A NEW TECHNIQUE FOR THE MEASUREMENT OF STELLAR MAGNETIC FIELDS: FIRST RESULTS *

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Abstract: A technique for determining strengths and filling factors of stellar magnetic fields is presented. It is based on a statistical analysis of a large number of unblended Fe I lines and was first introduced by Stenflo and Lindegren (1977). It has been tested in solar active regions and is now applied to late type stars. First results of an analysis of high S/N spectra of three stars are presented and compared to previous measurements. One advantage of the method is that unlike the often used Robinson technique (Robinson, 1980) it is relatively insensitive to the presence of small blends. Finally, the statistical method in principle allows us to decide whether the observed field is concentrated in stellar spots or in plages. Preliminary results for HR 1084 suggest that the field is in the form of plages.

1. Introduction

The activity of the sun and the stars is caused by magnetic fields and it is basic for our understanding of many stellar phenomena (e.g. spots, plages, flares, activity cycles and heating of coronae) to have direct measurements of magnetic fields. Stokes polarimetry has so far been unsuccessful in measuring magnetic fields on solar type and cooler stars, since, on the average, flux of both magnetic polarities is present in similar amounts on the visible stellar hemisphere, leading to a cancellation of the circular polarization signals (Bonsack and Simon, 1983; Borra et al., 1984). Therefore, methods based on unpolarized profiles have been used to measure stellar fields. The first to be successfully applied (by Robinson et al., 1980) has been that of Robinson (1980). It is based on the comparison of the profiles of two lines which are similar except for their Landé factors. However it suffers the disadvantage that it is acutely sensitive to the profile shapes of the two chosen lines and to any blends they may have (Kurucz and Hartmann, 1984). Even if lines which are practically unblended on the sun are used, one cannot be sure that they are also unblended on other late type stars.

Another technique is to compare a line on two stars of the same spectral type with each other, of which one is known to be active while the other is quiet (e.g. Giampapa et al., 1983). The problem with this approach is that despite the same spectral type both stars need not have exactly the same properties. For example, convection is strongly affected by the magnetic field itself as has been demonstrated theoretically and observationally on the sun. This would change the wings of the profiles and could thus seriously affect the magnetic field measurement.

The problems with blends are reduced if more than one or two lines are used. An analysis with 6 lines has been carried out by Saar et al. (1986) while Gray (1984) has used 16 lines. We propose an analysis based on an even larger sample of lines, so that small blends in the individual profiles give rise to a larger scatter in the data points with a resulting increase in the uncertainty, but they do not

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falsify the result to the same extent as for fewer lines.

2. Outline of the Analysis Technique

The technique used is based on a comparison between lines of small and large Zeeman splitting. Lines with large Zeeman splitting will be more broadened and their depths more decreased than lines with small splitting. An analysis of line depth or width at different levels in the line profile will therefore provide information on the field.

Let us consider the line width: The change in line width due to the magnetic field is determined by the Zeeman splitting, which is

$$\Delta\lambda_H = k g_{\rm eff} \lambda^2 B,$$

where $k = 4.67 \times 10^{-13}$ Å^{-1}G^{-1}, $g_{\rm eff}$ is the effective Landé factor, and B is the field strength. For a large sample of lines differences in width and depth due to other parameters like line strength, S, excitation potential, χ_e, and wavelength, λ, can be much larger than due to the usually rather small effects of the magnetic field. The influences of these other parameters can, however, be compensated for quite well with the help of a multivariate regression analysis. This approach was first suggested by Stenflo and Lindegren (1977) for a study of solar magnetic fields. For a derivation see that paper. We use the following regression equation:

$$v_D(z) = x_0 + x_1 v_m^2 \lambda^2/v_0 + x_2 \langle v_m^2 \rangle \lambda^2/v_0 + x_3 S + x_4 S^2 + x_5 \chi_e v_0, \tag{1}$$

where $v_D(z)$ is the width of the line at a level zd above line bottom (d = line depth, $z < 1$). v_D is expressed in velocity units in terms of the formal Doppler width of a Gaussian profile which has an equal width to the line at the chord level in question. To avoid problems with blends we only use the area below the half level chord to determine S. $x_0, \ldots, x_5$ are regression coefficients, v_0 is an approximation of v_D, $v_0 = y_0 + y_1 S^2$ (cf. Stenflo and Lindegren, 1977 for more details), and

$$v_m^2 = (g_{\rm eff}^2 + X_\sigma) \frac{(1 + \cos^2\gamma)}{2} + X_\pi \frac{\sin^2\gamma}{2} \tag{2}$$

for a magnetic field at an angle γ to the line of sight (Mathys and Stenflo, 1987a). In Eq. (2) X_σ and X_π are transition dependent constants taking into account the anomalous splitting of the lines to second order. Expressions and tables for X_σ and X_π have been given by Landi Degl'Innocenti (1982, 1985) and Mathys and Stenflo (1987a,b). Once x_1 is known we can use a very simple model, which neglects line saturation, to determine αB^2 (the product of filling factor α and field strength B) from it:

$$\alpha B^2 = \frac{x_1}{k^2 c^2 \delta_c \delta_l}, \tag{3}$$

where δ_c is the continuum contrast of the magnetic regions relative to the non-magnetic regions and δ_l is the average ratio of line strength in magnetic to that in non-magnetic regions. Of course a more sophisticated model involving e.g. radiative transfer is also possible.

We use only unblended lines of the same ion to avoid the complicating influence of different abundances and ionization potentials of various elements. Their number is limited only by observational constraints. For our spectra of 3-rd and 4-th magnitude stars we typically have 40–70 lines available. We use a subset of the 400 unblended Fe I lines in the visible portion of the solar spectrum selected by Stenflo and Lindegren (1977). Since we use a large number of lines, small blends will be stochastically distributed in lines of varying splitting. They will thus increase the scatter in v_D, but the chances of their giving rise to spurious correlations are greatly reduced as compared to analyses involving less lines.

From Eq. (2) we cannot in this first step obtain α and B individually but only their product (cf. Gray, 1984, who shows that with Fourier transform techniques αB^2 is also the best determined quantity, and α and B can be obtained independently only for favourable cases). However, in a second step it is possible to obtain an idea of α (assuming for the moment $\delta_c \delta_l = 1$) by comparing the coefficients x_1 derived from the regressions at two different chord levels. For $\alpha < 1$, the wings of the line are more strongly broadened than the line core. Thus e.g. the ratio $x_1(0.7d)/x_1(0.5d)$ is a measure of α as has been illustrated with the help of solar data by Brandt and Solanki (1987b). For $\alpha = 1$ this ratio approaches 1, and it becomes ever larger as α decreases.

The Stenflo-Lindegren technique also provides us with the possibility of deciding whether the stellar fields are concentrated in hot or in cool regions, i.e. in stellar plages or spots. For stars not too different from the sun Fe I lines are weakened in hotter regions, with low excitation lines being more weakened than high excitation lines. Thus δ_l will be different for these two groups of lines. The general weakening of Fe I lines with a rise in temperature is due to the increased ionization of Fe I into the more abundant Fe II. If we multiply Eq. (3) with $\delta_l\delta_c$ then instead of αB^2 we obtain $\alpha B^2\delta_l\delta_c$ from x_1. $\delta_c\alpha B^2$ is approximately the same for both groups of lines, so that

$$\frac{x_1^{\rm high}}{x_1^{\rm low}} = \frac{\delta_l^{\rm high}}{\delta_l^{\rm low}}. \tag{4}$$

Therefore, if we apply the regression to the high and the low excitation lines separately then, ideally, the difference in their coefficients x_1 is a measure of the difference in temperature between the magnetic and non-magnetic regions.

3. Tests with Solar Data

The Stenflo-Lindegren technique has been extensively applied to solar data and also to Ap stars with considerable success. Stenflo and Lindegren (1977), first used it to set an upper limit on the turbulent field in the quiet solar atmosphere. It was subsequently used by Solanki and Stenflo (1984) as an additional method of determining the field strength in solar magnetic fluxtubes from integrated Stokes V profiles which are an approximation of the line profiles formed only in the magnetic region. The results are compatible with the values obtained with other methods. Brandt and Solanki (1987a, b) have used the technique to deduce filling factors in solar active regions. They have also investigated $v_D(0.7d)/v_D(0.5d)$ and $v_D(0.3d)/v_D(0.5d)$. Interestingly these ratios are most sensitive to small $\delta_l\delta_c\alpha$ values. Note that for this and for all other spectral methods of deriving α, the result depends significantly on the values of δ_c and δ_l, for which reason we have always written $\delta_l\delta_c\alpha$. The Stenflo-Lindegren technique has also been successsfully applied to Ap stars by Mathys and Stenflo (1986).

We have tested on solar data whether it is possible to obtain an idea of the line weakening in the magnetic region and thus of its temperature, with the method described in Sect. 2 by carrying out the regressions separately for lines with $\chi_e^{\rm low} \le 2.5$ eV and $\chi_e^{\rm high} \ge 4$ eV. For active region plages on the sun with sizeable filling factors ($\alpha\delta_c \approx 35\%$) we find that $x_1^{\rm high}/x_1^{\rm low} \simeq 1.3$–$1.5$ which is indeed compatible with $\delta_l^{\rm high}/\delta_l^{\rm low}$ for the more temperature sensitive weaker lines. For network regions with small α the signal becomes too small if we analyse the different excitations separately.

4. Observations and Results

We have observed three stars taken from the list of Marcy (1984) with the 1.4m Coudé auxiliary telescope (CAT) of the European Southern Observatory (ESO) and the Coudé Echelle spectrograph (CES). The spectral resolving power was 100000 and a spectral range of approximately 40–50 Å could be recorded simultaneously. The S/N ratio is better than 250 for all three stars. We have carefully chosen a set of wavelength bands which were observed consecutively so that for each star a total wavelength range (not necessarily directly connected) of between 250–400 Å was recorded. More details on the data are to be found in Mathys and Solanki (1987). The three stars and the parameters of their data are listed in Table I.

As listed in Table I, we have a clear detection of magnetic fields on HR 1084, a probable detection on HR 1325, while for HR 509 we have at best a marginal detection at slightly above the 1σ level. Following Marcy (1984) we have listed $\sqrt{\delta_c\delta_l\alpha}B$ assuming a mean angle between the line of sight

Table I: List of observed stars and their magnetic parameters

HR Number	Name	Spectral type	No. of lines	$\sqrt{\delta_c\delta_l\alpha}B$ ($\gamma = 34°$) [G]	$\frac{\sqrt{\alpha}B}{\sigma(\sqrt{\alpha}B)}$	$\sqrt{\delta_c\delta_l\alpha}B$ of Marcy [G]
HR 1084	ϵ Eri	K2V	45	800	4.6	580–1275
HR 1325	40 Eri A	K1V	44	460	2.6	906
HR 509	τ Cet	G8V	65	220	1.2	—

and the magnetic field $\gamma = 34°$. Values of $\sqrt{\delta_c\delta_l\alpha}B$ derived from Marcy's (1984) measurements are tabulated in the last column of the table. For HR 1084 the two extreme values of his ten measurements are given. He found no field on HR 509. The $\sqrt{\delta_c\delta_l\alpha}B$ value for HR 1084 is compatible with Marcy's results, while for HR 1325 $\sqrt{\delta_c\delta_l\alpha}B$ is only half as large as Marcy's value.

For HR 509 Gray obtains $\sqrt{\delta_c\delta_l\alpha}B = 1200$ G and for HR 1084, 1000 G. The difference for HR 509 between Grays result on the one hand and ours and Marcy's result on the other is considerable. Although a part of the difference between the various results may be due to the intrinsic variability of the stellar fields, we feel that at least a part is due to the different methods used. For example, mixing lines of different elements with such different excitations and strengths as Gray (1984) did is a dangerous procedure.

For HR 1084 $x_1(0.7d)/x_1(0.5d) = 1.24$ and $x_1(0.3d)/x_1(0.5d) = 0.55$. From comparisons with solar data (Brandt and Solanki, 1987b) we derive a value for $\delta_l\delta_c\alpha$ between 10 and 20%. This is compatible with some of the $\delta_l\delta_c\alpha$ values found by Marcy (1984). The resulting field strength lies in the range 1790 G to 2530 G, which is within the limits observed by Marcy (1984) [670–2850 G] and by Saar (1987) [1700–2300 G]. For HR 1325 $x_1(0.7d)/x_1(0.5d) = 1.10$ and $x_1(0.3d)/x_1(0.5d) = 0.82$. This gives $\delta_l\delta_c\alpha$ values greater than 15%, which means that $B \lesssim 1190$ G.

Since our regression equation includes the anomalous splitting in the so called 'minimal equivalent' representation, which is sufficiently exact for late type stars at visible wavelengths (Landi Degl'Innocenti, 1985), we can also test how large an error is introduced into the results by assuming Zeeman triplets, as has generally been done in the past. We find that $\sqrt{\delta_c\delta_l\alpha}B$ increases by less than a few percent if we neglect the anomalous Zeeman splitting. Similar results are also obtained for data from solar active regions. We therefore conclude that neglecting the anomalous Zeeman splitting does not significantly affect the determination of $\sqrt{\delta_c\delta_l\alpha}B$ for solar type stars if one uses Fe I lines. The case is quite different for Ap stars with strong ordered fields covering a major portion of the stellar surface (Mathys and Stenflo, 1987c). Note, however, that the anomalous Zeeman splitting can itself serve as a major diagnostic, since it in principle allows us to determine the angle of the field to the line of sight by comparing two lines of very different Zeeman splitting patterns.

For HR 1084 $x_1/\sigma(x_1)$ is marginally large enough to determine $x_1^{\rm high}$ and $x_1^{\rm low}$ individually. Due to the small number of lines we choose $\chi_e^{\rm low} \leq 3$ eV (instead of 2.5 eV in the solar case) and $\chi_e^{\rm high} \geq 4$ eV. Even then we only have 10 lines with $\chi_e^{\rm low}$ and 28 lines with $\chi_e^{\rm high}$. We obtain $x_1^{\rm high}(0.7d)/x_1^{\rm low}(0.7d) = 2.5 = \delta_l^{\rm high}/\delta_l^{\rm low}$ and $x_1^{\rm high}(0.5d)/x_1^{\rm low}(0.5d) = 1.6 = \delta_l^{\rm high}/\delta_l^{\rm low}$ The values of $x_1^{\rm high}$ are certain at the 3.5σ level, while the $x_1^{\rm low}$ are certain at the 2σ level. Therefore, although $x_1^{\rm high}/x_1^{\rm low}$ is not as certain as one would wish, this result does indicate that the measured magnetic field on this star is concentrated into regions which are hotter than the non-magnetic part of the atmosphere with $\delta_l^{\rm high}/\delta_l^{\rm low} \approx 2.0$. This result is compatible with the discussion by Saar et al. (1986), who argue that, due to their low continuum intensity, starspots give a small contribution to the line profiles.

5. Discussion

We have presented the first application of the Stenflo-Lindegren technique to the measurement of stellar magnetic fields. Compared to other previously used techniques it has the advantages that it is rather insensitive to blends, and that it in principle allows us to determine the difference in temperature between the magnetic regions and the non-magnetic atmosphere. This means that δ_l

can be determined, although the practical problems (S/N, sufficient statistics) are considerable. δ_c is another matter. It has recently been shown by Grossmann-Doerth et al. (1987) and Schüssler and Solanki (1987) that for unresolved magnetic features no method exists (irrespective of whether it is based on polarized or unpolarized light), which can determine α directly: only $\delta_c\alpha$ is determined. For magnetic features on the sun δ_c is known to vary between approximately 0.2 for sunspot umbrae to over 1.4 for small fluxtubes. There is no reason for excluding such large differences in δ_c between magnetic and non-magnetic regions on other stars as well. It is therefore very dangerous to take the derived filling factors at face value.

Finally, since the individual spectral ranges were not observed simultaneously, it may be argued that fast variations in B and $\delta_l\delta_c\alpha$, as reported by e.g. Marcy (1984) for HR 1084, will affect our determination of these quantities. However, we wish to stress that the different wavelength ranges were not observed in the order of increasing or decreasing wavelength, or Zeeman splitting. This means that any changes in $\sqrt{\delta_c\delta_l\alpha}B$ during the course of the observation, will only cause an increase in the scatter of the points, but should not significantly affect the results.

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