

# Model atmospheres of magnetic chemically peculiar stars

## A remarkable strong-field Bp SiCrFe star HD 137509

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### ABSTRACT

**Context.** In the past few years, we have developed stellar model atmospheres that included effects of anomalous abundances and a strong magnetic field. In particular, the full treatment of anomalous Zeeman splitting and polarized radiative transfer were introduced in the model atmosphere calculations for the first time. The influence of the magnetic field on the model atmosphere structure and various observables were investigated for stars of different fundamental parameters and metallicities. However, these studies were purely theoretical and did not attempt to model real objects.

**Aims.** In this investigation we present results of modeling the atmosphere of one of the most extreme magnetic chemically peculiar stars, HD 137509. This Bp SiCrFe star has a mean surface magnetic field modulus of about 29 kG. Such a strong field, as well as clearly observed abundance peculiarities, make this star an interesting target for applying our newly developed model atmosphere code.

**Methods.** We used the recent version of the line-by-line opacity sampling stellar model atmosphere code LLMODELS, which incorporates the full treatment of Zeeman splitting of spectral lines, detailed polarized radiative transfer, and arbitrary abundances. We compared model predictions with photometric and spectroscopic observations of HD 137509, aiming to reach a self-consistency between the abundance pattern derived from high-resolution spectra and abundances used for model atmosphere calculation.

**Results.** Based on magnetic model atmospheres, we redetermined abundances and fundamental parameters of HD 137509 using spectroscopic and photometric observations. This allowed us to obtain better agreement between observed and theoretical parameters compared to non-magnetic models with individual or scaled-solar abundances.

**Conclusions.** We confirm that the magnetic field effects lead to noticeable changes in the model atmosphere structure and should be taken into account in the stellar parameter determination and abundance analysis.

**Key words.** stars: chemically peculiar – stars: magnetic fields – stars: atmospheres – stars: individual: HD 137509

## 1. Introduction

The atmospheric structure of magnetic chemically peculiar (CP) stars deviates from that of normal stars with similar fundamental parameters because of unusual chemistry, abundance inhomogeneities, and the presence of a strong magnetic field. These effects are not considered in the standard-model atmosphere calculations, possibly leading to errors in the stellar parameter determination and abundance analysis. To circumvent this long-standing problem of stellar astrophysics, we have developed a new line-by-line opacity sampling model atmosphere code LLMODELS (Shulyak et al. 2004). Using this tool in the series of recent papers, we investigated in detail the effects of anomalous Zeeman splitting (Kochukhov et al. 2005), polarized radiative transfer (Khan & Shulyak 2006a) and inclination of the magnetic field vector (Khan & Shulyak 2006b) on the model structure, energy distribution, hydrogen line profiles, photometric colors, and the magnitude of bolometric corrections for a grid of model atmospheres with different effective temperatures and metallicities. For the first time we were able to obtain new results applying direct and self-consistent modeling of all these effects and to answer the question of how the magnetic field acts at different temperatures and what one could expect if the magnetic

field is ignored in calculations of model atmosphere of magnetic CP stars. It was shown that the strength of the magnetic field is the key characteristic controlling the magnitude of the magnetic field effects, and the polarized radiative transfer should be taken into account. In contrast, the orientation of the magnetic field vector does not have much influence on any of the observed stellar characteristics and, thus, can be safely ignored in the analysis routines.

So far, our models with these magnetic field effects have been developed and applied only in the context of purely theoretical studies. Here we make the first attempt to model the atmosphere of a real star. We use the LLMODELS stellar model atmosphere code to investigate the atmospheric structure of the star, taking into account individual chemical composition, anomalous Zeeman splitting, and polarized radiative transfer.

HD 137509 (HIP 76011, NN Aps) is a B9p SiCrFe chemically peculiar star with a strong reversing longitudinal field and variable lines of Si II and iron-peak elements (Mathys 1991; Mathys & Lanz 1997). Kochukhov (2006) (hereafter Paper I) detected resolved Zeeman split lines in the spectrum of HD 137509, showing that this star is characterized by a non-dipolar magnetic field geometry with a mean surface field

strength of about 29 kG. This is the second-largest magnetic field ever found in a CP star (the first place is occupied by the well-known Babcock's star, [Preston 1969](#)). The atmospheric parameters,  $T_{\text{eff}} = 12\,750 \pm 500$  K and  $\log g = 3.8 \pm 0.1$ , were derived in Paper I using theoretical fit to the observed H $\beta$  and H $\gamma$  line profiles based on the ATLAS9 ([Kurucz 1993a](#)) model with enhanced metallicity,  $[M/H] = +1.0$ . The appearance of such a strong magnetic field and the presence of the outstanding abundance anomalies inferred in Paper I allow us to use HD 137509 as a test ground for applying the new generation magnetic model atmospheres.

In the next section we briefly describe the techniques employed to construct magnetic model atmospheres. Results of the calculations for HD 137509 are presented in Sect. 3. Main conclusions of our study are summarized in Sect. 4.

## 2. Model atmosphere calculations

To calculate magnetic model atmospheres we used the current version of the LLMODELS code, originally developed by [Shulyak et al. \(2004\)](#). The LLMODELS is an LTE, 1-D plane-parallel, hydrostatic, stellar model atmosphere code for early and intermediate-type stars. The direct line-by-line calculation of the bound-bound opacities implemented in this code allows one to account for arbitrary individual and stratified stellar abundance patterns and include various effects caused by the magnetic field. The VALD database ([Piskunov et al. 1995](#); [Kupka et al. 1999](#)) was used as a source of atomic line parameters. The extracted lines were subjected to a preselection procedure inside LLMODELS, with the default criterion  $\alpha_{\text{line}}/\alpha_{\text{cont}} > 1\%$  in at least one atmospheric layer allowing only those lines to be selected that significantly contribute to the opacity (here  $\alpha_{\text{line}}$  and  $\alpha_{\text{cont}}$  are the line center and continuum opacity coefficients, respectively). The numerical experiments showed that this criterion is sufficient for accurate representation of the energy distribution and T-P structure of the models. Decreasing this value leads to significant increase in the number of selected lines but without producing noticeable changes in overall blanketing (see [Shulyak et al. 2004](#)). The preselection procedure was performed twice per model atmosphere calculation: at the first iteration and at the iteration when the temperature correction at each model atmosphere layer is less than a few tens of K. The remaining model iterations are performed with the later line list, thus ensuring a consistency of the preselected lines and the model structure obtained. The spectrum synthesis for the magnetic model atmosphere calculations was carried out in the range between 100 and 40 000 Å, with a constant wavelength step of 0.1 Å.

Generally, due to the variation in the magnetic field vector across the visible stellar surface, one has to compute a number of local model atmospheres for each appropriately chosen surface grid element using individual values of the strength and inclination of the magnetic field. Then, the total flux coming from the star should be obtained by integration of the radiation field intensity corresponding to individual surface zones. However, as shown by [Khan & Shulyak \(2006b\)](#), the inclination of the magnetic field vector does not significantly influence the structure of magnetic models and the resulting energy distribution; i.e., the anisotropy effects can be neglected in the magnetic model atmosphere calculations. Consequently, we assume the magnetic field vector to be perpendicular to the atmosphere normal and, according to the results of Paper I, adopt the field strength of 29 kG. The approach for calculating magnetic models used here is equivalent to the one described in Sect. 2 in [Khan & Shulyak \(2006a\)](#).

**Table 1.** Element abundances of HD 137509.

Element	t12750g3.8 (Paper I)	t13750g42	Sun
He	<-3.50	<-3.50	-1.10
Si	-3.73	-3.58	-4.53
Fe	-3.19	-3.00	-4.59
Cr	-4.20	-3.90	-6.40
Ti	-4.54	-4.20	-7.14
Ca	-7.93	-7.50	-5.73
Mg	-5.71	-5.50	-4.51

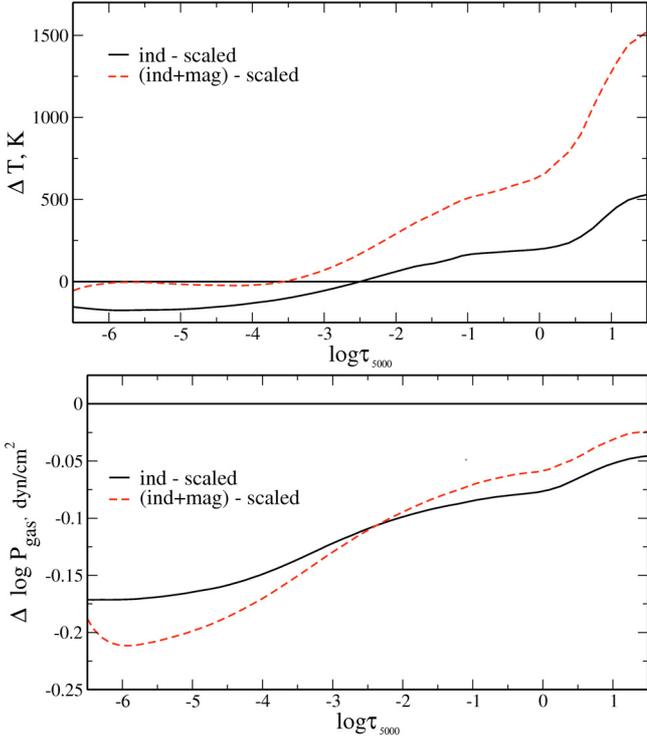
Solar abundances were taken from (1). The second and the third columns give, respectively, abundances derived using the scaled-solar abundance model atmosphere (2) and using model with  $T_{\text{eff}} = 13\,750$  K,  $\log g = 4.2$  with magnetic field included (see Sect. 3.4). Abundances are given in the logarithmic scale  $\log(N_{\text{el}}/N_{\text{total}})$ .

References. (1) [Asplund et al. \(2005\)](#); (2) [Kochukhov \(2006\)](#).

For all models presented in this study we assume a force-free configuration of the surface magnetic field. This agrees with the results of multipolar modeling of magnetic topology ([Kochukhov 2006](#)) and implies that possible modification of the hydrostatic equilibrium by the Lorentz force (see [Shulyak et al. 2007](#), and references therein) is absent in HD 137509. Thus, all differences in the pressure structure between magnetic and non-magnetic models that we obtain are only caused by additional opacity in the Zeeman components.

The necessity to perform polarized radiative transfer calculations over a wide wavelength range makes the models with magnetic field very computationally expensive. To reduce computational costs, we used the following approach. Fixing fundamental parameters and the abundance pattern we calculated a non-magnetic model. After this model was converged, a model with magnetic field was iterated using the temperature-pressure structure of the initial non-magnetic model as a first approximation.

The abundances of seven chemical elements for HD 137509 were derived in Paper I and are listed in Table 1, (second column). Due to the abnormal weakness of the He lines, the value of the He abundance should be considered only as an upper limit. One can note the strong overabundance of Si, Fe, Cr, and Ti, whereas Ca and Mg are underabundant by more than 1 dex relative to the solar chemical composition. We assume solar abundances from [Asplund et al. \(2005\)](#) for all other elements. Using available observations it is not possible to derive abundances of elements other than those listed in Table 1 with good accuracy due to complex line shapes and strong blending by iron-peak elements. There are no usable lines of intrinsically abundant elements such as C, N, and Ne, while the abundance of O that could in principle be determined from the IR triplet (7772–7775 Å) is unreliable due to large NLTE effects and instrumental artifact in the UVES spectrum of HD 137509 in this region. According to our recent investigation ([Khan & Shulyak 2007](#)), C, N, and O belong to the group of elements that produces only a small change in the model structure of A and B stars even if their abundances are reduced by 1 dex relative to the solar values. Finally, to ensure the consistency between the model atmosphere and the abundance pattern of the star, we constructed stellar atmosphere models with these individual abundances including magnetic field. Then we tried to assess relative importance of this sophisticated approach.



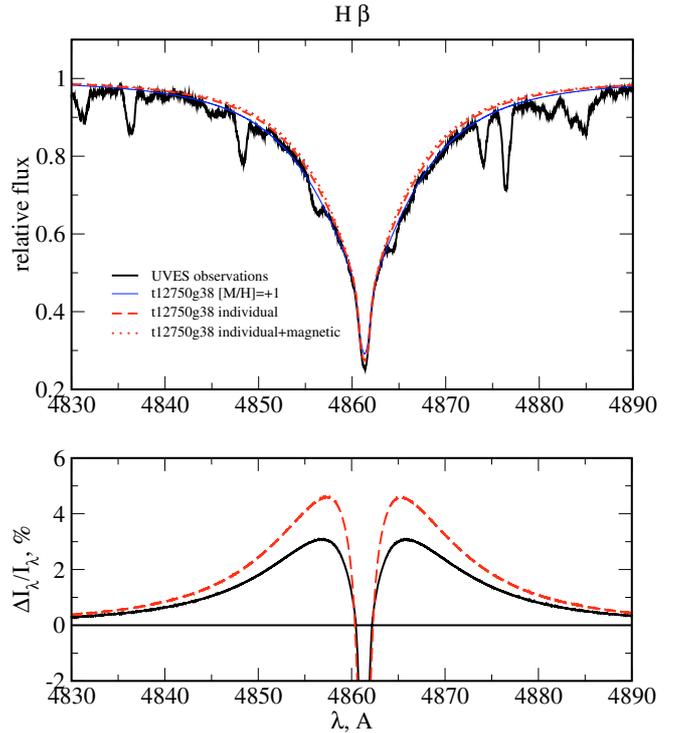
**Fig. 1.** Difference in temperature (*upper panel*) and gas pressure (*bottom panel*) of the models calculated with individual abundances (solid line) and with individual abundances+magnetic field (dashed line) with respect to the reference model atmosphere computed with scaled-solar abundances ( $[M/H] = +1$ ). For all models  $T_{\text{eff}} = 12\,750$  K and  $\log g = 3.8$  are adopted.

### 3. Results

#### 3.1. Model structure

The effect of the peculiar abundance pattern and magnetic field on the temperature-pressure structure of the model atmosphere of HD 137509 is shown in Fig. 1. The model with individual abundances exhibits a decrease in temperature in the surface layers, while the layers close to the photosphere ( $\log \tau_{5000} \approx 0$ ) are heated compared to the reference scaled-solar abundance model ( $[M/H] = +1.0$ ). The effect of magnetic field is, therefore, considerably different compared to a change in metal abundance. The inclusion of magnetic field leads to heating of the surface layers due to additional opacity in the Zeeman components. This occurs because a high line density in the dominant UV part of the stellar spectral energy distribution makes it possible for the backwarming effect to occur even in surface layers, which become opaque at these wavelengths (Kochukhov et al. 2005). The temperature distribution of the magnetic model in the surface layers tends to be close to that of the scaled-solar model. At the same time, magnetic field appears to influence the temperature structure more efficiently in deep atmospheric layers than do the non-magnetic model with individual abundances.

Both magnetic and non-magnetic models show a decrease in the gas pressure throughout the atmosphere compared to the reference model. However, the model with the magnetic field shows a steeper depth dependence of the pressure difference relative to the model where only individual abundances are taken into account. In our hydrostatic models the decrease of the gas pressure is caused by the respective increase of the radiative pressure due to enhanced opacity for models with individual abundances



**Fig. 2.** Observed and calculated H $\beta$  line profiles. *Upper panel*: thick line – UVES observations (Paper I); thin line – the model with solar-scaled abundances  $[M/H] = +1$ ; dashed line – the model with individual abundances; dotted line – the model with both individual abundances and the magnetic field. *Bottom panel*: difference (in per cent) between model with only individual abundances (solid line) and with individual abundance+magnetic field (dotted line) relative to the scaled-solar abundance model ( $T_{\text{eff}} = 12\,750$  K,  $\log g = 3.8$  for all models).

and magnetic field. Note that the model with the magnetic field included exhibits a noticeable increase of the radiative pressure in the outer atmospheric layers compared to other models. This behavior of the radiative pressure and corresponding changes in the overall temperature-pressure structure of the magnetic atmosphere are relevant for modern studies of the radiatively-driven chemical diffusion in the atmospheres of magnetic stars (e.g., Alecian & Stift 2007).

At this point it is difficult to predict the total effect of the magnetic field on the spectral characteristics of the star. In two different atmospheric regions (surface and photospheric layers), the magnetic field influences the model structure in a different manner, so that the properties of magnetic atmosphere of HD 137509 are not equivalent to the usual non-magnetic model with a different set of fundamental parameters. One can expect that spectral features that are selectively sensitive to either temperature or pressure may show different behavior. In the following section we examine the overall effect of the individual abundances and magnetic field on the hydrogen Balmer line profiles and metallic line spectra.

#### 3.2. Hydrogen line profiles and metallic line spectra

The introduction of peculiar abundances taken from Paper I (see Table 1) to the model atmosphere calculations for HD 137509, together with the magnetic field, leads to noticeable changes in the hydrogen line profiles. In Figs. 2 and 3, we compare theoretical profiles for different model atmospheres with those observed for HD 137509. Synthetic profiles were calculated using the

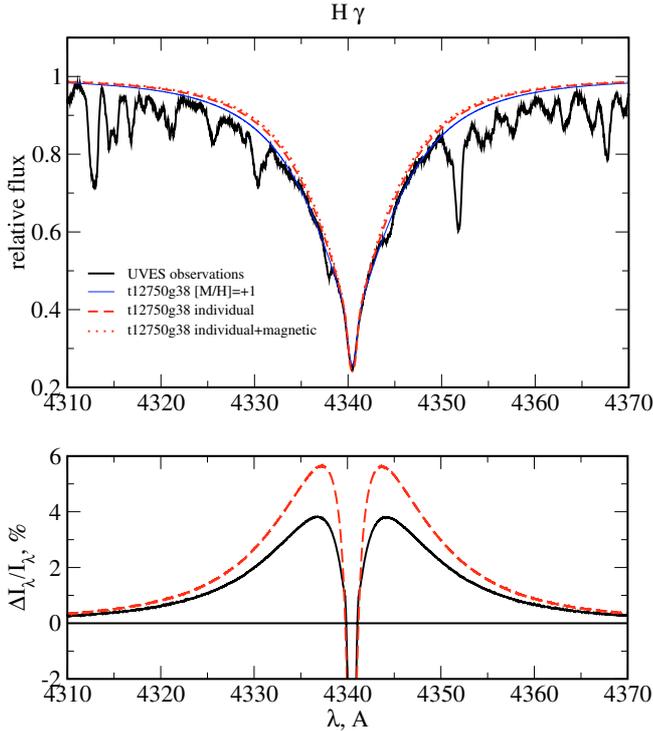


Fig. 3. Same as in Fig. 2 but for the H $\gamma$  line.

SYNTHMAG program (Kochukhov 2007). This code incorporates recent improvements in the treatment of the hydrogen line opacity (Barklem et al. 2000) and takes magnetic splitting of hydrogen lines into account. However, possible modification of the Stark broadening by magnetic field (Mathys et al. 2000) is neglected. The observed profiles of hydrogen lines are extracted from the UVES spectrum of HD 137509 described in Paper I.

One can see that, to retain acceptable agreement between observations and theory, it is necessary to increase the  $\log g$  value from 3.8 derived in Paper I to 4.0. Note that most of the changes in the hydrogen line profiles are due to anomalous abundances adopted for the star (mainly due to extreme He underabundance). Nevertheless, the changes in the temperature-pressure structure of the atmosphere produced by the magnetic field are also important and have to be incorporated to the model to retrieve an accurate estimate of the gravitational acceleration.

The metallic line spectra are not particularly sensitive to the changes in the atmospheric model structure associated with the inclusion of the magnetic field. Figure 4 shows the observed and synthetic profiles of some prominent spectral lines of silicon. All theoretical spectra were calculated using the SYNTHMAG code with the same abundances and the homogeneous surface magnetic field distribution, characterized by  $\langle B \rangle = 29$  kG, but using two different model atmospheres: one model only has individual abundances and another one includes both anomalous abundances and the magnetic field. For both models the fundamental parameters are  $T_{\text{eff}} = 12\,750$  K,  $\log g = 4.0$ . The calculated spectra were convolved with  $v \sin i = 20$  km s $^{-1}$  rotational broadening to allow comparison with observational data. The effects of the magnetic field in the model atmosphere distort different lines in different ways. Some of the spectral features considered here are not sensitive to the magnetic model atmosphere effects at all (for example, Si II 4130.872 Å and Si II 4130.894 Å), while other lines show a noticeable discrepancy between the spectra computed for magnetic and non-magnetic atmospheres

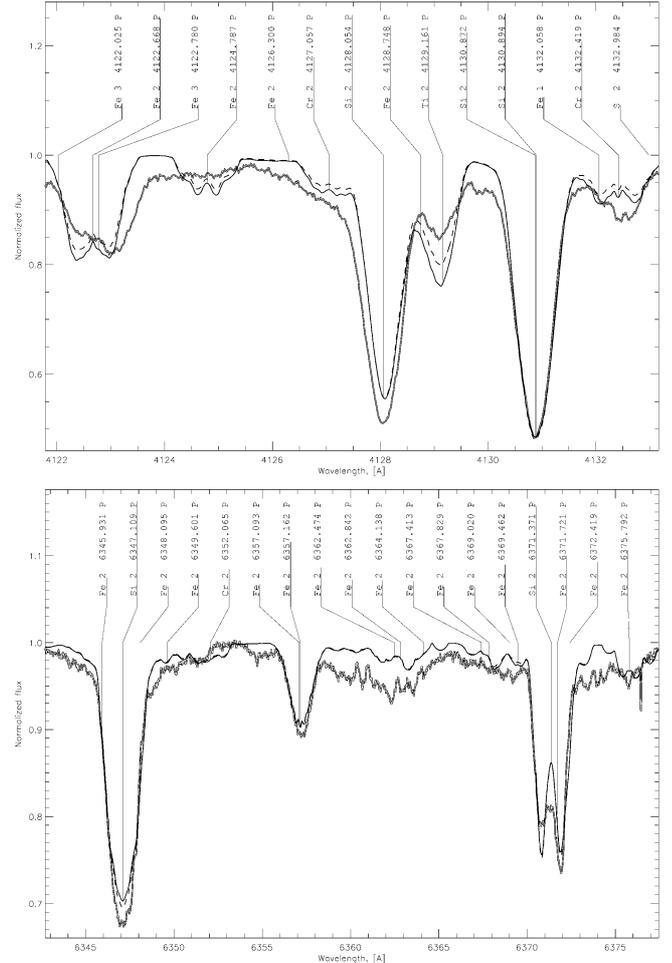
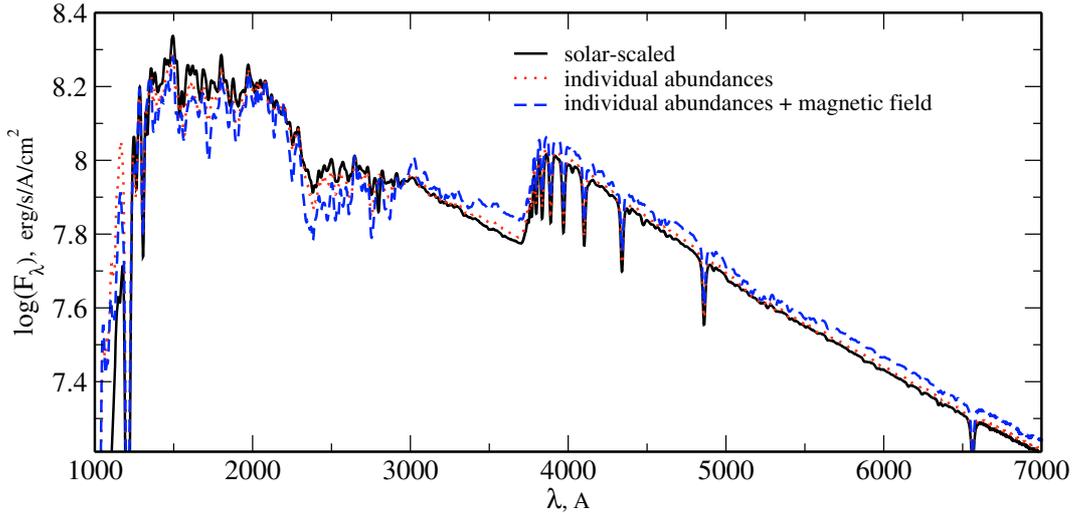


Fig. 4. Influence of magnetic model structure on the profiles of selected spectral lines for  $T_{\text{eff}} = 12\,750$  K,  $\log g = 4.0$  models. Double line – UVES observations; thin line – spectra calculated using the non-magnetic atmospheric model; dashed line – with the magnetic field included.

(e.g., Ti II 4129.161 Å). The average difference between the line profiles obtained from the magnetic and non-magnetic models was found to be a few per cent for the spectra already broadened by rotation. Due to a very large magnetic broadening (comparable to the rotational Doppler effect), the effect on unconvolved spectra is roughly the same magnitude for all spectral lines considered. These results are in a good agreement with our previous investigation (Kochukhov et al. 2005). However, the present results are more accurate because polarized radiative transfer was taken into account for both the model atmosphere and spectrum synthesis calculations.

### 3.3. Energy distribution

Generally, for self-consistent modeling of stellar atmospheres, the following observables must be reproduced simultaneously: hydrogen line profiles, energy distribution, and metallic line spectra. Among these, the flux distribution is especially sensitive to the overall energy balance in the stellar atmosphere over a wide range of optical depths. This observable is extremely useful for determining basic stellar parameters and is preferable in this respect to broad- and intermediate-band photometric data. The role of energy distributions is even more important for chemically peculiar stars because most of the widely used photometric



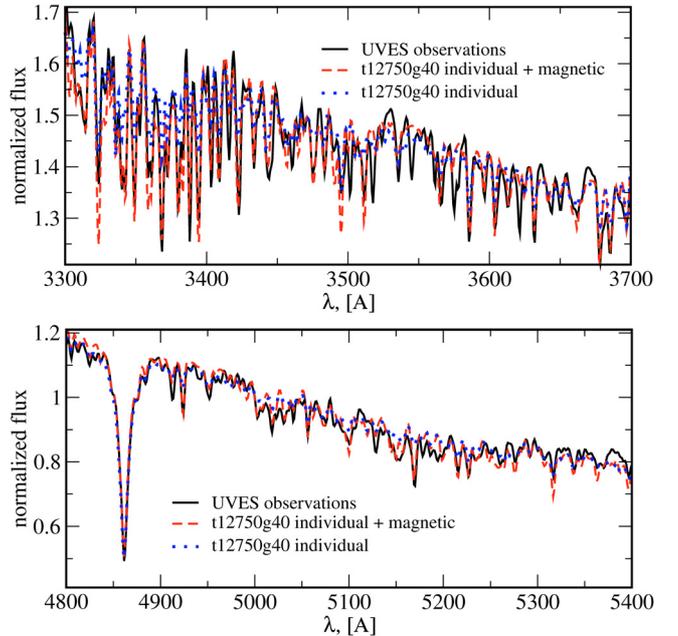
**Fig. 5.** Theoretical energy distributions for the models with  $T_{\text{eff}} = 12\,750\text{ K}$ ,  $\log g = 3.8$ . Solid line – scaled-solar abundance model, dotted line – the model with individual chemical composition, dashed line – the model with individual abundances and the magnetic field. Energy distributions are convolved with a Gaussian profile with  $FWHM = 15\text{ \AA}$ .

calibrations are based on observations of normal stars and, hence, may not be applicable to stars with strong magnetic fields and unusual abundances (Khan & Shulyak 2007).

Figure 5 illustrates the effects of individual abundances and the magnetic field on the energy distributions for the models of HD 137509 with  $T_{\text{eff}} = 12\,750\text{ K}$ ,  $\log g = 3.8$ . It is evident that both the model with individual abundances and the model combining the effects of unusual chemical composition and the strong magnetic field exhibit flux redistribution from the UV to the visual wavelength region. The most significant effect is found for the model with the magnetic field included, which agrees with our previous results.

Due to the increased level of flux in the visual region, the models with magnetic line blanketing are characterized by an anomalous bolometric correction. We find that the difference in this parameter with respect to the computations done for solar chemical composition reaches  $\Delta BC = 0.1\text{ mag}$  for the model with individual abundance, whereas  $\Delta BC \approx 0.15\text{ mag}$  for the model with individual abundance and magnetic field. Thus, the anomaly in the bolometric correction is quite substantial and has to be taken into account in determining absolute luminosity and comparing with evolutionary models of CP stars (e.g., Kochukhov & Bagnulo 2006), yet, even for such an extreme star as HD 137509, we cannot confirm the reality of  $\Delta BC > 0.2\text{ mag}$  proposed by Lanz (1984).

Unfortunately, no suitable observed energy distribution for HD 137509, which could be used for verifying theoretical models, is available in the literature. One can possibly use the flux-calibrated spectrum from the UVES Library<sup>1</sup>. The description of the reduction of these data can be found in Bagnulo et al. (2003). Despite the fact that the UVES pipeline provides a user with the spectra calibrated in relative units, these data can not be used for comparisons with models in a wide spectral range due to the flux calibration uncertainties (Bagnulo, private communication) that could affect the shape of the energy distribution. Nevertheless, the relative shape of the UVES spectra within small spectral regions (300–500 Å) is reasonably well-determined. Therefore, in Fig. 6 we compare relative fluxes (normalized at  $\lambda = 5000\text{ \AA}$ ) of the magnetic and non-magnetic models of HD 137509 with the



**Fig. 6.** Comparison between the observed and calculated fluxes of HD 137509 in the near UV (*upper panel*) and visual region (*lower panel*). Gaussian smearing with resolution  $R = 1500$  is applied to all the spectra to provide a better view. In the upper plot the fluxes for the non-magnetic model are shifted along the vertical axis to match the observed spectrum.

UVES spectrum in two short regions. Both theoretical models presented in the figure were calculated with the abundances from Paper I. Thus, the difference between the two model fluxes is entirely due to the magnetic field, which is responsible for producing the complex spectral features clearly seen in the observed spectra. In particular, the Zeeman splitting influences the strength of the line absorption around  $\lambda = 5200\text{ \AA}$ , which is associated with the well-known depression in the spectra of CP stars and its photometric characteristic ( $\Delta a$  photometry, discussed below). Note that for the comparison of fluxes in the UV region (upper panel in Fig. 6) we had to shift the energy distribution

<sup>1</sup> <http://www.eso.org/uvespop>

**Table 2.** Observed and reddening-corrected calculated photometric parameters of HD 137509.

	$b - y$	$m_1$	$c_1$	$\Delta a$	$U - B$	$V - B$	$G - B$	$B_1 - B$	$B_2 - B$	$V_1 - B$	$X$	$Y$	$Z$
observations	-0.095	0.183	0.411	0.066	0.761	1.136	2.294	0.811	1.566	1.836	0.762	0.076	-0.067
t12250g38, mag	-0.054	0.142	0.640	0.057	0.995	1.088	2.265	0.838	1.574	1.801	1.026	0.122	-0.045
t12250g38, non	-0.040	0.134	0.653	0.033	1.010	1.069	2.261	0.846	1.564	1.777	1.046	0.073	-0.028
t12750g40, mag	-0.057	0.141	0.572	0.054	0.923	1.094	2.277	0.838	1.574	1.806	0.937	0.088	-0.044
t12750g40, non	-0.044	0.135	0.586	0.031	0.941	1.075	2.271	0.846	1.565	1.783	0.957	0.045	-0.029
t13250g40, mag	-0.059	0.135	0.516	0.051	0.860	1.105	2.293	0.834	1.578	1.815	0.863	0.077	-0.041
t13250g40, non	-0.046	0.130	0.529	0.030	0.876	1.087	2.285	0.841	1.570	1.794	0.880	0.040	-0.028
t13750g42, mag	-0.062	0.138	0.455	0.046	0.798	1.106	2.299	0.839	1.574	1.815	0.780	0.029	-0.040
t13750g42, non	-0.051	0.138	0.468	0.030	0.815	1.081	2.282	0.850	1.561	1.788	0.790	-0.023	-0.030
t12750g38, mag	-0.056	0.135	0.573	0.054	0.919	1.101	2.283	0.833	1.579	1.812	0.936	0.107	-0.043
t12750g38, non	-0.043	0.129	0.588	0.032	0.936	1.082	2.277	0.841	1.570	1.790	0.957	0.066	-0.028
t12750g38, scaled	-0.026	0.116	0.581	0.014	0.932	1.061	2.264	0.847	1.564	1.766	0.942	0.032	-0.016
*t13750g42, mag	-0.081	0.153	0.453	0.062	0.800	1.136	2.321	0.829	1.585	1.847	0.799	0.081	-0.051
*t13750g42, non	-0.064	0.144	0.470	0.037	0.820	1.111	2.307	0.837	1.576	1.819	0.818	0.040	-0.036

Theoretical colors were calculated for the models with (“mag”) and without (“non”) magnetic field, using individual abundances. Predictions for the scaled-solar abundance non-magnetic model are given for comparison. The last row reports predictions for the magnetic and non-magnetic models with revised abundances determined in the present paper.

produced by non-magnetic model along the  $y$ -axis to match the observed data. This is a consequence of the substantial difference in the fluxes close to the Balmer jump where the model with the magnetic field shows a prominent flux excess compared to the non-magnetic model (see Fig. 5).

The only other possibility would be to use the flux-calibrated spectra of HD 137509 obtained by the Far Ultraviolet Spectroscopic Explorer<sup>2</sup> (FUSE) mission. However, these data were obtained in a very short wavelength range (910–1185 Å), which makes it impossible to use these spectra for accurately determining fundamental stellar parameters and testing theoretical models. For example, the overall radiative energy emitted inside 910–1185 Å region is about 1.6% of the total flux for the model with  $T_{\text{eff}} = 12\,750\text{ K}$  and about 2.5% for the  $T_{\text{eff}} = 13\,750\text{ K}$  model, which is unimportant for the overall radiative energy balance in the atmosphere of HD 137509. Moreover, the slope of the energy distribution in this region remains the same both models mentioned above. This means that, based on FUSE data, it is impossible to distinguish models different by as much as 1000 K. Well-calibrated energy distribution covering a wide spectral regions is needed.

### 3.4. Photometric colors

As a next step, we calculated a grid of model atmospheres with different effective temperatures ( $T_{\text{eff}} = 12\,250\text{--}13\,750\text{ K}$ ,  $\Delta T = 250\text{ K}$ ) and gravities ( $\log g = 3.8\text{--}4.2$ ,  $\Delta \log g = 0.2$ ) to assess the ability of our models to reproduce the observed photometric properties of HD 137509. To investigate the role of magnetic field, we included both magnetic and non-magnetic models with individual abundances in the grid. We also considered the reference scaled-solar abundances model from Paper I.

The theoretical colors were calculated following the procedure outlined in Kochukhov et al. (2005). We used modified computer codes by Kurucz (1993a), which take into account transmission curves of individual photometric filters, mirror reflectivity, and a photomultiplier response function. The synthetic  $\Delta a$  values were computed with respect to the theoretical normality line,  $a_0$ , determined in Khan & Shulyak (2007). The reddening, corresponding to  $E(B - V) = 0.06$ , was taken into account for all color indices, except  $X$ ,  $Y$ , and  $Z$ , which are

reddening-free (Cramer & Maeder 1979). This value of the color excess was found from the intrinsic  $[U - B]$  color and reddening-free Geneva  $X$  and  $Y$  parameters (Cramer 1982). This estimate agrees with the  $E(B - V)$  range of 0.04–0.08 that one can infer from the dust maps of Lucke (1978) and the revised Hipparcos parallax of HD 137509,  $\pi = 5.12 \pm 0.38\text{ mas}$  (van Leeuwen 2007). The observed Strömgren and Geneva photometric parameters of HD 137509 were taken from the catalog of Hauck & Mermilliod (1998) and Rufener (1989), respectively. The observed value of the  $\Delta a$  parameter was adopted from Pausen et al. (2005). These photometric characteristics of HD 137509 are summarized in the first row of Table 2, which also shows the results of the synthetic color calculations. We present results only for those models that fit the  $H\beta$  and  $H\gamma$  line profiles reasonably well. We also looked into the possibility of using infra-red photometric measurements (e.g., 2MASS<sup>3</sup> or observations by Groote & Kaufmann 1983) to constrain the model parameters. However, the difference between all model fluxes of HD 137509 considered below is less than the observational uncertainty in this spectral range.

There are several things to note in Table 2. First, it is evident that the change in photometric parameters associated with the introduction of the magnetic field and individual abundances in the model atmosphere calculations amounts to a few hundreds of a magnitude compared with the scaled-solar abundances model and that, generally, magnetic models allow us to improve the fit to the observed values of all photometric indices. The only exceptions are the parameter  $Y$  for the model with  $T_{\text{eff}} = 12\,250\text{ K}$ ,  $\log g = 3.8$  (its value for non-magnetic model is closer to the observed one compared to the magnetic model) and the index  $B_2 - B$  (which tends to increase if the magnetic field is introduced to calculations, while decreasing is needed to fit the observations). Although the overall changes in the color indices are not very large even for such a strong magnetic field, we conclude that taking into account Zeeman splitting and magnetic intensification of spectral lines clearly is a necessary ingredient for modeling photometric observables of magnetic stars. Of course, the dependence of photometric colors on the magnetic field is sensitive to the chemical composition of the star. The increased metal content of the stellar atmosphere has a big impact on the photometric colors and thus HD 137509 represents one of the extreme

<sup>2</sup> <http://fuse.pha.jhu.edu/>

<sup>3</sup> <http://www.ipac.caltech.edu/2mass/>

cases due to the strong overabundance of iron-peak elements in its atmosphere.

To distinguish between the effects of magnetic field and individual abundance we also compared synthetic colors for the models calculated with the same fundamental parameters ( $T_{\text{eff}} = 12\,750\text{ K}$ ,  $\log g = 3.8$ ) but different assumptions about abundances and magnetic field. Comparing the models with scaled-solar abundances with individual abundances model and the latter model with the magnetic model atmosphere+individual abundances, one can infer that the effect of the very strong magnetic field on photometric observables is generally comparable in magnitude with the effect of individual abundances alone. Interestingly, for some of the color indices, the difference between the models calculated with and without magnetic field is greater than the same difference between the non-magnetic model with individual abundances and the reference scaled-solar model. This is the case for  $c_1$ ,  $\Delta a$ ,  $U-B$ ,  $X$ ,  $Y$ , and  $Z$ . One should not forget that we are dealing with an effect depending on many parameters, i.e. the overall picture will depend upon the effective temperature and the abundance pattern, and thus could differ a lot from one star to another even if the field strength is the same. Limiting our conclusions to HD 137509, we find that the effect of the magnetic field is no less important than the effect of individual abundances for the majority of the photometric colors considered in the present study.

Finally, we have also investigated the importance of accurate photoionization cross-sections for individual states of Si I and Si II ions taken from the TOPBase database (Cunto et al. 1993). The importance of accurate photoionization cross-sections with the full resonance structure of Si II was noted by Lanz et al. (1996). They found that accounting for wide TOPBase resonances in the spectrum synthesis calculations leads to a good fit to the observed UV spectra of the Bp star HD 34452 ( $T_{\text{eff}} = 13\,650\text{ K}$ ,  $\log g = 4.0$ ), which has an enhanced Si abundance. This could be an important effect for HD 137509 because this star is also characterized by an excess in Si in its atmosphere. Thus, we have implemented available Si I and Si II cross-section data from the TOPBase web page<sup>4</sup> in the LLMODELS atmospheric calculations. In this modeling we did not use any additional techniques, such as resonance-averaging of photoionization cross-sections data or combining energy levels to superlevels, which are usually suggested to reduce computational expenses. All the energy levels for both ions were explicitly included in the opacity calculations. We found that, even for the hottest model considered here, the effect of detailed photoionization cross-sections is negligible for the majority of color indices in comparison with the bound-bound treatment of resonance structure via autoionizing lines. The strongest deviation between the model with the TOPBase data and the model with Si I and Si II continuous opacities taken from the ATLAS12 code (Kurucz 1993b) is found for  $c_1$  ( $-0.004\text{ mag}$ ),  $U-B$  ( $-0.007\text{ mag}$ ),  $X$  ( $-0.01\text{ mag}$ ), and  $Y$  ( $-0.01\text{ mag}$ ). We found that the main reason for such a weak influence of the detailed photoionization data is that some of the strong autoionizing lines of Si I and Si II are already included in the VALD database and hence in the standard LLMODELS input line list. This means that the photoionization cross-sections from ATLAS12, together with the autoionizing lines from VALD, provide a reasonably good approximation to the opacity calculated from the more accurate TOPBase data, at least for temperatures around  $12\,750\text{ K}$ . It is worth noting that here we are mainly interested in the color indices; however, the accurate photoionization cross-sections are

essential when it comes to the comparison of theoretical calculations with high-resolution UV spectra of Si-rich stars.

### 3.5. An improved model for HD 137509

The behavior of  $b-y$ ,  $c_1$  and  $X$  indices suggests that the effective temperature of HD 137509 could be higher than the initially derived value of  $12\,750\text{ K}$  that was used in Paper I. To improve the model parameters in a consistent way, we redetermined abundances of chemical elements using a model atmosphere with  $T_{\text{eff}} = 13\,750\text{ K}$ ,  $\log g = 4.2$  calculated with magnetic field and individual abundances from the second column of Table 1. The resulting new abundances, determined using the same methodology and spectral regions as in Paper I, are listed in the third column of Table 1. The new chemical abundances are systematically higher by  $0.2\text{--}0.4\text{ dex}$  compared to the values reported in Paper I. This is mostly a result of using the model atmosphere with  $1000\text{ K}$  higher effective temperature. The atomic lines used for abundances analysis become systematically shallower with the increase in atmospheric temperature, thus resulting in positive abundance corrections. Using these new abundances, we made a next iteration by re-calculating the model atmosphere to ensure consistency of the model temperature-pressure structure and adopted abundances. This final model allowed us to fit the hydrogen line profiles as well as in previous models. It also improves the agreement between observed and computed photometric parameters, with a few exceptions, as demonstrated by the two last rows of Table 2 (models marked with asterisks). Thus, we can conclude that the effective temperature of HD 137509 should be around  $13\,750\text{ K}$ .

We would like to note that exact fitting of the photometric indices is hardly feasible for any model due to additional, unknown parameters involved in the modeling process. One of the effects that we have ignored is inhomogeneous surface distribution of chemical elements in HD 137509. Mathys & Lanz (1997) discussed rotational modulation of the equivalent widths of Cr II, Si II, and Fe II lines, and the light variability in the  $U$ ,  $B$ , and  $V$  filters with the maximum amplitude of about  $0.05\text{ mag}$  for the  $U$  filter. These phenomena are usually attributed to the abundance spots on the stellar surface. Therefore, to fully characterize atmospheric properties of HD 137509, one would need to obtain time-resolved observations and reconstruct surface distribution of magnetic field and chemical abundances with the Doppler imaging technique (e.g., Kochukhov et al. 2004). Furthermore, the vertical stratification of chemical elements (e.g., Kochukhov et al. 2006) could also take place in the atmosphere of HD 137509. A refined analysis of these chemical inhomogeneity effects is outside the scope of our study.

## 4. Summary and conclusions

In the present paper we have constructed advanced theoretical stellar model atmospheres incorporating accurate treatment of the individual abundances pattern, Zeeman splitting, and polarized radiative transfer and have compared the results with the observations of extreme magnetic CP star HD 137509. With the mean surface field of  $\langle B \rangle \approx 29\text{ kG}$ , this object has the second largest magnetic field among CP stars. Strong overabundance of iron-peak elements and extreme underabundance of helium in the atmosphere of this star opens the possibility of investigating the importance of taking individual abundances into account when constructing model atmospheres of magnetic chemically peculiar stars. Theoretical model atmosphere calculations were compared with the hydrogen line profiles and metallic spectrum

<sup>4</sup> <http://vizier.u-strasbg.fr/topbase/topbase.html>

of HD 137509. The Strömgren and Geneva photometric parameters were also investigated. The main conclusions of our study can be summarized as follows:

- We found that the effect of individual abundances dominates the change in Balmer  $H\beta$  and  $H\gamma$  line profiles compared to the model with solar-scaled abundances. This implies that once the abundances of the star have been determined using an approximate model, it is necessary to recalculate the model atmosphere to ensure the consistency between abundance pattern and the model structure. The magnetic field has less influence on the hydrogen lines; however, it should be taken into account for stars with very strong magnetic fields.
- Modification of the atmospheric temperature-pressure structure due to the presence of the magnetic field and peculiar abundances generally has little impact on the metal line profiles compared to that of non-magnetic one.
- For HD 137509, the effect of magnetic field on photometric colors is very important for some photometric parameters. Occasionally the combined impact of the magnetic field and the realistic chemistry is more important than the effect of using only individual abundances. Generally, magnetic model atmospheres allow us to obtain better agreement between almost all observed and theoretical color indices. Thus, we can conclude that magnetic field should be taken into account in the analysis of stars with strong magnetic fields.
- We showed that the analysis of the spectra of such extreme Bp stars with strong magnetic fields and unusual chemistry as for HD 137509 requires a self-consistent approach. Once the abundances of the most important elements are derived using an approximate model atmosphere, it is necessary to recompute the model with new abundances, trying to fit various observables such as hydrogen line profiles, photometric colors, and energy distribution (if available). For HD 137509 we found that the simultaneous fit to the hydrogen line profiles and photometrical indices employing the model with both magnetic field and individual abundances included requires as much as 1000 K correction to the effective temperature and 0.4 dex correction to the surface gravity compared to the results obtained using simple scaled-solar models.
- We expect that the overall energy distribution of the star is strongly modified by magnetic line blanketing. However, the lack of accurate energy distribution covering meaningful wavelength region in the spectrum of HD 137509 precludes us from reaching robust quantitative conclusions. We emphasize that availability of the flux distributions for this and other magnetic CP stars is important for determining stellar parameters and for verifying the new generation model atmospheres of magnetic CP stars.

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