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Interpretation of broad band circular polarization measurements using Stokes V spectra

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Summary. The wavelength dependence and the centre to limb variation of the broad band circular polarization of solar active regions are determined by integrating over spectra with a large wavelength range obtained with a Fourier transform spectrometer (FTS). It is shown that the broad band circular polarization (BBC) is due mainly to the asymmetry of the Stokes V profiles and that the continuum polarization in solar magnetic features outside sunspots is less than $10^{-4}/(\alpha\delta_c)$, where α is the filling factor and δ_c is the continuum contrast of the magnetic features. The approximate contributions of lines of different depths to the total broad band signal are analysed.

The diagnostic contents of BBC observations with low spatial resolution, such as those of Kemp et al. (1987a), are discussed. These observations are reproduced with the help of simulated broad band polarization data obtained by integrating FTS spectra. It is shown that the spatial distribution of the net field on the solar surface (within a single large spatial resolution element) can affect the measured BBC signal considerably, and may even change its sign. Finally, the results obtained for the solar case are applied to the interpretation of stellar data, in particular of λ Andromedae.

Key words: solar magnetic fields – stellar magnetic fields – polarized light – Stokes V asymmetry

1. Introduction

The measurement of broad band circular polarization (abbreviated in the following as BBC) on the sun dates back to a series of papers by Illing et al. (1974a, b, 1975), who measured the broad band circular and linear polarization in sunspots at various positions on the solar disk. The spectral dependence of the BBC in sunspots has been published by Kemp and Henson (1983), while Henson and Kemp (1984) have analysed the BBC as a function of position in the sunspot. In a recent paper Kemp et al. (1987a) have presented BBC measurements integrated over large portions of the solar disk and even over the complete solar disk, while Kemp et al. (1987b) have detected a BBC signal from the star λ Andromedae.

Although these recent measurements represent a technical breakthrough, their interpretation in terms of the physical structure of the magnetic portions of the atmosphere has so far been elusive. Even the connection between the observed BBC and spectrally resolved observations of Stokes V has not yet been established beyond doubt. Although it appears likely that the BBC in the visible spectral range is due to an asymmetry between the areas of the blue and red wings of Stokes V (e.g. Stenflo et al., 1984; Solanki and Stenflo, 1984, 1985; Stenflo and Harvey, 1985; Scholiers and Wiehr, 1985; Wiehr, 1985), it has not yet been possible to rule out that continuum polarization is responsible for at least a significant part of the BBC, even if this is theoretically not expected for the field strengths found on the sun (Kemp, 1970) and some evidence for a connection between the BBC in sunspots and spectral lines has been presented by Makita (1986). We aim to establish a strong connection between the BBC and Stokes V asymmetry outside of sunspots.

Another aim is to analyse the general properties of the BBC. Stenflo (1984b) discussed the general characteristics of a white light magnetometer with the help of the BBC simulated by integrating resolved Stokes V spectra obtained in active regions and the network. Our approach shall in part be similar to his but more refined and considerably more extensive. Thus we study the centre to limb variation (CLV) and the spectral dependence of the BBC simultaneously in much greater detail than has so far been attempted.

There is yet another reason for carrying out this investigation. The sign of the BBC measured by Kemp et al. (1987a) is opposite to that expected from the observed asymmetry of Stokes V near disk centre (Kemp, private communication), where, for most iron lines, the blue wing is seen to be stronger than the red wing. Although the sign of the asymmetry changes as we move towards the limb (Stenflo et al., 1987; Pantellini et al., 1988), this happens rather close to the limb for the majority of the lines. In observations covering large portions of the solar disk, like those of Kemp et al. (1987a), the regions giving rise to the proper sign of the BBC give only a minor contribution to the light. However, the investigations of Stenflo et al. (1987) and Pantellini et al. (1988) are limited to Fe I lines. We neither know how lines of other elements behave, nor do we know how large the contribution of lines of different strengths is to the BBC. This last point is of some

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★ Visiting astronomer at the National Solar Observatory operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation importance, since Pantellini et al. (1988) have shown that the sign of the asymmetry of lines of different strengths changes at quite different distances from the solar limb.

In order to avoid confusion concerning the definition of the sign of Stokes V, we have in the present paper adopted the convention used by Kemp et al. (1987a): Stokes V is positive for left-handed circular polarization, i.e., when the electric vector in a stationary plane is rotating counter-clockwise as seen from the direction of the observer.

In the present paper we first simulate the BBC observed with a spatial resolution of 5–10″ by integrating spectrally over Stokes V spectra covering large spectral ranges at various positions on the solar disk. By adding together such suitably weighted "simulated broad band" (SBB) measurements referring to the different parts of the solar disk (spatial integration) we then attempt to quantitatively reproduce the observations of Kemp et al. (1987a), thus firmly establishing a connection between the observed BBC and the Stokes V asymmetry. This approach also allows us to greatly enhance the diagnostic value of BBC measurements outside sunspots. In particular it shows how sensitive the BBC is to the distribution of the net solar magnetic flux. Finally, we discuss observations of BBC and Stokes V asymmetry on the stars λ Andromedae and HD 147010 (Kemp et al., 1987a; Mathys and Stenflo, 1986). An analysis of this type is essential before we can make any confident interpretation of the BBC of other stars in terms of magnetic morphology.

2. Spectral integration: simulated broad band circular polarization

The data were obtained with the McMath telescope and the Fourier transform spectrometer (FTS) at Kitt Peak. Near disk centre ($\mu = \cos\theta > 0.9$, θ is the angle between the line of sight and the vertical direction in the atmosphere) we have used Stokes I and V spectra recorded in 1979. They cover a spectral range of 4104–6907 Å in the enhanced network, while in active region plages the total available spectral range is 4524–6907 Å. These data have been described in greater detail by Stenflo et al. (1984). We use these spectra to determine the detailed spectral dependence of the BBC. In addition we also use a set of seven Stokes I, V, and Q spectra recorded in 1984 to analyse the centre to limb variation (CLV) of the BBC. Each of these spectra covers a wavelength range of 4883–6002 Å and their μ values range between 0.83 and 0.16. This data set has been described by Stenflo et al. (1987). Additional information on all the data used has also been compiled by Pantellini et al. (1988) and Solanki (1987). We only wish to note here that the residual continuum polarization in these data is smaller than the noise level (which is of the order of 10^{-4}) since any such polarization was removed when compensating for a possible false zero-level offset introduced by the instrument.

The SBB signal is calculated from the Stokes V spectra by integrating over wavelength with a running integration window of fixed width. This is equivalent to convoluting the spectrum with a rectangular profile. We use an integration window of 130 Å width, which lies in the range of filter band widths (60–200 Å) used by Kemp et al. (1987a). We define the resulting SBB signal to be positive when the underlying Stokes V asymmetry is such that the blue wings are stronger than the red wings. This definition is independent of magnetic field polarity.

The first problem we face is that a spectral line with a strong Stokes V signal lying only partly within the integration window can strongly affect the SBB signal of the whole window. This leads to considerable unnecessary noise in the SBB curve. To remedy this problem we have made the integration boundaries slightly flexible so that lines lie either completely inside or outside the window. Secondly, it has been necessary to search for spikes in the Stokes V spectrum introduced by the FTS. The parts of the spectra containing the spikes are not integrated, since they could otherwise drastically influence the shape of the SBB curve in their vicinity. Thirdly, in order to minimize the influence of noise in the FTS spectra, no integration is carried out where no lines are present (i.e. for $I/I_c > 0.96$). Steps 1 and 3 mainly smooth the SBB curves, without leading to any significant loss of information. In particular step 3 produces an almost negligible change in the SBB curves of spectra with a low noise level, but a noticeable change for spectra with a high noise level.

In order to cover the complete wavelength range available at disk centre it is necessary to join different FTS spectra together. We only join the curves of regions with similar filling factors. The curves have been matched to each other by assuming that temperature and field strength insensitive Fe II lines present in two spectra have the same strength in both. By requiring their V amplitudes to be the same in both spectra we take into account to first order such differences between individual regions as caused by their filling factors, angles between the line of sight and the magnetic field etc. (cf. Sect. 3.1, for a more detailed discussion).

The final SBB V/I_c vs. λ curves near disk centre are plotted in Fig. 1. The vertical scale is in arbitrary units. The upper curve shows the SBB for network data ($\mu \gtrsim 0.98$), while the lower curve is for an active region plage ($\mu \approx 0.92$). Note the spectral dependence with the SBB increasing towards the blue, in general agreement with the sunspot BBC observations of Kemp and Henson (1983). The spectral dependence of the SBB correlates quite well with the amount of absorption by spectral lines in the Stokes I spectrum. The remarkable similarity in shape between the network and plage curves confirms that our SBB curves are

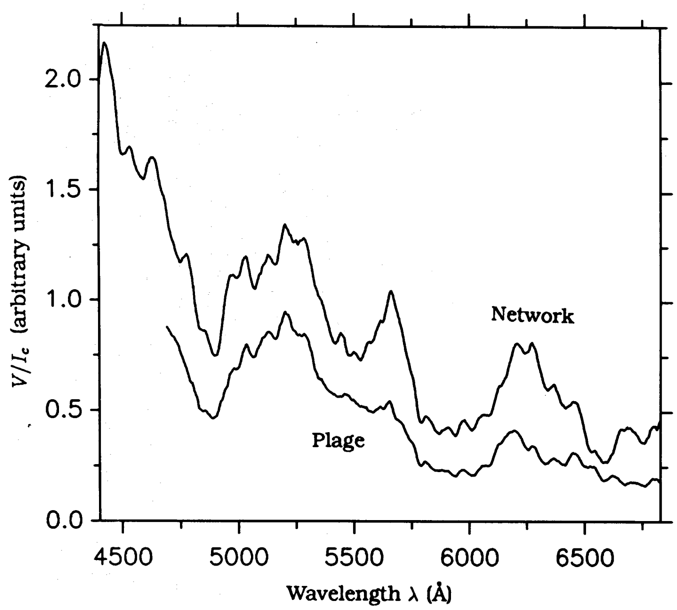


Fig. 1. SBB, i.e. broad band circular polarization simulated by integrating over FTS spectra with a running integration window of width 130 Å, plotted as a function of window central wavelength, λ. Upper curve: Enhanced network data at $\mu = 1$. Lower curve: Active region plage data at $\mu = 0.92$. The curves have been normalized such that Fe II lines have the same Stokes V amplitudes in both regions. The units of the vertical scale are arbitrary

resonably reproducible. The larger SBB signal of the network suggests a larger relative area asymmetry of the Stokes V profiles than in plages.

The general trend of these curves is similar to the one derived by Stenflo (1984b) from the same data, although the details are quite different. One reason for the differences is that his integration window was only 50 Å wide. Also, he did not take the additional precautionary steps we have taken. Finally, his curve is obtained from a mixture of plage and network data.

In order to derive the centre to limb variation (CLV) of the SBB, we now normalize all the curves once more by matching the Stokes V amplitudes of a chosen set of Fe II lines. Figure 2 shows the so normalized SBB curves for eight regions between $\mu = 0.92$ and 0.16. The SBB bluewards of 5300 Å changes sign between $\mu = 0.57$ and 0.67, suggesting that the sign of the Stokes V asymmetry of other elements behaves like that of Fe I Stokes V profiles (Stenflo et al., 1987; Pantellini et al., 1988). In addition to the sign, the spectral dependence of the SBB also changes markedly as μ is decreased. Note that in accordance with Fig. 1 the network region at $\mu = 0.83$ has a larger SBB signal than the plage regions at $\mu = 0.92$ and 0.67.

We have also compared the CLV of the SBB derived from our data with the trend of the sunspot BBC data of Illing et al. (1974b), derived from their Table 1 (maximum polarization obtained with 100 Å filter centred on 5300 Å). Both Table 1 and Fig. 1 of Illing et al. (1974b), clearly show that within the observed μ interval ($0.95 \geqq \mu \geqq 0.37$) the BBC of the major portion of the sunspot does not change its sign. Therefore, although the spectral signature of the BBC in sunspots and faculae is similar near disk centre, the CLV is quite different. Whether this is due to differences in the field geometry, the thermal structure, or the velocity structure is at present unclear.

The next question we wish to address is: Why does the spectral dependence of the SBB vary with limb distance? A possible explanation is based on the observation of Pantellini et al. (1988) that the V asymmetry of the strong Fe I lines changes sign at larger μ than the V asymmetry of weak Fe I lines. Since the ratio of the number of strong to weak lines increases rapidly towards the blue we would expect exactly the observed effect.

To test whether this explanation is the correct one, we have calculated the SBB separately for lines with depths in the quiet sun in the following ranges: $d < 0.4$, $0.4 \leqq d < 0.6$, $0.6 \leqq d < 0.8$ and $0.8 \leqq d < 1.0$, where $d = 1 - I/I_c$. Unfortunately the test is not completely rigorous for two reasons. Firstly, we have used only a simple automated technique to identify a line of a given depth. A spectral line is assumed to be present wherever $I/I_c \leqq 0.96$. The line is assigned to a given depth range by deriving the depth of the absolute minimum of Stokes I inside an uninterrupted interval with $I/I_c \leqq 0.96$. The main disadvantage of this technique is that the SBB contribution of weaker members of a blend are attributed to the depth range of the strongest member. However, since we only apply it to spectra with $\lambda > 4900$ Å, it should be reasonably accurate. Secondly, the line depths of the measured Stokes I profiles are somewhat dependent on filling factor and μ, so that in a few cases a given line may be assigned to different depth ranges in different regions.

In Fig. 3 we have plotted the resulting SBB curves for a plage region at $\mu = 0.28$. The weakest lines ($d < 0.4$) produce a positive SBB signal, even for this small μ value. However, this is of little consequence, since the lines with $d < 0.6$ give only a minor contribution to the total signal, except near the red end of the spectrum. By far the largest contribution comes from the medium strong lines with $0.6 \leqq d < 0.8$, despite their relatively small numbers. The strongest lines ($0.8 \leqq d$) give major contributions only near 5200 Å, due mainly to the presence of the Mg I b lines. The true Stokes V asymmetry of these lines is difficult to determine due to the prominent (strongly asymmetric) blends in their wings. However, a careful analysis suggests that away from disk centre they do indeed have a negative area asymmetry of approximately 10–20%.

By analysing the contributions of the lines of different depth at various μ we confirm that the main reason for the variation in spectral dependence of the SBB is indeed the change in strength of the SBB produced by the stronger lines relative to the weaker ones. Whereas near disk centre all lines give rise to positive SBB curves of roughly equal amplitude, nearer the limb the stronger lines completely dominate and produce strongly negative SBB curves, while the weak ones continue to give small and positive SBB signals.

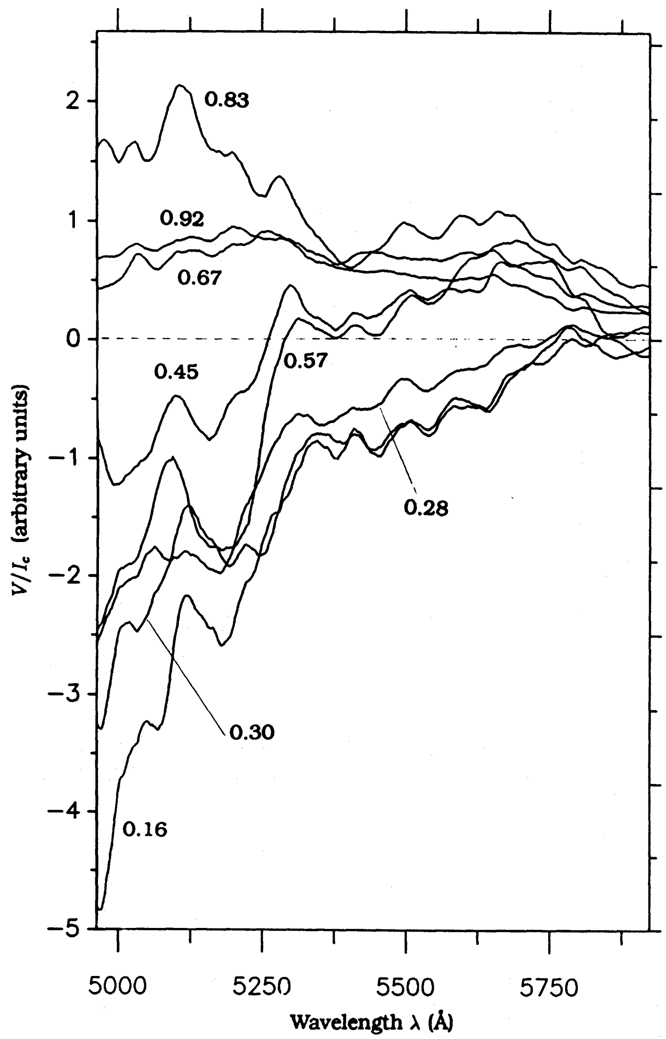


Fig. 2. SBB curves derived from FTS spectra of one network ($\mu = 0.83$) and seven active plage regions, observed at various positions on the solar disk. The μ values of the different regions are marked. The curves have been normalized as in Fig. 1. The zero-line is plotted dashed

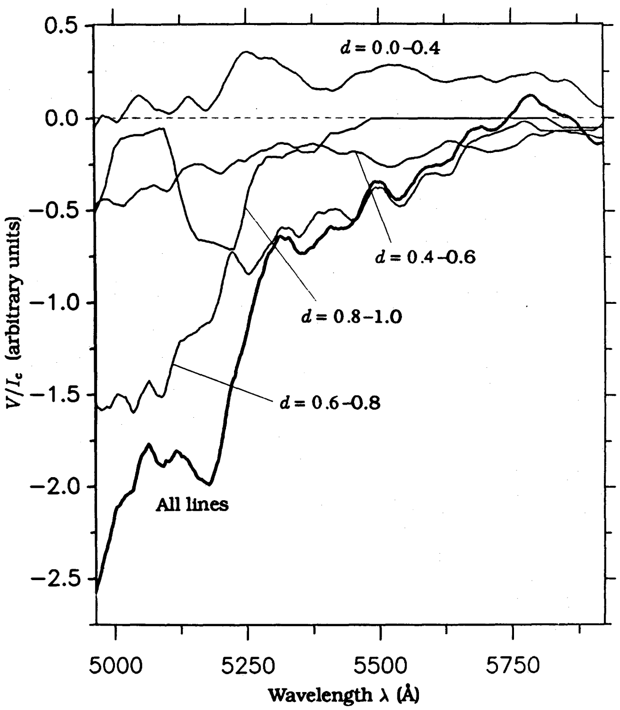


Fig. 3. Contribution of lines of different depths to the total SBB signal (thick curve) of an active region plage ($\mu = 0.28$). The range of line depths, d (relative to the continuum), which contribute to a given curve are marked. The zero-line is plotted dashed

3. Spatial integration

3.1. General considerations

To allow a comparison with the measurements of Kemp et al. (1987a) we must next simulate the BBC signal averaged over a considerable portion of the solar surface. Before carrying out the spatial integration we first briefly discuss how the spatially averaged BBC signal, K, is related to the asymmetry of each individual V profile observed with comparitively high spatial resolution. This illustrates which physical parameters of the solar atmosphere are important for the BBC. K may be represented by the following integral

$$K(\lambda_0, F) = \int_F dF \int_{\lambda_0 - \Delta\lambda}^{\lambda_0 + \Delta\lambda} \frac{V}{I_c} d\lambda \,, \qquad (1)$$

where dF is the surface area element, F the complete surface covered by the entrance aperture used for the BBC measurements, $2\Delta\lambda$ the width of the broad band polarization filter, and I_c the local mean continuum intensity which can be written as

$$I_c(\alpha, \lambda_0, \mu) = \alpha I_m(\alpha, \lambda_0, \mu) + (1-\alpha)\, I_s(\alpha, \lambda_0, \mu) \,,$$

where α is the filling factor, I_m the continuum intensity of the magnetic elements and I_s is the continuum intensity of the non-magnetic surroundings.

If we assume that line shifts due to solar rotation, granulation etc. are negligibly small compared to the width of the spectral integration window and if we also neglect the Zeeman saturation of Stokes V (i.e. we assume $K \sim g_{\mathrm{eff}_i} \lambda_i B$, see below for definitions), the differential saturation of the individual Zeeman components (i.e. we assume $K \sim \cos\gamma$), and changes in line saturation due to blends (i.e. $K \sim$ simple sum over lines), then we can rewrite Eq. (1) by replacing the integral over the wavelength interval $2\Delta\lambda$ by a sum over the lines in this wavelength interval. Note, however, that the above assumptions apply only to the simple illustrative model discussed in this section and not to the rest of the analysis. The resulting expression for K reads

$$K(\lambda_0, F) \sim \int_F dF\, S_m \frac{I_m(\alpha, \lambda_0)}{I_c(\alpha, \lambda_0)} B(\alpha) \cos\gamma \sum_i d_i^m(\alpha)\, \delta A_i(\alpha)\, g_{\mathrm{eff}_i} \lambda_i \,. \qquad (2)$$

Here S_m is the polarity of the field, B the absolute value of the magnetic field strength, γ the angle of the field to the line of sight, d_i^m the normalized depth in the magnetic features of spectral line number i, g_{eff_i} its effective Landé factor, λ_i the wavelength, and $\delta A_i(\alpha)$ signifies the relative area asymmetry of its V profile, assumed to be known for good spatial resolution, $\delta A_i = (A_{bi} - A_{ri})/(A_{bi} + A_{ri})$. A_{bi} and A_{ri} are the absolute areas of the blue and red wings of the V profile, respectively. Except for λ_0 and g_{eff_i}, all the quantities may be functions of position on the surface and may vary considerably even within F.

It appears to follow from Eq. (2) that bipolar regions which exhibit no net flux do not give rise to any BBC signal when spatially unresolved. However, there can be exceptions. Consider, for example, a large bipolar region (i.e. such that the two polarities can have measurably different μ values). Even if the net flux through the solar surface is zero, a distinct BBC signal may be produced. This may be due to projection effects (the *line of sight* flux of the two polarities need not be the same, due to different $\cos\gamma$), or it may more subtly result from the fact that the asymmetry of the Stokes V profiles varies with μ, so that the V profiles arising from the two polarities do not cancel each other. Differences in temperature etc. between the magnetic elements of the two polarities can also give rise to a net BBC signal. For example, one polarity may be composed mainly of spots, the other mainly of plages.

Since our spectra were observed neither concurrently nor cospatially with the BBC of Kemp et al. (1987a), we must first neutralise the region specific properties of the spectra (e.g. α_j, F_j, $\cos\gamma_j$ etc.: index j identifies the regions observed with the FTS). In order to achieve this we assume that the Stokes V amplitudes of a selected sample of temperature and field strength insensitive Fe II lines have the same amplitudes in all the spectra. By normalizing the spectra to equal Stokes V amplitudes of Fe II lines we are in effect replacing $\int dF_j S_{mj} I_{mj} B_j \cos\gamma_j$, which expression we shall call Φ_j (it is a rough approximation to the line of sight magnetic flux), by a single Φ value for all the regions. Thus *relative to each other* first order effects in the spectra due to the specific properties of the observed region are removed. However, this normalization does not remove second order region specific effects, such as the filling factor dependent weakening of the lines of neutral species (e.g. Solanki, 1986; Knölker et al., 1988; Knölker and Schüssler, 1988) or the filling factor dependent Stokes V asymmetry (e.g. Fig. 1). Also, this procedure does not provide us with an absolute calibration of the Stokes V spectra, i.e. it does not provide us with a value for the Φ now common to all the spectra. Since an absolute calibration requires knowledge of I_m and γ, which cannot be determined with sufficient accuracy from the present data set, we refrain from attempting to carry one out. As a result, we are basically limited to reproducing the ratio between the BBC measured in the northern and southern solar hemispheres by Kemp et al. (1987a). Even this aim requires that each FTS spectrum must now be multiplied by a Φ_{BBC} corresponding to the region for which the BBC measurements are to be simulated. This can be done at various levels of sophistication. In Sect. 3.2 we discuss briefly the results for a simple model of the solar magnetic flux distribution, while in Sect. 3.3 we consider a more realistic case by taking the approximated flux distribution from appropriate Kitt Peak magnetograms.

3.2. A simple model of the solar magnetic flux distribution

Since the measurements of Kemp et al. (1987a) were carried out during sunspot minimum, an α independent of position on the solar disk appears reasonable. We also assume the field strength to be independent of μ, α etc. (cf. Stenflo, 1984a), and the magnetic field to be vertical, i.e. $\cos\gamma = \mu$ (e.g. Schüssler, 1986; compare, however, with the empirical results of Solanki et al., 1987, which suggest inclined fields).

We are then left with two free parameters: $I_m(\theta, \alpha)$ and $S_m(\theta, l)$ (l = solar latitude and θ is the inclination of the line of sight to the normal direction in the atmosphere). For $I_m(\theta, \alpha)$ we have tried various functions of θ, since accurate observations of this quantity are notoriously difficult due to the small size of the magnetic elements (cf. Grossmann-Doerth et al., 1987; Schüssler and Solanki, 1988). We find that although the choice of $I_m(\theta)$ does affect the integrated SBB, the dominant influence on both sign and magnitude of the BBC is that of S_m, i.e. of the distribution of the magnetic polarities on the solar disk, or to be more precise, the distribution of the net magnetic field. A negative sign of the full disk BBC, as observed by Kemp et al. (1987a), is only achieved when the net flux is concentrated near the limb.

To describe the distribution of $\cos\gamma\, S_m(\theta, l)$ we introduce the quantity $\langle B_l \rangle / \langle |B_l| \rangle$ which is a measure of the "monopolarity" of the field averaged over a given (small) spatial element. Near solar activity minimum we expect the field to have a global bipolar structure, so that $\langle B_l \rangle / \langle |B_l| \rangle$ should mainly be a function of l. This function is used to weight the various SBB curves, so that the contribution to the total BBC of each spatial element on the solar surface is determined by SBB (μ) and $\langle B_l \rangle / \langle |B_l| \rangle (l)$. Note that the actual weighting in Eq. (2) is done with $\langle B_l \rangle$, but the monopolarity index $\langle B_l \rangle / \langle |B_l| \rangle$ provides us with a dimensionless number that gives the same relative weighting if the absolute amount of flux $\langle |B_l| \rangle$ is independent of disk position, which should be a good approximation around the time of minimum solar activity.

Extensive tests have been carried out with various $\langle B_l \rangle / \langle |B_l| \rangle (l)$ functions. $\langle B_l \rangle / \langle |B_l| \rangle$ is assumed to be the same function of l on the northern and southern solar hemispheres, but the 6–7° tilt of the solar axis towards the ecliptic is taken into account. From these tests we conclude that the measurements of Kemp et al. (1987a) can be reproduced only for a rather limited range of functions, namely those with $|\langle B_l \rangle| / \langle |B_l| \rangle \lesssim 0.1$ for $|l| \lesssim 65°$. For larger $|l|$ the $|\langle B_l \rangle| / \langle |B_l| \rangle$ value depends critically on its value at $|l| \lesssim 65°$. If $|\langle B_l \rangle| / \langle |B_l| \rangle \approx 0.1$ for $|l| \lesssim 65°$ then $|\langle B_l \rangle| / \langle |B_l| \rangle \gtrsim 0.8$ for $|l| \gtrsim 80°$. For smaller values of $|\langle B_l \rangle| / \langle |B_l| \rangle$ for $|l| \lesssim 65°$ it may be smaller for $|l| \gtrsim 80°$ as well. For such a distribution of polarities the polar fields give the dominant contribution to the BBC, thus naturally explaining both the sign of the BBC observed by Kemp et al. (1987a) and the ratio of the signal on the northern and southern hemispheres.

3.3. Solar magnetic flux distribution from Kitt Peak magnetograms

As a final step we attempt to reproduce the measurements of Kemp et al. (1987a) made on two specific days. We have chosen August 7 and 22, 1986 since they exhibit different SBB signals and reasonably complete, high quality, full disk Kitt Peak magnetograms are available for these days.

We proceed as follows: For the parts of the solar surface within the northern and southern entrance apertures of Kemp et al. (1987a) the net "longitudinal magnetic flux" on the magnetogram within a band of constant μ, centred on the μ of an FTS spectrum, is summed together to give $\langle B_l \rangle$. Each SBB curve is then weighted by the $\langle B_l \rangle$ of its respective μ band. We have written longitudinal magnetic flux in quotation marks, since the magnetograms are actually pictures of the distribution of the net circular polarization, which is proportional to $\Phi_{KP}\, \delta d^m$. Φ_{KP} is the Φ of a given Kitt Peak magnetogram pixel (Sect. 3.1) and δd^m is the weakening, in the magnetic features, of the line used to record the magnetograms ($\delta d^m = 1$ if the line has the same depth in both magnetic and non-magnetic regions. In general $\delta d^m < 1$ outside sunspots). For brevity we shall, however, simply write $\langle B_l \rangle$ for this quantity.

Since the FTS Stokes V spectra are not absolutely calibrated we have not tried to fit the absolute value of the BBC observations, but restrict ourselves rather to matching the ratio of the BBC observed in the northern hemisphere to the BBC observed in the southern hemisphere. The largest remaining uncertainty is due to the fact that the true zero of the polarization of the magnetograms is not known (Livingston and Harvey, 1971; Harvey, private communication). Since changing the zero-level can alter the amount of net flux, this is an important parameter. We have chosen it, the only free parameter in our simulations, such as to enhance the fit to the observations of Kemp et al. (1987a).

The resultant fit of the simulations (filled symbols) to the data of Kemp et al. (1987a) (open symbols) for August 7 (stars) and August 22 (circles) is shown in Fig. 4. We have plotted the results of our simulations at four wavelength points, although only one wavelength point (≈ 5250 Å) of the observations of Kemp et al. (1987a) lies within the wavelength range of our FTS data. Not surprisingly at 5250 Å a perfect fit to the Kemp et al. data is achieved. However, the wavelength dependence of the simulations does not correspond to a simple linear interpolation between the measured BBC points. In particular, the SBB curves must change considerably below 5000 Å if they are to reproduce the obser-

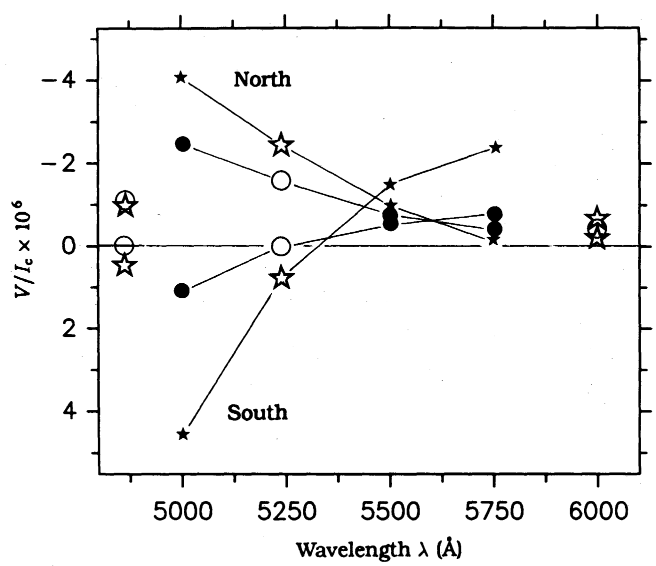


Fig. 4. Comparison between the direct broad band circular polarization observations of Kemp et al. (1987a) (open symbols) and the broad band circular polarization signal simulated by summing over individual SBB curves (filled symbols), each weighted with the help of Kitt Peak magnetograms for the relevant dates. Stars: August 7, 1986, circles: August 22, 1986. For greater clarity only the open symbols have been plotted at 5250 Å, since the filled symbols lie at exactly the same positions

vations of Kemp et al. (1987a) near 4900 Å. This is particularly true for the August 7 data. Of course, this may really be the case, but there are other possible reasons for the seeming discrepancy between the wavelength behaviour of the simulations and direct observations.

1. Our spectra are mostly restricted to strong active region plages near the solar equator, while most of the signal detected by Kemp et al. (1987a) comes from low filling factor quiet network regions near the poles, which probably have somewhat different physical properties (cf. Fig. 1).

2. Kitt Peak magnetograms are far from ideal maps of longitudinal flux (cf. second paragraph of this section and Sect. 3.1). In addition they are saturated for too strong concentrations of magnetic flux. This instrumental problem is particularly acute for August 7 when an active region was present in the resolution element of Kemp et al. (1987a).

3. Noise in the Kitt Peak magnetograms becomes considerable near the limb, so that $\langle B_l \rangle$ near the poles is somewhat uncertain.

4. Noise in the direct BBC measurements.

The dependence of $\langle B_l \rangle$ and $\langle B_l \rangle / \langle |B_l| \rangle$ on the solar latitude is illuminating, since it allows a comparison with the simple model of Sect. 3.2 and gives deeper insight into how the distribution of the magnetic field is coupled to the BBC integrated over large parts of the solar disk. Figures 5a and b show $\langle B_l \rangle$ and $|\langle B_l \rangle| / \langle |B_l| \rangle$, respectively, vs. l. Stars: August 7, circles: August 22.

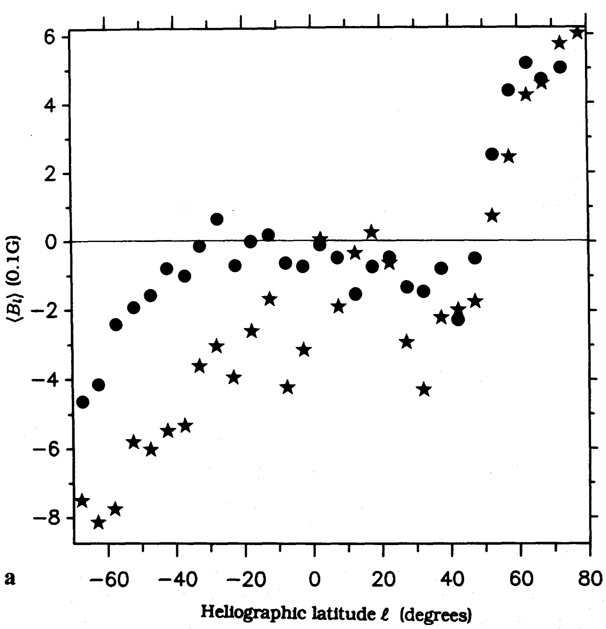
The diagrams are restricted to $-70° < l \leqq 80°$ since noise begins to degrade the data nearer the poles. In Fig. 5b the equatormost points of the circular entrance apertures of Kemp et al. (1987a) have been marked by vertical lines. The $|\langle B_l \rangle| / \langle |B_l| \rangle (l)$ curves plotted in this figure are gratifyingly similar to the curves required by the simple model described in Sect. 3.2. This shows that it is indeed the effect of the global solar dipole which gives rise to the observed broad band signal. The bipolar structure is best seen on Aug. 22 when no action region was present on the visible hemisphere.

In the absence of continuum polarization the zero-level of the Kitt Peak magnetogram of an activity free solar hemisphere (as seen e.g. on Aug. 22) may also be fixed through the requirements of the cancellation of the major part of the magnetic flux near disk centre and a general north-south antisymmetry in $\langle B \rangle$, requirements which are fulfilled to a high degree by the zero-level derived through fitting the BBC data of Kemp et al. (1987a). Since for this particular date the zero-level of the Kitt Peak magnetogram ceases to be a free parameter we have effectively been able to reproduce the BBC observations without the help of any continuum polarization. We have, therefore, indirectly demonstrated that the continuum polarization in magnetic elements outside sunspots is smaller than the rms noise level in our FTS data, i.e. $< 10^{-4}/(\alpha\delta_c)$. δ_c is the continuum contrast between the magnetic features and the quiet sun. Typical values of $\alpha\delta_c$ lie in the range 0.1–0.4 for our spectra. This result is in agreement with theoretical predictions (Kemp, 1970; Kemp et al., 1987a).

4. Application to other stars

In Sect. 3 we have demonstrated that for the sun, given a knowledge of the polarity of the net field and the sign of the BBC, a rough estimate of the global distribution of the field can be made, in particular whether the net field is concentrated mainly near disk centre or nearer the limb.

For other late type stars, where the polarity of the net field is usually not known (the Robinson, 1980, and related techniques give no information on the polarity), the diagnostic possibilities of the BBC for the distribution of the net field are greatly reduced. Changes in sign of the BBC may be due either to a change in polarity of the field or a reversal in the sign of the V asymmetry. If, as a simple first step, we assume the BBC on other stars to depend similarly on μ as on the sun, then it may be possible to disentangle the two effects somewhat by also considering the light curve, or, as suggested by Fig. 2, the spectral behaviour of the BBC.



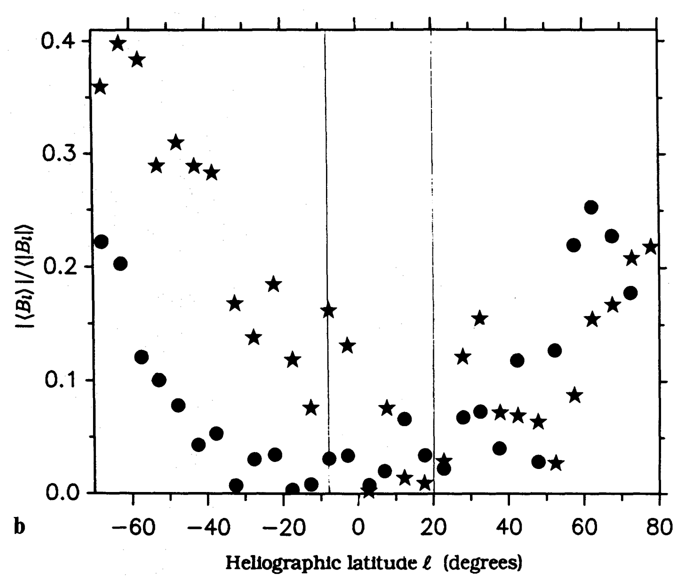


Fig. 5. **a** $\langle B_l \rangle$, the net line of sight magnetic field averaged over heliographic longitude, vs. heliographic latitude l. Symbols as in Fig. 4. **b** $|\langle B_l \rangle| / \langle |B_l| \rangle$ vs. l. The equatormost points of the entrance apertures used by Kemp et al. (1987a) to measure the BBC on the northern and southern hemispheres, respectively, are marked by vertical lines

The recent discovery of an asymmetry in the V profiles of the chemically peculiar star HD 147010 by Mathys and Stenflo (1986) and of BBC on λ Andromedae (G8 III-IV with chromospheric emission 10–100 times stronger than on the sun, Baliunas and Dupree, 1982) by Kemp et al. (1987b) have a significance beyond the simple detection of a magnetic field on these particular stars. It is proof that the asymmetry between the blue and red wings of Stokes V is not peculiar to solar magnetic features, but is present also on stars with quite different properties to the sun. We discuss these observations in the following.

The sign of the area asymmetry on HD 147010 is opposite to the one seen at solar disk centre (i.e. the red Stokes V wing is stronger than the blue wing). This may mean that the asymmetry producing mechanisms are different (e.g. a stellar wind with velocity amplitude increasing with height). However, if we assume that the dependence of the asymmetry on μ is similar to the solar case, it implies that the net-field was mainly concentrated near the stellar limb at the epoch of observations. This inference is supported by the fact, noted by Mathys and Stenflo (1986), that the V profiles are much narrover than and systematically blue-shifted with respect to Stokes I. This appears to us to be at least as plausible an explanation as a dense stellar wind in the magnetic regions having a velocity of $2\,\mathrm{km\,s^{-1}}$ in the stellar photosphere.

Next we wish to offer two qualitative models which aim to explain the 1982 BBC observations of λ Andromedae by Kemp et al. (1987b). These show a 54 day period in the light curve, suggestive of a single large spot or compact spot group. The BBC signal, on the other hand, enigmatically exhibits a 27 day period. Kemp et al. (1987b) suggest that a pair of spots may be involved, without giving further details. However, keeping in mind the inclination of the rotation axis to the line of sight of approximately 25° (Dorren and Guinan, 1983), the BBC curve can be explained qualitatively with a single spot at an intermediate latitude if we assume that the BBC changes sign whenever the spot passes a given μ. The observed temporal behaviour of the 1982 BBC can be reproduced if at its nearest approach to disk centre the starspot is near the μ at which its total BBC signal averaged over the spectral range 4000–7000 Å is practically zero, i.e. where its BBC changes sign. Therefore the BBC would be zero at this point and when the starspot is behind the disk. It would be maximal shortly after the spot appears from behind the disk and before it disappears again.

The fact that the BBC of sunspots does not appear to change its sign at any $\mu > 0.35$ (Illing et al., 1974b) speaks against this model. Alternatively, the combined BBC and photometric curves can also be explained by a stellar plage and a starspot of the same polarity on the hemisphere turned towards the observer (this picture requires the opposite hemisphere to have an excess of opposite polarity flux). They would be about 180° apart in longitude at a latitude at which they disappear behind the limb only briefly. Each would exhibit approximately the same amounts of BBC when nearest disk centre. The peaks in BBC in this model are produced when either spot or plage is nearest disk centre. The BBC disappears when they are both near the limb, since the sign of the BBC of the plage will have changed near the limb, while the sign of the spot will remain unaltered. As observations improve it may be possible to distinguish between such rival models by considering the phase relationships between the BBC and the white light curves.

We wish to caution that the extrapolation from the solar case, which we have made here is questionable. Only detailed and reliable knowledge of the mechanism responsible for the underlying Stokes V asymmetry will allow us to interpret observations of stellar BBC in terms of field distributions with a high measure of certainty. However, despite this caveat the BBC provides a valuable additional constraint to models of the distribution of starspots derived from photospheric light curves (e.g. Dorren and Guinan, 1983).

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