Magnetic stars, 2004, 205-209

Detection of nonuniform surface chemical abundance distributions on β Coronae Borealis*

Wade G.A., Smolkin S.

Physics Department, Royal Military College of Canada, Canada

Abstract.
We employ Stokes I and V LSD profiles of the cool magnetic Ap star β CrB, extracted for the elements Ti, Cr, Fe and Ba, to confirm systematic element-to-element differences in the longitudinal field variation of this star. We also detect for the first time convincing equivalent width variations in the spectral lines of β CrB. Using these new measurements, we derive coarse models of the distributions of these four elements across the stellar surface.

Key words: stars: magnetic fields – stars: abundances – stars: individual: β CrB

1 Introduction

β Coronae Borealis is a cool, well-studied magnetic Ap star with a moderately-strong magnetic field. It presents an optical spectrum rich in sharp lines of Fe-peak and rare earth elements. Due to its low projected rotational velocity ($v \sin i < 5$ km/s; Wade 1997) and nearly pole-on presentation (rotational axis inclination $i \simeq 10 - 20^{\circ}$; e.g. Landstreet & Mathys 2000), relatively little is known about the distribution of chemical elements across its surface. In fact, to date no convincing evidence has been presented indicating the presence of patchy abundances on the surface of β CrB. This fact stands in sharp contrast to the importance of this star within the context of our studies of Ap stars: β CrB has been dubbed a "Peculiar Rosetta Stone", and has been employed for detailed studies of the structure of magnetic fields of Ap stars (e.g. Bagnulo et al. 2001), fundamental parameters of Ap stars (Hubrig et al. 2000), studies of magnetic field evolution (Landstreet & Mathys 2000), diffusion and the stratification of chemical abundances (Wade et al. 2003), etc.

In 1999, Plachinda & Tarasova noted that systematic differences exist between variations of the mean longitudinal magnetic field of β CrB as measured in lines of Fe I and Ca I. They proposed that these differences resulted from the different sampling of the surface magnetic field by the different lateral abundance distribution patterns of these elements. However, these results relied on measurements obtained from individual spectral lines, and potential systematic line-to-line differences in the inferred longitudinal field make their conclusion quite tentative.

In this study, we explore in detail the systematic differences of the longitudinal field of β CrB as measured in lines of different elements. Moreover, for the first time we report convincing equivalent width variations of Fe peak element lines which appear to arise from rotational modulation of nonuniform abundance distributions. Finally, we use both the longitudinal field and equivalent width variations in order to place coarse constraints on the global surface distributions of the four elements Ti, Cr, Fe and Ba.

2 Observations

Observations of β CrB were obtained using the MuSiCoS spectropolarimeter mounted on the 2m Bernard Lyot telescope at Pic du Midi observatory, and are described by Wade et al. (2000). Least-Squares Deconvolved

* Based on observations obtained using the MuSiCoS spectropolarimeter at the Pic du Midi observatory, France.

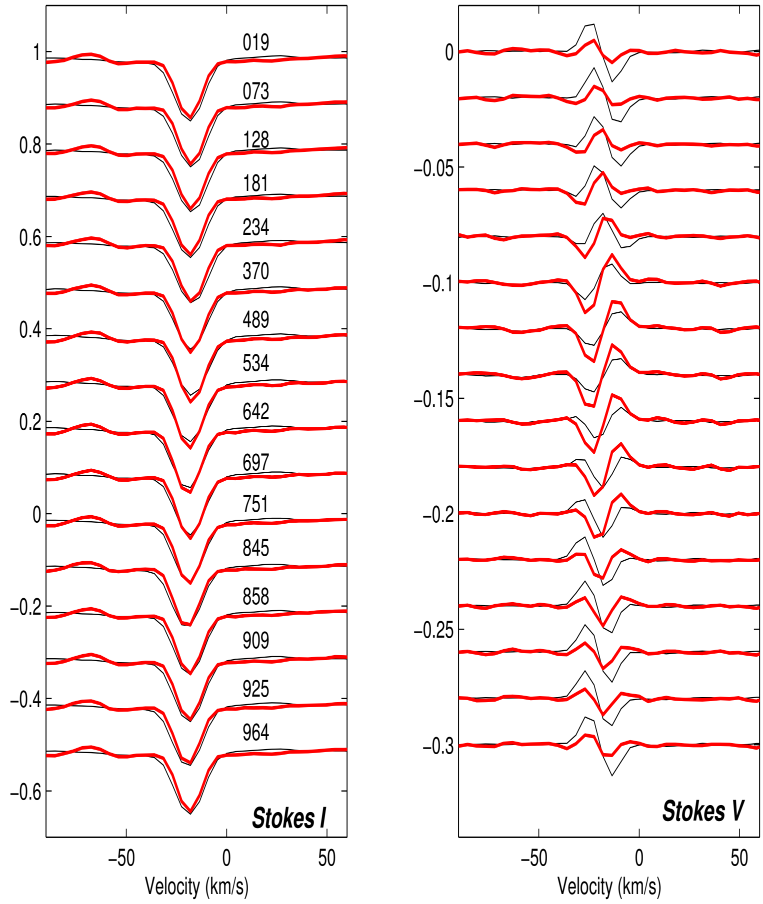

Figure 1: *LSD Stokes I and V profile variations of β CrB for lines of Fe (thin lines) and Ti (thick lines). Note the systematic differences in amplitude and shape between Stokes V profiles of the two elements at each phase. In particular, we point out that Ti profiles are never consistent with a significant positive longitudinal field, whereas Fe profiles are consistent with such fields for one-half the rotational cycle. Phases (according to the ephemeris cited by Wade et al. 2000) are shown at left.*

(LSD; Donati et al. 1997) Stokes I and V profiles were extracted using line masks appropriate to the stellar temperature and gravity, and filtered to include only lines of the 4 desired elements. Several additional elements (including Ca and Mg) have also been studied, but results are not yet complete.

3 LSD Stokes V profiles of individual elements

Phase variations of LSD Stokes I and V profiles are shown in Fig. 1. Stokes V profiles of Fe (thin black lines) and Ti (thick red lines) show clear mutual differences at essentially all rotational phases. These differences are analogous to those illustrated by Wade et al. (2000) for 53 Camelopardalis, and attributed by them to nonuniform abundance distributions.

4 Longitudinal field and equivalent width variations

Extraction of longitudal fields and equivalent widths for the 4 individual elements reveals strikingly different variations, as illustrated in Fig. 2. Clearly, magnetic desaturation is not the sole phenomenon producing changes of the equivalent widths of lines of β CrB's Fe peak elements (magnetic desaturation is in fact insignificant for the majority of lines employed in the LSD analysis. Furthermore, desaturation would result in similar equivalent width variations as a function of phase for uniformly-distributed elements). Rather, these variations are indicative of nonuniform distributions of these elements across the visible surface of the

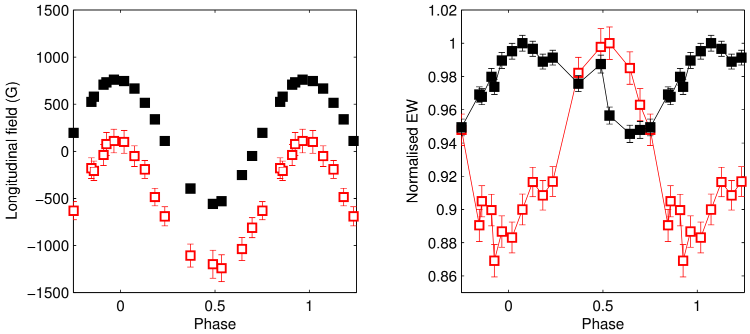

Figure 2: *Measured variation of the longitudinal magnetic field (at left) and normalised equivalent width (at right) of Fe (filled symbols) and Ti (open symbols) lines in the spectrum of β CrB. Note the clear systematic differences. These differences are qualitatively consistent with Ti being preferentially concentrated in regions of negative (inward-directed) magnetic field.*

star. In particular, they suggest a distribution of Ti which is concentrated primarily in the southern magnetic hemisphere, sampling primarily the inward-directed magnetic field. This picture agrees with the consistently negative longitudinal magnetic field (and Stokes V profiles), as well as the equivalent width variation which shows a peak at the phase of maximum negative longitudinal field.

5 Modeling the phase variations

The longitudinal field and equivalent width variations of β CrB potentially provide a useful method to probe the surface abundance distributions of this and other slowly-rotating magnetic stars. Preliminary modeling has been accomplished using a modified version of the program `fldcurv.f`, a stellar surface integration code originally written by J.D. Landstreet. Surface distributions of magnetic field and chemical abundance, suitably weighted according to limb-darkening and line-weakening laws, are integrated over the visible surface of the star (assuming an appropriate rotational and magnetic geometry, a dipolar magnetic field inferred from Hβ magnetic measurements, and a simple abundance distribution pattern symmetric about the magnetic axis) to produce synthetic longitudinal magnetic field and equivalent width variations. A first comparison between observed and best-fit computed variations is shown in Fig. 3.

We find that abundances of Fe and Cr are enhanced by about 50% in the magnetic equatorial regions and the northern magnetic hemisphere, above about $-30^{\rm o}$ magnetic latitude (enhancement is relative to the abundance south of $-30^{\rm o}$). Ba is more strongly concentrated in the northern polar regions, above about latitude $+30^{\rm o}$. The Ba enhancement in these regions (relative to regions south of $+30^{\rm o}$) is also about 50%. Ti is indeed found to be strongly depleted in the northern magnetic regions, with a relative enhancement of over 1 dex in regions south of $+45^{\rm o}$ magnetic latitude.

Although these results are both coarse and rather approximate, we are confident in the general properties of the distributions. A more sophisticated modeling is currently in progress.

6 Conclusions

Using Least-Squares Deconvolved (LSD) mean Stokes I and V profiles of the cool Ap star β CrB, extracted for individual chemical elements, we confirm systematic differences between the inferred longitudinal field variations and detect for the first time convincing evidence of equivalent width variations. These measurements strongly suggest that the elements Ti, Cr, Fe and Ba are distributed nonuniformly over the surface of this star. We employ these new measurements to infer coarse models of the distributions of these elements, finding Cr, Fe and Ba to be mildly enhanced in the northern magnetic hemisphere, whereas Ti is strongly depleted in these regions.

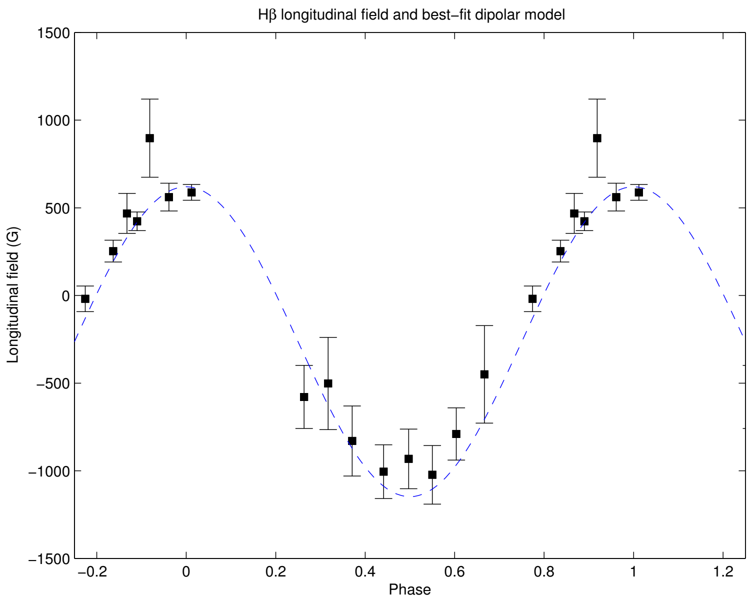

Figure 3: *Longitudinal magnetic field of β CrB obtained from Hβ circular polarisation measurements (Borra & Landstreet 1980). The solid curve is the best-fit dipolar magnetic field model assuming $i = 168°$ (Bagnulo et al. 2000), with magnetic obliquity $\beta = 86.5°$ and $B_p = 11690$ G. This model has been adopted as the magnetic field configuration of β CrB for this study.*

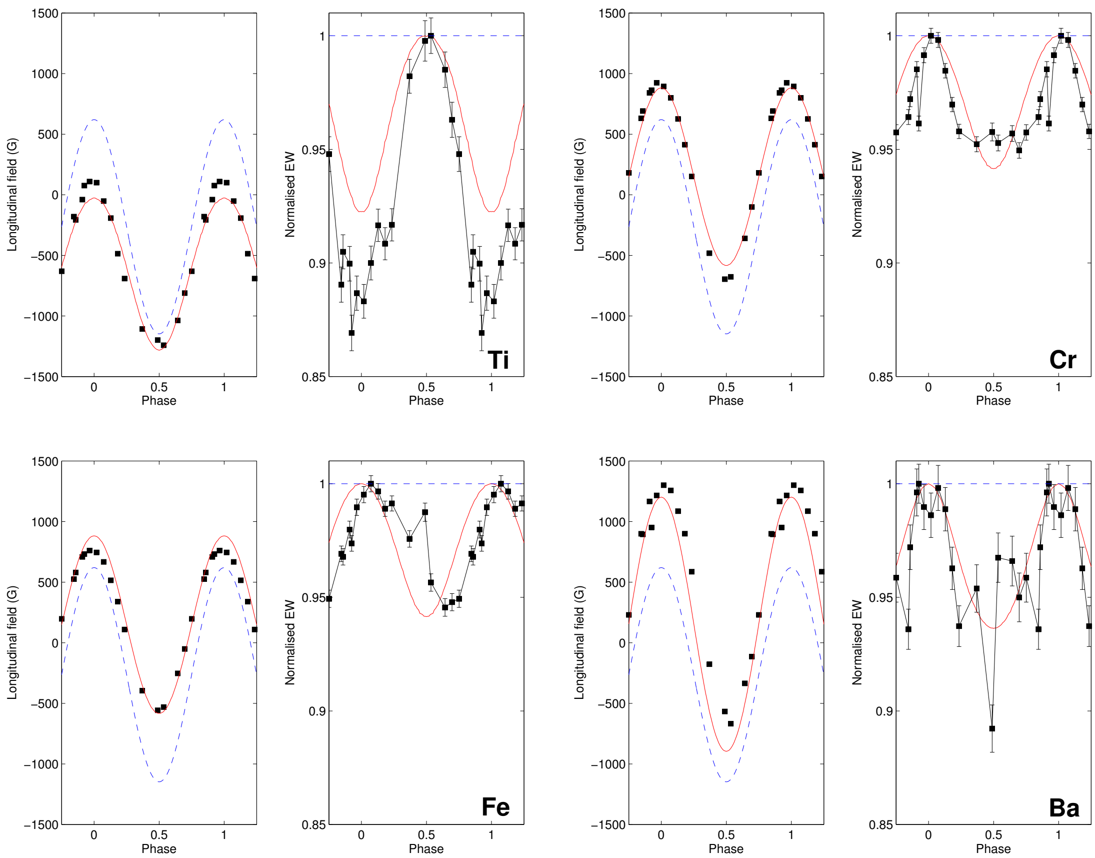

Figure 4: *Observed and computed longitudinal field and normalised equivalent width variations of Ti, Cr, Fe and Ba corresponding to uniform (dashed curves) and non-uniform (solid curves) distributions of the elements over the surface of β CrB.*

References

Bagnulo S., Wade G.A., Donati J.-F., Landstreet J.D., Leone F., Monin D.N., Stift M.J., 2001, Astron. Astrophys., **369**, 889

Bagnulo S., Landolfi M., Mathys G., Landi Degl'Innocenti M., 2000, Astron. Astrophys., **358**, 929

Borra E.F. & Landstreet J.D. 1980, Astrophys. J. Suppl. Ser., **42**, 421

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

Hubrig S., North P., Mathys G., 2000, Astrophys. J., **539**, 352

Landstreet J.D. & Mathys G., 2000, Astron. Astrophys., **359**, 213

Plachinda S. & Tarasova 1999, Astrophys. J., **514**, 402

Wade G.A., 1997, Astron. Astrophys., **325**, 1063

Wade G.A., Donati J.-F., Landstreet J.D., Shorlin S.L.S., 2000, Mon. Not. R. Astron. Soc., **313**, 823

Wade G.A., LeBlanc F., Ryabchikova T., Kudryavtsev D., 2003, in the proceedings of *Modeling of Stellar Atmospheres*, in press