Magnetic Doppler Imaging of Chemically Peculiar Stars

O. Kochukhov, N. Piskunov
Department of Astronomy and Space Physics, Uppsala University, Box 515, SE 751 20, Uppsala, Sweden

S. Bagnulo
European Southern Observatory, Casilla 19001, Santiago 19, Chile

J.D. Landstreet, T.A.A. Sigut
Physics & Astronomy Department, The University of Western Ontario, London, Ontario, N6A 3K7 Canada

P. Petit
Observatoire Midi-Pyrénées, 14 avenue Édouard Belin, 31400 Toulouse, France

G.A. Wade
Department of Physics, Royal Military College of Canada, Box 17000, Kingston, Ontario, K7K 4B4 Canada

Abstract. We discuss recent developments in the techniques of mapping magnetic topologies of chemically peculiar stars using high-resolution spectropolarimetric data and advanced inversion methods. Examples of application of the new magnetic Doppler imaging code to modelling circular polarization observations of the magnetic CP stars α² CVn and CS Vir are presented. Magnetic Doppler imaging analysis of the spectropolarimetric observations of the CP star 53 Cam has made it possible to achieve the first reconstruction of stellar magnetic topology using high-resolution spectra in all four Stokes parameters. The magnetic field of this star turns out to be considerably more complicated than can be represented by multipolar expansion of low degree.

1. Introduction

Doppler imaging has proved to be a very successful technique for obtaining in-depth knowledge about surface structures in active late-type and chemically peculiar (CP) stars. In these two classes of stars, magnetic fields are believed to be responsible for governing the emergence and evolution of the temperature and chemical inhomogeneities, observed through rotational modulation of the line profiles recorded at high temporal and spectroscopic resolution. However, despite recent impressive results on mapping abundance spots in CP stars and
imaging temperature inhomogeneities in active stars, a major shortcoming of many investigations is inadequate treatment of magnetic fields, which are often ignored altogether or studied with various proxies under fairly restrictive assumptions. Separate, inconsistent analyses of magnetic fields and chemical structures in CP stars are especially problematic, since in these objects magnetic fields are strong, and rotational modulations due to magnetic and abundance inhomogeneities often make comparable contribution to observed intensity and polarization profile variations.

A straightforward resolution of these difficulties can be achieved by mapping magnetic fields and related chemical and temperature structures simultaneously and self-consistently, using high-resolution spectra in all four Stokes parameters, and applying the Doppler imaging inversion based on accurate calculation of the polarized line profiles. The generalized magnetic Doppler imaging code Invers10, based on these principles, has recently been developed by Piskunov & Kochukhov (2002) (see also Piskunov, this volume). Our code computes Stokes spectra with the numerical integration of polarized radiative transfer equation through the model atmosphere, without resorting to simplifying weak field or Milne-Eddington approximations. Furthermore, when all four Stokes parameters are available for modelling, magnetic topologies of CP stars can be mapped directly, without assuming a low-order multipolar field expansion. Thus, our spectrum synthesis and inversion method can, in principle, include all relevant physics of magnetic stars and cover the whole range of field strengths and geometries in the photospheres of main sequence stars.

Performance, convergence properties and intrinsic limitations of the new Doppler imaging code have been verified with an extensive set of numerical experiments, as described by Kochukhov & Piskunov (2002). In these tests the code was used in the forward mode to generate time-series of Stokes spectra, and then in inversion mode to recover magnetic and abundance maps from these artificial observations. A typical comparison of the initial and reconstructed magnetic images is illustrated in Fig. 1.
Figure 2. Magnetic field topology of $\alpha^2$ CVn (a) reconstructed using the Stokes $I$ and $V$ spectra of the 13 different lines of singly ionized Cr, Si and Fe. The lower panel (b) shows distribution of magnetic field on the surface of CS Vir. This magnetic image is based on modelling the Stokes $I$ and $V$ observations of nine Fe II lines.

In general, we find good agreement between the initial and recovered images, suggesting that it is possible to achieve unique reconstruction of the orientation and strength of complex magnetic geometries by using observations in the four Stokes parameters, without imposing any a priori constraints on the global magnetic field structure. In addition, numerical tests revealed that magnetic imaging can handle much lower $v_\infty \sin i$ objects than conventional DI and can be applied to sufficiently high resolution observations of even very slow rotators. This becomes possible because rotational modulation of polarization signatures and Zeeman broadening of lines in the Stokes $I$ spectra provide enough information to constrain magnetic inversion.

2. Magnetic Doppler imaging of $\alpha^2$ CVn and CS Vir

Apart from recent pioneering observations by Wade et al. (2000), who detected linear polarization signatures in the line profiles of a few brightest CP stars, no systematic full Stokes vector spectropolarimetric observations have been carried out for any main sequence star so far. On the other hand, fairly extensive high-quality Stokes $I$ and $V$ datasets have already been acquired for a number of CP stars or can be readily obtained using many of the existing échelle spectrographs equipped with Zeeman analysers. Looking into the problem of reconstructing stellar magnetic fields from partial spectropolarimetric datasets, we found that the Stokes $I$ and $V$ spectra do not contain enough information for a stable and unique magnetic inversion. However, useful information can still be extracted from such observations by introducing external constraints on the possible magnetic geometries. For this purpose we use multipolar regularization (see Kochukhov & Piskunov 2002) which encourages the code to search for a solution close to general second-order multipolar expansion.

Our magnetic Doppler imaging code with multipolar regularization has been applied to real observations of CP stars. We used circular polarization spectra
obtained with the SOFIN instrument at the Nordic Optical Telescope. The most extensive dataset was acquired for the bright chemically peculiar star $\alpha^2$ CVn. High S/N and high resolution Stokes $I$ and $V$ time-series of this object allowed us to reconstruct magnetic field geometry and surface abundance distributions of six elements, and furnished the first realistic data on the interaction between the global magnetic field and chemical diffusion. A detailed description of the magnetic mapping of $\alpha^2$ CVn has been presented by Kochukhov et al. (2002). Fig. 2a illustrates the average magnetic map of $\alpha^2$ CVn, derived using the lines of Si, Fe and Cr. The magnetic geometry of this star turns out to be quite close to dipolar. A different example emerges from the Stokes $I$ and $V$ mapping of another CP star, CS Vir, whose analysis is currently in progress. The surface magnetic distribution of this star is clearly dominated by a strong quadrupolar component (see Fig. 2b).

![Figure 3](3d1fba178b6e4757a656f29d220bb2d0.png)

Figure 3. Comparison between phase variations of the magnetic observables of $\alpha^2$ CVn derived from the synthetic Stokes $I$ and $V$ profiles of 25 iron lines (symbols) and computed by direct geometrical integration of the magnetic field distribution (thick line).

In our investigation of $\alpha^2$ CVn, we observed the strong impact that abundance spots have on the high-resolution Stokes $V$ profiles and hence on classical magnetic observables, such as the mean longitudinal field, crossover field, etc. (see Bagnulo, this volume). This is illustrated in Fig. 3, where we compare observables derived from the profiles of iron lines (which are affected by both abundance spots and the magnetic field) with actual phase curves of the magnetic observables, obtained with geometrical integration of the surface magnetic field distribution. Abundance inhomogeneities tend to induce additional anharmonic modulation of the magnetic observables, which could be erroneously ascribed to the presence of non-axisymmetric quadrupolar components. This example suggests that one can expect misleading results from the derivation of magnetic topologies based on the modelling of magnetic observables if special care is not taken to avoid stars where primary diagnostic features, such as lines of chromium and iron, are affected by abundance spots.

3. Magnetic mapping of 53 Cam using observations in four Stokes parameters

53 Cam was among the stars observed in four Stokes parameters with the MUSICOS spectropolarimeter (Wade et al. 2000). This star is considered to
Figure 4. Comparison between observed (symbols) rotational modulation of the Stokes $I$, $Q$, $U$ and $V$ profiles of the Fe II 4923.93 Å line in the spectrum of 53 Cam and the fit (solid line) achieved by the magnetic Doppler imaging code. Spectra for consecutive rotational phases are shifted in the vertical direction. The bar in the lower part of each panel corresponds to 1 Å and 1% of the Stokes $I$ continuum intensity.

have a well-studied magnetic geometry, as many investigators (e.g. Landstreet 1988) have attempted to derive its field structure and abundance distributions by fitting various combinations of magnetic observables and using high-resolution unpolarized spectra. However, the unsatisfactory state of understanding of the structure of the magnetic field in this star became evident when Bagnulo et al. (2001) directly compared predictions of the two most sophisticated models with MUSICOS four Stokes parameter observations. Both models, which assume multipolar parameterization of magnetic field, failed to reproduce details of the shape of the Stokes $V$ spectra and displayed a major conflict with observations regarding the amplitude of the Stokes $Q$ and $U$.

This situation prompted us to attempt magnetic mapping with Invers10, which does not need to make assumptions about global field geometry, and derives the magnetic field map directly from the Stokes profiles. Fig. 4 shows the fit achieved by the code to the MUSICOS observations in the region of the Fe II 4923.93 Å line. The agreement between observations and synthetic spectra is quite good. The magnetic field geometry derived with the magnetic Doppler imaging is presented in Fig. 5. Evidently, the field of 53 Cam is considerably more complicated than can be accommodated by a multipolar approximation of low degree. The complexity of the magnetic distribution of 53 Cam is in agreement with the general trend of magnetic topologies of CP stars to deviate strongly from the pure dipole configurations (e.g., Bagnulo et al. 2002).

Thus, we conclude that the application of Invers10 code to the MUSICOS observations of 53 Cam solves the problem of modelling polarization spectra of
Figure 5. Distribution of the magnetic field strength (a) and field orientation (b) in 53 Cam as derived with modelling the four Stokes parameter observations of the Fe II line at 4923.93 Å.
	his star and represents the first successful attempt to derive a stellar magnetic geometry by utilizing high-resolution spectra in the four Stokes parameters.

References


Discussion

G. WADE: The contrast between magnetic configuration of 53 Cam (recovered with four Stokes parameters and Tikhonov regularization) and $\alpha^2$ CVn (recovered using circular polarization spectra and multipolar regularization) is striking – one very complex, the other very smooth. To what degree do you think multipolar regularization contributes to this difference? Or is it an indication of a huge range of field complexity amongst CP stars?

O. KOCHUKHOV: The magnetic field topology derived for $\alpha^2$ CVn is the simplest field map capable of describing the high-resolution Stokes I and V spectra. These observations do not contain evidence of complex magnetic structures. However, it is clear that Stokes-V spectra have limited diagnostic content and that further investigations will be worthwhile (e.g., modelling observations in all four Stokes parameters).