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Modelling complex magnetic fields in stars with radiative envelopes

J. Silvester

Department of Astronomy and Space Physics, Uppsala Universitet, Uppsala, Sweden, (E-mail: james.silvester@physics.uu.se)

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Abstract. Magnetic chemically peculiar A and B type stars (Ap/Bp) exhibit strong globally organised magnetic fields, this is combined with strong chemical abundance non-uniformities within the atmosphere. The presence of the magnetic field influences energy and mass transport within the atmosphere of a star, this is thought to cause these observed chemical non-uniformities. These stars offer the ideal laboratory for understanding the interplay between magnetic field structure, atmospheric transport processes and other stellar parameters. With the recent increase in the availability of spectropolarimetric data and by using magnetic Doppler imaging (MDI) techniques, the number of detailed maps of the magnetic structure of Ap/Bp stars is growing. It is now possible to begin to investigate correlations between the magnetic field structure, chemical abundance structures in the photospheres of Ap/Bp stars and other stellar parameters, the first steps in understanding the evolution of such magnetic fields.

Key words: stars: magnetic fields – stars: chemically peculiar

1. Introduction

The magnetic fields of stars with radiative envelopes have quite different characteristics than those of late-type stars. In the radiative envelope stars, the large-scale surface magnetic field is static on timescales of at least many decades and appears to be frozen into a rigidly rotating atmosphere. The magnetic field is globally organised, permeating the entire stellar surface, with a high field strength (typically of a few hundred up to a few tens of thousands of Gauss). The presence of a such a magnetic field can strongly influence energy and mass transport within the atmosphere of the star and results in the presence of strong chemical abundance non-uniformities in the atmosphere, the so-called chemically peculiar stars (the Ap and Bp stars). Because the atmospheric mixing processes are weak in the atmospheres of Ap/Bp stars (due in part to the magnetic field), these stars offer a unique insight into the internal processes, via the impression these processes leave on the surface of a star.

Historically, the magnetic field geometries of chemically peculiar Ap/Bp stars were modelled in the context of a simple dipole field. However, with the acquisition of increasingly sophisticated diagnostic data, it has become clear that the large-scale field topologies exhibit important departures from this simple model. High-resolution circular and linear polarisation spectroscopy have shown the presence of strong, small-scale field structures, which were completely unexpected based on earlier modelling.

Recent advances in tomographic imaging techniques and improvements in instrumentation offer the opportunity to improve our understanding of the magnetic field structure and the effect it has on atmospheric transport mechanisms. By mapping the magnetic field and chemical surface structure of Ap stars simultaneously, it is possible to directly investigate the relationship between the local magnetic field, the local surface chemistry and also to look for correlations between the magnetic field and other stellar properties.

1.1. Spectropolarimetric Observations and MDI

There has been a large increase in the availability of sophisticated spectropolarimetric data obtained for Ap/Bp stars in Stokes IQUV observations using instruments such as the ESPaDOnS, HARPSpol and NARVAL spectropolarimeters. These new spectropolarimeters have overcome the limitations of the previous generations of instrumentation, such as limited resolving power and sensitivity. The ESPaDOnS spectropolarimeter is installed on the Canada France Hawaii Telescope (CFHT) located on Mauna Kea, Hawaii, HARPSpol is installed on the ESO 3.6m telescope at ESO La Silla Observatory, Chile and the NARVAL spectropolarimeter on the 2m TBL telescope at l'Observatoire du Pic du Midi (France). ESPaDOnS and NARVAL are in fact identical instruments, with high spectral resolving power ($R = \lambda/\Delta\lambda = 65000$) and HARPSpol has an even higher spectral resolving power ($R = \lambda/\Delta\lambda = 110000$).

These three instruments have proven to be stable over long time-scales and have been shown to provide high-quality data suitable for the basis of long time-series observations which is a requirement for reliable MDI mapping (e.g. Silvester et al., 2012). With the vastly improved data available from these instruments and by using MDI techniques, we are able to reliably characterise the magnetic field geometry of the target stars. The reproducibility and reliableness of the maps extracted using the INVERS MDI codes have been clearly demonstrated (e.g. Kochukhov, 2017).

An example of such test which verified both that the newer instrumentation and INVERS codes can produce consistent results is given by the mapping of α^2 CVn (Silvester et al., 2014). It was shown that the derived magnetic field structure was consistent with the magnetic structure map previously derived for α^2 CVn using MuSiCoS data (illustrated in Fig. 1) and that maps reconstructed using differing spectral lines sets resulted in similar magnetic field structures.

With the reliability of the instrumentation and mapping techniques shown, it has been possible to concentrate on studying individual stars in detail, looking for correlations between magnetic structure and other stellar parameters.

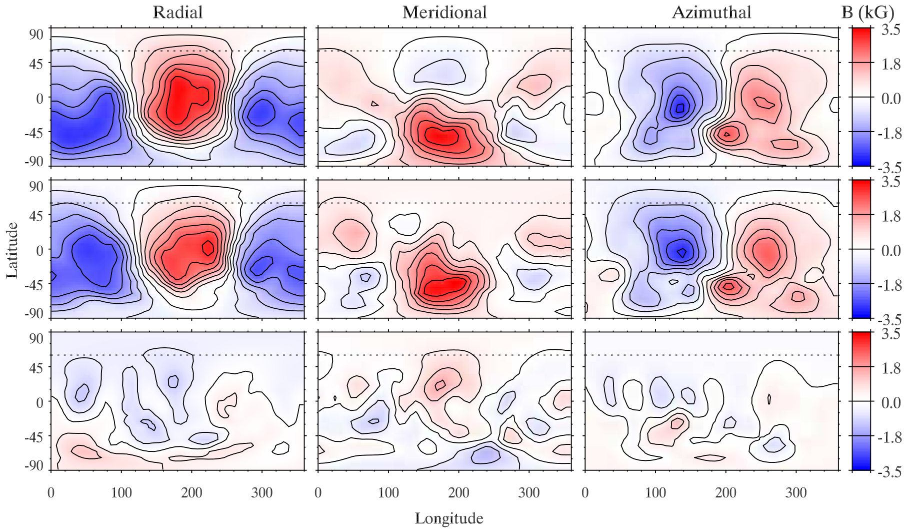

Figure 1. Comparison between magnetic field maps derived for α^2 CVn. The map based on ESPaDOnS / Narval data is shown in top row, MuSiCoS map middle row and the difference given in the bottom row. Taken from Silvester et al. (2014).

2. Recent Mapping Results

In recent years the number of Ap/Bp stars mapped has increased quite measurably, a full list of Ap/Bp stars mapped using imaging techniques is given in Kochukhov (2017). Below we summarize some of the most recent results/maps for Ap/Bp stars.

2.1. HD 32633

The star HD 32633 has an effective temperature of 12,000–13,000 K and is of the peculiar subclass SiCr (Renson & Manfroid, 2009). Observations were obtained with ESPaDOnS and Narval and mapping was performed using individual Stokes $IQUV$ lines. As described in detail in Silvester et al. (2015), the resulting magnetic maps of HD 32633 revealed a largely axisymmetric field topology (field shown in Fig. 2). Within the harmonic modes $\ell = 1$ dominates, with around 75% of the energy in that mode; 9% is contained in the poloidal quadrupolar $\ell = 2$ mode. In total 16% of the energy in toroidal components. Importantly it was shown that the Stokes parameter profiles of HD 32633 cannot be reproduced by assuming a pure dipole or dipole + quadrupole magnetic field geometry. This indicates that the field is definitely more complex than can expressed by such low-order multipolar parametrisation. The plot of the final derived harmonic energies for HD 32633 are shown as part of Fig. 5.

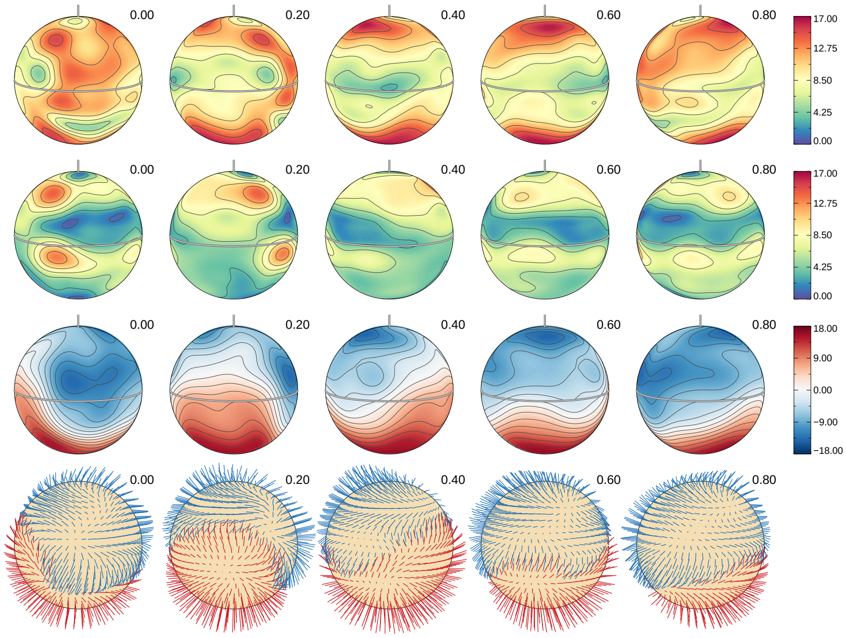

Figure 2. The spherical plots of the magnetic field map of the magnetic field map of HD 32633 taken from Silvester et al. (2015). Showing distributions of: the field modulus, horizontal field, the radial field, and the field orientation. Each column corresponds to a different phase of rotation (0.0, 0.2, 0.4, 0.6, and 0.8).

2.2. 49 Cam

49 Cam is a cool Ap star with classification as F0p (SrEu) by Cowley (1968) and later as A8p (SrEu) by Leone et al. (2000). Mapping was performed using Stokes $IQUV$ individual lines from ESPaDOnS and Narval observations (Silvester et al., 2017). A complex magnetic field structure for 49 Cam (shown in Fig. 3) was found, with a relatively large contribution in the $\ell = 3$ mode. The magnetic field of 49 Cam contradicts an earlier trend seen where cooler Ap stars showed simpler magnetic configurations and only hotter stars showing complex field structure. This gives a strong suggestion that the temperature of an Ap/Bp star is not a clear indicator of the expected magnetic field complexity.

2.3. 36 Lyn

36 Lyn (HD 79158, HR 3652) is a well known magnetic Bp star, classified as B8 IIImnp by the Bright Star Catalog (Hoffleit & Warren, 1995). Unlike the previous two stars, mapping (as described in Oksala et al., 2018) was performed using averaged Stokes IV profiles. Whilst the resulting magnetic map shows

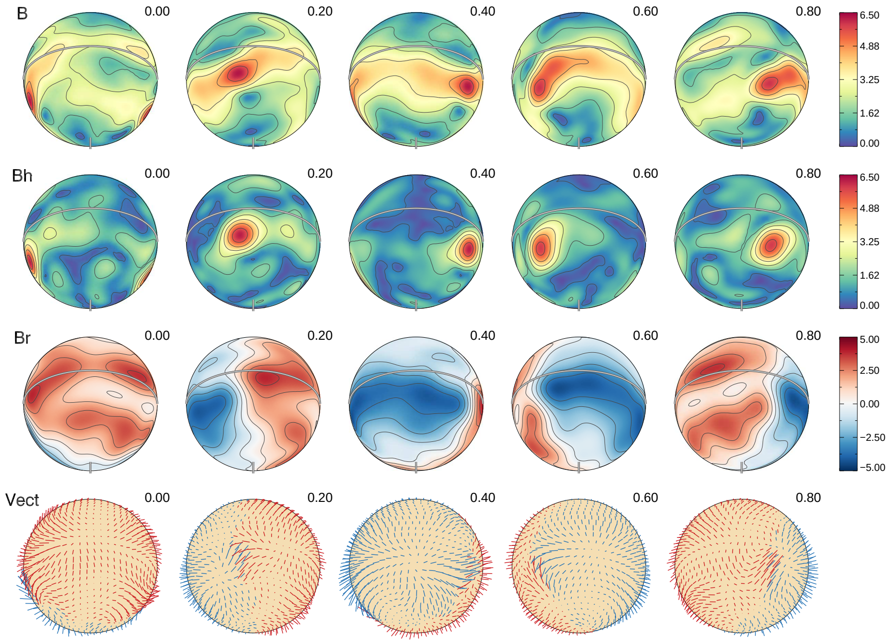

Figure 3. The spherical plots of the magnetic field map of 49 Cam taken from Silvester et al. (2017). Showing distributions of: the field modulus, horizontal field, the radial field, and the field orientation. Each column corresponds to a different phase of rotation (0.0, 0.2, 0.4, 0.6, and 0.8).

a very simple global structure, 36 Lyn does contains a large toroidal component ($\approx 36\%$), which has not been seen at this level in any other Ap/Bp stars mapped thus far. It was shown that this large toroidal component is required to successfully fit the observed Stokes V profiles. The resulting map is shown in Fig. 4 and the final derived harmonic energies are shown as part of Fig. 5.

2.4. Summary of Recent Harmonic Energies

Whilst the spherical magnetic field maps provide a useful illustration of the derived magnetic surface structure of the star, for direct comparison with other Ap stars using the spherical surface maps is not trivial. It is far more useful to describe the resulting magnetic field of a star in terms of spherical harmonics, something which is done as standard in the majority of the current inversion codes. It was thought that stellar mass or stellar temperature could correlate with magnetic field complexity. To look for any links between magnetic field complexity and for example temperature (and ultimately mass), the resulting spherical harmonic energies are plotted for a selection of Ap stars in different

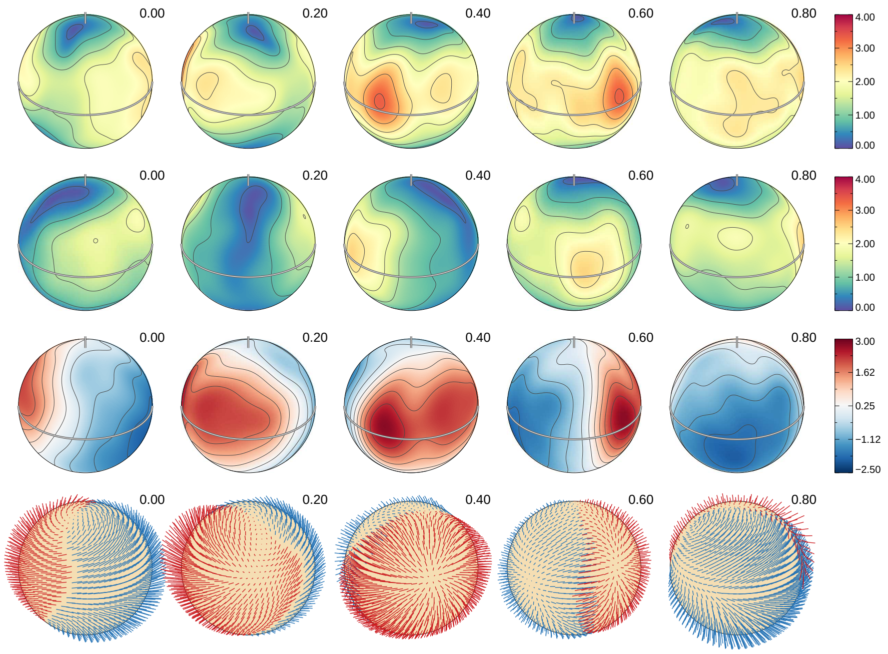

Figure 4. The spherical plots of the magnetic field map of 36 Lyncis taken from Oksala et al. (2018). Showing distributions of: the field modulus, horizontal field, the radial field, and the field orientation. Each column corresponds to a different phase of rotation (0.0, 0.2, 0.4, 0.6, and 0.8).

temperature bins. As illustrated in Fig. 5, it appears that there is little correlation between temperature and field complexity, with various levels of complexity being seen in all of the temperate bins. The most important parameter which is thought to correlate with magnetic field complexity is stellar age.

3. Conclusion

Both the current generation of spectropolarimeters and the current inversion codes have been shown to be for reliable and suitable for performing MDI mapping (e.g. Silvester et al., 2012; Kochukhov, 2017).

Magnetic Doppler imaging has now been performed for an increasingly large sample of Ap/Bp stars. With this recent surge in mapping, it has been shown that Ap/Bp stars exhibit a wide variety of magnetic field substructure, with complexity differing between each star. For many of the stars mapped, which showed complex structures, the requirement for such a complexity due was illustrated clearly the fact that the observed Stokes $IQUV$ profiles cannot be reproduced by using a simpler field geometry.

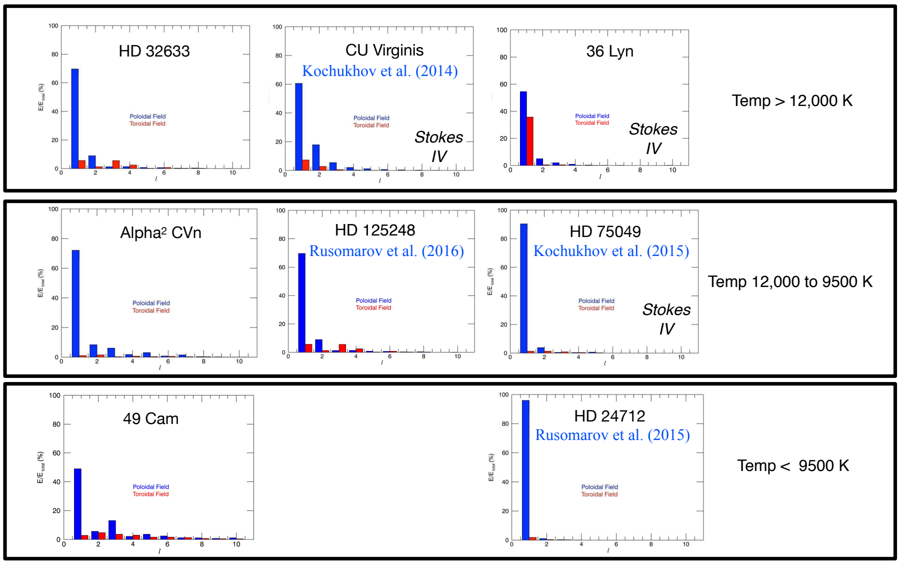

Figure 5. Harmonic Energies of Ap Stars Recently Mapped using MDI classified into temperature range bins. Additional stars shown with harmonic energies for HD 24712 (Rusomarov et al., 2015), HD 125248 (Rusomarov et al., 2016), HD 75049 (Kochukhov et al., 2015), and CU Vir (Kochukhov et al., 2014).

With the harmonic energy comparison shown between some of the most recently mapped stars (as shown in Fig. 5) it can be seen that temperature and magnetic field complexity show no direct correlation. It is still possible that field complexity correlates with the stellar age. However, because all of the current MDI targets have been field stars for which age determination is notoriously uncertain (Landstreet et al., 2007) they are not suitable for such investigations. To correctly investigate if correlations between field complexity and age exist requires the study of cluster stars for which reliable ages can be obtained.

Also, the observed diversity in the field structures between stars highlights the fact that the comparison of observed abundance structures to theoretical abundance models which use simplified magnetic field descriptions is not suitable, as stars show varying levels of magnetic field complexity even within the same spectral subclass. So any theoretical modelling of abundance structures should be performed ideally on a star by star basis taking into account this field diversity.

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