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A search for radial magnetic field gradients in Ap atmospheres

N. Nesvacil[1,2], S. Hubrig[1] and E. Jehin[1]

[1]European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago, Chile
email: nnesvaci@eso.org, shubrig@eso.org, ejehin@eso.org

[2]Department of Astronomy, University of Vienna, Türkenschanzstrasse 17, 1180 Vienna, Austria

Abstract. For the first time the possible presence of radial gradients of magnetic fields in the atmospheres of three magnetic Ap stars has been critically examined by measurements of the mean magnetic field modulus from spectral lines resolved into magnetically split components lying on the different sides of the Balmer jump. A number of useful diagnostic lines below and above the Balmer discontinuity, only slightly affected by blends, with simple doublet and triplet Zeeman pattern have been identified from the comparison between synthetic spectra computed with the SYNTHMAG code and the high resolution and S/N spectra obtained in unpolarized light with the ESO-VLT UVES spectrograph. For all three stars of our sample, HD 965, HD 116114 and 33 Lib (HD 137949), an increase of the magnetic field strength of the order of a few hundred Gauss has been detected bluewards of the Balmer discontinuity. These results should be taken into account in future modelling of the geometric structure of Ap star magnetic fields and the determination of the chemical abundances in Ap stars with strong magnetic fields.

Keywords. Stars: chemically peculiar, stars: magnetic fields, stars: individual (HD 965, HD 116114, 33 Lib)

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1. Introduction

The study of the radial magnetic field gradients in the atmospheres of Ap stars is of great importance for the further development and improvement of currently existing models of magnetic field geometries as well as for abundance studies, especially in the context of the growing evidence of vertical abundance variations of certain chemical elements in the atmospheres of magnetic Ap stars. A first attempt to search for the vertical gradients of magnetic fields in the atmospheres of Ap stars was made on photographic Zeeman-spectrograms of the Ap stars α^2 CVn, 78 Vir and β CrB by Wolff (1978) using measurements of the line-of-sight magnetic field component, the so-called mean longitudinal magnetic field. The results were rather inconclusive. The amplitudes, absolute values and shapes of the magnetic curves derived from Hβ and from iron-peak lines above and below the Balmer discontinuity were found identical for α^2 CVn. For both 78 Vir and β CrB, the magnetic curves showed small differences, which, however, could not be regarded as secure due to the uncertainties in the magnetic field measurements. Only a few attempts to measure radial magnetic field gradients in Ap stars have been made since then. Romanyuk (1984, 1991) and Romanyuk *et al.* (2004) studied the longitudinal magnetic field on both sides of the Balmer jump in the stars α^2 CVn, β CrB and 52 Her. Contrary to the previous result of Wolff, the authors found a weaker (by 200-300 G) longitudinal magnetic field bluewards of the Balmer discontinuity. However, the measurement uncertainties were of the same order as the detected difference. In the present study, high quality UVES spectra obtained with the highest resolution

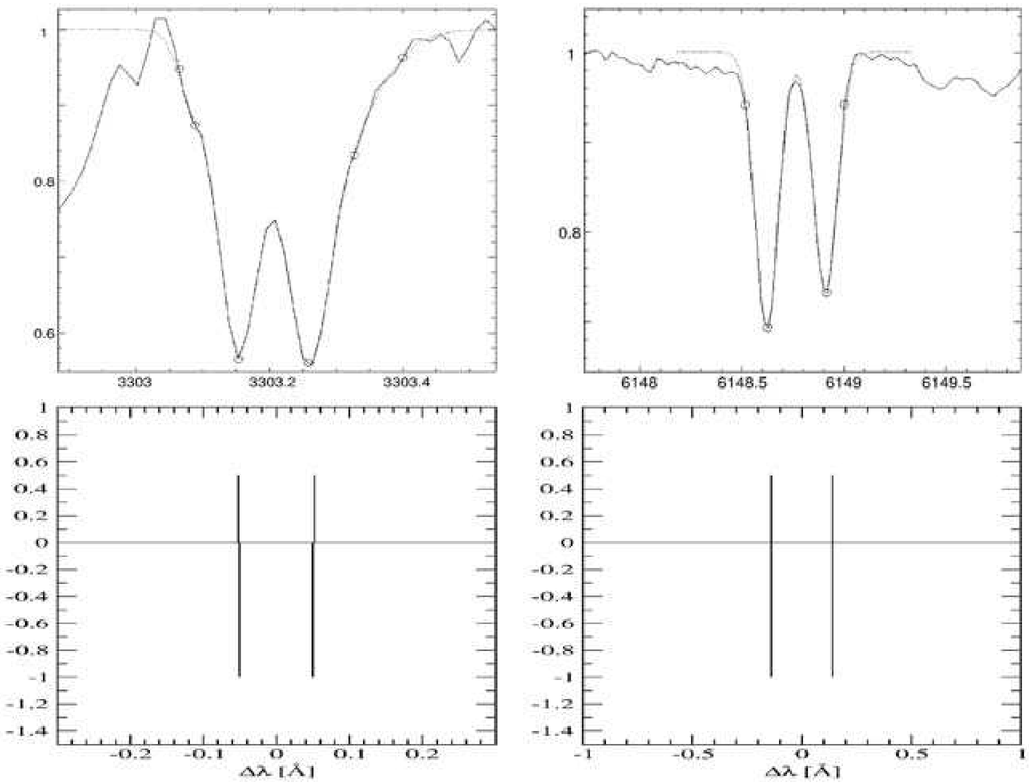

Figure 1. Zeeman patterns of the two Fe II lines (λ3303.464, λ6149.258) that could be used for measurements in all 3 stars.

(90000–110000) and high signal-to-noise ratio (200–400) have been used to search for the possible presence of radial gradients of the magnetic field in the atmospheres of three cool, strongly magnetic Ap stars, HD 965 (BD-00° 21), HD 116114 (BD-17° 3829) and the roAp star 33 Lib (HD 137949). In these stars the rotational Doppler effect is small in comparison to the magnetic splitting and the spectral lines observed in unpolarized light at high dispersion are resolved into several magnetically split components. The study of such stars provides an excellent opportunity to determine in a straightforward, mostly approximation-free, model-independent way, and with particularly high precision the mean magnetic modulus $\langle B \rangle$. The radial gradient of the mean magnetic modulus is then obtained by a comparative measurement of the Zeeman splitting of spectral lines which are formed on either side of the Balmer jump, in the UV and in the visual spectral region. In the spectra of A stars, where neutral hydrogen is the principal factor responsible for continuous absorption, the depth of formation of the continuum and lines on the two sides of the Balmer jump may differ considerably. According to our calculations carried out using the ATLAS9 code (Kurucz 1993), the difference in the optical depth τ for the analyzed spectral lines can be as large as 0.8, depending on the stellar parameters and the line strength.

2. Line selection and measuring the mean magnetic field modulus

For each star, the whole spectral region was thoroughly searched for magnetically split lines as much as possible free of blends by comparing observations with synthetic spectra

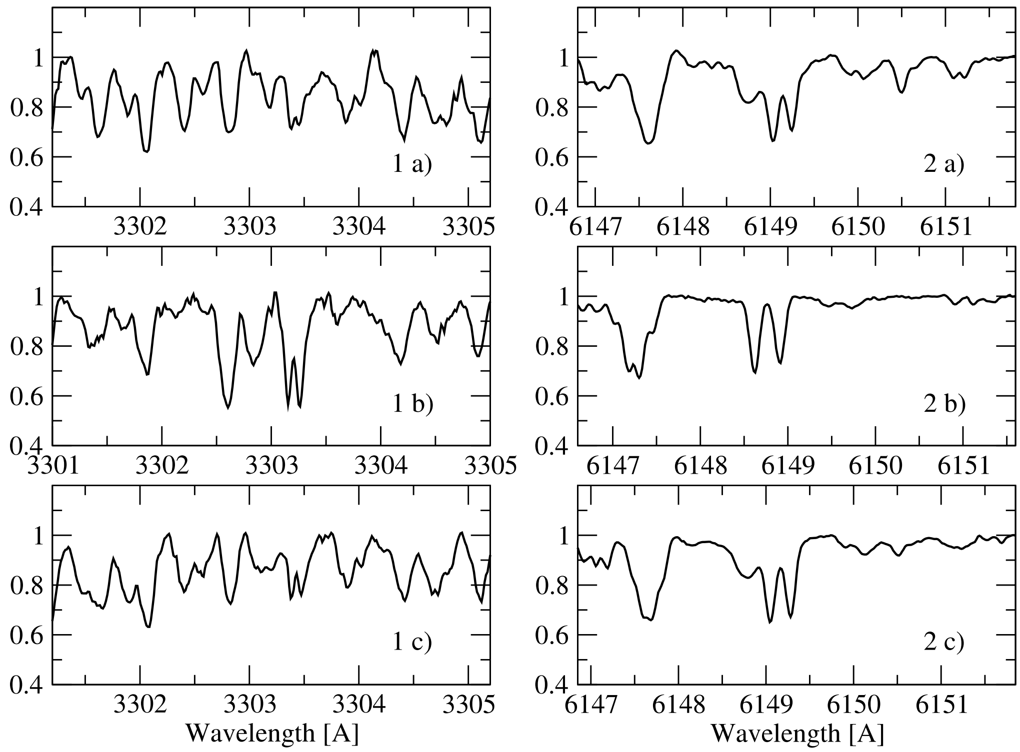

Figure 2. The Fe II lines at $\lambda 3303.464$ and $\lambda 6149.258$, useful for our measurements, are not equally well resolved or unblended in all 3 stars. From top to bottom: HD 965, HD 116114, 33 Lib.

calculated with SYNTHMAG (Piskunov 1999), based on atomic line lists extracted from VALD (Kupka *et al.* 1999). We compiled a list of resolved Zeeman doublets and triplets in the spectrum of each star. Even though in all spectra a large number of spectral lines appear split due to the presence of a strong magnetic field, for our purpose, only lines with simple Zeeman-patterns, like the ones shown in Fig. 1, were considered.

The line density in the red spectral region is much lower than in the UV and several suitable lines were easily detected for all stars. The largest number of useful magnetically split lines was identified in HD 116114 which has a chemical composition much less peculiar than the other two stars which exhibit spectra dominated by single and double ionized Rare Earth elements. As the Zeeman effect increases quadratically with wavelength, the smaller splitting of the π- and σ- components blueward of the Balmer discontinuity and their blending with other lines in this extremely crowded spectral region makes the determination of the magnetic field modulus difficult. As a consequence, only a small number of good lines has been found. The variable quality of the same split line in different stars is illustrated in Fig. 2. The magnetic field modulus is given by $< B >= \Delta\lambda / 9.34\,10^{-13}\,{\lambda_c}^2\,g_{\rm eff}$. To calculate $\Delta\lambda$, the wavelengths of the centres of gravity of the split doublet and triplet components have been determined by fitting a Gaussian simultaneously to each of them (if the lines are not fully split) or by direct integration of the whole component profile (if the splitting is large). When the lines were blended, a multiple fit of three or four Gaussians has been performed.

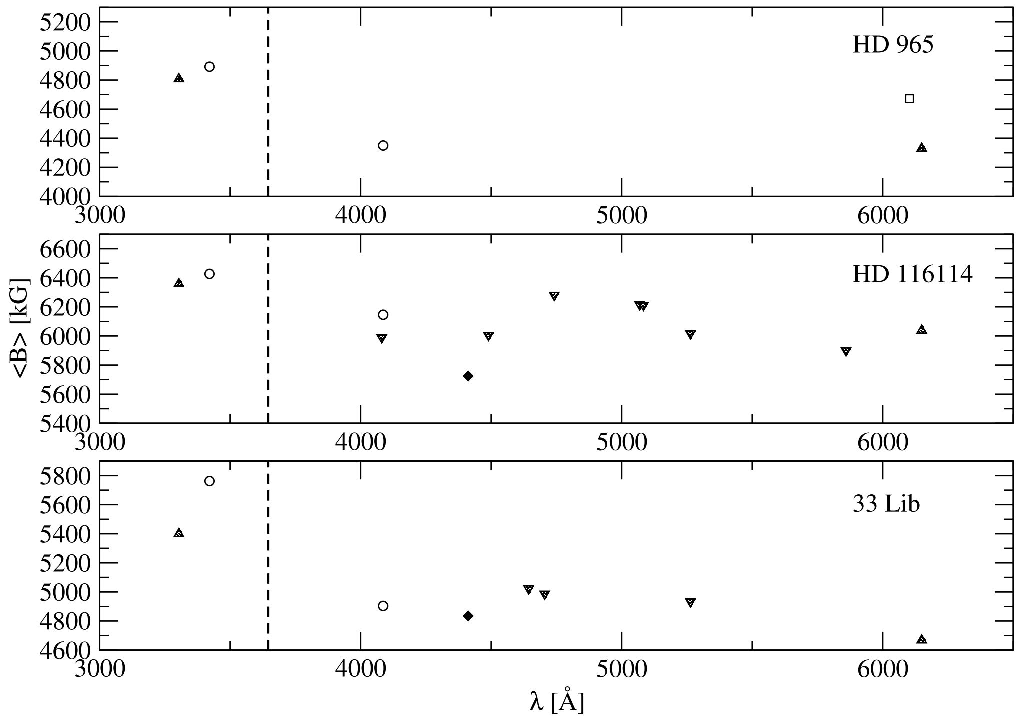

Figure 3. Measurements of the mean magnetic field modulus $\langle B \rangle$ in the three stars. The dashed line indicates the position of the Balmer jump. Different symbols mark different species. Triangle down: Fe I, triangle up: Fe II, circle: Cr II, diamond: Ti II, square: Ca I.

3. Results

Our determinations of the mean magnetic field modulus in the three stars are presented in Fig. 3. An error estimate can be obtained by comparing the mean magnetic field modulus of seven Fe I lines in the spectrum of HD 116114. We derive a mean value of 6089 G with a standard deviation of 145 G. On the other hand, the standard deviation of the mean magnetic field modulus from three Fe I lines is much less for 33 Lib (498 ± 45 G). We conclude that the accuracy of our measurements is, in the worst case, of the order of 145 G for lines redwards of the Balmer jump. However, only two lines belonging to different elements (Fe and Cr) have been studied on the blue side of the Balmer jump, and, therefore, a comparable error estimate cannot be made in this spectral region.

All three sets of measurements seem to indicate that the magnetic field strength decreases with the optical depth. For HD 116114, the difference $\Delta B = B_{uv} - B_{vis}$ between the magnetic field derived from the Cr II lines before and after the Balmer jump is $\Delta B_{\mathrm{Cr\,II}} \approx 280$ G and $\Delta B_{\mathrm{Fe\,II}} \approx 320$ G in the case of Fe II. For HD 965, we obtain $\Delta B_{\mathrm{Fe\,II}} \approx 480$ G and $\Delta B_{\mathrm{Cr\,II}} \approx 540$ G. We note that the results obtained from Cr II lines should be considered with caution as they are in this star significantly distorted by blends. The record holder is the star 33 Lib for which we obtain $\Delta B_{\mathrm{Fe\,II}} \approx 730$ G and $\Delta B_{\mathrm{Cr\,II}} \approx 860$ G. Hence, the significance of the detection in HD 116114 and HD 965 is not very high $(2 - 3\sigma)$, given the standard deviation deduced from the measurements of the Fe I lines. Nevertheless, the results for 33 Lib are highly significant and we, therefore, suspect that they might indicate a real decrease of magnetic field strength with atmospheric depth. Motivated by this result, more detailed investigations will have to be made to clarify if our suspicion is correct or if, e.g., surface inhomogeneities or unknown instrumental effects are causing the large deviations observed. It should also be noted that our preliminary estimates of the optical depths were based on standard model atmospheres which do not realistically correspond to the spectra of Ap stars. More realistic, stratified, individual model atmospheres for these stars are currently in preparation and will be used for further analysis of this problem.

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