Magnetic field models for A and B stars: some recent results

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Abstract.

Our understanding of the detailed structure of the strong, ordered magnetic fields possessed by some A and late B stars is steadily improving as we obtain and model new kinds of data. This paper explores the current scope of this understanding by describing some recent results for the Ap stars β CrB and HD 192678.

1 Introduction

It is apparent from the many peculiar phenomena exhibited by the Ap and Bp stars (chemical enhancement, depletion, segregation and stratification; nonradial pulsation; mass-loss) that complex, poorly understood physical processes operate within their atmospheres. The quasi-dipolar, kilogauss-strength global magnetic fields found in these stars have local photospheric energy densities several (~2-7) orders of magnitude greater than the photospheric thermodynamic kinetic energy density. In addition, the degree of chemical peculiarities is most extreme in those A and B stars which are strongly magnetic. It is therefore likely that many of these processes are caused, or at least influenced, by the presence of the magnetic field. Clearly, a description of the magnetic fields in a representative sample of these stars will greatly aid us in our understanding of the important underlying physics.

Recent contributions to the study of magnetic fields in A and B stars have been made by Leroy and collaborators (e.g. Leroy et al., 1996), Mathys and collaborators (e.g. Mathys et al., 1996) and by Wade and collaborators (e.g. Wade et al., 1996).

In this paper, we shall first look briefly at the types of data currently being employed to construct detailed magnetic models, and the kinds of constraints they can apply. The following section will describe modeling results for the Ap stars β CrB and HD 192678. We will then examine some of the physical implications of these results. Finally, we will look at possible improvements in modeling techniques, and prospects for their application in the near future.

2 The observational basis

As with all models, the most reliable stellar magnetic models are those which are constructed using several different kinds of data. In this section we will look at the types of data currently being used for detailed modeling.

Since Babcock's (1947) discovery 50 years ago of the strong magnetic field of 78 Virginis, measurement of circular polarization has been the method of choice for magnetic field diagnosis. One reason for this is that magnetic fields are by far the most likely cause of circular polarization within spectral lines. Furthermore, circular polarization is a characteristic which is technically fairly simple to measure, and which is obtainable for magnetic stars with both large and small $v_e \sin i$. While other methods of field diagnosis can be used for detailed modeling, polarization diagnostics provide a powerful constraint.

The mean longitudinal field can be deduced from measurements of the circular polarization within spectral lines, and is typically obtained using circularly polarized spectra or differential photoelectric polarization measurements. The longitudinal field is related to the disk-integrated line-of-sight component of the magnetic field vector. Currently, this is the only type of measurement which exists for the majority of magnetic stars.

Linear polarization measurements also provide very valuable constraints. The net broadband linear polarization, caused by the differential saturation of the Zeeman components of many spectral lines, is obtained from linear polarization measurements made through broadband filters. This quantity is considerably more difficult to measure than the circular polarization since it is a second-order effect and because its detectability is strongly dependent on the temperature and distance of the star (the former because only cool stars' spectra contain the necessary number of metal lines, and the latter because of interstellar polarization). Linear polarization provides a strong constraint on the disk-integrated transverse component of the magnetic field vector.

The mean field modulus can be deduced from unpolarized spectra for stars which show spectral lines to be split and resolved into their Zeeman components. Because resolved Zeeman splitting requires a mean field modulus of about 1 kG per km s^{-1} of $v_e \sin i$, only those stars which are the most slowly rotating and which possess the strongest fields are amenable to this sort of measurement. A related quantity, the mean quadratic field, can be deduced from magnetic broadening of spectral lines in unpolarized spectra. The quadratic field may help to constrain field geometries for the vast majority of stars which do not display magnetically split lines.

While all of these measurements are capable of effectively constraining the magnetic field, their relationship to the field is known only through approximate models. It is therefore preferable to use the more fundamental data from which these quantities are deduced. By modeling both the polarized and unpolarized spectra directly, we minimize the amount of massaging (measurement, reduction, inference using simple models of the stellar atmosphere) that the quantities we intend to model undergo. Althought this sort of modeling is considerably more expensive, both in time and in computational resources, it is the truly rigorous way to construct detailed magnetic models.

3 Results from detailed modeling

Detailed magnetic models are available for only a very small number of stars, all of which are intrinsically very strongly magnetic. In this section we will look at results for β CrB and HD 192678, the two stars for which the strongest constraints are currently available.

3.1 β CrB

This bright SrCrEu star (T_{eff} = 7750 K) has been extensively observed in the past, and a considerable database of magnetic observations is available. It has been known for some time that the longitudinal field and mean field modulus measurements of this star were not compatible with a dipolar field model. The situation became even more intriguing when Leroy (1993) presented broadband linear polarization measurements which also showed marked deviations from a dipolar magnetic configuration.

Leroy (1995), using an inversion technique designed to model deviations from a dipolar configuration, incorporated all of the available measurements of this star into his magnetic model. The inversion is a two-step process, in which the computation of local deviations of the field *strength* is performed, followed by computation of the local deviations of the field *direction*. β CrB is viewed at about 20° from the rotation axis, and so only about 2/3 of the surface of the star is made visible to

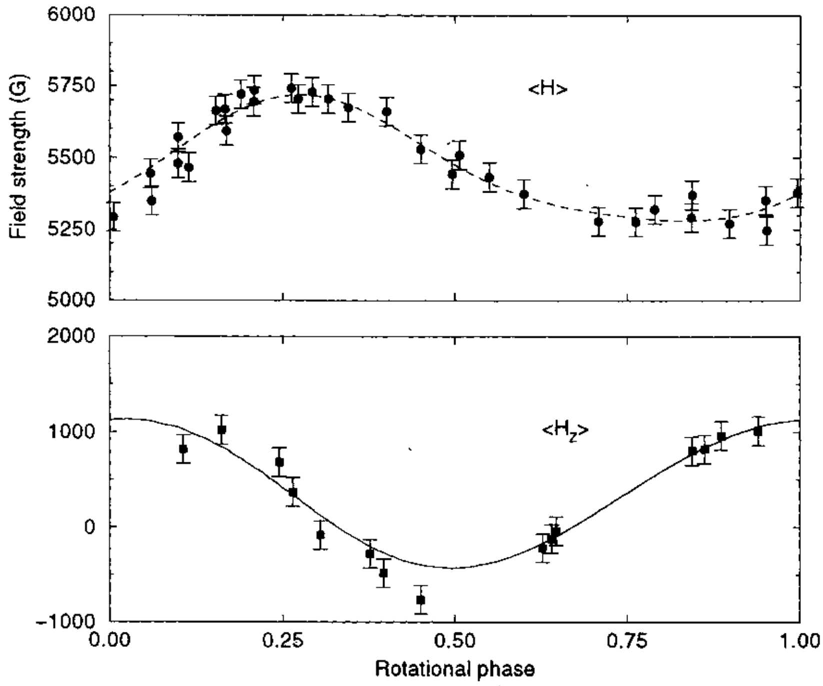

Figure 1: The longitudinal field (lower frame) and mean field modulus (upper frame; Mathys (1996)) variation of β CrB. The solid and dashed curves are the variations produced by the model.

us as the star rotates. The magnetic field is dominantly dipolar, with both poles crossing the visible disk during one rotation.

An acceptable reproduction of the mean field modulus variations requires a redistribution of field strength over the surface of the star. This is a fairly straightforward procedure in which the field modulus deviations, which are described by spherical harmonics, are solved for using a matrix inversion method including a penalty function. The best fit model has a depleted polar field, and a region of enhanced field strength near the magnetic equator. The dashed curve in Fig. 1 is the field modulus variation produced by this model, superimposed on the field modulus measurements of Mathys (1996). One of the most striking features of this solution is the degree of the field modulus deviations - the polar field is depleted some 25% from that of a pure dipole.

To perform a similar inversion of the broadband linear polarization and longitudinal field variations is a considerably more difficult task. Unlike the field modulus, there is no simple one-to-one relationship between the linear polarization and the field geometry. After considerable experimentation, Leroy settled on an inversion technique in which the lines of field within a band 36° wide about the magnetic equator could be rotated within the meridian plane. He computed the deviations, again described by spherical harmonics, which provided the best fit to both the linear polarization variations and the longitudinal field. The adopted model contains a region near the stellar rotational pole where the magnetic field lines tend to be more radially oriented than those of a pure dipole. This region of open field lines appears to be close to the region of enhanced field strength. Since the field modulus deviations and the field line inclination deviations were computed using independent data sets, this coincidence may be significant. Fig. 2 shows the observed and computed linear polarization variations, as well as the field configuration resulting from this model.

As explained previously, several of the field diagnostics employed in this model are related to the real magnetic field structure in ways that are poorly understood. Therefore we must ask, how

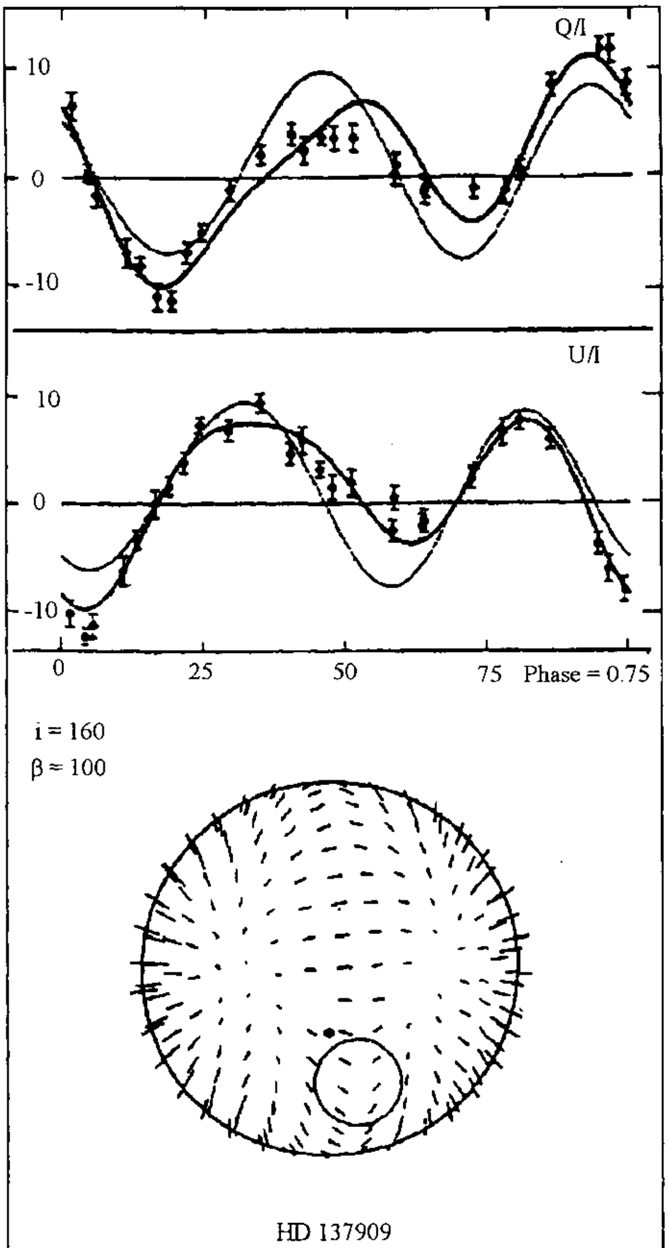

Figure 2: β *CrB*. *Upper frame* – Observed and computed linear polarization variations (Leroy, 1996). The light curve is the variation produced by a pure dipole, the heavy curve that produced by the adopted model; *Lower frame* – Magnetic field configuration. The larger circle indicates the region of open field lines, the smaller circle the location of the rotational pole.

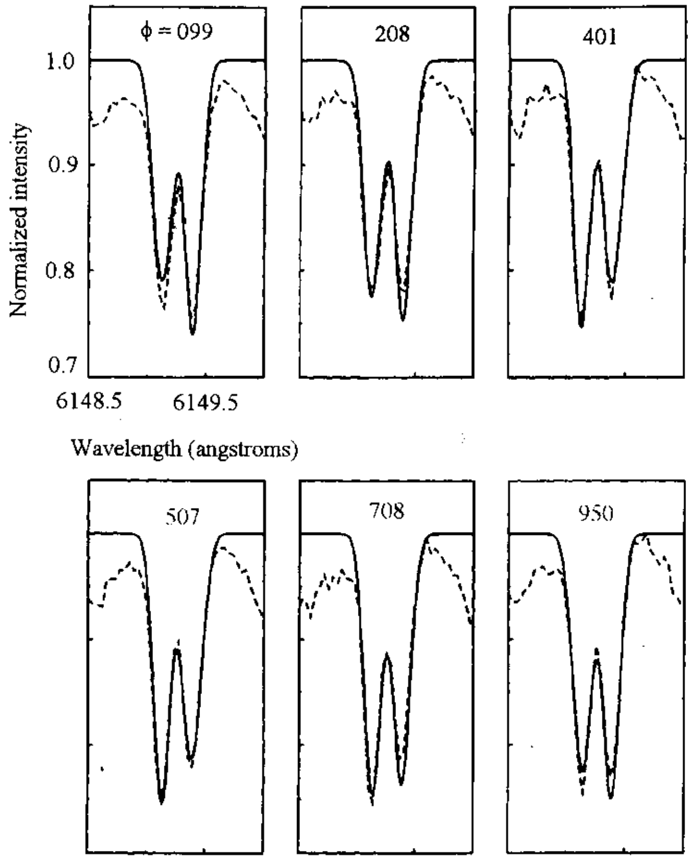

Figure 3: Fe II 6149.2 Å line profile variations of β CrB (Mathys, 1995). Dashed profiles – observed; solid profiles – computed for $v_e \sin i = 3.5$ km s^{-1} and a microturbulent velocity of 2.0 km s^{-1}.

well does this model reproduce the detailed line profiles from which the longitudinal field and mean field modulus are obtained? Although the circular polarization profiles have yet to be modeled, Fig. 3 shows that the variations of the Fe II 6149.2 Å Zeeman doublet (Mathys, 1995), recently modeled by the author, can be reproduced quite well by this model. This line provides us with another constraint on the field - namely, that because the components appear to be well separated for stars with sufficiently small $v_e \sin i$ (indeed, the central intensity is approximately the continuum intensity) we must conclude that local departures from simple field structures must be the exception, and not the rule. Were there regions of much weaker field, the intensity of this central feature would be depressed due to absorption from these regions.

3.2 HD 192678

This ApCr star is slightly hotter than β CrB, with T_{eff} = 9000 K. While it has garnered little attention in the past, HD 192678 is an ideal candidate for field modeling - it displays spectral lines resolved into their Zeeman components, a measurable broadband polarization variation, and it rotates sufficiently rapidly for some rotational Doppler effect to be visible in the line profiles.

Wade et al. (1996) attempted modeling the magnetic field of this star using a pure dipole. Indeed, it was considered likely that only a simple dipolar model could be derived, since the variability of

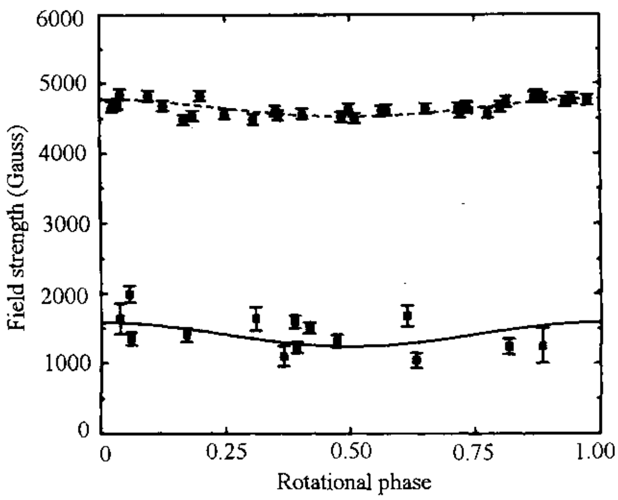

Figure 4: The longitudinal field (squares) and mean field modulus (circles) variation of HD 192678 (Wade et al., 1996). The solid and dashed curves are the variations produced by the model.

this star is quite subtle. As can be seen in Fig. 4, while quite a strong longitudinal field is measured at all phases, its variation cannot even be detected! The variation of the mean field modulus can be detected, although the amplitude is very small. HD 192678 is viewed even closer to the rotation axis than is β CrB, and so we see an even smaller fraction of its surface throughout one rotation. In this case we never see the negative magnetic pole, and the positive pole describes a small circle around the visible disk of the star as it rotates.

Wade et al. (1996) succeeded in fitting the longitudinal field and mean field modulus variations using a pure dipole. This would seem to indicate that the distribution of field strength on the surface of HD 192678 is not significantly different from that of a dipole. However, a very poor fit to the linear polarization measurements was obtained for this model. Using the same inversion technique described above to invoke local deviations in the field direction, a much better agreement with the linear polarization measurements was achieved. Fig. 5 shows the observed and computed linear polarization variations, as well the magnetic field which results from this model. As with β CrB, the polarization inversion produced a region in which the field lines tend to be more radially oriented than those of a pure magnetic dipole.

As a further test of their magnetic model, Wade et al. computed synthetic profiles of the Fe II 6149.2 Å line. As with β CrB, good agreement was obtained for a moderate rotational velocity and a small microturbulence. In this case, there may be some excess broadening of the doublet that may be due to small regions of high field strength. The observed and computed line profiles are shown in Fig. 6.

4 Implications of magnetic structure

It has been shown that local departures from simple field configurations exist in some Ap stars. What, if any, are the implications of these structures on other observations and on the state of the stellar atmosphere?

Leroy (1995) argues that regions of open field lines, such as are found in the magnetic fields of

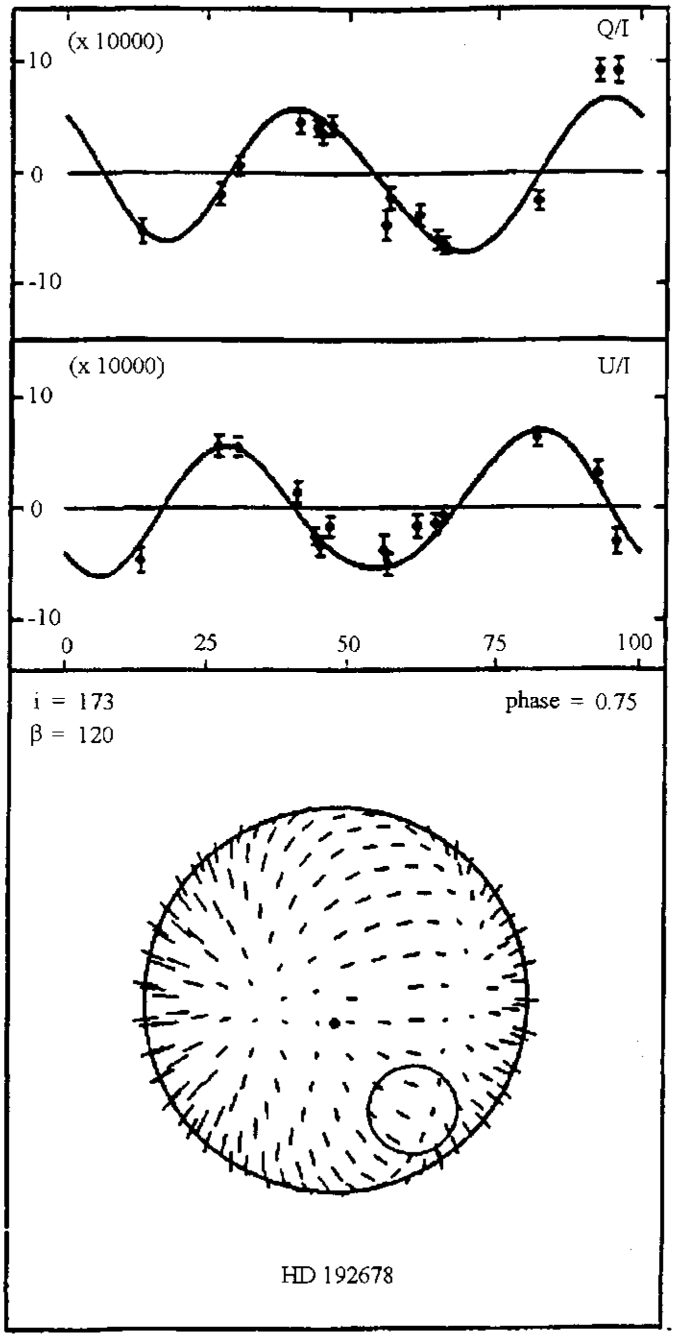

Figure 5: HD 192678. Upper frame – observed and computed linear polarization variations (Wade et al., 1996). The heavy curve is the variation produced by the adopted model. Lower frame – magnetic field configuration. The larger circle indicates the region of open field lines, the smaller circle the location of the rotational pole.

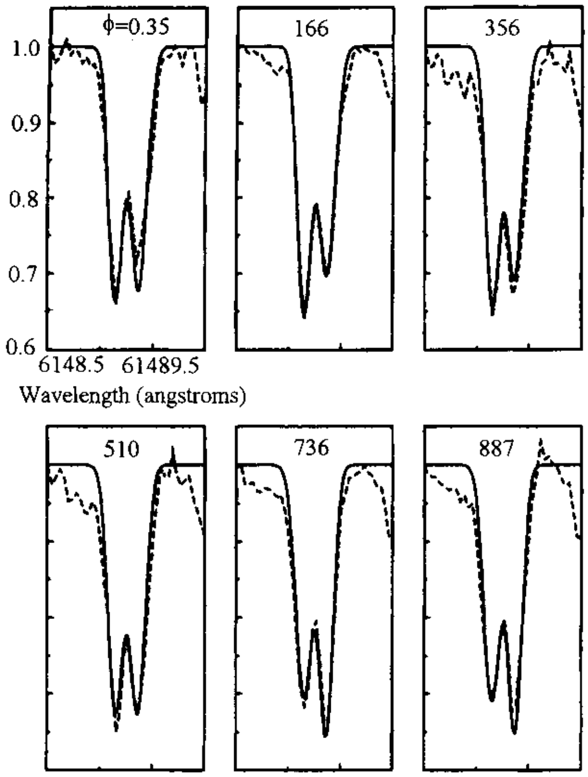

Figure 6: Fe II 6149.2 Å line profile variations of HD 192678 (Wade et al., 1996). Dashed profiles – observed; Solid profiles – computed for $v_e \sin i = 2.0$ km s^{-1} and a microturbulent velocity of 1.5 km s^{-1}.

β CrB and HD 192678, as well as in the fields of several stars not discussed here, may explain the Wolff-Romanyuk effect. This effect, a phase shift between longitudinal field observations made in the visible and shortward of the Balmer jump, was discovered by Wolff (1978) and confirmed by Romanyuk (1986). Since measurements made in the UV correspond to a level about 800 km higher than those made in the visible, a natural interpretation would be that the magnetic field changes with geometrical depth in the stellar atmosphere. This is exactly the trend we are seeing with the open magnetic structures inferred for β CrB and HD 192678.

Furthermore, in Leroy's (1995) model of β CrB the regions of open field lines and enhanced field strength are found close together on the star. Is this coincidental, or are they in some way related?

5 Prospects for the future

To conclude, let us consider the options available to us for more elaborate field modeling in the future.

It has been stated a number of times throughout this paper that the rigorous way to construct stellar magnetic models is to use primary data - the detailed line profiles themselves. While high-resolution unpolarized profiles were used in both of the analyses discussed here, very little modeling has been done using polarized line profiles. Currently, projects are under way to model the magnetic fields of HD 37776 using circularly polarized line profiles (Romanyuk and collaborators) and CS Vir using unpolarized line profiles, circularly polarized profiles, and broadband linear polarization measurements (Wade and collaborators). While these efforts will provide valuable information about the field structure in these stars, what is still lacking for *any* star is a set of circularly and linearly polarized spectra (in each of the I,Q,U and V Stokes parameters) with good phase coverage. A data set of this type would allow for a complete inversion of the vector magnetic field without any *a priori* assumptions about the large scale structure. The current instrumentation and computational resources are capable of meeting this challenge, and I expect to see results of this sort within the next year or two.

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