A SEARCH FOR SUNSPOT CANOPIES USING A VECTOR MAGNETOGRAPH

M. ADAMS
NASA Marshall Space Flight Center, AL 35812, U.S.A.

S. K. SOLANKI
Institute for Astronomy, ETH-Zentrum, CH-8092, Zürich, Switzerland

M. HAGYARD
Space Science Laboratory, NASA/MSFC, U.S.A.

and

R. L. MOORE
Space Science Laboratory, NASA/MSFC, U.S.A.

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Abstract. Using a magnetograph, we examine four sunspots for evidence of a magnetic canopy at the penumbra/photosphere boundary. The penumbral edge is determined from the photometric intensity and is defined to correspond to the value of the average intensity minus twice the standard deviation from the average. From a comparison of the location of this boundary with the location of contours of the vertical and horizontal components of the magnetic field, we conclude that the data are best represented by canopy-type fields close to all four sunspots. There is some evidence that the magnetic inclination in the canopies is 5°–15° with respect to the horizontal and that the canopy base height lies in the middle/upper photosphere. The observations further suggest that the magnetic canopy of a sunspot begins at its outer penumbral boundary.

1. Introduction

In the early eighties, Giovanelli and Jones (1982) postulated that beyond the penumbra, the magnetic field of a sunpot forms a low-lying canopy overlying a region which is nearly free of field. The magnetic canopy idea originated from studies of chromospheric and photospheric magnetic fields of active regions near the solar limb (Giovanelli, 1980; Giovanelli and Jones, 1982). The work was based on a comparison of spectral lines formed at three different heights in the solar atmosphere, C I at 9111 Å, formed in the deep photosphere, Fe I at 8688 Å, formed in the middle photosphere, and the Ca II infrared triplet line at 8542 Å, formed in the chromosphere. Thus, by comparing the information in these three spectral lines, the line-of-sight component of the sunspot magnetic field was seen to vanish at the lowest altitude but remained visible at the higher altitudes represented by Fe I and Ca II*.

Originally, such canopies were only detected close to the solar limb, where their longitudinal signal is largest. Recently, Solanki, Rüedi, and Livingston (1992)

* To more clearly visualize the canopy, refer to the sunspot schematic (Figure 7) in Giovanelli (1982).

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detected a sunspot magnetic canopy close to disk center using the strongly Zeeman-sensitive Fe I line at 1.5648 μm. This raises the question of whether canopies can also be detected close to disk center using lines in the visible. Since an almost horizontal magnetic field should best be visible by its signal in Stokes Q and U, we search for magnetic canopies surrounding sunspots in data from a vector magnetograph.

In this paper, we hope to at least broadly constrain the answers to the following questions: (1) Can the superpenumbral magnetic canopy of sunspots be seen in visible lines near the center of the solar disc? (2) If so, then what is the inclination of the magnetic field in the canopy? (3) Does the canopy continue into the penumbra? Using sensitive data from the Marshall Space Flight Center's (MSFC) vector magnetograph, we will first quantify an intensity value which defines the penumbra/photosphere boundary and then determine all three components of the sunspot magnetic field close to, but outside, that boundary.

2. Observations and Treatment of Data

The current study analyzes data acquired with the MSFC vector magnetograph, an instrument which obtains all three components of the magnetic field. The present MSFC vector magnetograph consists of a 30 cm ($f/13$) Cassegrain telescope, polarizing optics, Zeiss birefringent filter, and CCD camera. Data taken in 1980 had a field of view of 5 $\times$ 5 arc min with a resolution of 2.4 arc sec per pixel. By June of 1985, the field of view had been increased to 6 $\times$ 6 arc min with a corresponding increase of pixel size to 2.81 arc sec. The Zeeman sensitive spectral line of observation is Fe 5250.2 Å and the instrument may be tuned by ± 8 Å on either side of this line. For more details concerning the MSFC vector magnetograph, consult Hagyard *et al.* (1982) and Hagyard, Cumings, and West (1985).

Relationships between fractional polarizations and the magnetic field were determined by using the penumbral model atmosphere of Kjeldseth-Moe and Maltby (1968) and neglect magneto-optical effects. Particulars on the method of determining the magnetic vector are given by Hagyard *et al.* (1982) and are also contained within the SAMEX report edited by Hagyard, Gary, and West (1988). Since we are interested only in sunspot magnetic fields outside the visible sunspot boundary, i.e., fields with intrinsic strengths $\lesssim$800 G (Solanki, Rüedi, and Livingston, 1992), the employed calibration curves deviate only slghtly from the weak-field approximation. Furthermore, the neglect of magneto-optical effects should have no significant consequences, since the magnetic fields of interest are almost completely perpendicular to the line of sight and the main contribution to the magnetograph signal comes from the wings of the line, where magneto-optical effects are small for $B \lesssim 2000$ G (West and Hagyard, 1983) (the filter is positioned at 90 mÅ in the blue wing of the line and has a full-width-at-half-maximum of 125 mÅ). Finally, note that the field strengths are determined assuming a completely homogeneous field in the resolution element. In the presence of unresolved small flux tubes and

TABLE I
Summary of active region observations

Date	Active region	Location	Magnetic class	Time (UT)	Field strength
Apr. 6, 1980	2372	N12 E08	δ	21:10	2400 G
Sep. 23, 1980	2684	N22 W18	βp	15:00	2100 G
June 9, 1985	4660	S14 E12	β	13:37	2200 G

magnetic canopies, they will be underestimated. Therefore, the 'field strengths' quoted in the rest of the paper are spatially (vertically and horizontally) averaged values and should not be mistaken with intrinsic field strengths.

The three active regions examined for indications of a magnetic canopy were designated by NOAA active region numbers: AR 2372, AR 2684, and AR 4660. Table I lists dates and times of observation, positions of the active regions on the Sun, magnetic type, and the maximum magnetic field strength measured. These particular active regions were chosen for analysis because of relatively simple structure and proximity to disk center.

Although close to disk center, at least one of the active regions did exhibit projection effects. All three regions were therefore transformed to heliographic coordinates (Gary and Hagyard, 1990). In all figures, north is up with east to the left. Active region 2372 consists of a preceding and following sunspot, both of which are included in the analysis. Figures 1–4 show contours of the transformed magnetic field components for each sunspot in the following order: the vertical component of the field, the horizontal, and an overlay of the azimuth of the horizontal component on the vertical component. The noise level lies significantly below 30 and 200 G for the vertical and horizontal component, respectively.

2.1. Active Region 2372

Active region 2372 was a bipolar sunspot group with a small, opposite-polarity bipole between the main spots. The vertical component of the preceding spot, shown in Figure 1(a), has relatively evenly spaced, symmetric contours on the western side (beginning with the 200 G contour). Contrast the symmetry of the western part of the spot with the elongations of the eastern side. This asymmetry on the eastern side of the spot may be attributed to the presence of the bipole between the two main sunspots.

In Figure 1(b), the horizontal compoent of the magnetic field also shows asymmetrical features on the eastern side of the sunspot. Further, note that the 200 G contour of the horizontal component (i.e., the outermost contour) is farther from the geometrical 'center' of the sunspot than the 30 G contour of the vertical component of the field. The influence of the intruding bipole is also visible on the direction of

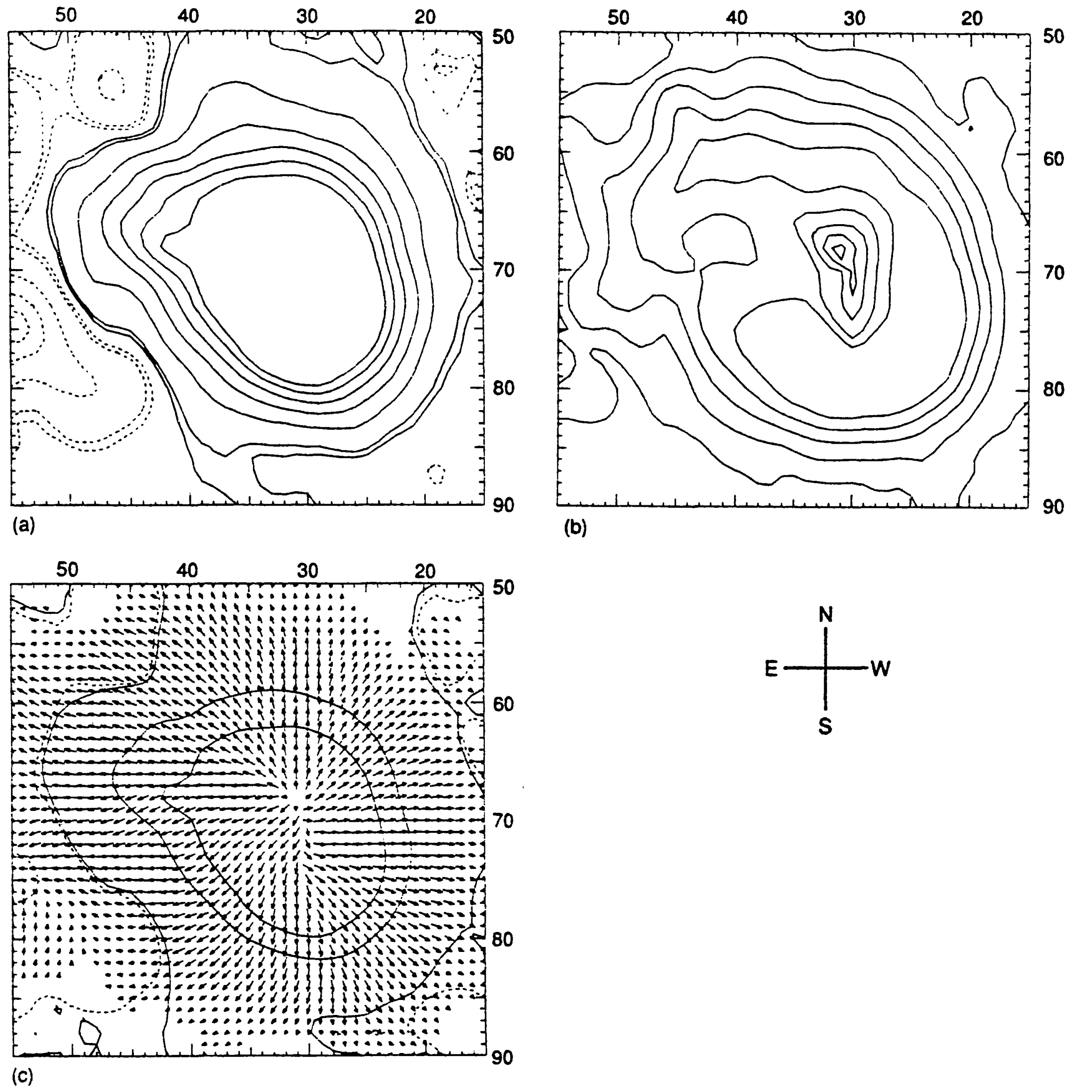

Fig. 1. Components of the field of NOAA active region 2372, the preceding spot. North is up and east is to the left. Each panel is 40 pixels square with each pixel representing 2.4 arc sec. (a) The vertical component of the field is shown in contour form with levels, in G, of ±30, ±50, ±200, ±400, ±600, ±800, ±1000 (similar for 2(a), 3(a), and 4(a)). (b) The horizontal component of the field increases from 200 G at the center of the sunspot, to 1000 G in the penumbra, in 200 G increments, before dropping again outwards (similar for 2(b), 3(b), and 4(b)). (c) The azimuth of the transverse component is overlaid on the contoured vertical component of the field and is scaled by setting to zero all values less than 200 G. The plotted contours of the vertical components are ±10, 500, and 1000 G (similar for 2(c), 3(c), and 4(c)).

the magnetic field in the eastern portion of the sunspot (Figure 1(c)).

The following sunspot of AR 2372 exhibits a conjugate asymmetry to the preceding spot (Figure 2). The western side of this sunspot is more asymmetrical than the eastern of the preceding sunspot of Figure 1, probably also due to the proximity of opposite polarity fields from the intermediate bipole. Dashed contours indicate a field which is opposite in polarity to the preceding spot.

Again, as with the preceding spot, the 200 G contour of the horizontal field in Figure 2(c) is farther from the 'center' of the spot than the 30 G contour of the

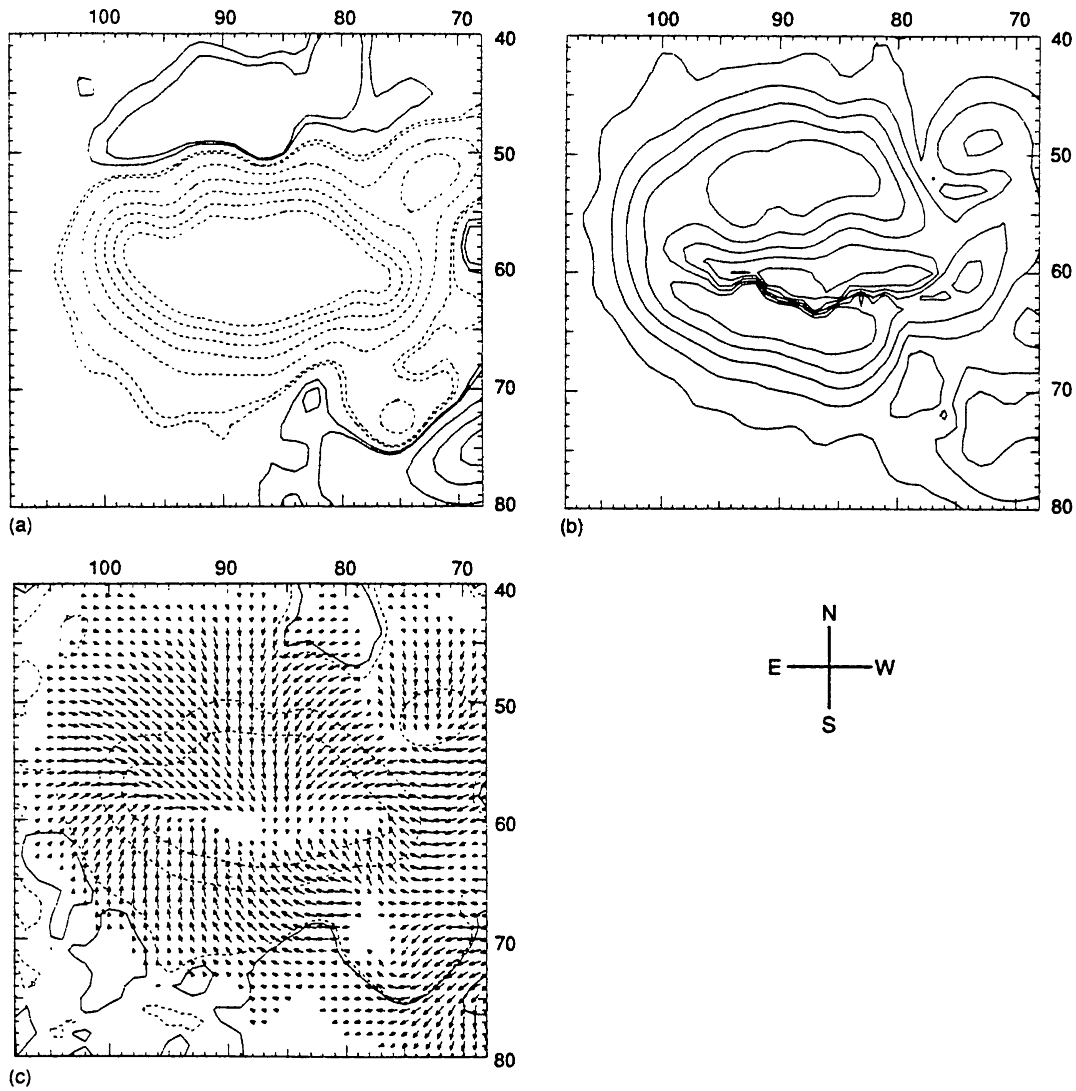

Fig. 2. Components of the field of NOAA active region 2372, the follower spot. As in Figure 1, each panel is 40 pixels square, 96 arc sec on a side. (a) Contours of the vertical component of the field; levels are identical to Figure 2(a). (b) Contours of the horizontal component. (c) The azimuth of the transverse component overlaid on contours of the vertical component. Levels are the same as for Figure 1(c).

vertical component of the field, particularly on its symmetric eastern end.

The azimuth of the horizontal component (Figure 2(c)) displays some twisting of the fields on the western side due to the presence of the intermediate bipole. On the eastern side however, the field appears to be relatively symmetrically distributed.

2.2. Active Region 2684

The next sunspot under study is the leader spot of a large bipolar group. The opposite polarity field on the east side of the sunspot (Figure 3) belongs to a following group of spots.

As with AR 2372, note the position of the outermost contour (200 G) in Figure 3(b) with respect to the center of the spot. This outermost contour of the

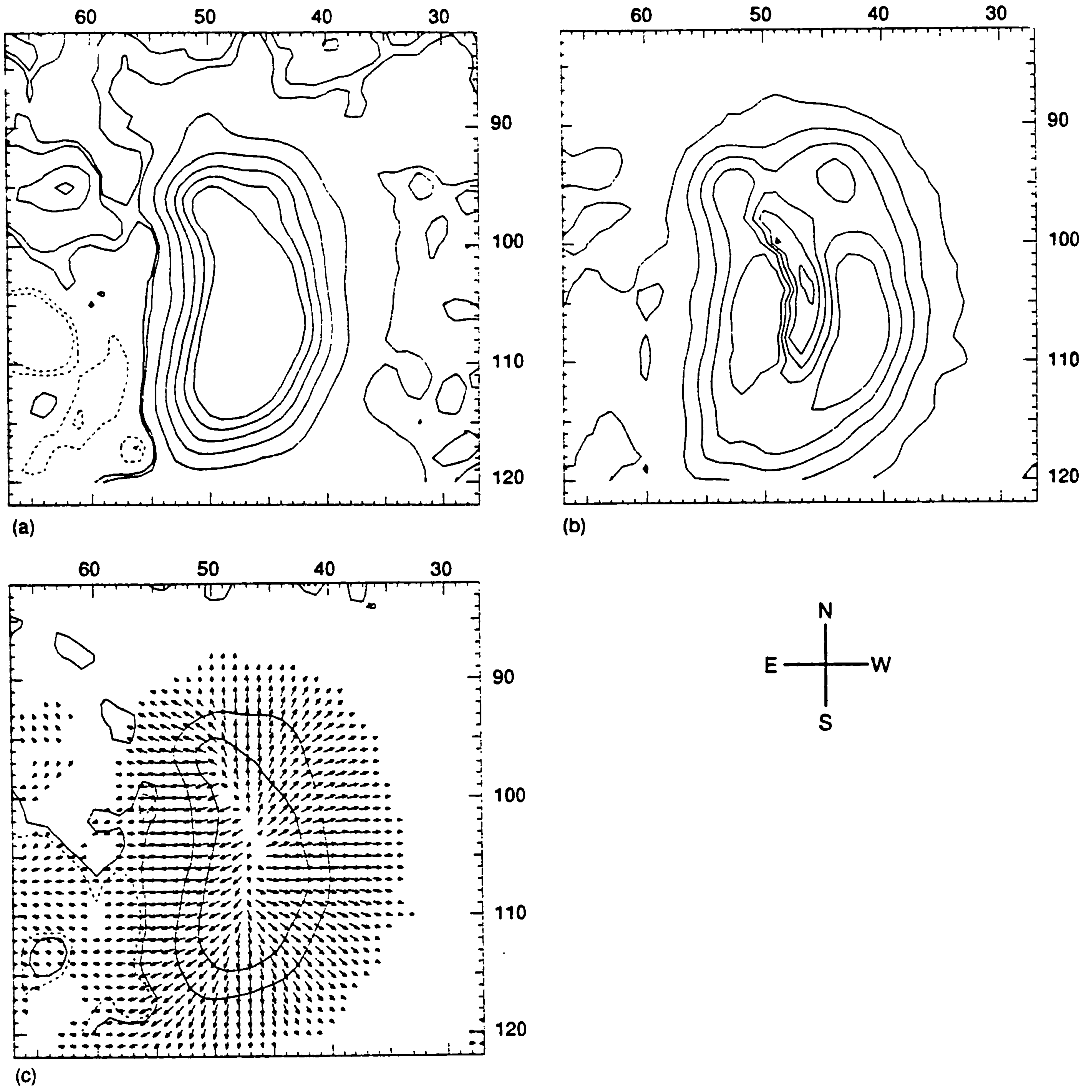

Fig. 3. Components of the field of NOAA active region 2684. The field of view is the same size as Figures 1 and 2 with 2.4 arc sec pixels. (a) Contours of the vertical component of the field. Contour levels have the same values as Figures 1 and 2 for all three panels. (b) Contours of the horizontal component of the field. (c) An overlay of the azimuth of the transverse on the vertical component.

horizontal component extends farther from sunspot center than the 200 G contour of the vertical component of the field, which implies that although the field is very flat, it is not completely horizontal.

Figure 3(c) illustrated the radial distribution of the magnetic field, with very little twist of shear. Note, however, the asymmetry on the side of the sunspot closest to the other associated spots of the active region (the southeast and northeast sides).

2.3. Active Region 4660

Active region 4660 is composed of a relatively isolated, negative-polarity, sunspot which is in decline. In Figure 4 one sees that the contours of both the vertical and horizontal magnetic components are reasonably symmetrical about the center of the sunspot; however, there is a slight ‘bulge’ on the southern side of the spot. Although

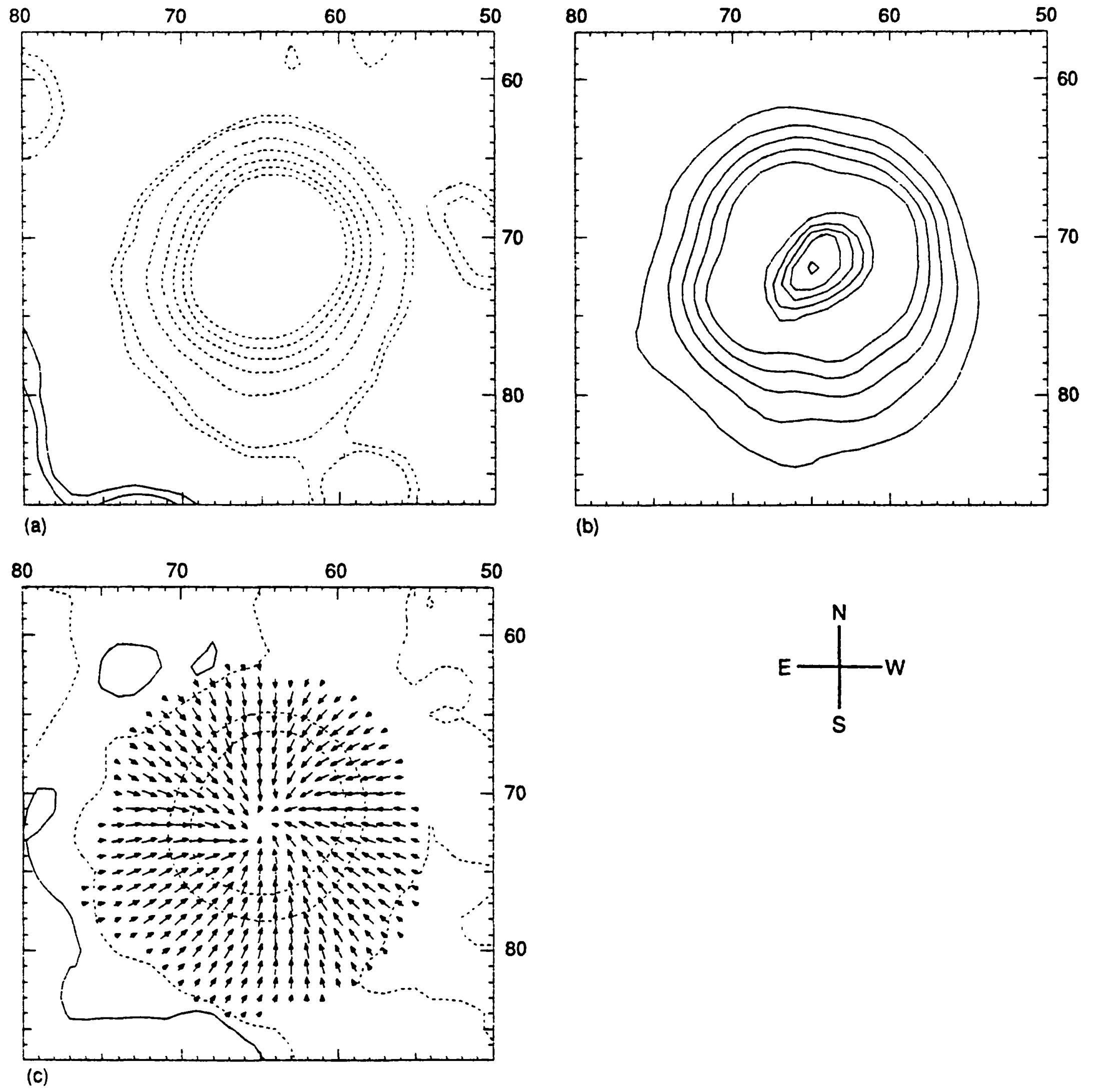

Fig. 4. Components of the field of NOAA active region 4660. Each panel is 30 pixels square with each pixel representing 2.8 arc sec. (a) Contours of the vertical component of the field. Contour levels for all three panels, are the same as in the previous figures. (b) Contours of the horizontal component. (c) An overlay of the azimuth of the transverse on the vertical component.

there are no strong concentrations of field which would cause this asymmetry, there are local weak fields with values between 100 and 500 G (not shown in this field of view) positioned in the direction of the perturbation.

The azimuth of the horizontal component of the field (Figure 4(c)) illustrates the radial symmetry of the field about a center which is only slightly displaced from the geometric center of the sunspot.

The three active regions described in this section exhibit two similar behaviors close to the edge of the sunspot in both the vertical and horizontal components of the magnetic field. First, the vertical component at a value of 30 G and the horizontal compoent at a value of 200 G show asymmetries on the sides closest to opposite polarity field. Second, the horizontal component of the field remains stronger than the vertical component at the sunspot edge.

3. Data Analysis

To identify possible canopy fields, we must first define the sunspot boundary and then determine the relation of the vertical and horizontal magnetic components to that boundary. The penumbral border of each sunspot was determined by finding the mean of the photometric intensity of the obviusly unspotted part of each image and calculating the standard deviation from the mean. The penumbral edge is then defined to be the locus of points where the intensity falls to the average intensity of the obviously unspotted photosphere minus 2σ. This method counts much of the seeing-induced smearing of the penumbral edge of the sunspot. Consequently, magnetic parameters seen outside the thus defined penumbral edge should not be too strongly affected by polarized straylight from the penumbra. In Section 3.4 we briefly estimate the influence of penumbral straylight on the results.

The second group of figures for each data set includes a grey-scale image of white-light intensity in Figures 5(a), 6(a), 7(a), and 8(a). These have been purposely scaled such that the penumbra is heavily contrasted with the photosphere. Consequently, the umbra/penumbra boundary is no longer visible. In part (b) of each figure, a mask was created by painting black all intensity values less than the mean photospheric value minus 2σ of the intensity fluctuations outside the sunspot; all higher values are painted white. The result is a completely black sunspot and white unspotted photosphere. In the present paper, for convenience, we refer to the relatively field-free surroundings of sunspots as simply, the photosphere. In part (c) of each figure, an image of the vertical component of the magnetic field is exhibited. The mask shown in part (b) of the figure is shaded grey. Residual field with values greater than 30 G outside this mask appear black and represent the vertical component of the magnetic field outside the penumbral boundary. A similar figure (panel d) is created for the horizontal component of the field with the difference that values greater than 200 G are displayed as black. The black portions of parts (c) and (d) are probably somewhat contaminated by straylight from the penumbra, but we estimate (Section 3.4) that the straylight does not affect the results significantly. In the following sections, we discuss in detail the figures for each individual sunspot.

3.1. Active Region 2372

There is an irregular ring of vertical field around the mask of the sunspot (part c of Figures 5 and 6), indicating that magnetic field does exist outside the visual boundaries of the spot. The horizontal component (Figures 5(d) and 6(d)) is still quite strong outside the border of the penumbra, of order 200 to 400 G, while the vertical component has dropped to 50 G and less. Therefore, the field in this region is relatively horizontal (Solanki, Rüedi, and Livingston, 1992). It will be seen in the next sections that this structure is not peculiar to this active region.

An inspection of the figures shows that whereas a transverse component greater than 200 G is always geometrically connected to a dark, spot-like feature, this is

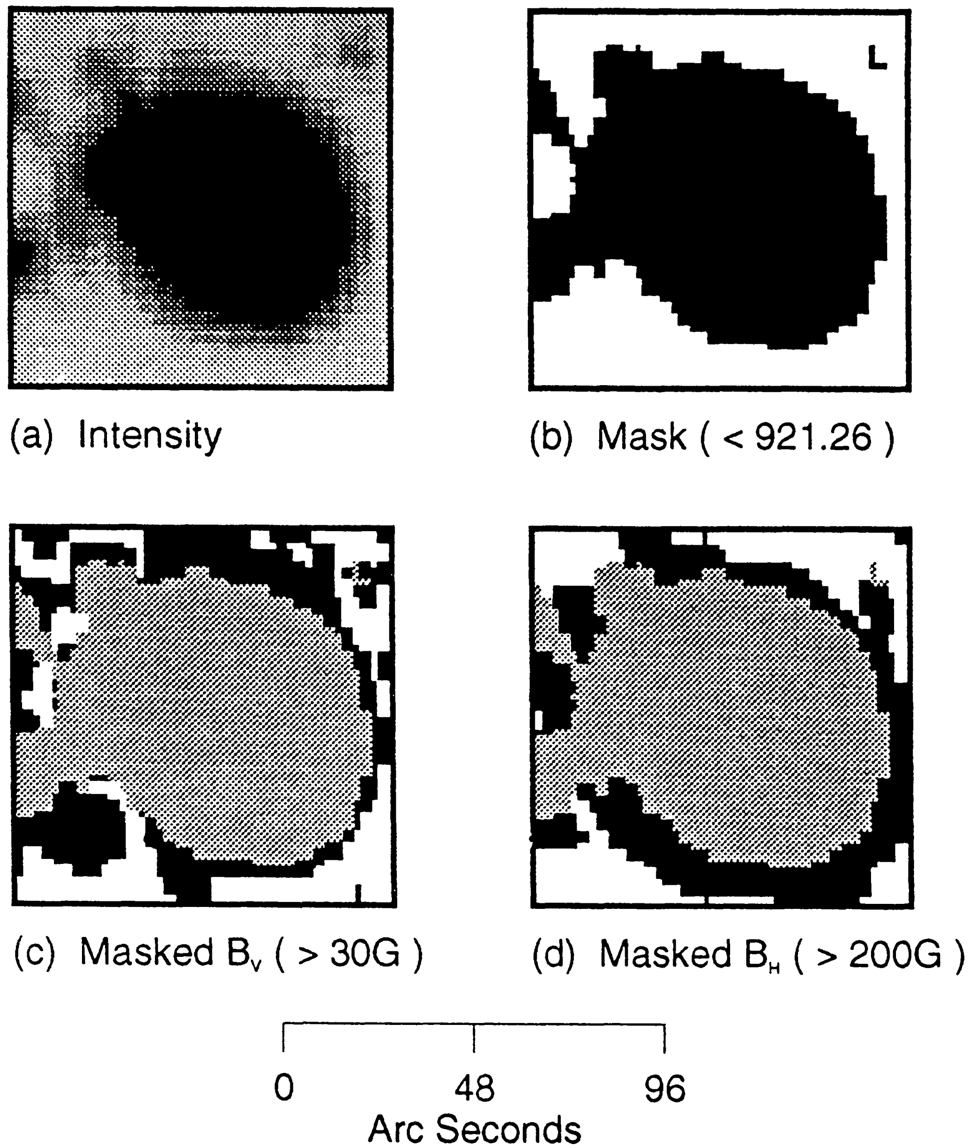

Fig. 5. Masks of the white-light photometric intensity overlaid with the various components of the magnetic field of the preceding spot of AR 2372. The field of view is the same as Figure 1. (a) The grey-scaled white-light image. The scaling was chosen to emphasize the penumbra/photosphere boundary. (b) A mask of the sunspot, created by painting black all pixels with intensity value <921 (the statistically determined penumbral edge of the sunspot, the $\bar{I} - 2\sigma$ value). (c) The central gray region represents the coincidence of points in which the value of the vertical component of the field is greater than 30 G and intensity value is <921. The black areas represent regions where the field strength is >30 G and the intensity value is >921. (d) Similar to 5(c), but the interior gray represents a region in which the value of the horizontal component of the field is >200 G and the intensity value is <921. Black represents the area where the field strength is >200 G and the intensity is >921.

not the case for the longitudinal field. It is probable that a part of the longitudinal field seen in this figure is not physically connected to the sunspot either, but rather has its origin in small-scale plage fields. This is most probable for those fields not visually connected to the sunspot. Taken at face value, a 30 G longitudinal plage field means that any spatial element that is covered to more than 3% by vertical

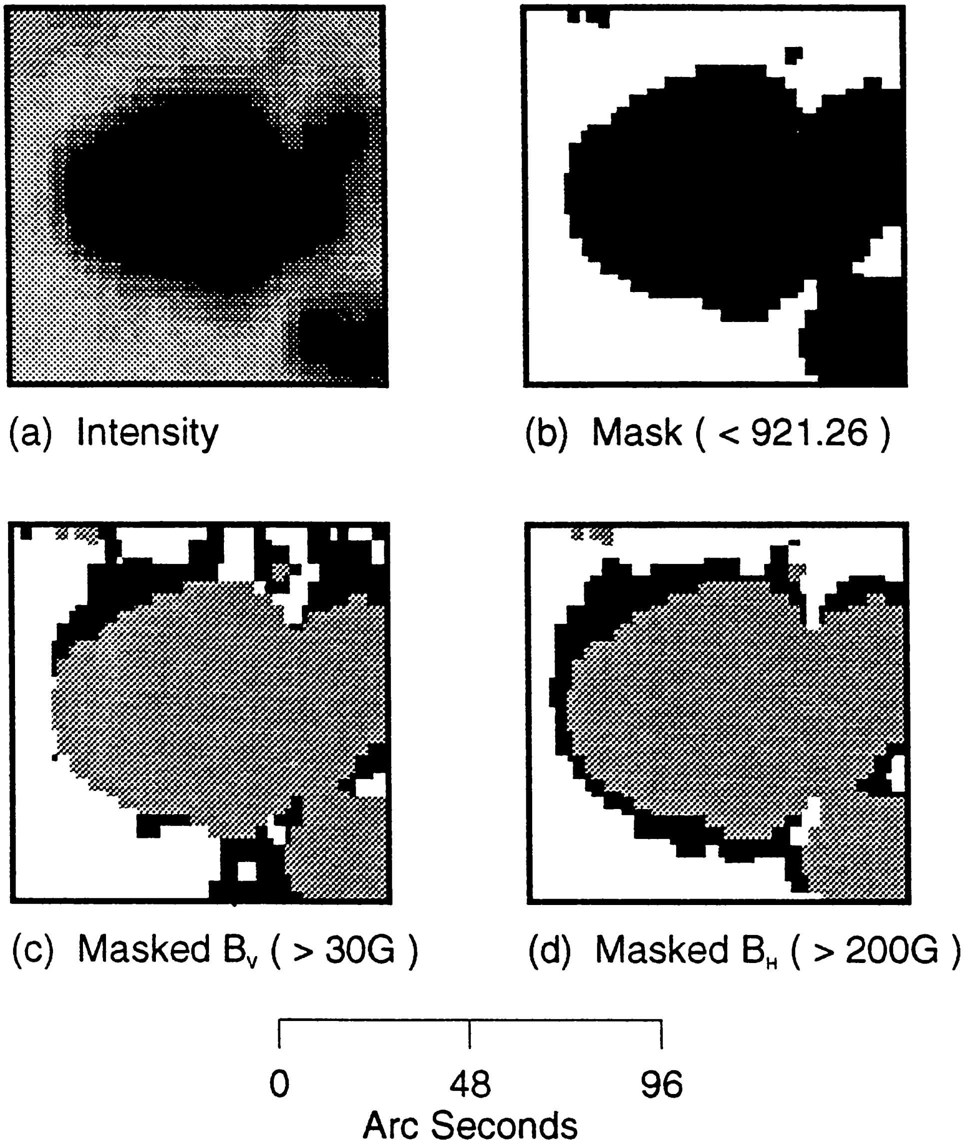

Fig. 6. The masks for AR 2372 follower spot. The field of view is the same as Figure 2. (a) The grey-scaled white-light image. As in Figure 5, the scaling was chosen to emphasize the boundary between photosphere and penumbra. (b) The mask of pixels which are <921. (c) The mask overlaid onto the horizontal component of the field (in the same way as 5(c)). (d) The intensity mask overlaid on the vertical compnent of the field (with values identical to 5(d)).

kG (flux-tube) fields would appear black in frame (c). Even after compensating for thermal line weakening, Zeeman saturation, etc., we still expect that plage areas with filling factors greater than approximately 6–10% are blackened. Since such filling factors are relatively common in active-region plages, it is not surprising that such a large fraction of frame (c) is black.

Due to the proximity of the obsrved sunspots to disk center, the transverse field is unlikely to have its origin in plages. The limits on the inclination of small-scale magnetic fields set by Solanki, Keller, and Stenflo (1987) and Bernasconi (1992) imply that the plage contribution to the transverse field is expected to be much smaller than its contribution to the longitudinal field (cf. Schüssler, 1986). The most straightforward explanation for the horizontal field outside the mask is a low-lying magnetic canopy formed by the field of the sunspot.

3.2. Active Region 2684

Figure 7(a) shows that there are two small spots on the east side of the main sunspot. The southern one has opposite polarity to the sunspot (cf. Figure 3(a)). The horizontal component of the field extends farthest in this direction, which is just what is expected for a low-lying magnetic canopy. The canopy is expected to stay low between fields of opposite polarity, but to lie higher in the direction in which large fluxes of the same polarity exists.

3.3. Active Region 4660

In agreement with the other three sunspots, AR 4660 is characterized by a magnetic field which is very weak in the vertical component and fairly strong in the horizontal at the boundary between unspotted photosphere and penumbra (Figure 8). Notice in Figure 8(c) the absence of vertical component of the field (above the threshold of 30 G) on the eastern side of the spot outside the sunspot boundary. There is, however, an annulus of the horizontal component of the field greater than 200 G, almost completely encircling the sunspot.

3.4. The Problem of Straylight

We find a halo of the horizontal component of the magnetic field just beyond the outer edge of the sunspot penumbra for all three sunspot groups studied. Furthermore, the vertical component corresponding to these locations is weak, so that a similar ring-like structure is less obvious in the vertical field. In some directions the vertical field is visible much further from the sunspot than the horizontal field component, while in others it drops below the instrumental sensitivity of 30 G much closer to the sunspot. Thus, by utilizing a vector magnetograph to provide information about the full vector of the magnetic field and analyzing the data in the manner presented, we infer a magnetic field configuration consistent with a magnetic canopy with a slightly inclined field. However, we must still settle the problem of straylight. We give below a rough estimate of its magnitude and influence on the magnetic vector measured outside the visible boundaries of the sunspots.

The -2σ level corresponds roughly to an intensity contrast of 4%. A typical penumbra has a contrast at 5000 Å of 25–30% (Maltby, 1972). Consequently, at the position at which the continuum contrast has dropped to 4%, the scattered transverse magnetic signal, i.e., $\sqrt{Q^2+U^2}$, should have decreased by a factor of 6–8 compared to its value in the outer penumbra. Now, the average transverse field at 4% contrast level in our measurements is 400–600 G, while published measurements suggest that the horizontal magnetic component in the outer penumbra is 600–800 G (Kawakami, 1983; Lites and Skumanich, 1990; Solanki, Rüedi, and Livingston, 1992). Taking into account that $\sqrt{Q^2+U^2} \sim B^2$ for such weak

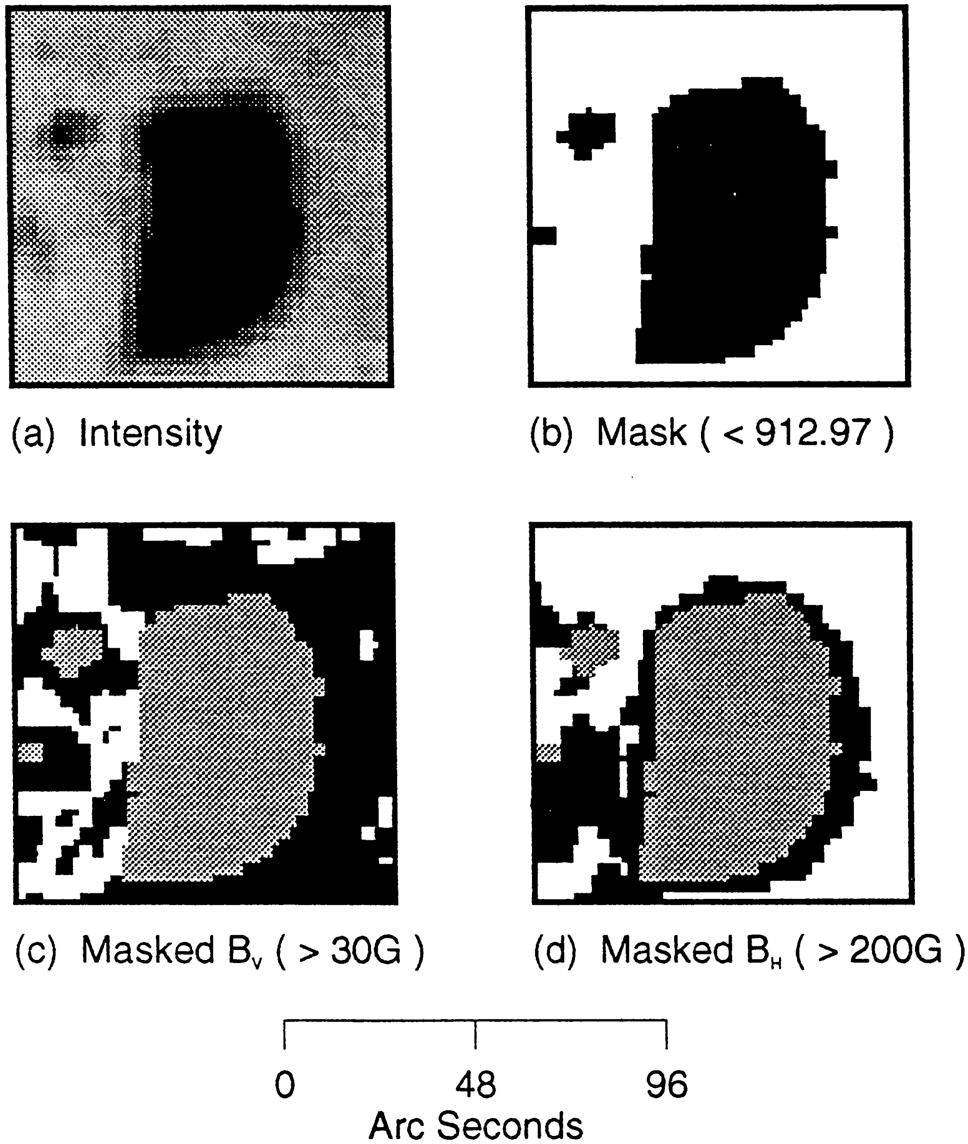

Fig. 7. The masks of AR 2684. The field of view is the same as Figure 3. (a) The grey-scaled white-light image. Scaling is similar to Figure 6. (b) The mask of pixels which are <913. (c) The mask overlaid onto the vertical component of the field in the same way as Figure 5(c). (d) The intensity mask overlaid onto the horizontal component of the field in the same way as Figure 5(d).

fields implies that the signal observed at $I_c - 2\sigma$ is approximately 1.5–3 times smaller than in the outer penumbra. Thus, it is considerably larger than the signal due to straylight. Furthermore, even if we take the worst case, i.e., assume that straylight contributes half the transvese-field signal at the $I_c - 2\sigma$ contour, this still does not affect our results seriously, since the transverse field is reduced by only a factor of $\sqrt{2}$. Consequently, the true (non-straylight affected) transverse field-strength at the $I_c - 2\sigma$ contour outside the sunspot is greater than roughly 300 G. In addition, the straylight component decays exponentially with distance from the sunspot and should affect the signal further away from the boundary to

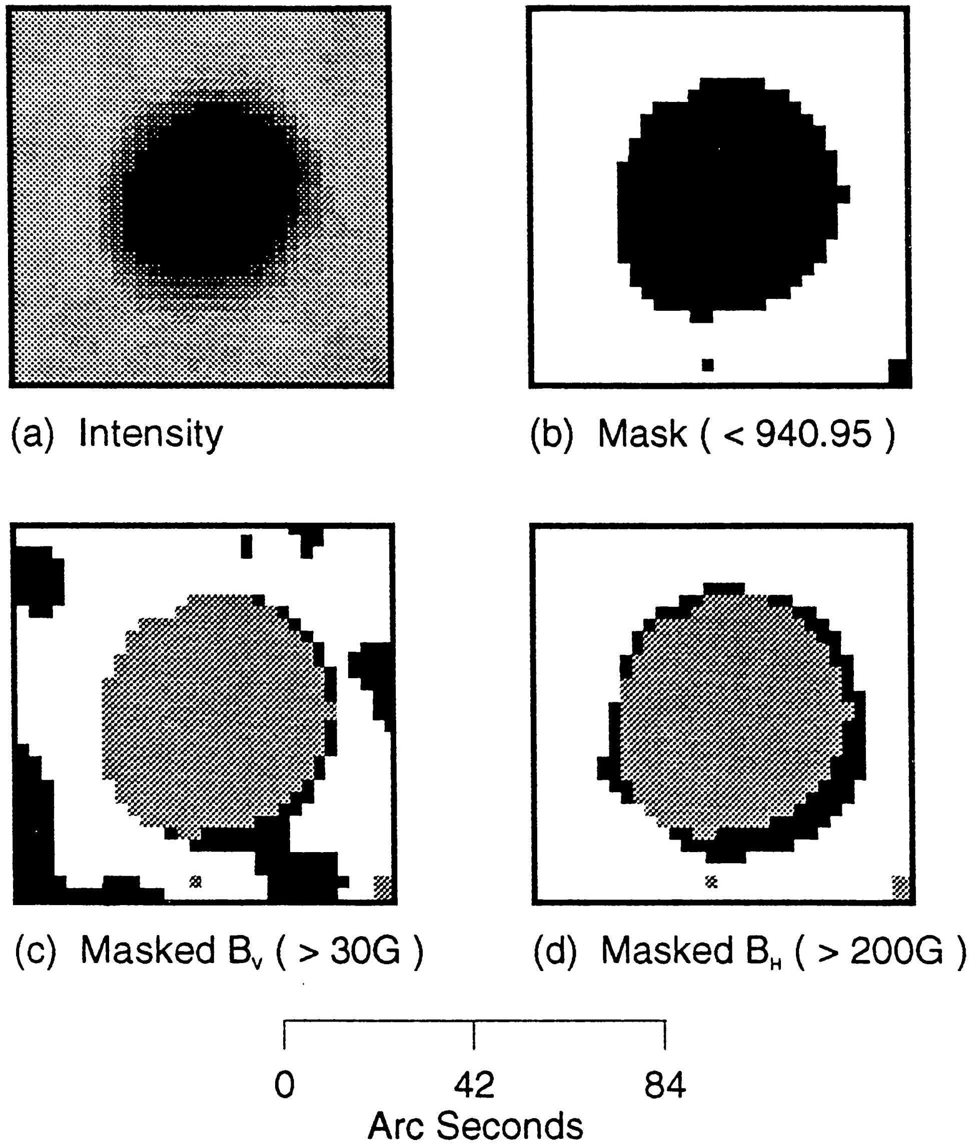

Fig. 8. The masks for AR 4660. The field of view is the same as Figure 4. (a) The grey-scaled white-light image. Again, the scaling emphasizes the penumbra/photosphere boundary. (b) The mask of pixels with a threshold intensity value of 941. (c) Similar to 5(c), an overlay of the intensity mask on the vertical component of the field with threshold intensity of 941 and vertical field threshold of 30 G. (d) Again, similar to Figure 5(d), an overlay of the intensity mask with the horizontal component of the field; as before, the horizontal field threshold is 200 G.

a much smaller extent. Thus, the blackened regions seen in Figures 5(c)–8(c) (in the horizontal field) represent magnetic canopies, and straylight from the sunspots affects the transverse-field signal there by only a minor amount.

Consider next the vertical magnetic component. Recently published values are typically 100–200 G near the penumbral boundary, so that the vertical field due to the sunspot, smeared out to the $I_c - 2\sigma$ level, should be 15–30 G. The 30 G contour in Figures 5(b)–8(b) lies well outside the $I_c - 2\sigma$ contour. Further, we find that the measured strength of the vertical magnetic component at the penumbral boundary is on average 50–100 G. Consequently, the blackened regions in these figures should represent canopy (or plage) fields, although the possible influence of straylight is somewhat greater than for the horizontal magnetic component.

Thus, we conclude that although the areas shaded black in Figures 5–8 are somewhat affected by straylight from the sunspot, they mainly reflect the presence of magnetic fields at the measured positions.

3.5. Contribution Functions and Canopy Height

Before finally deciding that we have detected magnetic canopies, we have to judge whether Fe I 5250.2 Å is sufficiently sensitive to magnetic fields in the middle and upper photosphere, at which heights previous investigations have typically shown the canopy base to lie. To this end we have calculated, in a quiet-Sun model, the V/I_c line depression contribution functions (Grossman-Doerth, Larsson, and Solanki, 1988) of Fe I 5250.2 Å, and of two lines used by Giovanelli and Jones (1982), namely, C I 9111 Å and Fe I 8688 Å. For Fe I 5250 Å we have assumed the angle between the magnetic field and the line of sight, γ, to be 85°, which should correspond approximately to the γ of a canopy seen close to $\mu = \cos\theta = 1$, i.e., solar disk center. For the other lines we have used $\gamma = 45°$ and $\mu = 0.7$, corresponding roughly to the values at which Giovanelli and Jones observed their sunspots.

As an illustration, the contribution functions, at the wavelength of the center of gravity of the Stokes V lobes for $B = 600$ G, a field strength typical of magnetic canopies (Solanki, Rüedi, and Livingston, 1992), are plotted in Figure 9. All calculations were carried out in the quiet-Sun atmosphere of Maltby *et al.* (1986) *. Obviously, C I 9111 Å, which showed no sign of a canopy in the images of Giovanelli and Jones (1982), obtains most of its contribution in the lowest part of the atmosphere, below $\log\tau_{5000} = -1$, which corresponds to a geometrical height <150 km above $\tau_{5000} = 1$).

The contribution functions of the Stokes V profiles of Fe I 8688 Å, which did show canopies extending a short distance in the Giovanelli and Jones images, and Fe I 5250 Å peak at the same optical depth, namely, $\log\tau \approx -1.6$ (approximately 250 km above $\tau_{5000} = 1$) and these lines even obtain some contribution from $\log\tau_{5000} = -3$ (450 km above $\tau_{5000} = 1$).

The absolute value of the 5250 Å contribution function is smaller, due to the large λ under which it was calculated. This implies that at solar disk center Stokes V of 5250 Å is not as sensitive to canopies as Fe I 8688 Å near the limb and can probably not follow them as far from the spot as observations near the limb. However, the

* The sign reversals in the contribution functions of C I 9111.2 Å and Fe I 8688 Å are typical for Stokes V prfiles of lines that are not completely Zeeman split. Fe I 5250 Å does not show this reversal in its Stokes V contribution function due to its larger effective Zeeman sensitivity (which takes into account Landé factor, wavelength, and non-magnetic line width). Note that closer to the line core Fe I 5250.2 Å does show such reversals. Further examples and a thorough discussion of Stokes line depression contribution functions showing reversals are given by, e.g., Murphy (1990).

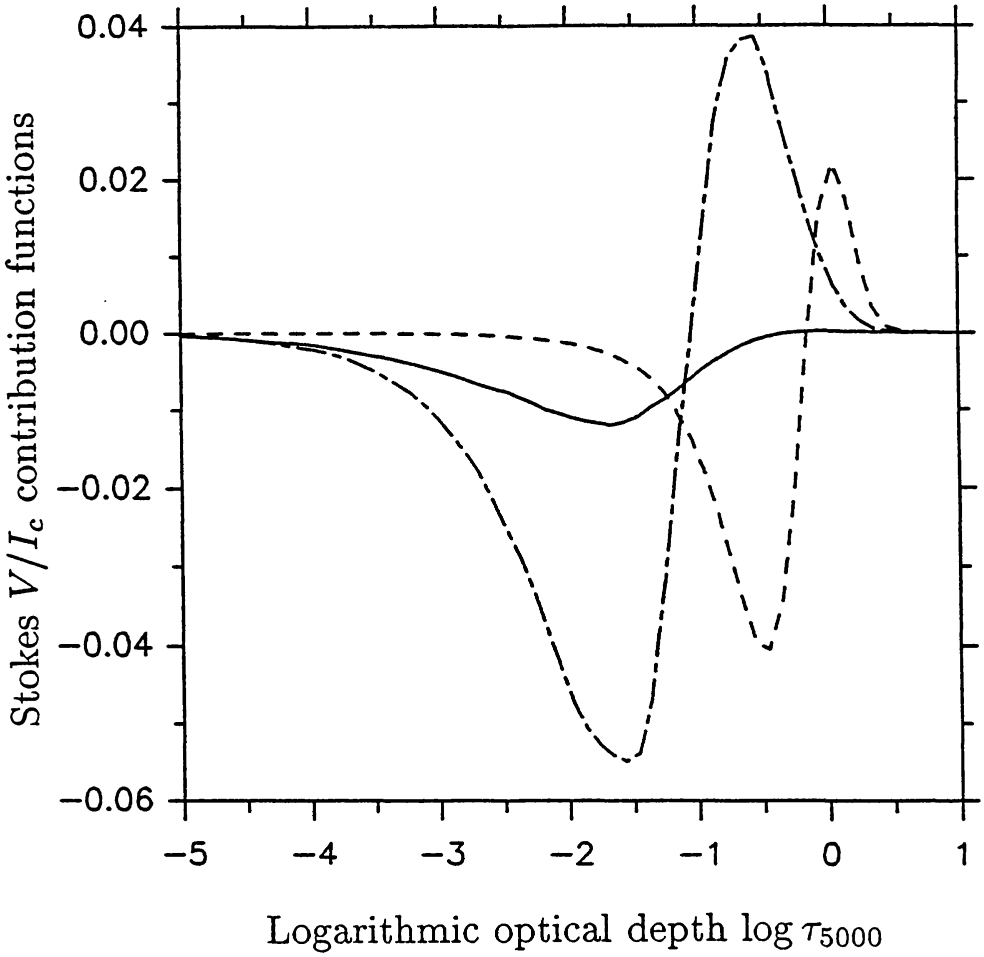

Fig. 9. The Stokes V/I_c contribution functions. The dashed curve represents C I at 9111 Å, the solid one represents Fe I at 5250 Å, and the dot-dashed curve is Fe I at 8688 Å.

Stokes Q contribution function of Fe I 5250 Å has exactly the same shape as its Stokes V contribution function, but at $\gamma = 85°$ it has 4 times the amplitude, so that the canopies should be considerably more visible in Stokes Q and U measurements. The similarity between the shapes of the Q and V contribution functions also means that the $V/\sqrt{Q^2 + U^2}$ ratio, or, equivalently, the vertical and horizontal B values derived from V and $\sqrt{Q^2 + U^2}$, should reliably give the inclination angle of the field in the canopy.

We now use the Stokes contribution function to estimate the height of the canopy base. For each Stokes parameter, Q, U, and V, we add together the line depression contribution functions to Fe I 5250 Å over the wavelength range corresponding roughly to the filter position and width, assuming an appropriate field strength (500 –800 G) and inclination angle (75°–85°). The integral from $\tau = 0$ to ∞ over this 'wavelength-averaged contribution function' simulates the magnetograph signal for the chosen magnetic parameters in the absence of a magnetic canopy (i.e., a field reaching down to the continuum-forming level). If, for example, the measured signal is half the signal expected without a canopy (e.g., 300 G instead of 600 G), then we only have to determine the height above which half the area under the 'wavelength averaged contribution function' lies. This gives us the height of the canopy base. Thus a rough estimate of the canopy base height can be obtained easily from the ratio of the measured to the expected field strength. We stress that we are only interested in a rough estimate, and do not attempt to determine the base height very accurately.

This technique has the advantage of speed compared to direct fits to the measured signals using Q, U, and V profiles calculated in models with different canopy heights (for our technique a single profile and contribution function calculation is sufficient for a given field strength and inclination). One disadvantage is that the approach neglects changes in the Zeeman desaturation of the line profiles due to the presence of the canopy base. For not too strong lines, like Fe I 5250 Å, and the relatively weak fields considered here this is only a minor drawback. Another disadvantage is that the intrinsic magnetic field strength in the canopy must be assumed. This point, however, is shared with all quantitative determinations of the canopy base height based on spectral lines which are not completely Zeeman split.

From an application of the outlined technique we find that the present observations are consistent with the presence of relatively low-lying magnetic canopies around sunspots. Close to the sunspot ($3''$–$6''$ from the penumbral boundary) the magnetic field in the canopy lies roughly 150–300 km above the quiet-Sun $\tau = 1$ level and is inclined by roughtly 5°–15° to the horizontal. Further away from the sunspot, the canopy is almost horizontal and lies roughly at a height of 300–400 km.

4. Discussion and Conclusions

This study has utilized vector magnetograph measurements from three active regions and analyzed them for the presence of a canopy at or close to the penumbral boundary. As a first step, the location of the penumbral boundary was defined by taking an average of the unspotted photospheric intensity. The penumbral edge then, is defined to be that location where the photospheric intensity has fallen to 2σ below the average. The next step in the analysis of the data was to mask out the sunspot and flag those regions surrounding the sunspot where the magnetic signal is well above the noise.

All the analyzed sunspots show a halo of almost horizontal field which is considerably larger than the noise and the expected straylight from the spot. This halo is best represented by a magnetic canopy. An almost horizontal field encircling a sunspot cannot be due to small flux tubes, since these possess considerably larger vertical than horizontal magnetic components.

Solanki, Rüedi, and Livingston (1992) and Solanki, Montavon, and Livingston (1993) derived an intrinsic field strength of 500–800 G for the canopy fields close to the sunspot from the direct splitting of 1.56 μm spectral lines. Since the average field strength measured by us in the immediate surroundings of the sunspots is

200–400 G, i.e., well below the intrinsic field strength, we infer that the observations show a canopy-like field, with a base corresponding roughly to the height of line formation (see the analysis in Section 3.5). Furthermore, the vertical component of the magnetic field does not drop to zero at the penumbral edge; indeed, in all the data sets, the vertical field component is well above both the noise level and the level of straylight at most points at the penumbral boundary.

The ratio between the horizontal and vertical magnetic values suggests that the inclination angle to the horizontal of the field forming the canopy lies between 5° and 15° just outside the penumbra (in the absence of plage contributions to the vertical magnetic component). Further away, the transverse magnetic component retains a ring around the sunspot, while the vertical component only continues in certain directions. The vertical magnetic component extending far from the sunspot cannot be due to the canopy, since this would imply a field inclination that would rapidly make the canopy lie above the formation height of 5250 Å with distance from the sunspot. Therefore, the vertical component farther away from the sunspot, which is irregularly distributed there, must be due to plage fields. An indication of a diminishing inclination of the canopy field with distance from the sunspot, results from observations of the presence of horizontal field at positions where no vertical field is detected. This picture is in excellent agreement with the results of Solanki, Rüedi, and Livingston (1992) and Solanki, Montavon, and Livingston (1993).

The major advantage of observing transverse fields around sunspots near disk center is that canopies can be observed equally well on all sides of the sunspot, while longitudinal field observations near the limb fail to detect those parts of the canopies whose magnetic vector is almost perpendicular to the line of sight. Furthermore, the observation of all four Stokes parameters allows the inclination of the magnetic vector in the canopy to be determined directly. One advantage of possessing an inclination measurement is discussed below.

Although we cannot completely rule out a perfectly horizontal magnetic canopy, our observations susggest that the canopy field is inclined by 5°–15° close to the sunspot. This is in good agreement with the results of Solanki, Rüedi, and Livingston (1992), but conflicts with the interpretation of Giovanelli and Jones (1982) and in particular Giovanelli (1982). They favored a canopy base that lies 180 km above the quiet Sun $\tau = 1$ level at the edge of the sunspot and remains almost unchanged with distance; i.e., they proposed an almost perfectly horizontal field. The field-line inclination of 5°–15° also does not support the presence of a magnetic canopy in the penumbra of a sunspot, as proposed by Giovanelli (1982), since a penumbral canopy requires the field lines to be horizontal at the penumbral edge. Solanki and Schmidt (1992) present additional, stronger evidence against a penumbral canopy. Therefore, we conclude that the magnetic canopy of a sunspot begins at its outer boundary.

There are two possible explanations for Giovanelli's (1982) result that the height of the sunspot canopy base lies well above $\tau = 1$ even right at the outer penumbral edge. (1) His definition of the sunspot boundary may have been different from ours.

(2) His low photospheric line, C I 9111 Å, is formed only 50 km above $\tau_{5000} = 1$ (Figure 9). Even if the magnetic canopy begins at the outer penumbral edge, then for a magnetic inclination of 5°–15° the canopy base lies above the formation level of this line within 0.3″–1″ of the sunspot boundary, which is well below his spatial resolution. Thus, Giovanelli (1982) could not distinguish a *horizontal* canopy with a base height of 180 km at the penumbral boundary, as he assumed, from one with a base height of 0 km that is *inclined* outward by 5°–15° close the the sunspot.

We stress that we do *not* argue against a penumbral canopy on the basis of the spatial resolution of our observatons, which is not higher than that of Giovanelli's (1982) data, but rather based on the fact that we measure the inclination angle of the field: an inclined field just outside the sunspot is not compatible with a penumbral canopy.

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