

Magnetic Structure in Cool Stars

II. Observational Evidence for Transverse Magnetic Fields +

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Received February 2, accepted March 3, 1981

Summary:

The apparently intrinsic linear polarization of the light from nearby F, G, K and M stars is attributed to transverse magnetic fields near the stellar limb in activity belts on either side of the stellar equator. The polarization results from the π components of strong spectral lines being more saturated than the σ components (Leroy, 1962). The proposed mechanism is compatible with existing observational data. Stringent tests and prospects for further observations are indicated.

Key words: stellar magnetic fields - stellar polarization - late-type stars

1. INTRODUCTION

An attractive hypothesis relates the chromospheric and coronal emissions from cool stars to their magnetic structure (see Zwaan, 1981). In stars with convective envelopes, the magnetic field is expected to be concentrated in limited areas of high field strength. The emission in the line cores of the Ca II H and K lines of stellar spectra is assumed to originate in discrete magnetic structure, such as is observed on the Sun. The hypothesis interprets the properties of the Ca II emission from stars in terms of stellar dynamos. In the present context the following properties are of particular interest:

(i) Ca II emission is found in many cool stars from early F onwards (Wilson, 1968, 1976; Middelkoop, 1981).

(ii) The Ca II emission fluxes vary in strength on time scales from minutes to many years (Wilson, 1978; Middelkoop et al. 1981).

The Ca II emission yields no direct information on the magnetic structure, however. There is little hope of detecting magnetic fields by measuring circular polarization in σ the components of magnetically sensitive lines, since the polarities of the magnetic elements over the stellar disk largely cancel. In this paper we consider the intrinsic linear polarization, for which there is statistical

evidence for stars of spectral type F and later (Piirola, 1977; Tinbergen, 1981). We summarize the data and then discuss a mechanism for linear polarization due to magnetic fields.

2. OBSERVED POLARIZATION IN F- TO M-TYPE STARS

One of us has completed a broadband linear polarization survey of nearby stars (Tinbergen, 1979, 1981), with the aim of detecting the local interstellar magnetic field. It has turned out that the dust content of the solar neighbourhood (out to about 35 pc at least) is so extremely low that intrinsic polarization, if present at a level of more than about 10^{-4} (degree of polarization), can be detected as a statistical effect. Piirola (1977), when reporting on a more limited survey of the same kind, plotted the degree of polarization against spectral type and remarked: "... all values of $p > 0.015\%$ are observed for stars later than F1. This might indicate the presence of small intrinsic effects... the effects are so small and close to the error limits that no further conclusions seem possible". We now have more extensive material that fully bears out Piirola's observation (Fig. 1).

Since the larger polarization survey was carried out in three wavelength bands (Fig. 2), it is possible to investigate the wavelength dependence to some extent. We have divided the stars into 3 rough classes, according to their observed degree of polarization $\bar{p}$ averaged over bands 1 and 2: a) $\bar{p} \leq 10^{-4}$,

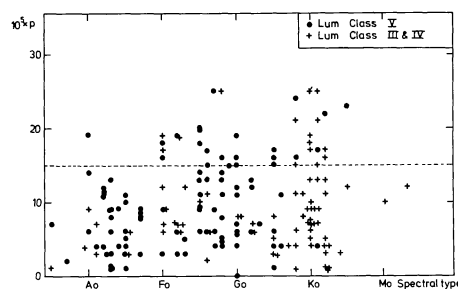


Figure 1: Observed degree of linear polarization p against spectral type. The measurements in band (1) and (2) (see Fig. 2) have been averaged; Piirola's (1977) results are included. The dotted line represents $\bar{p} \approx 2 \sigma_p$.

+ Based in part on observations made at the European Southern Observatory at La Silla, Chile

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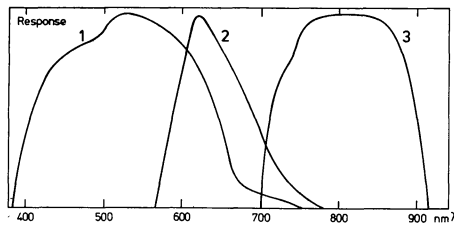


Figure 2: The pass bands. The ordinate "response" is the photocathode sensitivity, as modified by the filters and normalized on the peak values for each band separately.

b) $10^{-4} < \bar{p} \leq 1.5 \times 10^{-4}$ and c) $\bar{p} > 1.5 \times 10^{-4}$. This average $\bar{p}$ of bands 1 and 2 is less affected by residual scintillation noise than the results in the two separate bands. It is therefore the best criterion for separating the stars with the highest polarization from the rest. The mean error σ_p ($\approx 0.7 \times 10^{-4}$) has been determined from independent observations of each star on 4 different nights. We have calculated, for every class and for each passband, the mean-square degree of true (as opposed to observed) polarization; the results may be found in Table 1.

The conclusion from Table 1 is that, for stars with a detectable intrinsic polarization, the mean-square true polarization $\langle p_0^2 \rangle$ is on the average greater in the blue-green (band 1) than in the red (band 2); this effect disappears for stars of low polarization. We ignore the data of band 3 (near-infrared) because of the very large errors.

Examination of the internal scatter in repeated measurements of the same stars indicates that the intrinsic polarization is probably variable (Tinbergen, 1981).

3. TRANSVERSE MAGNETIC FIELDS AS THE SOURCE OF THE POLARIZATION

Linear polarization in the stellar light indicates an anisotropy in the stellar atmosphere. It is tempting to attribute it to some ordered magnetic structure. Broadband linear polarization has been found in largely transverse magnetic fields in the Sun: in penumbrae of sunspots and in faculae near the

limb (Leroy, 1962; Dollfuss, 1965). The interpretation has been that the polarization is the sum of contributions from many spectral lines, each of which is split by the Zeeman effect (Leroy, 1962). The central π component for each line is more saturated than the corresponding σ components, therefore the π component absorbs less light than the σ components do together. Hence every saturated spectral line within the passband contributes to the linear polarization, the electric vector being parallel to the magnetic field.

Let us consider the net linear broadband polarization that might be expected if the Sun were observed as a star. The circularly symmetric penumbrae of sunspots hardly contribute to the polarization signal, since the directions of polarization are distributed at random. The vertical fields in umbrae may contribute, for spots close to the limb, but the amount is quite small, since umbrae are much darker than the photosphere and those near the limb are strongly foreshortened. The largest contribution is to be expected from faculae in the active regions (with or without spots) located in the activity belts on both sides of the solar equator. The faculae not far from the (East and West) limbs contribute most, because they present the strongest transverse component of the magnetic field. This transverse component is perpendicular to the limb, so that the resultant polarization has its electric vector parallel to the equator.

According to Leroy's (1962) calibration, the polarization in the blue amounts to about 1% for a transverse component $B \sin \gamma = 1000$ Gauss. For weaker transverse fields it varies as $(B \sin \gamma)^2$, for stronger transverse fields, the polarization increases more slowly. The field strengths within the facular magnetic elements range between 1000 and 2000 Gauss (see Harvey, 1977), so the expected degree of polarization is of order 1% for elements not far from the limb. We estimate that in faculae (as seen on high-resolution magnetograms or on Ca II spectroheliograms) about 10% of the photospheric area is actually occupied by strong magnetic fields and that, when the level of activity is high, the faculae sufficiently close to the East and West limbs occupy about 2% of the Solar disk. The net polarization would therefore amount to a few times 10^{-5} , too small to be detected in the surveys discussed in this paper. However, many cool stars show much more Ca II emission than the Sun; for these stars the density of magnetic

Table 1: Mean-square true polarizations (intrinsic plus possible interstellar) for certain classes of nearby stars. The quantity tabulated, $10^8 \times \langle p_0^2 \rangle$, has been corrected for the error of measurement. The entries are in the format: observed - errors = true : $\langle p^2 \rangle - \langle \sigma_p^2 \rangle < p_0^2$.

Polarization class	(a)	(b)	(c)
Passband	$10^{-4} \cdot \bar{p} \leq 1.0$	$1.0 < 10^{-4} \cdot \bar{p} \leq 1.5$	$10^{-4} \cdot \bar{p} > 1.5$
1(blue-green)	5.1- 1.6= <u>3.5</u>	5.4- 1.5= <u>3.9</u>	7.8- 1.8= <u>6.0</u>
2(red)	6.5- 2.9= <u>3.6</u>	4.7- 3.3= <u>1.4</u>	6.3- 3.8= <u>2.5</u>
3(infrared)	18.1-10.9= <u>7.2</u>	11.2- 7.1= <u>4.1</u>	10.1- 8.5= <u>1.6</u>

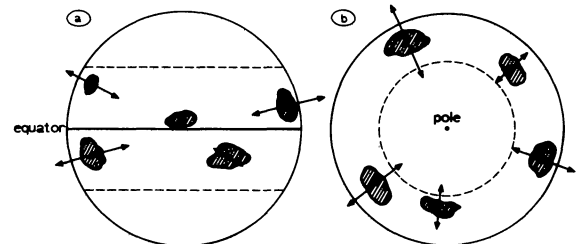


Figure 3: The contributions of magnetic regions (hatched) to the net polarization signal for a star observed in the equatorial plane (a) and pole-on (b). The arrows indicate the direction and the degree of linear polarization.

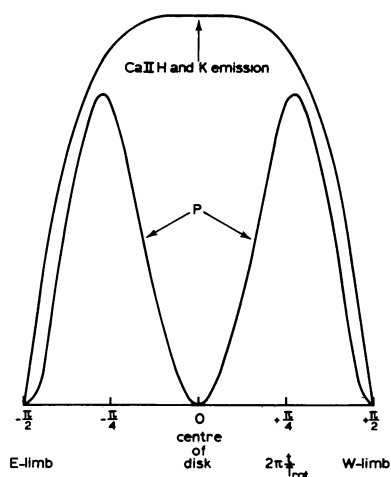


Figure 4: Estimated degree of polarization p and Ca II H and K flux for one single and constant magnetic region crossing the stellar disk along a diameter (compare Fig. 3a). The figure is schematic; a more quantitative treatment would be premature.

elements is at least one order of magnitude higher and the predicted polarization is of the same order as those measured for the F to M stars in the survey.

The expected net polarization depends strongly on the aspect of the stellar rotation axis and on time. The above discussion for the Sun holds for a star viewed nearly in its *equatorial plane*. Since the magnetic regions grow and decay, and are carried across the disk by rotation, the *degree of polarization* will fluctuate; however, the *direction of polarization* will always be roughly *parallel to the stellar equator* (Fig. 3a). During the passage of one active region across the disk we expect that the contribution to the polarization signal will show two peaks, somewhat more than one quarter of the rotation period apart. Averaged over several stellar rotations, we expect a correlation of the mean polarization with the mean Ca II H and K emission flux.

For a star observed *pole-on* (Fig. 3b), the magnetic regions are distributed randomly along the stellar limb. Since the polarization everywhere is perpendicular to the limb, the *net polarization* is expected to be *small* and, in the long run, random in direction.

4. TESTS AND PROSPECTS

The ideas outlined in this paper are compatible with the observational data at hand: (i) apparently the light from many cool stars shows an intrinsic linear polarization; (ii) the polarization is strongest in the passband for which the density of spectral lines is greatest; (iii) the polarization is probably variable. The following stringent tests are possible:

The linear polarization and the Ca II H and K emission should correlate in the ways discussed in the previous section. We intend to investigate these correlations in the near future.

The linear polarization should be strongest in those parts of the spectrum where there are concentrations of saturated, magnetically sensitive lines. The ideal type of instrument to test this effect would be a photoelectric radial-velocity spectrometer equipped with a polarization modulator. The degree of polarization in such multiple-narrowband observations is expected to be at least an order of magnitude above the broad-band measurements obtained so far.

For stars which produce sufficiently strong linear-polarization signals, linear polarization promises to be a powerful diagnostic, being a more direct indicator for magnetic structure than the Ca II H and K emission. The discussion in Section 3 suggests that time series of simultaneous measurements of linear polarization and H and K emission may reveal some general properties of the stellar magnetic structure, such as the width of the activity belt and the aspect of the rotation axis.

ACKNOWLEDGEMENTS

H.C. van de Hulst, B.J. Oranje and F. Middelkoop have critically read the draft.

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