Solar Polarization 4
ASP Conference Series, Vol. 358, 2006
R. Casini and B. W. Lites

Spectro-Polarimetry of Magnetic Hot Stars

O. Kochukhov

Department of Astronomy and Space Physics, Uppsala University, Box 515, SE-75120 Uppsala, Sweden

Abstract. This overview summarises recent advances in detection of the magnetic field and modeling the field topology in magnetic hot stars. I describe modern spectro-polarimetric techniques employed to characterise the properties of the stellar magnetic field and briefly review results of their application to several classes of hot stars. A special emphasis is given to the detailed simultaneous modeling of chemical and magnetic structures in the atmospheres of chemically peculiar stars. For these objects a novel Doppler imaging analysis based on the spectro-polarimetric data in all four Stokes parameters was recently used to reconstruct the first self-consistent maps of magnetic field and chemical inhomogeneities. Magnetic Doppler imaging studies reveal unexpected complexity of the surface magnetic topologies and large star-to-star scatter in the level of field complexity.

1. Introduction

Magnetic hot stars span spectral classes from early B to early F and show substantially different manifestation of the magnetic phenomena compared to the late-type active stars. In late-type stars superficial convection zone plays a primary role in generating and shaping complex magnetic fields. But at the effective temperature of about 7000 K the envelope convection zone is no longer capable of supporting surface activity and the character of stellar magnetism and related variability changes rather abruptly. A small fraction of hot stars host well-ordered, probably fossil, strong magnetic field. The fossil field hypothesis (Cowling 1945; Moss 1989; Braithwaite & Spruit 2004) relates the origin of magnetism in these stars to the processes occurring during the pre-main sequence contraction rather than to the action of a contemporary dynamo mechanism. The presence of strong magnetic field at the stellar surface is closely related to several other interesting phenomena, collectively known as *chemically peculiar* (CP, also known as Ap/Bp) stars of the upper main sequence. Peculiar stars constitute 5–10% of the hot main sequence stars and were recognized long ago due to their anomalous surface chemical composition. They often show enhanced concentration of the iron-peak elements, silicon and, especially, extreme overabundances of the rare-earth elements. Helium can be over- or underabundant as well. These superficial abundance anomalies are built up by the *chemical diffusion* (Michaud 1970)—a slow process of differential gravitational settling and radiative levitation of chemical species in the stable atmospheric environments of A and B stars.

A key property of CP stars is their slow rotation in comparison with normal A and B stars (Abt & Morrell 1995). Significant loss of angular momentum takes place before CP stars reach the main sequence, which points at the interaction between the stellar field, accretion disk, and magnetised wind in young stars (Stępień 2000). During the main sequence evolutionary phase, chemical elements show inhomogeneous distribution over the surfaces of magnetic CP stars (e.g., Kochukhov et al. 2004b), revealing modification of the chemical diffusion processes by the global magnetic field (Michaud, Charland, & Megessier 1981). The surface field strength in magnetic CP stars is confined in the range between a few hundred G up to 35 kG in HD 215441 (Preston 1969). The field covers the whole stellar surface and is organised on large scale. In the first approximation magnetic structure is axisymmetric and resembles that of an oblique dipole with eventual contribution of the higher-order multipolar magnetic components. The field is "frozen" in the surface layers of stars and is believed to be constant on timescale of at least hundreds of years, although some modulation of the observed field characteristics may occur due to the precession of the field axis with respect to the rotation axis of the star (Adelman et al. 2001). At the same time, spectacular periodic changes of the disk-averaged magnetic field strength and orientation are observed in most magnetic hot stars. This variation occurs with periods from 0.5 d up to several decades and is synchronised with the line profile changes. A common explanation of this phenomenon—*oblique rotator model* (Stibbs 1950)—attributes observed changes to the rotational modulation of the geometrical aspect at which surface magnetic and chemical structures are visible from Earth.

For many CP stars the field is strong enough to have a profound effect on the appearance and variability of the emergent radiation. Consequently, peculiar stars were the first objects after the Sun in which magnetic field was discovered (Babcock 1947). Today CP stars constitute by far the most numerous class of magnetic stars (the field has been detected in more than 300 objects; see Bychkov, Bychkova, & Madej 2003) and provide the only opportunity for detailed, direct, and statistically viable investigation of the stellar magnetism and related phenomena of the atmospheric structure formation.

2. Magnetic Field Diagnostic Techniques

The Zeeman effect is so far the only tool available for direct detection and analysis of magnetic fields in non-degenerate stars. Splitting of the atomic energy levels in magnetic field results in several effects on spectral lines, which can be used to study the field properties (Mathys 1989). We see broadening and splitting of the magnetically sensitive lines in the intensity spectra. Significant broad-band linear polarization arises in the rich spectra of the cooler magnetic A stars and, finally, the circular and linear polarization inside profiles of individual spectral lines contains the most unambiguous and rich information about the stellar magnetic structures.

2.1. Longitudinal Field

The most straightforward polarimetric measurement is determination of the disk-averaged line-of-sight (longitudinal) component of the stellar magnetic field using circular polarization observations. This technique was used to discover fields and monitor field variation over rotation cycle in the majority of known magnetic hot stars (e.g., Mathys 1991; Bohlender, Landstreet, & Thompson

1993). The longitudinal field diagnostic turns out to be very efficient due to the smooth topology of the global field in hot stars. This property substantially reduces cancellation of the polarization signal coming from different surface zones and hence enables precise magnetic measurements at the variety of large and medium size telescopes equipped with diverse polarimetric instrumentation.

An impressive recent contribution to the studies of hot star magnetism became possible through the development of the low-resolution spectro-polarimetry with FORS1 at the ESO Very Large Telescope (VLT). In this observational approach, introduced by Bagnulo et al. (2002a), longitudinal field is determined from the circular polarization signal in the wings of the hydrogen Balmer lines. A straightforward quantitative derivation of the disk-averaged line-of-sight field is based on the weak field approximation, which is adequate for hydrogen lines even in kG fields. In practice, each pixel of the observed Stokes-V spectrum in the Balmer line wings is plotted against the quantity proportional to the derivative of Stokes I. The slope of the resulting linear correlation gives the field value.

The FORS1 instrument is currently the only spectro-polarimeter at the 8-m class telescope available to the stellar community. The large collecting area of VLT and multi-object capabilities of FORS1 allowed to extend magnetic field studies to fainter stars and made possible the first systematic large-scale investigation of the incidence of magnetism in open clusters—the study aiming to answer a fundamental question about the link between stellar magnetism and evolution (Bagnulo et al. 2006). Discovery of extremely large magnetic fields in young cluster CP stars NGC 2244-334 (Bagnulo et al. 2004) and HD 66318 (Bagnulo et al. 2003) was among recent successes of the FORS1 magnetic survey of open clusters. At the same time, FORS1 has been also extensively used in polarimetric mode to measure magnetic fields in hot stars in advanced evolutionary stages, for instance in white dwarfs (Aznar Cuadrado et al. 2004), in hot subdwarfs (O'Toole et al. 2005), and in the central stars of planetary nebulae (Jordan, Werner, & O'Toole 2005).

Important application of the FORS1 and other longitudinal field measurements is to investigate evolutionary state of the field magnetic CP stars. This work has been recently completed by Kochukhov & Bagnulo (2006). We have compared predictions of the stellar evolutionary models with the observed parameters of *all* magnetic CP stars for which accurate parallaxes are available from the Hipparcos catalogue. Anaysis of the sample, containing about 200 stars, suggests that the mechanism that originates and sustains the magnetic field in the upper main sequence stars may be different in CP stars of different mass. Massive magnetic stars seem to be distributed homogeneously over the whole width of the main sequence band. On the other hand, stars below $2\,M_{\odot}$ are rare close to the zero-age and terminal-age main sequence.

On the other extreme of the longitudinal field diagnostic of hot stars lie the ongoing efforts to detect variation of magnetic field with pulsation cycle in rapidly oscillating Ap (roAp) stars (Kurtz & Martinez 2000). These cool magnetic A stars are unstable to the magneto-acoustic p-modes in the period range of 6 to 21 min. RoAp stars are extremely interesting asteroseismic targets because they provide unique astrophysical laboratory for studying effects of rotation, non-radial pulsation, and magnetic field in the same objects. Detection of the pulsational variation of magnetic field is very important because it will add new significant constraints for pulsation theories. Due to the vertical stratification of chemical elements in roAp stars, the upper atmospheric layers showing hihg-amplitude pulsational variation are probed only by the rare-earth elements and hence magnetic measurements have to be limited to lines of these species. Furthermore, high spectral resolution and time resolution of 1 min are necessary to resolve pulsational variability. This type of time-resolved spectro-polarimetry is quite a challenge even for a 3–4 m telescopes. Recently Leone & Kurtz (2003) claimed discovery of a half-kG, peak-to-peak pulsational field variation in the bright roAp star γ Equ. However, subsequent more detailed observations of the same target by Kochukhov, Ryabchikova, & Piskunov (2004) showed no pulsational field variation above 40 G. These contradictory results are hotly debated, and the question of the reality of the pulsational modulation of longitudinal field in roAp stars remains open. Clearly, a definite detection of the rapid magnetic oscillation in stars presents an interesting challenge for the new generation spectro-polarimeters, such as the ESPaDOnS instrument at CFHT.

2.2. Least-Squares Deconvolution

A major progress in spectro-polarimetric analyses of hot stars became possible with the introduction of the least-squares deconvolution (LSD) method (Donati et al. 1997). In this technique information about the shape of intensity profiles and the line polarization signatures is extracted from all suitable metal lines. The LSD approach assumes that line profiles are self-similar and hence can be combined into an average profile of extremely high signal-to-noise ratio. Mathematically stellar spectrum is represented by a convolution of the line mask – a set of delta functions – and the average profile. This equation is then inverted, obtaining a best-fit average profile for a given observed spectrum and its error bars. Computational efficiency of the method comes for the price of ignoring radiative transfer in the treatment of blends and therefore rather poor accuracy is achieved in reproducing individual lines. Yet, by including many spectral lines, LSD technique boosts precision of the average line profile tremendously and hopefully avoids systematic errors.

Donati et al. (1997) were the first to apply magnetic version of the LSD method to the Stokes-V spectra of active stars. For these objects the assumption of similarity of the Stokes-V signatures of different lines is justified by the properties of the circular polarization profiles in the weak field limit. Subsequently, Wade et al. (2000b) used the Stokes-V LSD method to obtain very precise measurements of the longitudinal field in CP stars. For bright stars an order of magnitude improvement in the precision was achieved compared to previous results, and typical error bars reached down to 20–50 G for some of the targets. Improved sensitivity to weak fields permitted definite magnetic detections for many bright weakly magnetic CP stars. In the currently ongoing survey, Aurière et al. (2004) find magnetic field in essentially every Ap and Bp star they look at and report possible lower threshold of fields in CP stars. There seems to be lack of stars with dipolar field component weaker than ~ 250 G—a value curiously close to the equipartition field strength expected for the atmospheric conditions of A and B stars. If confirmed, this discovery may shed a new light on the physics responsible for the phenomenon of hot star magnetism.

At the same time, longitudinal field measurements based on the LSD technique deepened the mystery of the dichotomy in the magnetic properties of different classes of CP stars. Shorlin et al. (2002) conducted a sensitive search of fields in Am and Hg-Mn stars and found that these objects definitely do not host large-scale fields typical of magnetic CP stars. Furthermore, the Stokes-V line profile analysis by Wade et al. (2003) gave no evidence of the complex magnetic topologies similar to those found in late-type active stars. Thus, there exists a striking division and no evidence of a smooth transition between apparently non-magnetic and strongly magnetic stars of similar rotation rates and effective temperatures. Contributing to this puzzle, Wade et al. (2006) have recently used the ESPaDOnS spectro-polarimeter to obtain unprecedented longitudinal field measurements for the brightest Hg-Mn star α And. Spotted surface distribution of mercury was discovered in this star (Adelman et al. 2002), yet there is no magnetic field stronger than ≈ 10 G. This appears to be the first example of a star showing structure formation at the surface without any relation to magnetic field.

Stokes-V spectro-polarimetry in combination with the LSD procedure has also allowed to extend magnetic field studies to the pre-main sequence HAeBe stars (Wade, these proceedings) and hotter objects, which were not previously associated with CP stars. In particular, during the last few years magnetic field was detected in classical Be (Neiner et al. 2003b), in slowly pulsating B (Neiner et al. 2003a), in β Cep and even in an O-type star (Donati et al. 2001, 2002). In these most massive magnetic stars the field plays a primary role in defining geometry of the stellar wind which feeds powerful magnetospheres. Resonance UV lines forming in the wind show very pronounced rotational modulation which correlates with the field variation. Unfortunately very small number of such massive magnetic objects are known and magnetic detections are tentative for some of the stars. This is due to the fact that in the spectra of hottest stars one can measure polarization only in a small number of metal lines and even those are significantly broadened by various mechanisms. These difficulties notwithstanding, characterisation of the magnetism of most massive stars promises to be very rewarding since it will help to clarify interaction between g-mode pulsations and magnetic field, and to understand behaviour of the magnetically controlled magnetospheres. Another important question is the origin of magnetic field observed in early B and O stars. Do these objects sustain the fossil field via the same mechanisms as cooler magnetic CP stars or their magnetism is related to the possible action of the Taylor-type shear dynamo in differentially rotating radiative envelope (Spruit 2002) or to the field generation in the convective cores of massive stars (Brun, Browning, & Toomre 2005)? This plethora of well-developed theoretical scenarios calls for further detailed exploration of the nature of magnetic fields in massive stars.

The LSD processing was extended to the linear polarization spectra by Wade et al. (2000a). They used proportionality $Q, U \propto \mathrm{d}^2 I/\mathrm{d}\lambda^2$ as a justification of the assumption of self-similarity of the line linear polarization patterns. However, unlike the respective relation for Stokes V (valid for all lines forming in the weak field regime), proportionality of the Q parameter to the second derivative of Stokes I implies both weak-field *and* weak-line approximations. Even with these restrictive assumptions in construction of the LSD profiles, Wade et al. (2000a) were able to carry out the first systematic study of the linear polarization in spectral lines of magnetic CP stars. Remarkable variability with rotation phase was detected in the LSD Stokes Q and U profiles for several stars. However, no methods suitable for quantitative interpretation of these average linear polarization signatures were suggested. In reality, shapes of polarization signals in individual lines differ considerably, both due to dissimilar Zeeman patterns and due to difference in line strengths. As a result, no physical line parameters can be associated with the LSD Stokes Q and U profiles. Clearly, an improvement in the methodology of constructing the Stokes Q and U average linear polarization profiles would be extremely useful. A PCA-based analysis, presented by Semel et al. (these proceedings), may represent a promising step in this direction.

3. Magnetic Field Topology

3.1. Multipolar Field Modeling

Even very high quality determinations of the longitudinal field alone are usually insufficient to constrain the simplest model of the magnetic field geometry. Additional information can be extracted with the so-called moment technique. It was introduced by Mathys (1989), and was applied primarily to moderate quality Stokes-V observations of CP stars. In the moment technique, relations are established between the integral characteristics of line profiles and disk-averaged magnetic quantities. For instance, splitting of the Zeeman resolved lines is a measure of the mean field modulus (Mathys 1990). Consideration of the differential magnetic broadening of unpolarized line profiles allows to deduce the mean quadratic field (Mathys 1995b). The first moment of the Stokes-V profile corresponds to the longitudinal field (Mathys 1991), whereas the second moment, crossover (Mathys 1995a), diagnoses asymmetry in the surface distribution of the line-of-sight field component. The field modulus measurements are essentially assumption-free, but ignore possible influence of chemical spots. In addition to that restriction, derivation of all other magnetic observables relies on weak line and weak field approximations.

Interpretation of the phase curves of magnetic observables remains the most common technique for the analysis of the field structure in hot stars. Its main advantage is relative simplicity, computational efficiency, and possibility to study consistently sizable samples of magnetic stars. In practice, one of several possible low-order multipolar parameterisations of the global field is assumed and the field parameters are optimised iteratively to reduce discrepancy between model predictions and observations. Recent statistical analyses of the multipolar field structure in CP stars were presented by Landstreet & Mathys (2000) and Bagnulo et al. (2002b). Caution has to be exercised in interpretation of these multipolar modeling results. In many individual cases multipolar models are non-unique and unreliable, as shown by the discrepancy of magnetic models deduced by Landstreet & Mathys (2000) and Bagnulo et al. (2002b) for several stars in common. Nevertheless, simple models are useful in constraining main statistical properties of the field geometries and allow one to probe correlations between magnetic and fundamental stellar parameters. One such interesting and robust result has emerged from recent studies: it was found that the symmetry axis of magnetic field tends to be nearly aligned with rotation axis in stars with rotation periods in excess of 35 days.

3.2. Magnetic Doppler Imaging

Thanks to the high amplitude of the line polarization signatures observed in many magnetic hot stars, a direct analysis of the Stokes spectra of these objects is currently within our reach. Only a modest equipment at a medium-size telescope is necessary to obtain high-quality Stokes-V spectra for bright magnetic stars. These observations are suitable for the circular polarization magnetic imaging, such the analysis presented by Kochukhov et al. (2002) for the prototype magnetic CP star α^2 CVn. This Stokes I and V Doppler mapping is similar to the LSD-based Zeeman Doppler imaging (ZDI) procedure applied to active late-type stars (e.g., Petit et al. 2004; see also Petit, these proceedings), but has the advantage of working directly with the polarization profiles of individual metal lines and being based on realistic spectrum synthesis calculations. However, circular polarization alone does not permit full reconstruction of the global hot star field topology from first principles. Additional information in the form of multipolar regularisation (Kochukhov & Piskunov 2002) is required to ensure uniqueness of the solution.

For several bright stars detection of the linear polarization signatures in a few strongest spectral lines has been achieved in addition to the acquisition of high-quality Stokes-V spectra (Wade et al. 2000a). With the additional constraints on the transverse field, these data proved to contain sufficient information for the very first assumption-free mapping of magnetic fields in hot stars. Magnetic Doppler imaging (MDI) in four Stokes parameters developed by Kochukhov & Piskunov (2002) is currently the most advanced method to interpret the Stokes spectra of magnetic stars. This technique provided the first possibility to infer the stellar magnetic topology using spectra in all four Stokes parameters. The inversion procedure is based on the detailed polarized radiative transfer spectrum synthesis, which includes all relevant physics of line formation. No a priori assumptions are used to recover the field structure. This is the first time such an approach is adopted for hot stars. Finally, chemical maps and magnetic field are derived simultaneously and self-consistently. This means that the influence of chemical spots is taken into account not only for Stokes I, but also when computing linear and circular polarization profiles. Of course, MDI of hot stars has the main principles in common with the ZDI of cool active stars. Yet, methodology is quite different, mainly due to the nature of the available observational material: all four Stokes parameters in individual lines for hot stars and only Stokes I and V LSD profiles for cool stars. As a result, many advantages of our magnetic mapping scheme cannot be realised with existing spectro-polarimetric observations of cool stars. Situation will certainly improve with the availability of the higher-quality polarization spectra of late-type stars. Examples of such data recorded with ESPaDOnS were presented at this conference by Petit, and by Berdyugina et al.

Magnetic CP star 53 Cam became the first target of the MDI in all four Stokes parameters. The mapping of this star by Kochukhov et al. (2004a) showed that only a fairly complex magnetic distribution could reproduce observed details of the Stokes V profiles and anomalously low amplitude of the linear polarization signal detected in the MuSiCoS spectra of this star (Wade et al. 2000a). The agreement between observations and theoretical Stokes spectra generated with the MDI model is far better than can be achieved for any low-order mul-

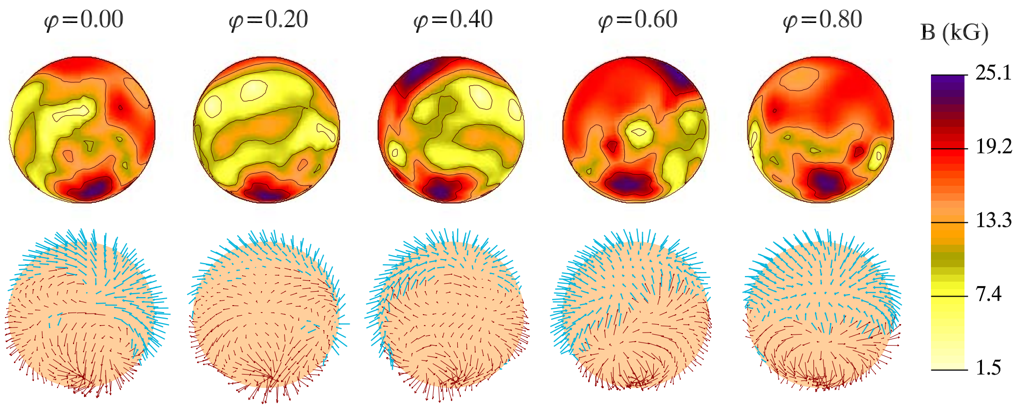

Figure 1. Magnetic field map inferred with the MDI inversion of all four Stokes parameter time-series observations of the CP star 53 Cam. The upper panel shows distribution of the magnetic field strength, whereas the lower panel illustrates the field orientation (lighter thick arrows correspond to the field vectors directed inwards). The star is shown at five equidistant rotation phases. The aspect corresponds to the inclination angle $i = 123°$ and vertically oriented rotation axis.

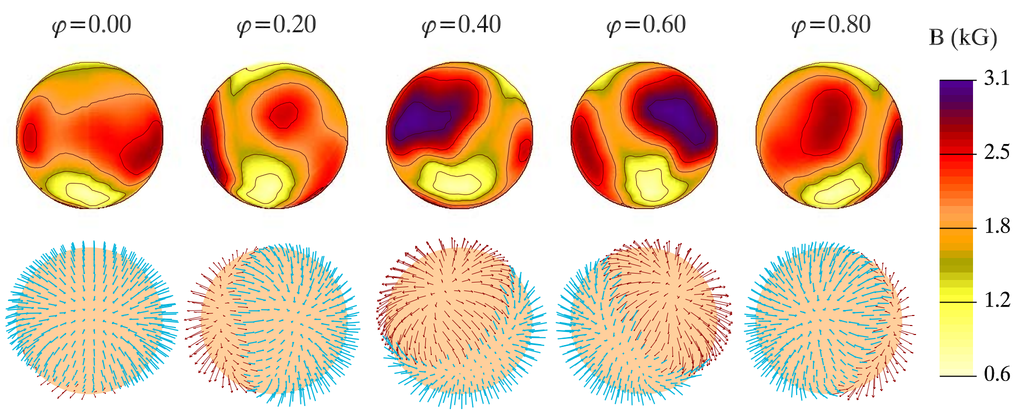

Figure 2. Magnetic field map of α^2 CVn inferred from the MDI inversion of spectro-polarimetric time-series observations in all four Stokes parameters.

tipolar field geometry. The field topology reconstructed for 53 Cam (Fig. 1) is quite remarkable in its combination of a relatively simple, basically dipolar, field orientation with a complicated structure visible in the field strength maps. Consistent results obtained from independent inversions of different lines confirm reality of the major details in the magnetic maps and of the overall level of field complexity. Quantitative analysis of the MDI magnetic map was performed using high-order multipolar decomposition (Kochukhov et al. 2004a). We have inferred that the maximum contribution to the surface field topology comes from the spherical harmonic components with $\ell = 5$–6, corresponding to the angular scale of $\approx 30°$. Substantial toroidal field contribution was also detected.

Application of the MDI mapping to the MuSiCoS spectro-polarimetric observations of another CP star, α^2 CVn, revealed a field structure with a dramatically different level of complexity compared to 53 Cam (Fig. 2). We have obtained the field distribution not deviating far from a dipole and certainly lacking small-scale structures found for 53 Cam. For both stars chemical abundance maps were recovered simultaneously with the magnetic field. In α^2 CVn Fe and Cr lines used for the field mapping indicate the presence of large horizontal abundance gradients. Thus, despite a relatively simple field geometry, reliable analysis of the magnetic field in α^2 CVn was impossible with a technique other than MDI because all other methods do not account for the major effects of chemical spots.

Successful mapping of the fields in 53 Cam and α^2 CVn confirms efficiency and robustness of the MDI approach and brings us to the conclusion that available inversion methods and four Stokes parameter observations make possible obtaining high-resolution magnetic stellar maps. The sample of stars studied so far is too small for any firm conclusions to be put forward. However, we can certainly expect to find diverse and complex fields in other hot stars. Among the future challenges of the magnetic Doppler imaging I would like to highlight extension to a larger number of stars and investigation of the field structure in stars at different evolutionary phases. We also want to address the question raised by the apparent complexity of the field in 53 Cam. Are the small-scale features seen in the MDI map indeed represent a signature of higher-order multipoles, or they approximate unresolved fields at even smaller scales? Finally, we hope to be able to compare our empirical magnetic maps with the predictions of time-dependent 3D MHD simulations of the evolution of stable fields in the radiative stellar envelopes (Braithwaite & Spruit 2004). The main feature of the magnetic topology emerging from these pioneering theoretical calculations is a mixture of poloidal and toroidal field components, not unlike the field structure we found in 53 Cam.

Acknowledgments. I thank the organizers of the 4th Solar Polarization Workshop for inviting me to present this review. My participation to the conference was supported by the Swedish Foundation for International Cooperation in Research and Higher Education (STINT). The funding by the Kungliga Fysiografiska Sällskapet is also gratefully acknowledged.

References

Abt, H. A., & Morrell, N. I. 1995, ApJS, 99, 135

Adelman, S. J., Malanushenko, V., Ryabchikova, T. A., & Savanov, I. 2001, A&A, 375, 982

Adelman, S. J., Gulliver, A. F., Kochukhov, O. P., & Ryabchikova, T. A. 2002, ApJ, 575, 449

Aurière, M., Silvester, J., Wade, G. A., et al. 2004, in IAU Symp. 224, The A-star puzzle, ed. J. Zverko, J. Žižňovský, S. J. Adelman & W. W. Weiss (Cambridge: Cambridge Univ.), 633

Aznar Cuadrado, R., Jordan, S., Napiwotzki, R., et al. 2004, A&A, 423, 1081

Babcock, H. W. 1947, ApJ, 105, 105

Bagnulo, S., Szeifert, T., Wade, G. A., Landstreet, J. D., & Mathys, G. 2002a, A&A, 389, 191

Bagnulo, S., Landi Degl'Innocenti, M., Landolfi, M., & Mathys, G. 2002b, A&A, 394, 1023

Bagnulo, S., Landstreet, J. D., Lo Curto, G., Szeifert, T., & Wade, G. A. 2003, A&A, 403, 645
Bagnulo, S., Hensberge, H., Landstreet, J. D., Szeifert, T., & Wade, G. A. 2004, A&A, 416, 1149
Bagnulo, S., Landstreet, J. D., Mason, E., et al. 2006, A&A, 450, 777
Bohlender, D. A., Landstreet, J. D., & Thompson, I. B. 1993, A&A, 269, 355
Braithwaite, J., & Spruit, H. C. 2004, Nat, 431, 819
Brun, A. S., Browning, M. K., & Toomre, J. 2005, ApJ, 629, 461
Bychkov, V. D., Bychkova, L. V., & Madej, J. 2003, A&A, 407, 631
Cowling, T. G. 1945, MNRAS, 105, 166
Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E., & Collier Cameron, A. 1997, MNRAS, 291, 658
Donati, J.-F., Wade, G. A., Babel, J., et al. 2001, MNRAS, 326, 1265
Donati, J.-F., Babel, J., Harries, T. J., et al. 2002, MNRAS, 333, 55
Jordan, S., Werner, K., & O'Toole, S. J. 2005, A&A, 432, 273
Kochukhov, O., & Bagnulo, S. 2006, A&A, 450, 763
Kochukhov, O., & Piskunov, N. 2002, A&A, 388, 868
Kochukhov, O., Piskunov, N., Ilyin, I., Ilyina, S., & Tuominen, I. 2002, A&A, 389, 420
Kochukhov, O., Bagnulo, S., Wade, G. A., et al. 2004a, A&A, 414, 613
Kochukhov, O., Ryabchikova, T., & Piskunov, N. 2004, A&A, 415, L13
Kochukhov, O., Drake, N. A., Piskunov, N., & de la Reza, R. 2004b, A&A, 424, 935
Kurtz, D. W., & Martinez, P. 2000, Baltic Astron., 9, 253
Landstreet, J. D., & Mathys, G. 2000, A&A, 359, 213
Leone, F., & Kurtz, D. W. 2003, A&A, 407, L67
Mathys, G. 1989, Fund. of Cosmic Phys., 13, 143
Mathys, G. 1990, A&A, 232, 151
Mathys, G. 1991, A&AS, 89, 121
Mathys, G. 1995a, A&A, 293, 733
Mathys, G. 1995b, A&A, 293, 746
Michaud, G. 1970, ApJ, 160, 641
Michaud, G., Charland, Y., & Megessier, C. 1981, A&A, 103, 244
Moss, D. 1989, MNRAS, 236, 629
Neiner, C., Geers, V. C., Henrichs, H. F., et al. 2003a, A&A, 406, 1019
Neiner, C., Hubert, A.-M.; Frémat, Y., et al. 2003b, A&A, 409, 275
O'Toole, S. J., Jordan, S., Friedrich, S., & Heber, U. 2005, A&A, 437, 227
Petit, P., Donati, J.-F., Oliveira, J. M., et al. 2004, MNRAS, 351, 826
Preston, G. W. 1969, ApJ, 156, 167
Shorlin, S. L. S., Wade, G. A., Donati, J.-F., et al. 2002, A&A, 392, 637
Spruit, H. C. 2002, A&A, 381, 923
Stępień, K. 2000, A&A353, 227
Stibbs, D. W. N. 1950, MNRAS, 110, 395
Wade, G. A., Donati, J.-F., Landstreet, J. D., & Shorlin, S. L. S. 2000a, MNRAS, 313, 823
Wade, G. A., Donati, J.-F., Landstreet, J. D., & Shorlin, S. L. S. 2000b, MNRAS, 313, 851
Wade, G. A., Aurière, M., Donati, J.-F., et al. 2003, in IAU Symp. 210, Modelling of Stellar Atmospheres, ed. N. E. Piskunov, W. W. Weiss & D. F. Gray (San Francisco: ASP), D29
Wade, G. A., Aurière, M., Bagnulo, S., et al. 2006, A&A, 451, 293