Broadband linear polarization and modelling of magnetic fields in CP stars

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Abstract. The observations in broadband linear polarization (BBLP) represent a powerful diagnostic tool for detecting the magnetic morphology of CP stars. In several cases, BBLP observations are not consistent with the prediction of the oblique rotator model with a simple dipolar field. Discrepancies between theoretical predictions and observations may partially be ascribed to the effect of desaturation due to the blending of spectral lines, which has not been taken into account so far in the models. However, there are strong evidences that in many cases the simple dipolar model is not sufficient to describe the magnetic configuration of CP stars.

Key words: Polarization – Magnetic fields – Stars: chemically peculiar

1. Diagnostic techniques for detecting magnetic fields in CP stars

The detection of magnetic fields in CP stars is based on the analysis of the Zeeman effect in the Stokes parameter profiles of spectral lines. Roughly speaking, the line intensity profile is sensitive to the mean magnetic field modulus, whereas the spectrum of the radiation observed in left and right circular polarization gives information on the mean longitudinal magnetic field. The linear polarization profile of a spectral line is sensitive to the transverse component of the magnetic field. Magnetic fields can be detected with several techniques, which have different constraints and provide different kinds of information.

From the relative wavelength shift of the line components split by the magnetic field, one can derive the *mean magnetic field modulus* $\langle |B| \rangle$, that is, the average over the visible stellar disk of the modulus of the magnetic field. So far, $\langle |B| \rangle$ has been measured in 42 CP stars. About a dozen of them are well monitored throughout the entire stellar rotation cycle (Mathys et al. 1997).

The wavelength shift of the spectral lines between right and left circular polarization is proportional to the average over the stellar disk of the component of the magnetic field along the line of sight, $\langle B_z \rangle$. This quantity is called *mean longitudinal magnetic field.* An alternative method to derive the same quantity is based on the anaylsis of the wings of the H_β line (Borra & Landstreet 1980). Most of our knowledge of magnetic fields in CP stars relies on the observations of $\langle B_z \rangle$. Observations were performed e.g., by Babcock (1958), Borra & Landstreet (1980), Mathys (1991). About 150 stars have been monitored so far.

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A quantitative analysis of the cross-over effect allows one to derive the average over the stellar disk of the component of the magnetic field along the line of sight times the distance between the point on the stellar surface and the plane defined by the line of sight and the stellar rotation axis (Mathys 1995a). This quantity, named *mean asymmetry of the longitudinal magnetic field*, $\langle dB_z \rangle$, has been detected in 44 stars. About a dozen of them were well monitored throughout the rotation cycle.

The second order moment of the profile I about the line centre is proportional to the sum of the squares of the two previous quantities, $\langle B^2 + B_z^2 \rangle$ (Mathys 1995b). This quantity, shortly called *mean quadratic magnetic field*, has been detected in about 40 stars, 11 of them well monitored in the rotation cycle.

The transfer of radiation in the stellar atmosphere is responsible for a differential saturation of the σ and π components of the Zeeman multiplet, which gives rise to a phenomenon of *broadband linear polarization.* This phenomenon has been known for a long time to be observable on sunspots (Leroy 1962), but only very recently this kind of observations have been systematically performed on CP stars (Leroy 1996). The observed BBLP is roughly proportional to some bilinear forms built up with the transverse components of the magnetic field, namely, $\langle B_x^2 - B_y^2 \rangle$ and $\langle B_x B_y \rangle$, where xyz represents an orthogonal reference system with the z axis oriented as the line of sight, and x towards the north celestial pole (Landolfi et al. 1993). BBLP has been detected in 55 CP stars, 16 of them are well monitored throughout the rotation cycle.

2. The magnetic observable quantities and the oblique rotator model

Let us consider a star with a dipolar field. The oblique rotator model (ORM) can be characterized by the angle between line of sight and rotational axis, i ($0° \leq i \leq 180°$), and the angle between rotational axis and magnetic axis, β ($0° \leq \beta \leq 180°$). The observed quantities related to the magnetic field may be calculated as a function of the stellar phase. The dotted lines in Fig. 1 show the various observable quantities as predicted for some magnetic configurations. Instead of plotting Q and U as a function of phase, it is more interesting to plot the expected values of BBLP in the $Q - U$ plane. The patterns so obtained are called "BBLP diagrams".

3. Observations and modelling

Among 16 CP stars, in only one case (HD 24712) the observations of BBLP are consistent with the theoretical predictions (Bagnulo et al. 1995, Leroy 1996). There are two strong assumptions that we have done in order to derive the theoretical BBLP diagrams.

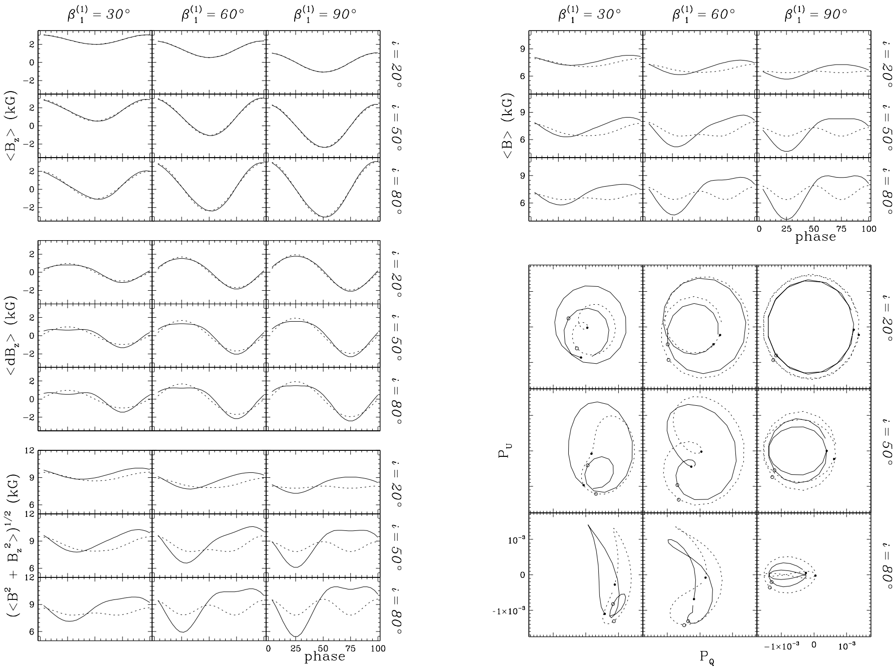

Figure 1. Dotted lines: the various observable quantities calculated for the magnetic configurations corresponding to the ORM with a dipolar field with a strength of 10 kG, and with different values of i and β. Solid lines: the observable quantities are calculated for the same magnetic configuration as for the dotted line, but with the superposition of a quadrupole perpendicular to the stellar rotational axis. ($\langle dB_z \rangle$ is calculated with Eq. (69) of Bagnulo et al. (1996) with its sign changed in order to be consistent with the definition of Mathys (1995a.)

So far, it has been assumed that the entire stellar spectrum might be characterised by a single "typical" line, rather than a more realistic model atmosphere (Landolfi et al. 1993). Indeed, in many cases, the BBLP does not depend strongly on the Zeeman patterns of spectral lines. However, there is an effect of depolarization due to the blending of several spectral lines, which might affect the shape of the BBLP diagrams in the presence of strong magnetic fields. Figure 2 shows the BBLP for a Zeeman triplet formed in a Milne-Eddington atmosphere (left) compared to the BBLP calculated for a stellar atmosphere of 10 000 K. For magnetic fields of 20 kG and more, there is an effect of depolarization due to the blending of spectral lines. This might explain why some stars with strong magnetic fields do not show detectable signals of BBLP.

The second assumption to be addressed is whether a dipolar field is sufficient to approximate the magnetic field of CP stars.

A natural way to describe a (potential) magnetic field is to consider a multi-

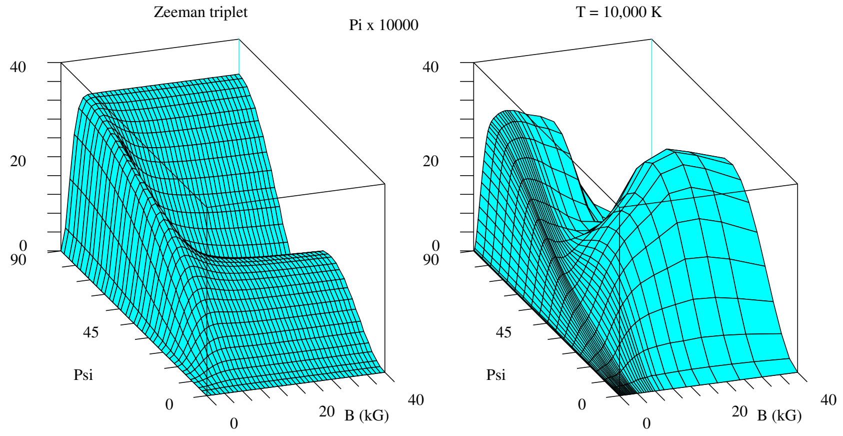

Figure 2. Left: the BBLP (in units per 10^{-4}) calculated for a normal Zeeman triplet formed in a Milne-Eddington atmosphere, as a function of the modulus of the magnetic field (expressed in kG), and the angle between the line of sight and the direction of the magnetic field. Right: the same for a stellar model atmosphere (see Stift 1998)

polar expansion. From a dipole, one can build up a quadrupolar field by considering two opposite dipoles displaced by a vector which in general is not parallel to the direction of the dipoles. The magnetic configuration is specified by three directions (one for the dipole, and two for the quadrupole) and by the strengths of the dipolar and of the quadrupolar components. An advantage of this formalism is that many observable quantities related to the magnetic field *have an analytical representation* (Bagnulo et al. 1996). The solid lines in Fig. 1 show the observable quantities for a sample of magnetic configurations described with a dipole plus a quadrupole. BBLP shows again to be the most sensitive to the magnetic morphology. It should be noted that the *longitudinal magnetic field is not sensitive to the quadrupolar component of the magnetic field*, unless the quadrupole largely dominates the magnetic morphology. The longitudinal magnetic field is described by a simple sinusoidal curve, even when the magnetic field shows severe departures from the dipolar geometry. Severe departures from the dipolar morphology – not detected via $\langle B_z \rangle$ measurements – are probably responsible for the lack of consistency between observed and predicted BBLP. The assumption that a dipolar field is sufficient to approximate the magnetic field of CP stars should be revisited.

In principle, a quick way to discover whether a star has a magnetic field more complicated than the dipolar one is simply to plot $\langle B^2 + B_z^2 \rangle^{1/2}$ vs. $\langle B_z \rangle$, which gives a line if the magnetic field is dipolar and a (single) loop if the field has a quadrupolar component. Figure 3 clearly shows that the magnetic field of β CrB exhibits severe departures from the simple dipolar configuration.

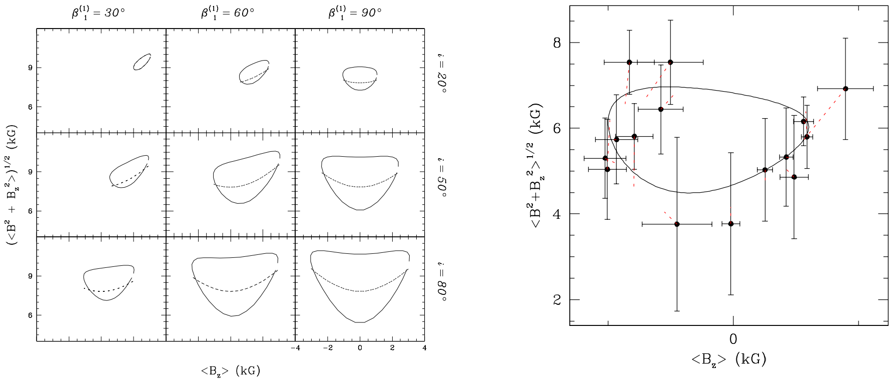

Figure 3. Clues to a quadrupolar magnetic field. Left: $\langle B^2 + B_z^2\rangle^{1/2}$ vs. $\langle B_z\rangle$ for a dipolar field (dotted lines) and dipole + quadrupole (solid lines). Departures from the dipolar morphology are responsible for a loop in the $\langle B^2 + B_z^2\rangle^{1/2} - \langle B_z\rangle$ plane. Right: observations of β CrB by Mathys (1994; 1995b) and Mathys & Hubrig (1997). The solid line is a fit obtained with a Fourier expansion

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References

Babcock, H.W.: 1958, *Astrophys. J., Suppl. Ser.* **3**, 141

Bagnulo, S., Landi Degl'Innocenti, E., Landolfi, M., Leroy, J.L.: 1995, *Astron. Astrophys.* **295**, 459

Bagnulo, S., Landi Degl'Innocenti, M., Landi Degl'Innocenti, E.: 1996, *Astron. Astrophys.* **308**, 115

Borra, E.F., Landstreet, J.D.: 1980, *Astrophys. J., Suppl. Ser.* **42**, 421

Landolfi, M., Landi Degl'Innocenti, E., Landi Degl'Innocenti, M., Leroy, J.L.: 1993, *Astron. Astrophys.* **272**, 285

Leroy, J.L.: 1962, *Ann. Astrophys.* **25**, 127

Leroy, J.L.: 1996, *Astron. Astrophys., Suppl. Ser.* **25**, 127

Mathys, G.: 1991, *Astron. Astrophys., Suppl. Ser.* **108**, 547

Mathys, G.: 1995a, *Astron. Astrophys.* **293**, 733

Mathys, G.: 1995b, *Astron. Astrophys.* **293**, 746

Mathys, G., Hubrig, S.: 1997, *Astron. Astrophys., Suppl. Ser.* **124**, 475

Mathys, G., Hubrig, S., Landstreet, J.D., Lanz, T., Manfroid, J.: 1997, *Astron. Astrophys., Suppl. Ser.* **123**, 353

Stift, M.: 1998, *these Proceedings*, 390