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BROADBAND MEASUREMENTS OF THE TRANSVERSE MAGNETIC FIELD OF COOL AP STARS *

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ABSTRACT Observations of variable broadband linear polarization in magnetic Ap stars (due to the transverse Zeeman effect), when combined with measurements of the mean longitudinal field B_l can in some cases allow one to determine the angles i and β (which describe the inclination of the stellar axis of rotation and the obliquity of the magnetic axis to the rotation axis) much more accurately than these angles can be determined from observations of B_l alone. Such variable intrinsic linear polarization has been observed for a number of stars; the effect is generally detectable only in cool Ap stars of unusually large field strength. We discuss the data and simple modelling for the stars HD 24712 = HR 1217, HD 137909 = β CrB, and HD 62140 = 49 Cam.

INTRODUCTION

An important current interest in work on magnetic Ap stars at present is determination of the magnetic field geometry of a sample of stars with the best precision possible. The most sensitive method of detecting the modest fields of such stars is by means of the circular polarization induced in the

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spectral lines by the longitudinal Zeeman effect, from which one can infer the mean longitudinal magnetic field B_l. For most Ap stars, the only magnetic observations available are measurements of the variation of this quantity with rotational phase. B_l is usually observed to vary sinusoidally. This is the behaviour predicted for a star having an oblique dipole field structure inclined to the rotation axis at an angle β; the field is expected to vary approximately as

$$B_l(\phi) = 0.4B_d(\cos\beta\cos i + \sin\beta\sin i\cos\phi),$$

where B_d is the polar strength of the dipole, i is the inclination of the rotation axis of the star to the line of sight of the observer, and ϕ is the rotational phase (Stibbs 1950; Landstreet 1982). The two observational quantities available from the variation of B_l, say the mean value of B_l and the semi-amplitude of its variation, are not sufficient to determine the three parameters i, β, and B_d of even this simple dipole field model. Furthermore, i and β can be interchanged without altering the predicted variation. No information at all is available about further possible complexity of the field structure (for example the presence of higher multipole components) unless the variation of $B_l(\phi)$ is not sinusoidal. This is not very satisfactory for efforts to model field distributions.

One means of obtaining further constraints on magnetic models is to measure the transverse components of the mean vector magnetic field. This is possible using the linear polarization produced by the Zeeman effect in regions of the visible stellar hemisphere where the field is transverse. The resulting polarization is quadratic in field strength for small fields; as a result, the transverse Zeeman effect is difficult to detect except in stars with relatively large fields ($B_l \gtrsim$ 1-2 kG; $B_s \gtrsim 5$ kG). Almost no observations of the transverse Zeeman effect in individual spectral lines are yet available, except for a few measurements of β CrB reported by Borra and Vaughan (1976).

An interesting characteristic of the transverse Zeeman effect is that in a saturated spectral line the linear polarization integrated through the line profile is not zero. This occurs because the π component of the spectral line normally saturates before the σ components, leaving a small residual linear polarization in the integrated light of the spectral line that is usually parallel to the projection of the local field on the sky. When integrated over the star, light from a particular spectral line is then linearly polarized parallel to the magnetic axis of the star (for a simple roughly axisymmetric field distribution). Because all spectral lines behave in essentially the same way, this linear polarization is present even in the integrated light from the star, making it possible to measure the direction and estimate the amplitude of the mean transverse field component from broadband polarimetry.

This characteristic of the Zeeman effect offers a very interesting possibility for obtaining important new constraints on the field structure of a number of magnetic Ap stars. The variation of the linear polarization with rotational phase in the case of a roughly dipolar magnetic field structure is given approximately by (Landi Degl'Innocenti *et al.* 1981; Leroy *et al.* 1992; Landolfi *et al.* 1993)

$$Q/I = K[0.5\sin^2 i(3\cos^2\beta - 1) - 0.5\sin 2i\sin 2\beta\cos\phi + 0.5\sin^2\beta(1+\cos^2 i)\cos 2\phi]$$
$$U/I = K[-\sin i\sin 2\beta\sin\phi + \sin^2\beta\cos i\sin 2\phi].$$

In these expressions the angles i and β play quite different roles than in the equation for B_l above . Because of this it is possible to determine more or less uniquely these two angles from phased observations of both B_l and linear polarization, and to estimate the polar field strength of the dipolar field component. The determination of i also makes it possible to derive the radius of a star of known period P and $v \sin i$.

OBSERVATIONS

Linear polarization measurements of some three dozen magnetic Ap and Bp stars have been obtained at the Observatoire du Pic-du-Midi using the Sterenn polarimeter on the Bernard Lyot Telescope, starting in 1990. On the basis of these data, it clear that variable intrinsic broadband linear polarization rarely exceed 10^{-1}%, and reaches this level only in cool ($T_e \lesssim 9000$ K) Ap stars with rich line spectra and unusually strong fields. Measurement is only possible with a polarimeter that can reach an accuracy of 10^{-2}% or less. The intrinsic polarization is largest in the B band, and filters 10^3 Å wide are quite adequate for measurements. Variable intrinsic linear polarization has now been detected in nearly a dozen stars, and reasonable information about its phase variation is available for more than half this sample. Stars in which variable polarization is detected include HD 24712 = HR 1217, HD 62140 = 49 Cam, HD 65339 = 53 Cam (the variable broadband linear polarization was discovered by Kemp and Wolstencroft 1974), HD 71866, HD 98088 = Abt's star, HD 115708, HD 118022 = 78 Vir, and HD 137909 = β CrB. We discuss here observations of HD 24712, β CrB, and HD 62140.

HD 24712 = HR 1217

This is one of the coolest Ap stars known, with a rich and variable spectrum (Mg and the rare earths are particularly variable) and a field B_l that varies between about 0.5 and 1.5 kG with a period of 12.46 d (Preston 1972). Further observations of B_l have been obtained with the Balmer-line Zeeman analyser; these are consistent with Preston's observations. The exact period is not completely certain; we use the period derived by Mathys (1991)

The linear polarization of this star in the B band reaches a maximum value of about 0.07 %. In the plane of the Stokes parameters Q/I and U/I (the $Q-U$ plane), the linear polarization makes a single loop with a small cusp near phase 0.0 when the longitudinal field reaches its maximum value. This behaviour, shown in Figure 1, is characteristic of a star with β slightly less than i, and in fact the data are completely consistent with the variations expected from a centred dipolar field with $i = 39°$ and $\beta = 33°$. Both these angles have an uncertainty of only a few degrees. The measured variation of linear polarization exhibits little scatter around the best fit theoretical variation.

HD 137909 = β CrB

β CrB is essentially as cool as HD 24712, and has an even richer spectrum of strong lines which vary only slightly. The longitudinal magnetic field varies periodically between about +700 and −500 G (Borra and Landstreet 1980).

Variable intrinsic linear polarization measured in an intermediate-width band at 4200 Å reaches nearly 0.1 % in amplitude. The individual data points

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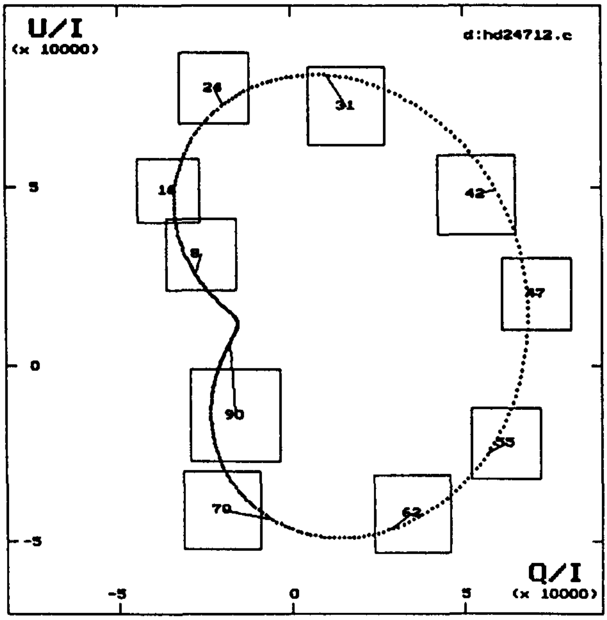

Fig. 1. Figure 1. Variation of linear polarization of HD 24712 is shown in the $Q - U$ plane. Each point is represented by its error box with the associated magnetic phase given inside. Diagonal lines join each box to its expected position on the best fit curve calculated for $i = 39°$ and $\beta = 33°$.

scatter rather badly about the mean curve, but the variation is clearly a double loop in the $Q-U$ plane, with one loop somewhat smaller than the other. This is the behaviour expected for an oblique dipole rotator having i somewhat smaller than β; in the limit of $i = 0°$, the variation is a double loop with both loops equal in amplitude. The amplitude of the B_l curve and also the shape of the linear polarization variations can be fit with $i = 51°$ and $\beta = 76°$. However, the relative phases of the two curves are not consistent with the predictions of the model. Another model which fits the data even less well than the fit above but for which the phase variations are consistent may be found, but it is not clear that this model is adequate. On the whole, the situation is rather puzzling, and suggests that the magnetic field structure of β CrB departs seriously from an axisymmetric, roughly dipolar field, a possibility suggested by the observations of Wolff (1978).

<u>HD 62140 = 49 Cam</u>

49 Cam is another F0p star with a very rich metallic spectrum. Fe, Cr and the rare earths are variable. The field B_l varies periodically between about +2 and -2 kG with a period of 4.29 d (Bonsack *et al.* 1974).

Very large variations of intrinsic linear polarization are observed, with the level of linear polarization reaching 0.2 %. The observed variations traverse a loop clockwise in the $Q - U$ plane, starting and ending near zero polarization, and then return counterclockwise on a similar loop. These variations resemble those of a dipole field structure with $i = 80°$ and $\beta = 80°$, except that it is the tips of the loop that approach zero polarization rather than the middle of one of the loops. It appears that there is some source of constant linear polarization of more than 0.1 % amplitude added to the variable polarization. The star is too near (about 60 pc) for interstellar linear polarization to be expected at this magnitude, but no other obvious explanation is available. The situation is quite puzzling.

If we accept the value of $i = 80°$ inferred from our data, and take $v \sin i = 22$ km s^{-1}(Bonsack *et al.* 1974), a radius of $R = 1.9 R_{\odot}$ is deduced, with an accuracy of perhaps 20 %, limited mainly by the precision of $v \sin i$.

CONCLUSIONS

The results presented above indicate that the use of broadband linear polarimetry to constrain the magnetic geometry of some Ap stars is not simply a theoretical possibility, but a genuine new source of valuable information for suitable stars, primarily the cool Ap stars of strong fields. The most important result obtained to date is constraints on the geometric angles i and β of the oblique rotator model, but in some cases the data hint at the possibility of detecting departures from dipolar geometry as well. The method is capable of increasing our fund of information about stars which are well described by the models currently in use, and also of revealing interesting new phenomena.

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