetic field lines of the preceding spots are inclined at a smaller angle in the east-west direction than the field lines of following spots, and therefore they represent a more stable and long-lasting magnetic configuration. This may be true of sunspot fields, but from Table II it is clear that it is not a consistent feature of the bulk of the magnetic flux at sunspot latitudes.

In a recent analysis of interplanetary magnetic field data, Svalgaard and Wilcox (1974) have averaged the inclination angles of these fields in the ecliptic as a function of time. The average inclination angle of the interplanetary field is close to 45°, the Archimedes spiral angle near the earth. Taking each polarity separately, Svalgaard and Wilcox found that there were significant differences from 45°, and these angles varied slowly with time. Early in the interval (1967) the negative (toward) fields were more tightly wound than 45°, i.e. they trailed the rotation compared to the 45° average. At the same time the positive (away) fields were less tightly wound than 45°. The angular difference between the position angles of the two polarities increased (taking yearly averages) until 1970, when both polarities were nearly aligned with the 45° Archimedes spiral angle. In the following years the inclinations of the two polarities changed as the angle between them continued to increase. In this interval the positive fields were more tightly wound than the average, and the negative fields were less tightly wound than the average.

The direction of change indicated by the results of Svalgaard and Wilcox is the same as that shown by the northern hemisphere fields of the Sun in Figure 4. The amplitude of the effect at the Sun is roughly the same as that at the Earth. This correlation suggests that the variations seen at the Earth in the east-west direction of the magnetic field lines is caused by the initial field line direction at the solar surface. The northern hemisphere of the Sun has dominated solar activity during most of this cycle, and it has dominated also in its influence on the interplanetary magnetic field (Wilcox and Howard, 1968). This simple correlation must be viewed with some caution because the physical situation is very complicated. A more detailed correlation analysis of the inclination angles of the solar and interplanetary fields is planned.

4.2. Small scale fields

The close relationship between the appearance of chromospheric features and the geometry of the magnetic fields in active regions (Howard and Harvey, 1964; Veeder and Zirin, 1970) is good evidence that the chromospheric filamentary structures delineate nearly horizontal magnetic field lines over large areas of the chromosphere near the boundaries of active regions. However, such steep inclinations in such large areas of the photosphere cannot exist because of the evidence from the magnetograms as mentioned above.

Some interesting questions arise from this result. The first is: Why do the chromospheric magnetic-field lines bend over so that they are sharply inclined away from an active region near its edge? It is likely that at chromospheric densities the fields, which thread up from below, are force-free. They are rooted in the dense photospheric and subphotospheric gas, but in the tenuous chromosphere and corona the Lorentz forces are free to expand the field of the whole active region, producing a marked outward inclination of the field lines near the perimeter of the region. This sharp inclination of the field lines will produce currents in the chromosphere. In active regions which contain complicated magnetic configurations, the fibril structures, and therefore the current systems, may be large and complicated, and may provide the energy for solar flares as suggested by Alfvén and Carlqvist (1967). Another question suggested by the results in this paper is: Why are the magnetic fields in the photosphere so nearly radial in the east-west direction? If, as is generally assumed, active-region magnetic fields are loops of magnetic flux pulled up from subsurface flux ropes, why should they end up in the photosphere so nearly radial on the large scale? If, as is often assumed, magnetic field lines are brought to the surface from the subsurface flux ropes by buoyant forces, then one might expect that the buoyant forces would maintain a more-or-less vertical orientation of the field lines, as a harbor buoy maintains a more-or-less vertical orientation. Further and more detailed study of the orientation of individual features may help to clarify this point.

4.3. Variations with time

The interval covered by these observations (7 yr) is not long enough for us to determine whether the variations in east-west inclinations represent a repeatable, cycle-related phenomenon. Within 2 or 3 yr, as fields of the new cycle begin to appear, it may be possible to determine whether or not the orientation angles of the new cycle fields are shifted.

If the variations seen in these data are correlated with phase in the activity cycle, it is not clear what the reason could be. One possible explanation concerns the different rotation speeds of the magnetic fields and the photospheric gas. If the inclination of the field lines result in part from forces exerted by the photospheric material through which the field lines are moving, then a variation of the relative motion will affect the inclination. In recent years the photospheric rotation has accelerated slightly (Howard, 1973), thus the difference between the rotation rates of the photosphere and the field lines has decreased, so the inclination angles may also be expected to decrease.

This explanation is put forward only as a tentative hypothesis. There is no real evidence to link the field inclinations with the difference in rotation rates; perhaps the two quantities only vary coincidentally. There may be some totally different explanation for the variation in inclination. For example perhaps the depth of the subsurface flux ropes increases with phase in the cycle, exerting a varying influence on the field line orientations. In any case, as pointed out above, only the individual polarities in some latitude zones show systematic changes during the 7-yr interval. The total flux does not vary smoothly during this interval.

The inclinations poleward of 70° are uncertain because so much data is lost due to the inclination of the solar rotation axis. However, the data in the 60°–70° latitude range may be used to examine the behavior of the polar fields. In Paper I it was shown that the north polar fields changed sign in mid-1971. In the north polar regions, the east-west inclinations of the field lines of both polarities appeared to change sign in late 1971 or early 1972 – the date is uncertain by several months. Before late 1971, the preceding and following polarities were inclined toward each other, and after that date they were inclined apart from each other. In the south the situation is not so clear. The polar fields changed sign in mid-1969, and there is evidence in Figure 5 that the preceding (positive) polarity in the south (60°–70°) changed sign in late 1969, roughly, but the following polarity behaved in a very irregular manner.

Both polarities contributed to this east-west inclination sign change in the north. It is interesting to note that this sign change at the high latitudes represents, in a sense, a reorganization of the high-latitude fields to the configuration of the new cycle. That is, before the sign change the fields of the two polarities were inclined toward each other in the preceding and following polarity configuration of the present cycle. After the inclination sign change (late 1971), the opposite polarity fields were inclined toward each other in the polarity configuration of the next cycle.

Acknowledgements

The observations were made at Mount Wilson by Thomas A. Cragg, John M. Adkins, Thomas S. Gregory, and Merwyn G. Utter. It is a pleasure to acknowledge a helpful discussion with Dr. Leverett Davis, Jr. The figures for this and the other papers in this series were drawn by Felice Woodworth. Financial support for the continued operation of the magnetograph system has been provided in part by the U.S. Office of Naval Research under contract N00014-66-C-0239 and the National Aeronautics and Space Administration through grant NGR09-140-015.

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