EVIDENCE FOR NON-RADIAL FIELDS IN THE SUN'S PHOTOSPHERE AND A POSSIBLE EXPLANATION OF THE POLAR MAGNETIC SIGNAL

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Abstract. The appearance of the Hα fibrils suggests the presence of magnetic fields inclined at noticeably non-radial angles in the Sun's chromosphere. We present evidence to suggest that these angles continue into the photosphere.

The presence even of small non-radial inclinations can significantly affect the appearance of regions observed by a longitudinal magnetograph. In particular, a simple bipolar loop can appear unbalanced when viewed near the limb. We suggest that the observed polar signal may be nothing more than a geometric effect arising when a balanced but systematically aligned array of bipolar pairs is viewed at an angle.

1. Introduction

A number of authors (from Hale, 1908 to Zirin, 1972) have shown that by assuming the iron-filing-like fibrils of the Sun's chromosphere to trace out the paths of magnetic lines of force one can, to a remarkable extent, predict the magnetic pattern of the underlying photosphere. A simple extension of this reasoning would seem to imply that many field lines penetrate the surface in a non-radial fashion, for, when seen on the limb, the fibrils (spicules) appear as a forest of inclined projections; yet one generally tends to think of the photospheric field (at least away from sunspots) as an essentially vertical phenomenon (Howard, 1974a). We have collected a number of pieces of evidence to suggest that the vertical nature of the photospheric field is a property which exists only on the average, and that when viewed in sufficient detail, individual flux tubes will indeed be found to display the kinds of inclinations characteristic of the associated chromospheric features.

2. Evidence for Non-Radial Fields in Sunspots

The most obvious examples of non-radial fields are to be found in sunspots – presumably because the fields there are large and easily measured. The presence of non-radial fields is revealed by variations in the magnetic appearance of the spot as it moves from center to limb. As an example, Figure 1 shows the videomagnetogram of a simple bipolar region observed about 50° from the west limb. In white light both spots are quite regular in appearance, yet magnetically they seem strangely complicated.

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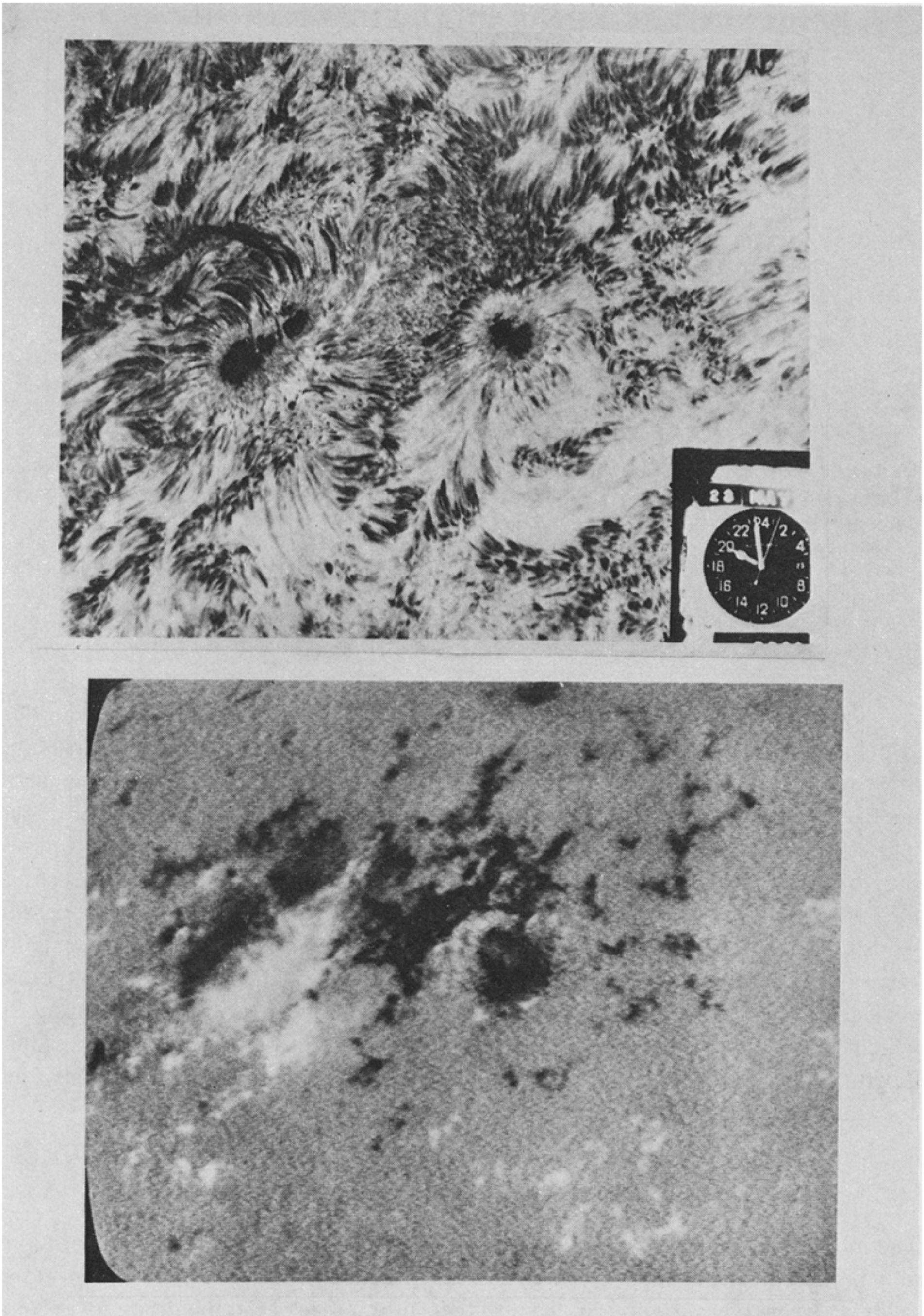

Fig. 1. Bipolar spot group observed near the west limb on May 23, 1972. *Top*: $H\alpha - 0.5$ Å. *Bottom*: Videomagnetogram. The size of the frames is roughly $4\overset{\prime}{.}7 \times 5\overset{\prime}{.}8$. The limb is out of view to the upper left, about $5\overset{\prime}{.}8$ from the center of the group. Due to saturation the sunspot umbras appear as gray 'holes' on the magnetogram. Note that the field of the black spot extends beyond the apparent penumbral boundary. *(Courtesy Big Bear Solar Observatory)*.

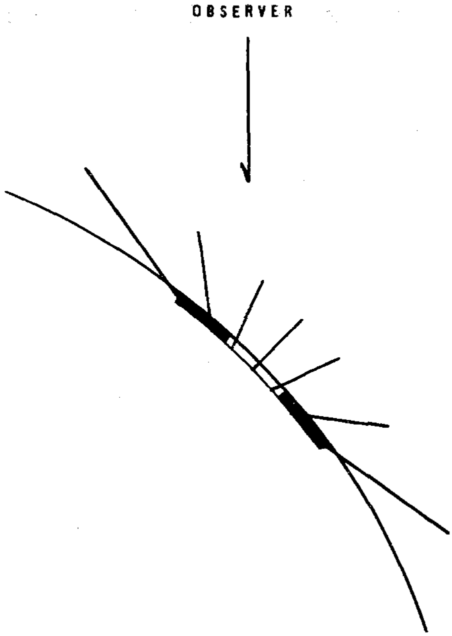

Fig. 2. The magnetic configuration of a sunspot, after Hale (1919). Part of the lines point towards the observer and part away. The effective 'neutral line' marches across the spot as it rotates from center to limb.

Basically, the side of the spot towards disk center exhibits the true polarity of the spot, while the side towards the limb exhibits an apparent reversed polarity. This effect (Hale *et al.*, 1919) is well known, and can be easily understood if one merely assumes that the field lines fan out as they rise through the atmosphere (Figure 2). The basic truth of this explanation can be verified by direct spectral measurement of the transverse field component when the spot is seen near disk center. Hale *et al.* found angles as large as 73° at the outer edges of penumbras. For the example shown, where the black spot is 37° from disk center and the white 44°, angles of at least 53° are required to explain the fact that most of the limbward penumbra of the former, and all of the limbward penumbra of the latter exhibit a reversed polarity.

3. Evidence for Non-Radial Fields in Faculae

The magnetic fields associated with photospheric faculae are much harder to study, because of their small size, but, as far as we can tell, they are merely small reproductions of a basic spot-like geometry. Again the magnetograph shows an apparent 'doubling' of features as they move towards the limb. The observation is difficult, however, because if viewed with imperfect resolution the two magnetic components generated by the diverging field will merge to yield a single net signal identical to that which would be produced by a purely radial field.

Chapman and Sheeley (1968) were apparently the first to obtain magnetograms showing the doubling effect in faculae. They inferred angles on the order of 10–20°. Recent magnetograms would suggest much larger angles. Figure 3 shows an enlargement of the Kitt Peak daily magnetogram for July 4, 1974. Towards the limb, each facular point is fringed by a 'false' field of reversed polarity. The effect becomes apparent within about 45° of the limb, and is quite pronounced in the last 35° or so, proving that at least some of the field is inclined at angles of more than 45°. The spacing between the magnetic features, when corrected for projection, is on the order of 5–10.″ Since this is comparable with the width of Hα plage features, the observation is consistent with the idea that the reversed fields correspond, physically to that outward-fanning fringe of spicules which creates the impression of 'rosettes' at disk center (Beckers, 1968), and of 'porcupines' on the limb (Lippincott, 1957).

Surprisingly, the doubling effect in faculae is only marginally visible with the Caltech videomagnetograph (cf. Figure 1), even though the spatial resolution is comparable, if not better. The problem is presumably due to its somewhat lower magnetic sensitivity coupled with an unknown effect making it particularly difficult to detect fields near the limb when their inclination is unfavorable (cf. Section 5).

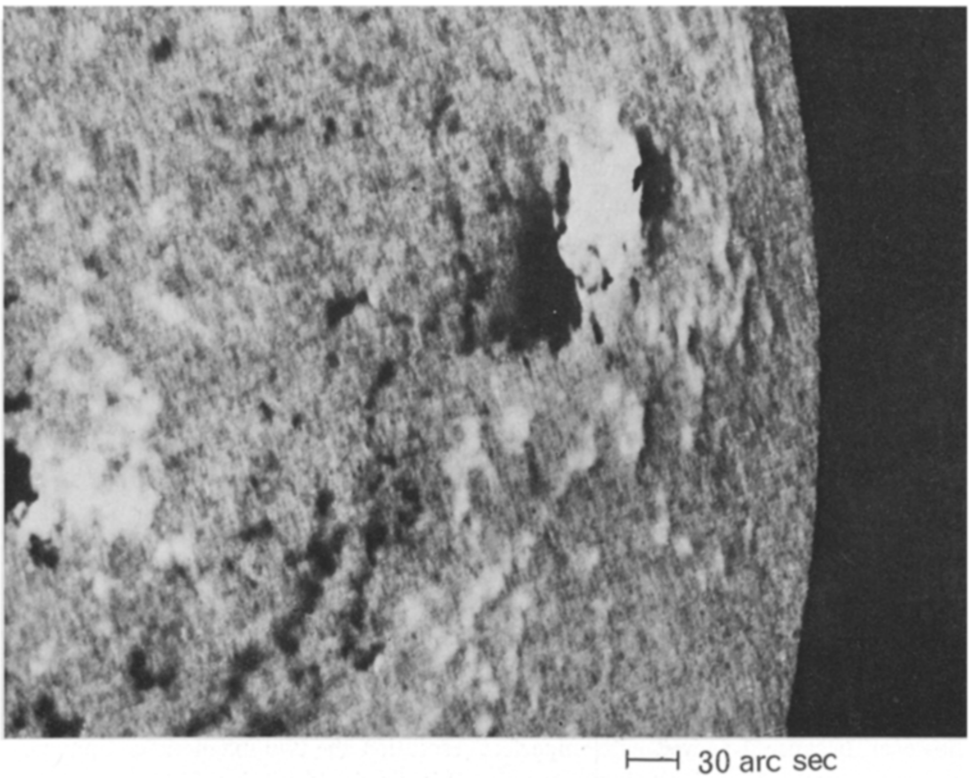

Fig. 3. Enlargement of a portion of the Kitt Peak daily magnetogram for July 4, 1974. Note particularly the apparent 'doubling' of the white network fields closest to the limb. *(Courtesy Kitt Peak National Observatory)*.

4. Evidence for Non-Radial Fields in Emerging Flux Regions

The divergence of field lines in spots and faculae, while of interest, is actually of little consequence magnetically since it does not affect the total flux through the surface and since the net effect is the same as that of a single purely radial field. What is of interest is whether the *axes* of the flux tubes (about which the field lines fan) can be inclined to the surface, for then the apparent strengths of different features could behave differently as they move across the disk, appearing 'balanced' at one point and 'unbalanced' at another.

Intuitively one would expect the largest angles to occur in young, emerging regions where the field lines have not had enough time to get pulled out into the corona. While we know that there is very little systematic tendency for the preceding and following portions of established regions to lean either towards or away from one another (Howard, 1974a), there is surely a moment during the emergence of each flux tube when it lies nearly horizontally in the surface. This suspicion seems to be confirmed by the appearance of emerging flux in Hα: one sees prominent absorption loops ('arch filament systems') throughout the early stages of development (Bruzek, 1967, 1969). The filaments can be traced through a considerable height in the atmosphere; their legs often appear to be inclined at angles of more than 60° with respect to the vertical (i.e., they lie very nearly in the surface); and there is no obvious tendency for them to suddenly bend into a radial configuration at the point where they reach the photosphere (Figure 4).

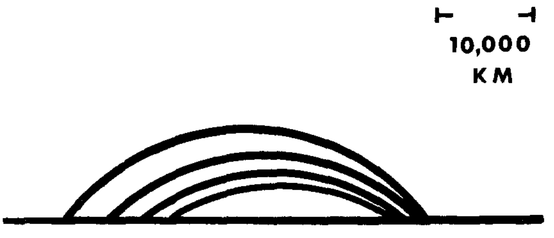

Fig. 4. The geometry of an arch filament system, after Bruzek (1967). When viewed off disk center, the limbward ends will have the most favorable angle with respect to the line of sight, and appear to dominate magnetically.

When such a feature is viewed magnetically at disk center the two footpoints can appear to be of different *strengths* (if the angles are different), but their *fluxes* will balance. When seen near the limb, however, even the measured fluxes can be different. Figure 5 shows an example of this effect, first published by Bumba and Howard (1965), in which a young bipolar region is seen emerging close to the east limb. The K-line spectroheliogram clearly indicates that the two footpoints are of nearly equal strength, yet, on the first day, the magnetograph could detect only the polarity of the limbward end – just as one might expect for a steeply inclined magnetic loop. (Since the invisible end is at 45° from the limb, the angles in the legs of the arch would have to be on that order as well.)

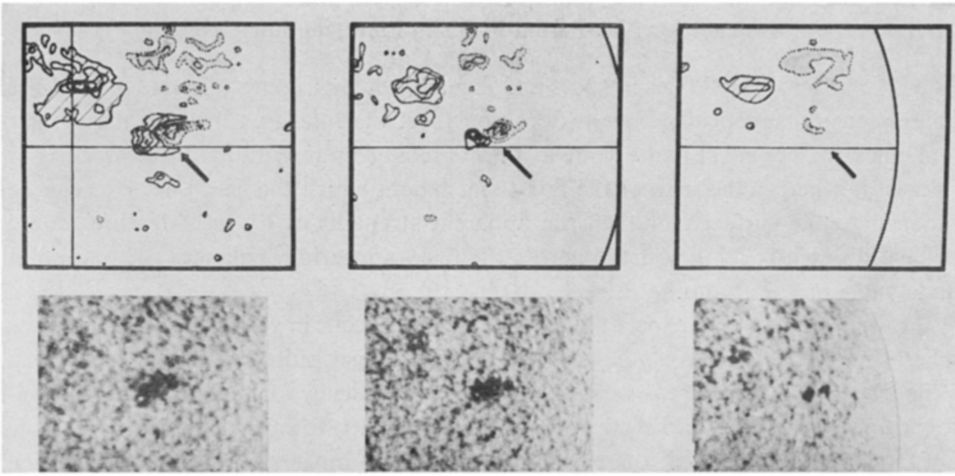

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Fig. 5. An emerging flux region as observed on three successive days. *Top row*: Contour magnetograms. *Bottom row*: K-line spectroheliograms (negative prints). Note that the initial polarity is that associated with the limbward end of the emerging region. The Sun rotates to the left. (From Bumba and Howard, 1965; *courtesy R. Howard*).

To determine whether such a large imbalance is a general property, or not, we have examined a great number of videomagnetograms taken at Big Bear Solar Observatory during the summer of 1972. While the 'classic' behavior exhibited in Figure 5 is not at all common, very young regions *do* tend to appear unbalanced when seen near the limb, and the end nearest the limb generally dominates. Moreover, one can become moderately successful at predicting the visibility of network features on the basis of the orientation of their associated Hα spicules.

5. A Possible Explanation of the Polar Magnetic Signal

The tendency of Hα spicules to assume non-radial inclinations is not at all confined to the equatorial active zones. Their appearance at the poles, for example, is much the same as elsewhere. In particular they exhibit a similar dispersion of angles. Lippincott (1957), in a study of Dunn's (1965) spicule movies, found that even the *average* inclination of her relatively-orderly 'wheat field'-like arrays could change by as much as 45° over short periods of time. Beckers (1964), examining the appearance of high-latitude spicule bushes (as seen on the disk) also deduced a large dispersion in angles.

Previous authors (Van de Hulst, 1953; Babcock and Babcock, 1955) have tended to ascribe to the polar fields the rather static geometry defined by the 'polar rays' – a weak coronal feature which becomes visible only at the time of sunspot minimum. It should be noted, however, that this is an identification which was made before the variability of the polar signal was fully understood, and may not be acceptable by modern standards. It is not at all clear, for example, that the seasonal variation in the apparent strength of the polar field (due to the tilt of the Sun's polar axis) is of the sort which would be expected for such a geometry (Howard, 1974b); nor is it easy to understand the apparent *anti*-correlation between the level of coronal activity at the poles (Van de Hulst, 1953) and the number of polar faculae (Sheeley, 1964).

The variety of inclinations seen among the high latitude spicules may be nothing more than a reflection of the general tendency of field lines to fan out around the edges of magnetic features, but we feel that it could also be indicative of the fact that a substantial part of the field is involved in relatively short bipolar connections. Such a possibility is made increasingly attractive by the recent discovery of the widespread distribution of X-ray and EUV bright points (Golub *et al.*, 1974; Tousey *et al.*, 1973), which clearly indicates that at least some intermingling of polarities occurs at the poles. It is our contention that even a completely 'balanced' magnetic configuration (with equal amounts of both polarities) could appear 'unipolar' as a result of simple geometric effects. Essentially this would require nothing more than that the field be organized into bipolar pairs, similar to those which we have been describing in the previous section, and that these pairs be systematically aligned in a north-south direction.

Figure 6 indicates the appearance of one of the many bipolar connections assumed to be present in such a model. If the arch bends inwards, as shown, the end nearest the

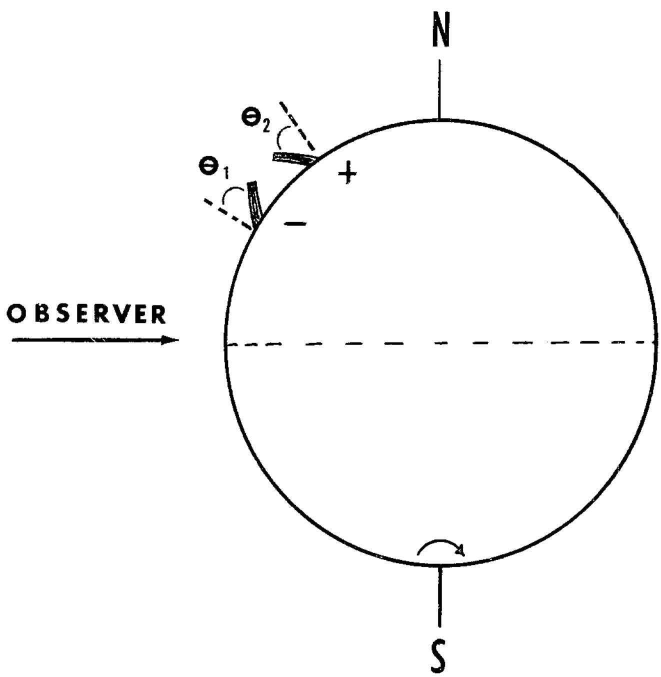

Fig. 6. A schematic representation of inclined fields occurring near the poles (size greatly exaggerated). The correction due to the tilt of the polar axis is small ($\leqslant 7\frac{1}{4}°$).

pole (positive) will dominate magnetically. If the same pair were slid to the other pole, the opposite (negative) end would dominate.

The magnitude of the imbalance can be estimated on the basis of a simple $\cos\theta$ line-of-sight calculation, but this is not too likely to be entirely accurate, since the performance of a magnetograph may well be affected by other factors when attempting to detect inclined fields close to the limb. The end tilted away from the observer might, for example, tend to be preferentially obscured by intervening 'non-magnetic' material. The observation at the limb also refers to a different height in the atmosphere than that at disk center. With this reservation, Figure 7 presents the result of such a calculation, arbitrarily assuming inclinations of $\theta_1 = \theta_2 = 20°$. The imbalance is strongest at the pole and declines to zero at disk center. Note that within the last 20° of the pole the negative footpoint actually changes sign, so that both ends have the same apparent polarity. The net effect of the two footpoints taken together is the same as that which would be produced by a single field lying horizontally in the surface (the vector sum of the two component fields).

If the average tilt is not in a precise north-south sense, then the 'center of gravity'

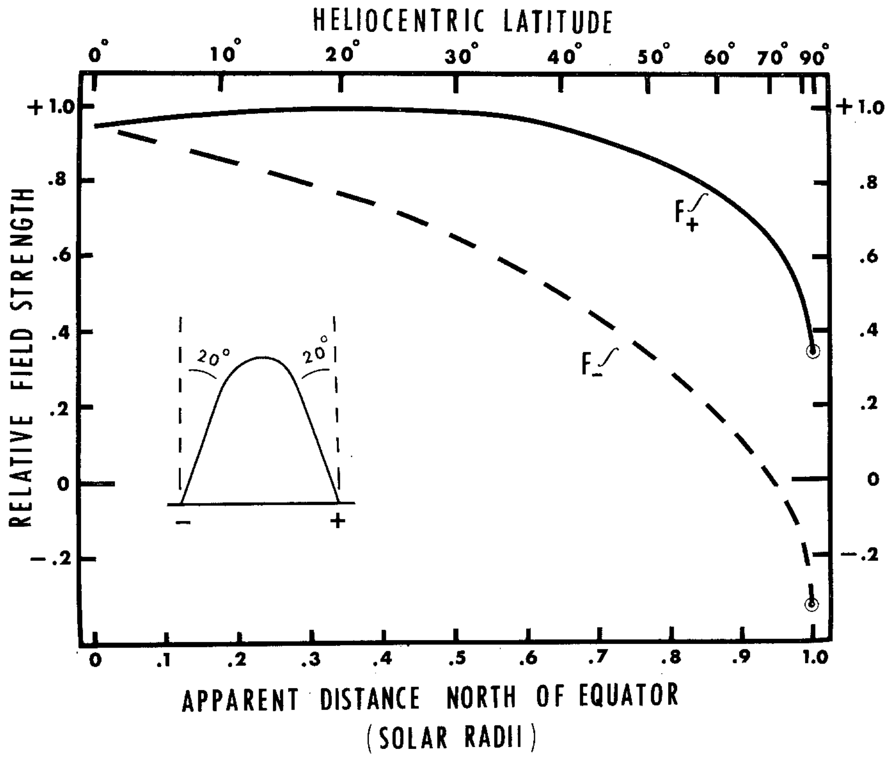

Fig. 7. Relative field strengths for the two footpoints of the magnetic arch indicated in Figure 6 as a function of latitude. More precisely, this refers to the apparent flux as measured by a longitudinal magnetograph. Pairs occurring off the central meridian will be attenuated by an additional factor of $\cos\phi$ (ϕ=heliocentric longitude).

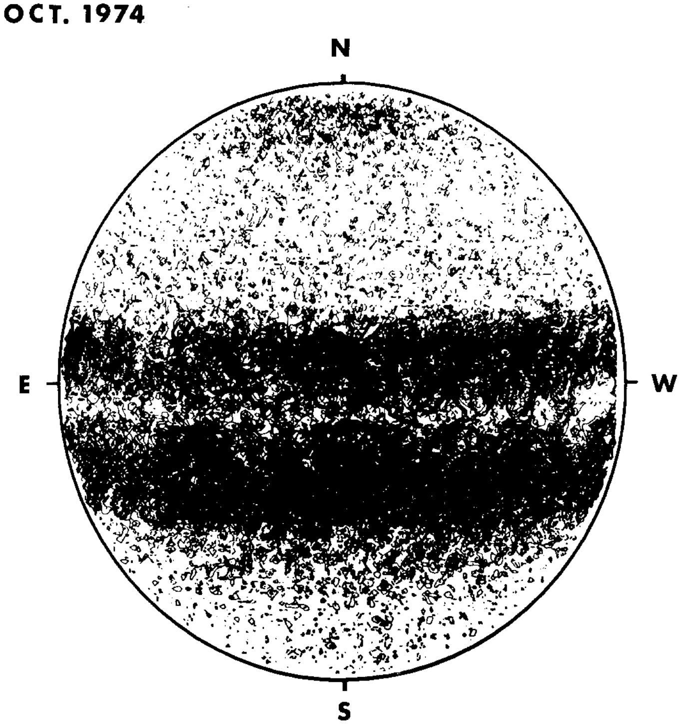

Fig. 8. The Sun's polar field as observed in October, 1974. This is a composite of Mount Wilson daily magnetograms. Away from the equatorial active zones, most of the field appears to be concentrated in a cap-like patch at the north pole. The size and intensity of the polar field are consistent with those which could be produced by an array of aligned bipoles. Note that the data do not extend completely to the limb. *(Courtesy R. Howard)*.

of the effective polar field will be shifted, either to the east or to the west. A slight effect of this sort has already been detected by Howard (1974a), but evidently the east-west tilt is not very great. The fact that the sign of the polar signal alternates with the 11-yr cycle would, however, seem to imply that the alignment with which the pairs erupt also reverses.

A complete comparison of the predictions of this model with those of the more conventional one in which the polar signal is explained in terms of the remnants of bipolar fields erupting in the active latitudes (Babcock, 1961; Leighton, 1964) is beyond the scope of the present paper. Neither explanation is entirely satisfactory. We note only that the character of the polar signal predicted by the bipolar flux pair model is very similar to that actually observed (Figure 8).

6. Conclusions

Clearly, not all field lines leave the photosphere in a precisely radial fashion. There is evidence to suggest not only that the lines fan out about the axes of the flux tubes, but also that the axes themselves are inclined with respect to the local vertical. The presence of such effects can significantly alter the appearance of regions seen close to the limb. In particular, bipolar units can appear unbalanced.

While a concentration of such pairs at the pole would be sufficient to explain the observed magnetic signal, it is not clear, observationally, that a sufficient degree of alignment exists to explain the entire signal. However that may be, the distributions of both X-ray bright points and ephemeral active regions (Harvey *et al.*, 1975) argue for the existence of significant amounts of bipolar flux at the poles, and that will surely play some role in the interpretation of the magnetic data.

If the polar signal is actually due to the presence of bipolar pairs, then the Sun's true 'general field' could, if present, be much weaker than previously supposed.

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