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Eu III identification and Eu abundance in CP stars

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Abstract. We report the first identification of the Eu III λ 6666.347 line in optical spectra of CP stars. This line is clearly present in the spectra of HR 4816, 73 Dra, HR 7575, β CrB, and α^2 CVn, while it is marginally present or absent in spectra of the roAp stars (rapidly oscillating Ap stars, cf. Kurtz 1990) α Cir, γ Equ, HD 203932, GZ Lib (33 Lib), and HD 24712.

Careful synthetic spectrum calculations for the Eu II λ 6645.11 line taking into account hyperfine, isotopic, and magnetic splittings allow us to obtain more accurate Eu abundances in the atmospheres of 9 CP stars. In most cases the derived abundances are significantly lower than the previous results reported for some of the stars based on coarse analysis of the famous blue Eu II lines. Assuming an ionization balance in the stellar atmospheres we give an estimate of the astrophysical oscillator strength $\log(gf)$=1.18 ± 0.14 for the Eu III λ 6666.347 line. This value is obtained without taking into account a possible hyperfine-splitting which is unknown for this Eu III line. We also provide astrophysical gf-values for Eu III $\lambda\lambda$ 7221.838, 7225.151, and 8079.071.

Key words: atomic data – stars: abundances – stars: chemically peculiar – stars: magnetic fields

1. Introduction

Magnetic Chemically Peculiar (CP2) stars are known to have large overabundances of rare-earth elements (REE) in their atmospheres. If the star has a measurable and variable magnetic field, then the REE line intensity always varies in phase with the magnetic field (see, for example, Pyper 1969 for α^2 CVn). Among all REE europium shows the most prominent overabundances of up to +5.0 dex, in many CP2 stars violating the odd-even pattern observed in the solar atmosphere.

The strongest resonance lines of Eu II are observed in the blue spectral region, lines of medium strength are located in the red spectral region. All Eu II lines suffer from large hyperfine-splitting. The combined effect of the hyperfine-splitting and the magnetic field leads to an obvious overestimation of the Eu abundance by more than 1.0 dex in extreme cases (Landi Degl'Innocenti 1975, Hartoog, Cowley & Adelman 1974). Anyway, even taking into account possible corrections, Eu overabundances obtained for the atmospheres of CP2 stars remain large (Hartoog et al. 1974).

In the atmospheres of hot CP2 stars the dominant Eu ion is Eu III. The strongest lines of Eu III are located in the UV region. Leckrone (1976) and Fuhrmann (1989) noted that resonance Eu III lines are not as prominent as one might expect in UV spectra of the Eu-rich stars α^2 CVn and HR 465. On the other hand, working on the abundance analysis of the CP2 star HR 7575 we found a rather strong spectral line near the position of the strongest Eu III line λ 6666.347 in the optical spectral region. This fact justified a careful study of a few CP2 stars in the spectral region 6620–6680 Å, where unblended lines of both Eu II λ 6645.11 and Eu III λ 6666.35 are located.

2. Observations

A list of the program stars with the journal of observations is given in Table 1. CCD spectra of six stars: α^2 CVn, HR 4816, 73 Dra, HR 7575, β CrB, and GZ Lib (33 Lib) were obtained at the coudé focus of the 2.6-m telescope of Crimean Astrophysical Observatory. For all spectra the S/N ratio is at least 200 and the resolving power is 35000. For the remaining stars we used spectra described in the papers by Kupka et al. (1996) for α Cir, by Gelbmann et al. (1997) for BI Mic, and by Ryabchikova et al. (1997a) for γ Equ.

The spectrum of the star HD 24712 in the spectral region 6610–6665 Å was obtained at the Nordic Optical Telescope (La Palma) with the SOFIN spectrometer. The resolving power was 80000. Unfortunately, this spectrum does not include an Eu III line, but we used it to check the Eu abundance, which was estimated previously by Ryabchikova et al. (1997b) with two very weak blended lines and therefore may be considered uncertain.

Spectra of α^2 CVn were obtained in three phases of intensity of the Eu II lines, and the Nordic Optical Telescope spectrum of HD 24712 was obtained in a phase close to the maximum of Eu II lines.

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Table 1. Journal of observations.

Star name	HD	JDH 2400000+	Central λ
α^2 CVn	112413	50558.338	6645
		50588.306	7222
		50588.372	6645
		50912.364	6645
HR 4816	110066	50501.531	6645
		50501.543	6359
		50501.558	6160
		50501.577	4921
73 Dra	196502	50288.374	6645
HR 7575	188041	50294.338	6160
		50294.345	6359
		50294.353	6645
		50294.361	4921
β CrB	137909	50504.541	6645
		50504.546	6645
		50907.551	8079
		50907.562	7222
		50907.565	7690
		50917.477	6645
GZ Lib (33 Lib)	137949	50504.583	6645
DO Eri	24712	50383.746	6645

The reduction of the spectra was made using the software "SPE" written by S. Sergeev at the Crimean Observatory. The reduction procedure includes the night sky subtraction, flat field correction, cosmic ray subtraction by visual inspection of the spectra and wavelength calibration. The normalization of the spectra to the continuum level was done using both "SPE" and pcIPS reduction packages (Smirnov & Piskunov 1994).

3. Identification of the Eu III λ 6666.347 line

The Vienna Atomic Line Database (VALD, Piskunov et al. 1995) was extensively used for line identifications, based on preliminary abundances extracted for the program stars from the literature. At the time of writing this paper VALD did not contain any information on the second ions of the REE. A list of the Eu III lines compiled by Sugar & Spector (1974) was used by us. The strongest optical line Eu III λ 6666.347 ($^6\mathrm{I}^0_{17/2} - ^6\mathrm{H}_{15/2}$) with an intensity of 50 produces a very strong feature in the spectra of non-roAp stars, and we found no other candidates for its identification. This line is detectible in roAp stars, too, but it is very weak, and partially blended from both sides with unidentified lines. Figs. 1 and 3 show Eu II (λ 6645.11) and Eu III (λ 6666.347) line regions in the spectra of the program stars.

We also searched for other Eu III lines. The two next strongest lines, λ 7221.838 (30) and λ 7690.435 (20), are located in a region with telluric H_2O lines, and the latter is blended with Fe II λ 7690.500 (intensities are given in paranthesis here). We identified both lines in the spectrum of β CrB, although Eu III λ 7690.435 is strongly blended with telluric lines. We also identified Eu III λ 7225.151 (1) and λ 8079.071 (10). Parts of the spectrum of β CrB centered at 7222 Å and at 8079 Å are shown in Fig. 2.

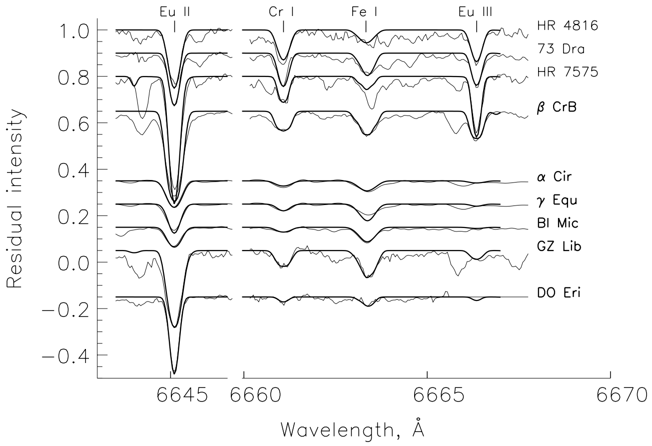

Fig. 1. A comparison between observations (thin line) and synthesized lines of Eu II, Eu III, Cr I, and Fe I (thick line).

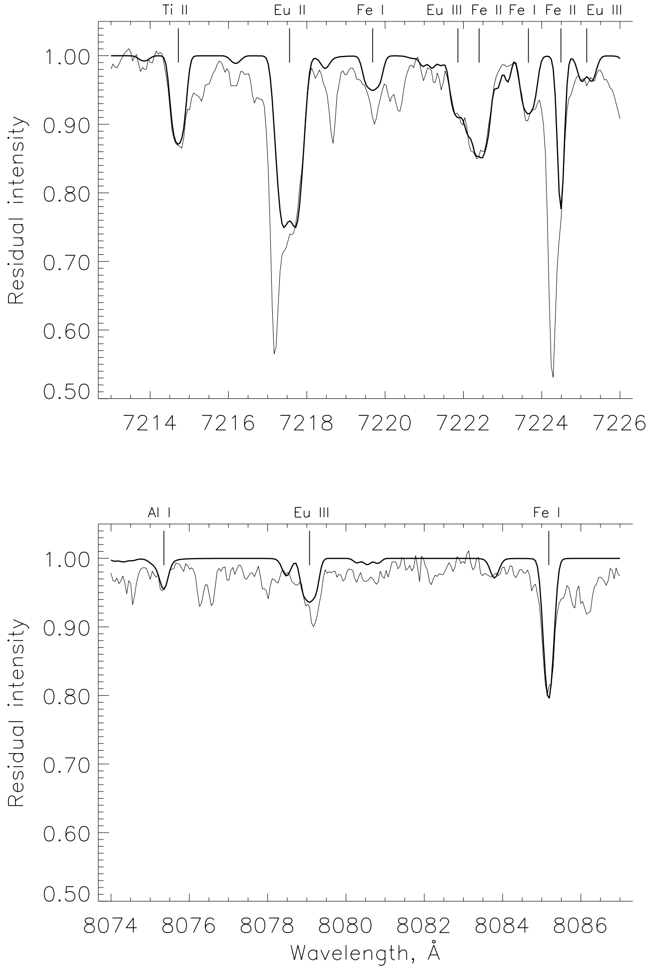

Fig. 2. A comparison between observations (thin line) and synthesized lines of Eu II, Eu III, Al I, Ti II, Fe I, and Fe II (thick line) in the spectrum of β CrB. A few strong telluric lines are seen in the upper spectrum.

Table 2. The main atmospheric parameters for 6 of the program stars estimated from photometric calibrations and extracted from the literature. For details on the Cohen (1970) values see Sect. 5.2.

Star name	Strömgren phot.			Geneva phot.			Others			Reference (for others)
	$T_{\rm eff}$	$\log g$	[M/H]	$T_{\rm eff}$	$\log g$	[M/H]	$T_{\rm eff}$	$\log g$	[M/H]	
α^2 CVn	12840	4.26		12260	4.37		12000	4.0	+1.5*	Cohen (1970)
							11500	4.0	indiv.	Muthsam & Stépien (1980)
HR 4816	9345	4.31	+0.6				10000	4.0	+0.0	Adelman(1973)
							9100	3.8	+1.0	Adelman et al. (1995)
73 Dra	8875	3.81		9031	3.87		8150	3.6	+0.0	Lyubimkov (1986)
HR 7575	8159	4.13	+1.2	7621	4.10	+0.5	8000	4.0	+0.0	Allen (1977)
β CrB	8087	4.34	+0.6	7658	4.27	+0.4	9700	4.0	+0.0	Adelman (1973)
							8300	4.0	+0.0	Savanov & Malanushenko (1990)
							7750	4.0	+0.5	Faraggiana & Gerbaldi (1993)
GZ Lib	8090	4.38	+1.3	7299	4.47	+0.8	8800	4.0	+0.0	Adelman (1973)
							7500	4.0	+0.0	Adelman (1981a)

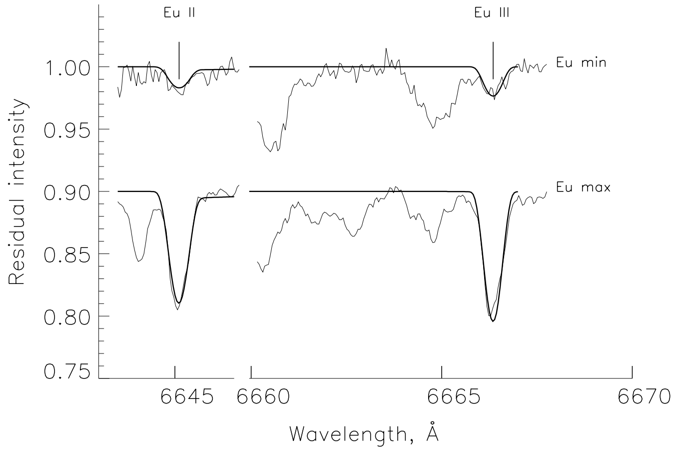

Fig. 3. The same as in Fig. 1 for α^2 CVn in the phases of minimum and maximum intensity of Eu lines.

Unfortunately, one spectrum of α^2 CVn, obtained in the 7222 Å spectral region, was taken at the phase of Eu minimum, when Eu lines are 5 times weaker than at maximum. Fig. 3 shows parts of the spectra of α^2 CVn in the phases of minimum and maximum of europium line intensity near the positions of the Eu II λ 6645 and Eu III λ 6666 lines.

4. Method of the analysis

4.1. Parameter determination

Recently, we have completed the abundance analysis of four of our program stars – α Cir (Kupka et al. 1996), γ Equ (Ryabchikova et al. 1997a), BI Mic (Gelbmann et al. 1997), and DO Eri (Ryabchikova et al. 1997b). Here, we are using the atmospheric parameters derived in those papers. For the other stars we first estimated the atmospheric parameters from Strömgren and Geneva photometric calibrations using a program by Rogers (1995). The results are listed in Table 2. We also show in columns 8 and 9 effective temperatures and surface gravities for these stars found in the literature. For most of the stars there is a difference between the effective temperatures derived from Strömgren and Geneva photometry. This difference reaches 800 K for GZ Lib. Therefore, we used optical spectrophotometry for the final decision.

For the stars HR 4816 and GZ Lib spectrophotometric data are taken from Adelman (1981ab), while for α^2 CVn, 73 Dra, HR 7575, and β CrB, we used data from the spectrophotometric catalogue by Adelman et al. (1989). The adopted atmospheric parameters for all program stars are given in Table 4. Fig. 4 shows a fit of the predicted fluxes to the observed energy distribution for 6 stars.

There is a big difference between effective temperatures obtained by Adelman (1973) and recent calibrations. Adelman started with effective temperatures extracted from UBV data which were not very different from our adopted values, and after that modified them by requiring ionization balance between Fe I and Fe II. There are at least two reasons which lead to much higher effective temperatures in Adelman's study. First, he used unblanketed atmospheric models. Later he substantially decreased his early estimates with the blanketed models (Adelman 1981a, Adelman et al.1995). Second, Adelman used Baschek et al. (1970) oscillator strengths for Fe II lines whose absolute scale was found to be too small by 0.16 dex (see NIST compilation by Fuhr et al. 1988). The iron abundance derived from Fe II lines was overestimated and led to the use of higher temperatures to obtain the same iron abundance from Fe I lines. Magnetic fields also play a significant role in line formation, and neglecting detailed Zeeman patterns one may find ionization balance for different effective temperatures when using different samples of Fe I and Fe II lines. Our estimates for the effective temperature and surface gravity in HR 4816 is slightly different from the $T_{\rm eff}$=9100 K and $\log g$=3.8 obtained by Adelman et al. (1995), but our parameters allow for a better fitting of both the Balmer jump and, especially, the Paschen continuum. Our effective temperature for 73 Dra is 550 K higher than that obtained by Lyubimkov (1986), but the final model is in a better agreement with optical spectrophotometry, especially in the region of the Balmer jump as can be seen in Fig. 4 where the flux

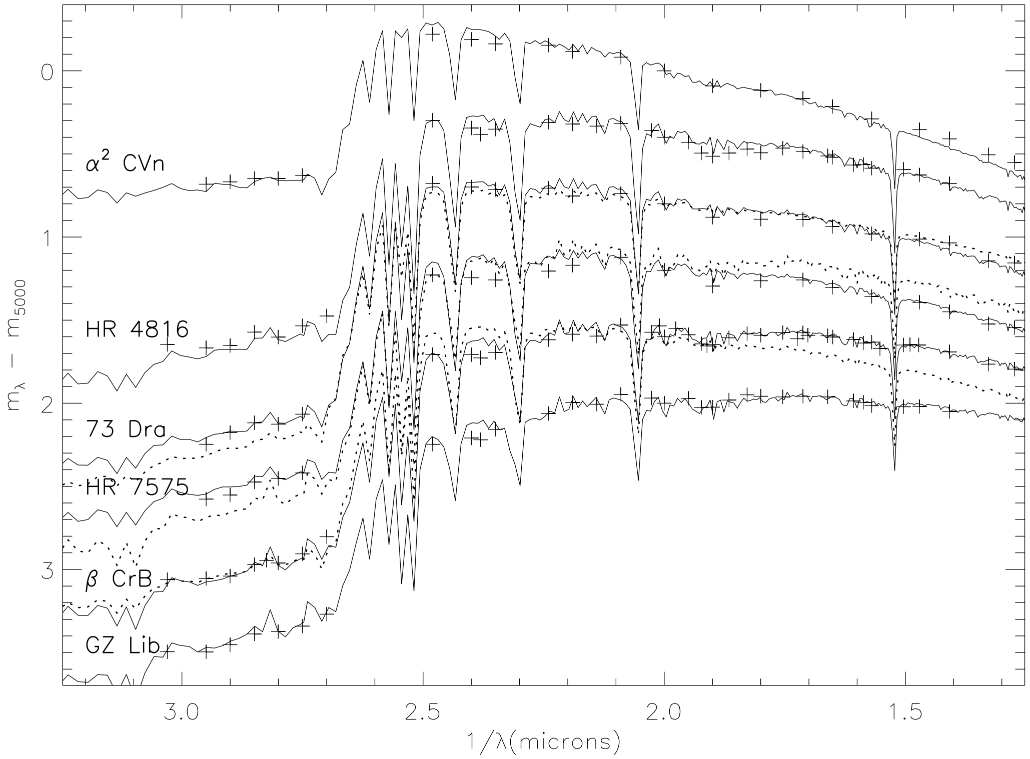

Fig. 4. A comparison between observed and calculated fluxes. Full lines represent calculations with the adopted atmospheric parameters from Table 3, dotted lines represent calculations with: 8150, 3.6, +0.0 (73 Dra); 8150, 4.1, +1.0 (HR 7575); 8300, 4.0, +0.0 (β CrB).

Table 3. Hyperfine structure components of Eu II $\lambda\lambda$ 6645.11.

Wavelength	$\log(gf)$
6645.068	−0.396
6645.081	−0.754
6645.093	−0.512
6645.100	−0.915
6645.107	−1.000
6645.114	−0.664
6645.133	−0.954
6645.148	−1.038
6645.160	−1.121

Table 4. The main atmospheric parameters for the program stars. Effective temperatures, surface gravities, surface magnetic fields, rotational velocities, and model metallicities (in dex relative to the solar value) are given.

Star name	HD	$T_{\rm eff}$	$\log\ g$	$B_{\rm s}$ (kG)	$v \cdot \sin i$ (km s^{-1})	Metallicity
α^2 CVn	112413	11500	4.0	5.0	15.0	+1.0
HR 4816	110066	9000	4.3	3.6	9.0	+1.0
73 Dra	196502	8700	3.8	2.0	9.0	+1.0
HR 7575	188041	8500	4.5	3.6	2.0	+0.5
β CrB	137909	7750	4.3	5.7	3.5	+0.5
α Cir	128898	7900	4.2	2.0	12.5	+0.0
γ Equ	201601	7700	4.2	4.0	~ 0.0	+0.5
BI Mic	203932	7450	4.3	~ 0.0	12.5	+0.0
GZ Lib	137949	7350	4.4	4.9	$\leq$8.0	+0.5
DO Eri	24712	7250	4.3	3.0	5.6	+0.0

predicted with Lyubimkov's model is shown as a dotted line. For β CrB Fig. 4 shows predicted fluxes calculated with two models: 7750, 4.3, +0.5 (full line), and 8300, 4.0, +0.0 (dotted line). HR 7575 is the only star for which the adopted effective temperature and surface gravity exceed the corresponding values obtained from both photometric calibrations. Our choice is justified by the comparison between calculated and observed fluxes shown in Fig. 4 for two models: 8500, 4.5, +0.5 (full line – adopted model) and 8150, 4.1, +1.0 (dotted line – calibration of Strömgren photometry).

For HR 4816 and 73 Dra we calculated models with metallicity +1.0 dex, for HR 7575, β CrB, and GZ Lib we used a metallicity of +0.5 dex. Note that for all stars with a surface magnetic field larger than 3 kG we used an enhanced microturbulence, usually 4 km s^{-1}, in model atmosphere calculations to take into account magnetic intensification effects through pseudo-microturbulence. All synthetic spectrum calculations were made with zero microturbulence and a realistic magnetic field. (See Ryabchikova et al. 1997a for a discussion).

The fifth and sixth column of Table 4 provide the adopted mean surface magnetic field and rotational velocity. For α^2 CVn the surface magnetic field was estimated from the decentered dipole model obtained by Glagolevskij et al. (1985). The mean surface magnetic fields are taken from Preston (1971) for HR 4816 and 73 Dra, and from Mathys & Lanz (1992) for HR 7575, β CrB, γ Equ, and GZ Lib. For α Cir, BI Mic, and DO Eri surface magnetic field estimates are taken from the corresponding papers on abundance analysis. For α Cir, γ Equ, BI Mic, and DO Eri the $v \cdot \sin i$ value was taken from the literature discussed in Sect. 2 while for most of the other program stars it was obtained from the spectrum synthesis presented here. Only for β CrB we used a rotational velocity estimated by Wade (1997). A horizontal line separates the roAp stars (lower part of the table) from the non-oscillating CP2 stars (upper part).

Our model atmosphere and flux calculations are based on the ATLAS9 code by Kurucz (1993). Line opacities were taken from CDROM 2 of the 1993 CDROM distribution of Kurucz issued together with the ATLAS9 code. A recent study of Smalley and Kupka (1997) revealed that synthetic uvby colors from model atmopsheres for A and early F stars are in better agreement with observed ones, if the convection theory of Canuto and Mazzitelli (1991) is used to replace the mixing length theory implemented in ATLAS9. Their conclusion was based on a comparison between T_{eff} and $\log\ g$ determined from synthetic colors with T_{eff} and $\log\ g$ obtained from fundamental and secondary methods (i.e. which are completely or essentially independent of model atmospheres and convection modelling). Therefore, we used the version of ATLAS9 modified by Kupka (1996) to include the new treatment of convection.

To synthesize Eu lines properly one needs to know a full hyperfine-splitting for all isotopes. For the Eu II λ 6645.11 line hyperfine-splitting data were taken from Biehl (1976). Both stable isotopes Eu^{151} and Eu^{153} are splitted on 11 hyperfine structure components each. In our calculations we included only the strongest 12 components for both isotopes and, combining the closest ones into single lines, we ended up with 9 components, describing both hyperfine and isotopic structure. The wavelengths and oscillator strengths for the 9 hyperfine structure components are given in Table 3.

For Eu III lines hyperfine-splitting is unknown, therefore we neglect this effect in our study. Synthetic spectrum calculations which take into account the presence of a magnetic field and nine hyperfine components for the Eu II line were carried out with the help of the new code SYNTHMAG (see below). Besides Eu II and Eu III lines we also synthesized lines of Cr I and Fe I to derive chromium and iron abundances. Zeeman patterns for all synthesized lines were taken from Beckers (1969). The full Zeeman pattern of Eu II λ 6645 consists of 11 π and 22 σ components.

The oscillator strength for Eu II lines were taken from Biemont et al. (1982). For the Eu III lines we varied the f-value to fit the observations. The synthetic spectra which give the best fit to the observations are shown in Fig. 1, Fig. 2, and Fig. 3 by thick lines.

4.2. *Spectrum synthesis for magnetic stars*

SYNTHMAG is a new code for computing spectral synthesis in the presence of a magnetic field. The code is based on the Diagonal Element Lambda Operator (DELO) algorithm described by Rees et al. (1989). This method takes advantage of the fact that all diagonal elements of the absorption matrix in the Stokes vector transfer equation are identical and dominate the other elements by several orders of magnitude. Therefore, it is possible to write the analytical solution for an elementary depth step through the atmosphere using a linear approximation to the source function. The resulting method can be described as a non-iterative one-way integrator for radiative transfer in the presence of a magnetic field. The new method is much faster then magnetic Runge-Kutta (Landi Degl'Innocenti 1976) and Feautrier (Auer at al. 1977) integrators, but suffers slower convergence with increasing grid density compared to Feautrier. On the other hand, we found DELO to be robust against numerical instabilities, in particular, when magneto-optical effects are taken into account. This property is related to the fact that the DELO algorithm requires much less inversions of the Stokes absorption matrices, in comparison with other methods such as the Feautrier approach (for details see Sect. 2 of Piskunov 1998).

The investigation for the main sources of accuracy loss in the DELO algorithm pointed at the linear approximation to the source function. The solution we found was to resample the model atmosphere on a new depth grid which guarantees good accuracy of the linear approximation throughout the line forming region. This is implemented in the SYNTHMAG code. Although resampling requires some additional book-keeping and computing time, the new code proves to be at least 2 times faster than the Feautrier version, has very similar accuracy and convergence properties, and is much more robust against numerical errors. A more detailed description of the new algorithm is given by Piskunov (1998).

The new algorithm, as implemented in SYNTHMAG, has the following logical parts:

- Input of the line list, model atmosphere, abundance and magnetic field data.
- Construction of the new depth grid by computing the total opacity at the central wavelength of each line and verifying if the linear approximation for the source function provides adequate accuracy.
- Computing the spectral synthesis for 4 Stokes parameters at different limb angles. At this point SYNTHMAG can handle 3 models for the magnetic field: radial, uniform, and dipolar. In all cases the field needs to be axis-symmetric in respect to the line of sight.

In our calculations we used a simplified model of the magnetic field with a constant modulus and orientation over the stellar surface. In order to compare the results to the observations we use a set of programs written in IDL. The first of them, RDMAG (written by J. Valenti), takes the output of SYNTHMAG, convolves it with the rotational profile using a very accurate quadrature algorithm (Valenti & Piskunov 1996) and normalizes the synthetic spectrum to the continuum. The resulting spectrum can be compared to the observations using the ROTATE program which allows interactive adjustments of instrumental broadening, radial velocity, and other parameters.

5. Results

5.1. *Cool stars*

The results on the Cr, Fe, and Eu abundances in the atmospheres of the program stars with the exception of α^2 CVn, which will be discussed below, are presented in Table 6. Eu abundances obtained for some of the stars by other investigators are given in the fifth column of Table 6. A reasonable agreement between Eu abundances obtained in the present investigation and those obtained earlier exists for those stars that exhibit only a moderate Eu overabundance, i.e., when the hyperfine-splitting is not very important. However, for stars where log(Eu/H)≥ -9.0, most previous investigations overestimated the Eu abundance by more than 1.0 dex. This is explained by complex hyperfine and Zeeman splitting both leading to desaturation and increase of equivalent widths of Eu lines. Ignoring those effects results in overestimated element abundances. Hartoog et al. (1974) presented corrections for the hyperfine-splitting for blue Eu II lines to the abundances obtained by Adelman (1973). We have four stars in common with Hartoog et al., and our abundances are systematically lower. We attribute the remaining differences to the higher effective temperatures and different $\log(gf)$'s (from Corliss & Bozman 1962) used by Adelman rather than to the magnetic intensification. To test this hypothesis we calculated Eu abundances for β CrB with Adelman's atmospheric parameters ($T_{\rm eff}$=9700 K, $\log\ g$=4.0, solar metallicity) and the Corliss & Bozman $\log(gf)$ for Eu II λ 6645, and obtained log(Eu/H)=-5.85. This value is in excellent agreement with the corrected Eu abundance of -5.94 of Hartoog et al. (1974). To show the effects of the hyperfine structure and the magnetic field separately we also calculated abundances with and without the hyperfine-splitting and the magnetic field for HR 7575. Our calculations resulted in -5.90 for the case of the absence of both the hyperfine-splitting and the magnetic effects and -6.60 when either hyperfine-splitting or the magnetic field have been taken into account. The latter value is still by one order of magnitude higher than the final Eu abundance obtained for HR 7575.

For 73 Dra the lower Eu abundance obtained by Lyubimkov (1986) is explained by the lower effective temperature and enhanced microturbulence he used for his model atmosphere, while the significantly higher Eu abundance obtained by Savanov & Malanushenko (1990) for β CrB is explained by the neglection of hyperfine structure and magnetic field effects.

From Table 6 one immediately sees that in our sample non-roAp CP2 stars are more chemically peculiar than their roAp counterparts. It is the main conclusion of the present paper, which still needs confirmation based on observations and analyses of a larger sample of stars of both groups. Only one roAp star, GZ Lib, is closer to non-roAp stars concerning the metallicity. Because different photometric systems provide largely different effective temperatures for this star, a more careful abundance analysis of GZ Lib is certainly worthwhile.

Assuming an ionization balance in the stellar atmospheres we estimated the astrophysical oscillator strength of the Eu III λ 6666.347 line. Individual values are given in the last column of Table 6, which results in a mean oscillator strength $\log(gf)$=1.18 ± 0.14. This value is comparable with the oscillator strengths for the strongest Ce III lines in the optical spectral region (Bord, Cowley & Norquist 1997). The value is an upper limit for the oscillator strength because we did not take hyperfine-splitting for this line into account. We also make estimates of the astrophysical gf-values for three other Eu III lines using the spectrum of β CrB. The individual values are given in the third column of Table 5. Values of gf scaled to the mean value obtained for Eu III λ 6666.347 are given in the fourth column. All four spectral lines from Table 5 belong to the same multiplet, therefore it is possible to estimate oscillator strengths expected from the relative intensities given by Sugar & Spector (1974). Predicted oscillator strengths are presented in the last column of Table 5. Taking into account that those intensities are visual estimates and are not qualitatively meaningful beyond indicating order-of-magnitude differences we find our relative oscillator strengths in agreement with the intensities. A comparison between observed and synthesized lines of Eu III and other ions in spectra of β CrB, centered at 7222 Å and at 8079 Å, is shown in Fig. 2. One can recognize Eu II λ 7217.56 showing a rather good agreement with the observations although it is blended with a telluric line. We did not take hyperfine-splitting for this line into account.

Table 5. Astrophysical oscillator strengths for Eu III lines. See text for details.

Wavelength	Configuration	$\log(gf)$		
		β CrB	scaled	sc. int.
6666.347	$^6I_{17/2} - ^6H_{15/2}$	1.35	1.18	1.18
7221.838	$^6I_{15/2} - ^6H_{13/2}$	1.15	0.98	1.06
7225.151	$^6I_{13/2} - ^6H_{13/2}$	0.50	0.33	−0.41
8079.071	$^6I_{11/2} - ^6H_{9/2}$	0.90	0.73	0.73

Astrophysical oscillator strengths provide only relative values because they depend on the correct choice of atmospheric parameters as well as on the assumption of ionization balance in the stellar atmosphere. We also neglected a possible vertical stratification of europium. In the temperature region around 8000 K the Eu II lines are sensitive to the effective temperature and are, practically, not sensitive to the surface gravity, while the opposite is true for the Eu III lines. Our calculations for a model with $T_{\rm eff}$=8500 ± 250 K and $\log\ g$=4.0 ± 0.5 show that the error in the Eu III oscillator strength scale is $\mp$ 0.25 dex due to temperature errors and ± 0.15 dex due to surface gravity errors. A decrease of the surface gravity by 0.5 dex leads to a decrease by 0.15 dex of the relative oscillator strength for the Eu III λ 6645 line, which coincides with our error bar of ± 0.14 dex obtained from 9 individual estimates.

5.2. *α^2 CVn*

The effective temperature and surface gravity we used for our model atmosphere for α^2 CVn agree with the parameters obtained by Muthsam & Stépien (1980). These authors calculated atmospheric models with opacities based on a chemical com-

Table 6. Chromium, iron, and europium abundances in the atmospheres of the program stars. Astrophysical $\log(gf)$-values for the Eu III λ 6666.347 line are given in the last column.

Star name	log(Cr/H)	log(Fe/H)	log(Eu/H) (present)	log(Eu/H) (literature)	Reference	$\log(gf)$ Eu III
HR 4816	−3.56	−3.51	−8.36	−6.76	Hartoog et al. (1974)	1.15
73 Dra	−3.66	−3.26	−8.76	−9.16	Lyubimkov (1986)	1.35
HR 7575	−4.21	−3.98	−7.66			1.10
β CrB	−4.56	−4.01	−8.46	−5.94	Hartoog et al. (1974)	1.35
				−6.91	Savanov & Malanushenko (1990)	
α Cir	−5.31	−4.46	−9.66	−9.40	Kupka et al. (1996)	0.95
γ Equ	−5.31	−4.31	−9.86	−9.16	Hartoog et al. (1974)	1.07
				−9.97	Magazzu & Cowley (1986)	
				−10.24	Ryabchikova et al. (1997a)	
BI Mic	−5.51	−4.46	−9.96	−9.15	Gelbmann et al. (1997)	1.25
GZ Lib	−4.91	−4.11	−8.96	−7.23	Hartoog et al. (1974)	1.20
DO Eri	−5.76	−4.96	−9.36	−9.00	Ryabchikova et al. (1997b)	...

Table 7. Europium abundance in the atmosphere of α^2 CVn. The results for this star are unique for this study in the sense that comparably large differences between Eu II and Eu III abundances were not found for the other program stars. See Sect. 5.2 for a discussion and Table 6 (scatter around mean value in the last column) to compare with other stars.

JD+2400000	Phase	log(Eu/H)		
		Eu II	Eu III	Cohen (1970)
50558.338	0.976	−6.90	−8.38	−5.25
50912.364	0.705	−7.60	−9.28	...
50588.372	0.456	−7.80	−9.58	−6.45

position obtained from an abundance analysis. Europium abundances obtained from Eu II and Eu III lines for three phases of Eu line intensities in α^2 CVn are given in Table 7. We used our mean oscillator strength for the Eu III line for an abundance analysis. For comparison, in the last column of Table 7 we give Eu abundances obtained by Cohen (1970) from Eu II near the minimum and maximum. She also measured only red lines, and the difference between our results can be explained by the higher effective temperature she used and the oscillator strengths from Corliss & Bozman (1962), as well as by neglecting the effects of hyperfine structure and the magnetic field. Cohen made her abundance analysis using a model atmosphere with $T_{\rm eff}$=12000 K, $\log g$=4.0, and an overabundance of Si by a factor of 30. According to her paper, this is approximately equivalent to a model with $T_{\rm eff}$=13000 K, $\log g$=4.0, and solar Si abundance. If we use Cohen's model atmosphere for α^2 CVn (or rather its analogue with $T_{\rm eff}$=13000 K, $\log g$=4.0, solar chemical composition) and the Corliss & Bozman oscillator strength for the Eu II 6645 line, then without taking into account hyperfine-splitting and magnetic effects we obtain log(Eu/H)=-5.25 and -6.40 for the maximum and minimum of the Eu line intensities which is in good agreement with Cohen's results.

6. Discussion

If the astrophysical gf-value for the Eu III λ 6666 line is correct, then in α^2 CVn the Eu abundance deduced from Eu III lines is about 1.5 dex smaller than the value obtained from Eu II lines. It confirms the result by Leckrone (1976) that resonance lines of Eu III in the spectrum of α^2 CVn are too weak for a star with a large Eu overabundance. The same discrepancy is observed in the CP2 star HR 465 for Er (Cowley & Greenberg 1987) and for Eu (Fuhrmann 1989). NLTE effects are hardly responsible for this large difference. Abundance spots also cannot explain the observed abundance difference. Calculations show that we may equalize abundances using an effective temperature slightly less than 10500 K, but in this case we cannot fit the spectrophotometric observations. The intensity of the Eu III line is not very temperature sensitive in a wide temperature region of 7500–12000 K, whereas that one of Eu II decreases by more than a factor of 10. Perhaps the Eu stratification in the upper layers of the stellar atmosphere might give an observable effect. It will be of great interest to get high resolution spectra of both α^2 CVn and HR 465 in the UV region for investigating the behaviour of the REE elements in different ionization stages. Calculations or measurements of the transition probabilities for the second ions of REE are necessary to confirm the scale of our (relative) $\log(gf)$-values for Eu III and to obtain a detailed picture of the REE abundance pattern in the atmospheres of chemically peculiar stars.

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