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Probable detection of radial magnetic field gradients in the atmospheres of Ap stars[⋆]

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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, 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.

Key words. stars: atmospheres – physical data and processes: atomic processes, atomic data – stars: abundances – stars: chemically peculiar – stars: individual: HD 965 – stars: individual: HD 116114 – stars: individual: 33 Lib

1. Introduction

The study of 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 vertical gradients of magnetic fields in the atmospheres of Ap stars has been made on photographic Zeeman-spectrograms for 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 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 that time. 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.

High resolution, highly efficient spectrographs such as UVES at the ESO VLT, allow nowadays to record stellar spectra of unprecedented quality in the visible and near UV region. In the present study, high quality UVES spectra obtained with the highest resolution (90 000−110 000) 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 strongly magnetic Ap stars, HD 965 (BD-00 21), HD 116114 (BD-17 3829) and 33 Lib (HD 137949). 33 Lib is a rapidly oscillating (roAp) star with a pulsation period of 8.3 min and a photometric B amplitude of 3 mmag. 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 gives an excellent opportunity to determine in a straightforward, mostly approximation-free, model-independent way, and with particularly high precision the mean magnetic modulus $\langle B \rangle$, that is, the average over the visible stellar hemisphere

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[⋆] Based on observations obtained at the European Southern Observatory, Paranal, Chile (ESO program No. 70.D-0470).

Table 1. Atmospheric parameters used for spectrum synthesis.

	HD 965[1]	HD 116114[2]	33 Lib[2]
$T_{\rm eff}$ [K]	7400	8000	7550
$\log g$	3.6	4.0	4.3
$v \sin i$ [km s^{-1}]	3	3	≤ 1
$\langle B\rangle$ [kG]	4.4	6.0	4.7

References: 1: Hubrig et al. (2002); 2: Nesvacil et al. (2003).

of the modulus of the magnetic vector, weighted by the local line intensity. The radial gradient of the mean magnetic modulus is then obtained by applying 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 Kurucz's code ATLAS9 (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. Observations and data reduction

The spectra of HD 965, HD 116114 and 33 Lib have been obtained in service mode during the period 2002–2003 at ESO with the VLT UV-Visual Echelle Spectrograph UVES at UT2. We used the UVES DIC1 standard setting covering the spectral range from 3290 Å to 6650 Å. The slit width was set to $0\farcs3$ and $0\farcs4$ for the red and blue arms respectively, corresponding to a resolving power of $\lambda/\Delta\lambda \approx 1.1 \times 10^5$ and $\approx 0.9 \times 10^5$. The spectra have been reduced with the UVES pipeline Data Reduction Software (version 1.2.0), which is an evolved version of the ECHELLE context of MIDAS. The signal-to-noise ratios of the resulting UVES spectra are very high, ranging from 200 in the near UV to 400 in the visual region.

3. Line selection and measurements of 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. The technique of spectrum synthesis is ideally suited to study line blending, and we have made fits to our observations using model atmosphere calculations to compute matching profiles. Based on ATLAS9 (Kurucz 1993) atmospheric models, synthetic spectra were computed with the SYNTHMAG code (Piskunov 1999) for each star with parameters taken from our previous papers (Table 1). Line lists including oscillator strengths and other atomic parameters have been extracted from the Vienna Atomic Line Database VALD (e.g. Kupka et al. 1999). For HD 116114 and 33 Lib the abundances are well known (Nesvacil et al. 2003), which simplified the line identification. According to Hubrig et al. (2002), the spectrum of HD 965 corresponds best to a model atmosphere with the parameters $T_{\rm eff} = 7400$ K, $\log g = 3.6$ and $v \sin i = 3.0$ km s^{-1}.

By comparison of the observed and synthetic spectra 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 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 has been 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 bluewards 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 in the UV. Table 2 gives the line list for the three stars including wavelengths, lower excitation potentials, J and g values for lower and upper levels and the effective Landé factors taken from the VALD Database. For all the lines employed in this study we have used the Kurucz's values of the Landé factors taken from the GFIRON list (Kurucz 1994). The last three columns present the individual measurements of the mean magnetic field modulus. While many selected lines are almost free of blends in HD 116114, only a few measurements could be done in the stars HD 965 and 33 Lib because of the severe blending with other lines. Examples of the variable quality of the same lines in the three stars are given in Fig. 1. It shows the bluest (λ 3303.464) and the reddest (λ 6149.258) Fe II lines used in our analysis.

In the approximation of the linear Zeeman effect, the mean magnetic field modulus is related to the wavelength separation of the Zeeman components through the relation

$$\langle B\rangle = \Delta\lambda / \left(9.34 \times 10^{-13}\, \lambda_{\rm c}^2\, g_{\rm eff}\right) \qquad (1)$$

where $\lambda_{\rm c}$ is the central wavelength of the line (in a Zeeman triplet this corresponds to the position of the π-component), $\Delta\lambda$ is the wavelength separation between the centroids of the σ-components and $g_{\rm eff}$ is the effective Landé factor. 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. Examples of typical fits are given in Fig. 2.

4. Results

Our determinations of the mean magnetic field modulus in the three stars are presented in Fig. 3. In order to estimate the accuracy of these measurements, we repeated the measurements of each line several times. The typical standard deviation for the best resolved lines determined in this way are of

Table 2. Line list and individual measurements of $\langle B \rangle$.

Ion	λ [Å]	E_{low} [eV]	J_{low}	g_{low}	J_{up}	g_{up}	g_{eff}	$\langle B \rangle_{\text{HD965}}$	$\langle B \rangle_{\text{HD116114}}$	$\langle B \rangle_{\text{33 Lib}}$
Fe II	3303.464	1.097	0.5	–0.05	0.5	3.35	1.65	4807	6357	5399
Cr II	3421.202	2.421	0.5	0	0.5	2.84	1.42	4891	6426	5762
Fe I	4080.877	3.292	0	0	1	1.89	1.89	–	5989	–
Cr II	4086.128	3.714	0.5	2.68	0.5	0.01	1.35	4349	6146	4903
Ti II	4411.952	1.224	0.5	2.6	0.5	0	1.30	–	5724	4834
Fe I	4489.739	0.121	0	0	1	1.55	1.55	–	6005	–
Fe I	4643.463	3.654	2	1.84	2	1.84	1.84	–	–	5023
Fe I	4704.948	3.686	1	2.49	0	0	2.49	–	–	4986
Fe I	4741.529	5.446	2	1.5	3	1.48	1.46	–	6281	–
Fe I	5068.765	2.940	4	1.75	3	1.75	1.75	–	6216	–
Fe I	5083.338	0.958	3	1.25	3	1.25	1.25	–	6211	–
Fe I	5263.306	3.266	2	1.5	2	1.5	1.50	–	6017	4933
Fe I	5859.578	4.549	4	1.25	3	1.26	1.23	–	5899	–
Ca I	6102.723	1.879	0	0	1	2	2.00	4672	–	–
Fe II	6149.258	3.889	0.5	0	0.5	2.7	1.35	4329	6037	4668

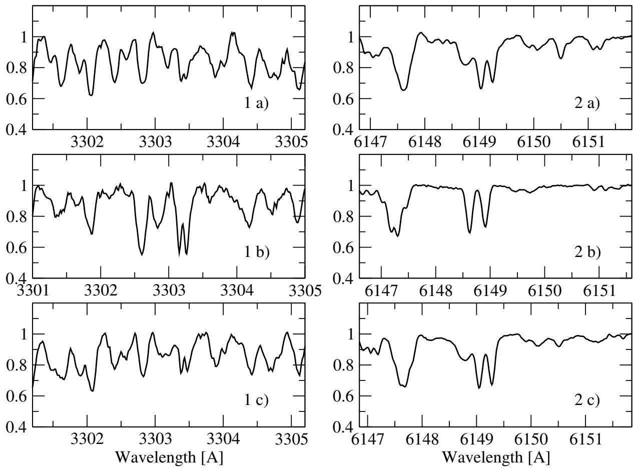

Fig. 1. Fe II lines at λ 3303.464 (1) and λ 6149.258 (2) in HD 965 **a)**, HD 116114 **b)** and 33 Lib **c)**.

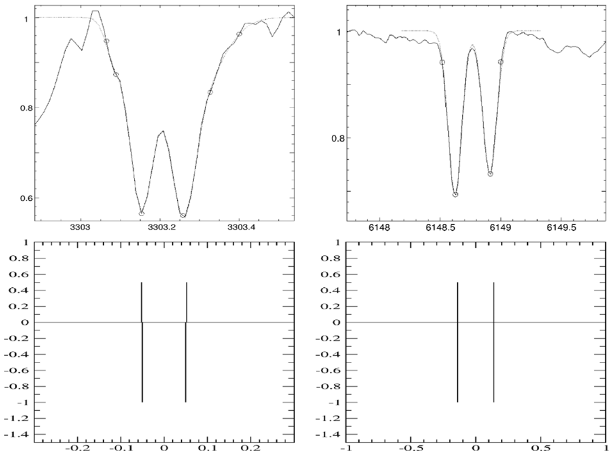

Fig. 2. Examples of Gaussian fits of two Fe II lines at λ 3303.464 (*left*) and λ 6149.258 (*right*) in the spectrum of HD 116114. The lower panels show the Zeeman patterns of both lines where the π-components are above the horizontal axis, and the σ-components below it. The length of the vertical bars is proportional to the relative strength of the components.

the order of ≈10 G. It is obtained for the lines in which the Zeeman components are well resolved, mostly symmetric and only marginally affected by blends, and present the low boundary to the uncertainties of our measurements. In such cases, the accuracy of the measurements appears to be limited primarily by the accuracy of the wavelength calibration (see Mathys et al. 1997), which is for the UVES spectra at most 2 mÅ, corresponding to 42 G. A more realistic error estimate can be obtained by comparing the mean magnetic field modulus of the 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 the three Fe I lines is much less for 33 Lib (4980 G ± 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 done in this spectral region.

For all three stars our measurements indicate that the magnetic field strength decreases with the optical depth. For HD 116114, the difference $\Delta B = B_{\text{uv}} - B_{\text{vis}}$ between the magnetic field derived from the Cr II lines before and after the Balmer jump is $\Delta B_{\text{CrII}} \approx 280$ G and $\Delta B_{\text{FeII}} \approx 320$ G in the case of Fe II. For HD 965, we obtain $\Delta B_{\text{FeII}} \approx 480$ G and $\Delta B_{\text{CrII}} \approx 540$ 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

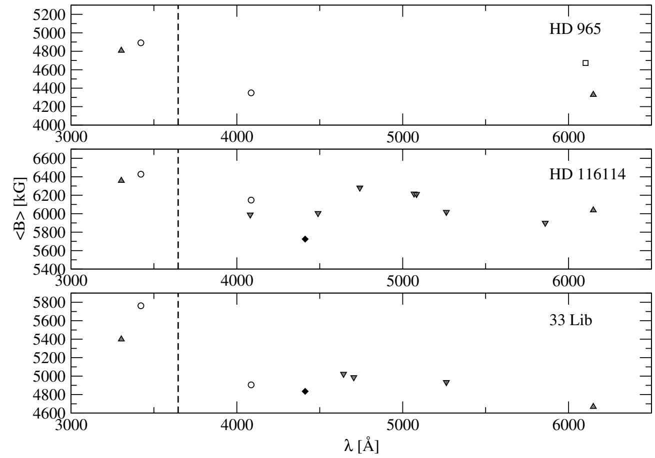

Fig. 3. Measurements of the mean magnetic field modulus $\langle B \rangle$ in the three stars. The dashed line indicates the position of the Balmer jump. Different symbols mark different species. Triangle down: Fe I, triangle up: Fe II, circle: Cr II, diamond: Ti II, square: Ca I.

is the star 33 Lib for which we obtain $\Delta B_{\rm FeII} \approx 730$ G and $\Delta B_{\rm CrII} \approx 860$ G. Admittedly, the significance of the detection in HD 116114 and HD 965 is not very high (2–3 σ), 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 indicate a real decrease of magnetic field strength with atmospheric depth.

From the results shown in Fig. 3, it seems plausible that certain elements may be distributed in the atmosphere inhomogeneously in vertical or horizontal direction. In fact, the horizontal inhomogeneities of abundances and field strengths might mimic a vertical field gradient. To account for such an anomalous distribution, it is crucial to measure the lines of the same ions on both sides of the Balmer jump. Unfortunately, apart from both the Cr II and Fe II lines, no other good lines have been found usable for our study. In HD 116114, for example, the field strengths calculated from Fe and Cr lines longward of the Balmer jump are in good agreement, whereas the field derived from the Ti II λ 4411.9 line is ~300 G lower. It could be possible that Fe, Cr and Ti are concentrated in patches located on different regions across the visible stellar disk with different local field strengths. A similar large discrepancy is found in HD 965, for which the mean magnetic field modulus measured from the Ca I λ 6102.7 line is by ~350 G larger than the one derived from Fe II.

5. Conclusion

The magnetic field modulus has been determined for three Ap stars using various resolved Zeeman-doublets and -triplets covering a large spectral range from 3290 Å to 6650 Å. In comparison to previous studies, our data have been acquired at much higher spectral resolution ($R \geq 90\,000$) and signal-to-noise ratio ($S/N \geq 200$). We found evidence for radial gradients of the magnetic field strength in all three studied Ap stars indicating a significant decrease of the magnetic field by 5−18% with atmospheric depth. This result is especially intriguing because all previously modelled magnetic field geometries of Ap stars show predominantly a dipolar structure or a superposition of a dipole and a quadrupole field which would produce just the opposite result, that is, a higher magnetic field strength in the deeper atmospheric layers. While for the least peculiar star in our sample, HD 116114, the smallest ΔB at the level of $\sim 2\sigma$ was found, the rapidly oscillating star 33 Lib shows the largest difference (up to 6σ) in the mean magnetic field modulus measured on the different sides of the Balmer jump. The vertical stratification of chemical abundances has been recently studied by several authors in a number of roAp stars (e.g. Ryabchikova et al. 2002) where the effect of stratification seems to be much larger than in the magnetic non-oscillating stars. At this point, we wish to note that our estimates of the optical depth τ for the analyzed spectral lines have been done using the atmosphere models for normal non-magnetic stars, but taking into account the magnetic intensification of individual lines. Due to the presence of vertical abundance stratification and strong magnetic fields in the atmospheres of the studied stars, the realistic optical depths for the analyzed spectral lines are probably different. However, identification of the physical conditions in atmospheres of magnetic stars is far from being complete, and further studies are needed towards understanding the different processes on play.

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