# Linear spectropolarimetry of Ap stars: a new degree of constraint on magnetic structure

**G.A. Wade**[1], **J.-F. Donati**[2], **G. Mathys**[3] **and N. Piskunov**[4]

[1] *Physics & Astronomy Department, University of Western Ontario, London, Ontario, Canada, N6A 3K7*

[2] *Observatoire Midi-Pyrénées, 14 Avenue Edouard Belin, 31400 Toulouse, France*

[3] *ESO, Casilla 19001, Santiago 19, Chile*

[4] *Uppsala Astronomical Observatory, Box 515, S-751 20 Uppsala, Sweden*

**Abstract.** We present preliminary results from a programme aimed at acquiring linear spectropolarimetry of magnetic A and B stars. Linear polarization in the spectral lines of these objects is due to the Zeeman effect, and should provide detailed new information regarding the structure of their strong magnetic fields. To illustrate the impact of these new data, we compare observed circular and linear polarization line profiles of 53 Cam with the profiles predicted by the magnetic model by Landstreet (1988).

Linear polarization in the spectral lines of *all* stars studied is extremely weak; in most cases, below the threshold of detectability even for very high SNRs. In order to overcome this problem, we employ the Least-Squares Deconvolution (LSD) multi-line analysis technique in order to extract low-noise mean line profiles and polarization signatures from our échelle spectra. Tests show that these mean signatures can be modelled as real spectral lines, and have the potential to lead to high-resolution maps of the magnetic and chemical abundance surface distributions.

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

## 1. Introduction

Recent observations of the broadband linear polarization variability of magnetic Ap stars have been shown to be very sensitive to the detailed topology of their magnetic fields. Using these data, Leroy et al. (1996) have presented models of the magnetic field structure of several stars which resolve clear departures from the simple multipolar geometries assumed in the past. Following these studies, we have taken an important next step by acquiring systematic linear *spectropolarization* measurements of a number of strong-field Ap stars. Due principally to the additional information contained in line profile shapes, these data promise important new constraints on the structure of the magnetic fields of these objects, and also offer the possibility of constructing mutually consistent, detailed magnetic field and chemical abundance distribution maps for individual stars. This will in turn provide new information about the interaction of the magnetic field with the atmospheric processes responsible for abundance inhomogeneities, as well as motivate new theoretical investigation into the mechanisms responsible for magnetic fields in early-type stars.

## 2. Spectropolarimetric observations

Using the new MuSiCoS spectropolarimeter and ESO CASPEC spectropolarimeter, we have acquired multiple observations of a number of strong-field magnetic A and B stars in each of the four Stokes parameters. Fig. 1 shows that, in the case of the cool Ap star $\beta$ CrB, circular polarization (Stokes V) and linear polarization (Stokes Q) are clearly detected in individual spectral lines. $\beta$ CrB is unusual in this respect; most stars studied display linear polarization amplitudes which are too weak to be detected in our high SNR ($\geq 300$) spectra. However, it turns out that even marginal detections or upper limits of the linear polarization can provide some surprising new results.

### 2.1. First results for 53 Cam

The magnetic field and chemical abundance distributions of the Ap star 53 Cam were modelled by Landstreet (1988). This model makes specific predictions about the shapes and amplitudes of the circular and linear polarization profiles of individual spectral lines at any rotational phase. In Fig. 2 we compare the observed Stokes I, V, Q and U profiles of Fe II $\lambda$4923.9 on 1997 February 16 with those predicted for this line at this phase by Landstreet's model. The agreement is not very good; the amplitude of the circular polarization (Stokes V) profile is overestimated by a factor of 2, while the linear polarizations (Stokes Q and U) are respectively overestimated by factors of 2.8 and at least 7.7. Similar behaviour is observed throughout the entire rotation of the star, at six other observed rotational phases. This represents a serious disagreement, and indicates that these new data will provide important new refinements to the best magnetic field models currently available.

## 3. Least-Squares Deconvolution

Our inability to detect linear polarization in the spectral lines of most stars studied indicates that the linear polarization profiles must be extremely weak. While marginal detections and upper limits are sufficient for illustrations such as that presented above, detailed modeling requires a reasonable relative SNR for the polarization profiles. To usefully detect the weak linear polarizations and to obtain a higher relative SNR, we exploit the similar information contained in the many spectral lines found in our échelle spectra using the Least-Squares Deconvolution (LSD) technique (Donati et al. 1997).

### 3.1. Technique

LSD is a technique for the simultaneous analysis of many spectral lines. LSD assumes that all spectral features in a given spectrum (Stokes I, V, Q or U) are identical in shape - they differ only in amplitude by known scaling factors. This assumption implies that the stellar spectrum is effectively the convolution of a shape function (called the *mean signature*) with a "spectrum" of weighted delta functions (called the *line mask*). LSD consists of deconvolving the mean signature from the spectrum, given knowledge of the line mask.

Of course, the principal assumption is not strictly true (the scaling relations employed are strictly valid only for weak lines and weak magnetic fields; shapes of different spectral lines are not identical: Zeeman splitting patterns vary from line to line, thermal width of lines varies with atomic weight, etc.), and it is not clear *a priori* that LSD should produce useful results. We have therefore performed realistic tests with synthetic spectra to determine to what degree the mean signatures produced by LSD resemble representative individual spectral lines.

### 3.2. Tests

A synthetic spectrum was computed using VALD linelists for a known surface distribution of magnetic field and chemical abundances. The spectrum was convolved with a gaussian instrumental profile with a FWHM of 8 $\mathrm{km\,s^{-1}}$ and infected with random noise in order to generate a SNR of 250:1. In this way the spectra were made to simulate the real data obtained by the MuSiCoS spectropolarimeter. For all but the strongest lines in this spectrum the linear polarization signatures were below the level of the noise, similar to the situation encountered in the observed spectra.

Finally, the spectrum was Least-Squares Deconvolved and mean signatures (in each of the Stokes I, Q, U and V parameters) were extracted. How well do these mean signatures agree with a "representative" spectral line (assumed, as a first approximation, to be a pure Zeeman triplet with a depth and Landé factor equal to the mean of all lines used) computed assuming identical surface distributions of chemical abundance and magnetic field? In Fig. 3 the mean signatures extracted from the synthetic spectrum are compared with the "representative" spectral line described above. The agreement is excellent, and indicates that the mean signatures extracted by LSD can be modelled as real spectral lines, assuming a line profile model for which the parameters are known *a priori*. As well, the relative SNR of the LSD mean signatures is very high, allowing for detailed modeling which would not have been possible using individual lines in the original spectrum.

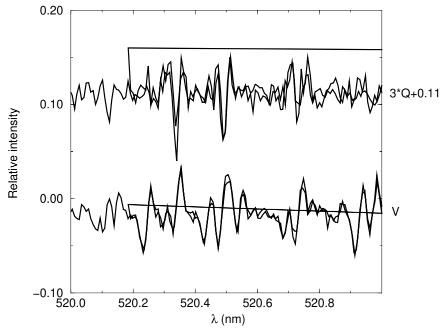


**Figure 1.** Stokes V (bottom) and Q (top) spectra of $\beta$ CrB, obtained using the MuSiCoS spectropolarimeter. Each spectrum shows two overlapping échelle orders. Both V and Q are clealy detected above the noise level.

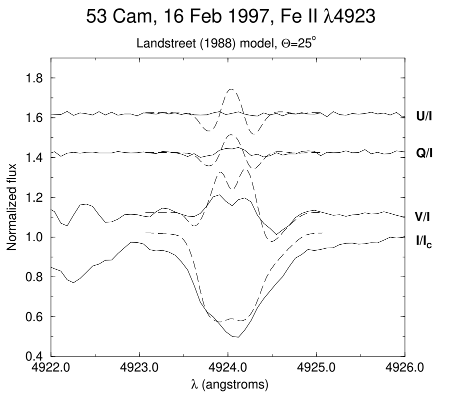


**Figure 2.** *Solid curves (bottom to top)* – Stokes I, V, Q and U profiles of Fe II $\lambda$4923.9 for the Ap star 53 Cam, observed on 16 February 1997. *Broken curves* – Predictions of Landstreet's (1988) model. The amplitudes of all polarizations are severely overestimated by the model (by a factor of 2 for Stokes V, by a factor of 4.3 for Stokes Q, and by at least a factor of 8.3 for Stokes U).

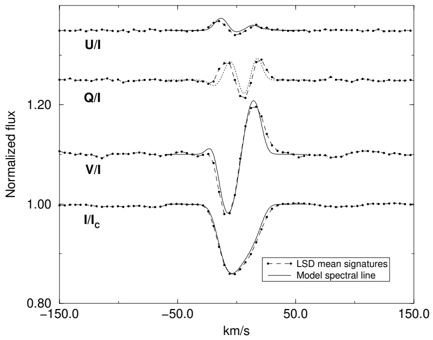


**Figure 3.** Tests of LSD using synthetic spectra: LSD mean signatures are extracted from a synthetic spectrum, and then compared for fidelity with the spectrum. Here, LSD mean signatures are compared with a synthetic spectral line with identical mean parameters. The amplitudes and shapes of the circular and linear polarization profiles are extremely well reproduced.

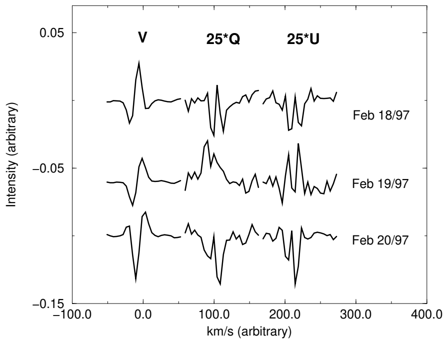


**Figure 4.** LSD Stokes V, Q and U mean signatures for the Ap star 78 Vir, observed on successive nights in Feb. 1997. For clarity the linear polarization profiles have been magnified by 25×, although they are clearly detected above the noise.

### 3.3. Results

LSD has been employed to extract mean Stokes signatures from polarization spectra of more than 10 magnetic Ap stars. Since most of these stars do not display a sufficiently large linear polarization amplitude to allow its detection in our spectra, LSD provides a unique opportunity to characterize and model the line profile linear polarization. In Fig. 4 we show LSD mean Stokes signatures for the Ap star 78 Vir, obtained over three nights in February 1997. Clear rotational modulation of all three Stokes parameters is visible. By obtaining polarization spectra of individual stars with good sampling of the entire rotational cycle, mutually consistent magnetic field and chemical abundance maps can be constructed using a mapping code such as INVERS10 (Piskunov, these proceedings). Such maps will comprise important contributions to our knowledge of the structure of the magnetic fields of A and B stars, as well as to our understanding of how the transport processes responsible for chemical peculiarities are affected by the presence of a magnetic field.

## 4. Conclusion

The results presented herein show that spectral line linear polarization measurements provide important new constraints on the magnetic field structure of A and B stars. Least-Squares Deconvolution is shown to be an effective technique for the extraction of mean Stokes signatures which can be accurately modelled as real line profiles. Such modelling has the potential to lead to the construction of mutually consistent, high-resolution maps of the magnetic and chemical surface structure of these stars.

**Acknowledgements.** Thanks to the Time Allocation Committees of l'Observatoire du Pic du Midi and the European Southern Observatory, La Silla, for continued support of this programme.

## References

Donati, J.-F., Semel, M., Carter, B.D., Rees, D.E., Cameron, A.C.: 1997, *Mon. Not. R. Astron. Soc.* **291**, 658

Landstreet, J.D.: 1988, *Astrophys. J.* **326**, 967

Leroy, J.-L., Landolfi, M., Landi Degl'Innocenti, E.: 1996, *Astron. Astrophys.* **311**, 513