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Detailed abundance analysis of five field blue horizontal-branch stars

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ABSTRACT

Previous studies have shown that hot blue horizontal-branch (BHB) stars in globular clusters present abundance anomalies of certain chemical elements in their atmosphere; some metals are overabundant while helium is underabundant. Vertical stratification of chemical species, including iron, is also found in the atmosphere of a number of these objects. The aim of our work is to do a detailed abundance analysis of BHB stars found in the field. We studied the stars HD 128801, HD 143459, HD 213781, and HZ 27, using our high-resolution spectra in the visible region obtained with ESPaDOnS at the Canada–France–Hawaii Telescope, and also Feige 86, using existing Ultraviolet and Visual Echelle Spectrograph visible spectra from the ESO archives. We searched for vertical stratification of the elements identified in our five stars, with the ZEEMAN2 code and stellar model atmospheres of PHOENIX. We confirm here the star rotational and radial velocities previously found, along with their average abundances. For the three cooler stars in our sample (HD 128801, HD 143459, and HZ 27), most elements detected are underabundant. For the two hotter stars (Feige 86 and HD 213781), the abundances of most elements are near or above their solar value. Of all the elements studied, only phosphorus is clearly found to be vertically stratified in the atmosphere of HD 213781. Marginal indications of vertical stratification of iron is observed for Feige 86. The chemical properties of the five field BHB stars are consistent with those of their globular-cluster counterparts.

Key words: diffusion – stars: abundances – stars: atmospheres – stars: horizontal branch.

1 INTRODUCTION

Stars found on the horizontal branch burn helium in their core (e.g. Hoyle & Schwarzschild 1955). Since these are evolved stars, a relatively large number of them are found in globular clusters. Already, many efforts (see studies cited below) have been deployed to study horizontal-branch stars in globular clusters. The so-called blue horizontal-branch stars (hereafter BHB stars) are those hotter than objects on the RR Lyrae instability strip. BHB stars are of particular interest, since some of them show several observational anomalies as compared to red horizontal-branch stars.

Several studies have shown that BHB stars hotter than $T_{\rm eff} \simeq$ 11 500 K found in globular clusters display abundance anomalies such as an underabundance of He and an overabundance of several metals compared to the average cluster abundances (Glaspey et al. 1989; Behr et al. 1999; Moehler et al. 1999). Since the distance of stars belonging to the same cluster are generally assumed to be identical, relative photometric errors for cluster BHB stars are greatly reduced. Detailed studies of BHB stars in globular clusters have shown other anomalies such as photometric jumps (Grundahl et al. 1999) and photometric gaps (Ferraro et al. 1998). These jumps and gaps occur near $T_{\rm eff} \simeq 11\,500$ K. Stars hotter than this effective temperature also show a relatively sudden drop in their rotational velocities to typical values of $V \sin i \simeq 10$ km s^{-1} or less (Peterson, Rood & Crocker 1995; Behr et al. 2000a; Behr, Cohen & McCarthy 2000b; Behr 2003a), as well as lower spectroscopic gravities compared to those predicted by canonical evolutionary models (e.g. Crocker, Rood & O'Connell 1998; Moehler, Heber & de Boer 1995).

The small rotational velocities for the globular-cluster BHB stars with $T_{\rm eff} \geq 11\,500$ K suggest that their atmosphere could be hydrodynamically stable and that atomic diffusion, as described by Michaud (1970), could therefore be important. This physical process could then be responsible for the abnormal abundances detected as well as the other anomalies described above, because diffusion may lead to vertical stratification of the elements which may modify the physical structure of the atmosphere of hot BHB stars. Recently, Khalack et al. (2007, 2008) and Khalack, LeBlanc & Behr (2010) have detected vertical stratification of several elements, including iron in eight BHB stars in globular clusters, and nitrogen and sulphur in one BHB star in the field (HD 135485). These results confirm the presence of atomic diffusion in the atmospheres of hot BHB stars.

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Since the abundance stratification of chemical elements can affect the atmospheric structure, Hui-Bon-Hoa, LeBlanc & Hauschildt (2000) and LeBlanc et al. (2009) constructed self-consistent model atmospheres that take into account the stratification caused by diffusion. These models demonstrated indeed that the structural changes brought to the atmospheres of hot BHB stars by the presence of vertical stratification are responsible for the photometric anomalies discussed above. These models can also explain the lower spectroscopic gravities observed for such stars (Hui-Bon-Hoa et al. 2000; LeBlanc, Hui-Bon-Hoa & Khalack 2010). Since the diffusion time-scales in stellar atmospheres are much smaller than evolutionary ones (e.g. LeBlanc 2005), abundance stratification may be created relatively quickly there. Unfortunately, these atmospheric models are not time-dependent and it is therefore not known if such abundance stratification profiles are transient in nature, and if so, on what time-scales.

The main goal of this paper is to increase the quantity of detailed information about the chemical abundances and their possible vertical stratification in the atmospheres of field BHB stars (where different properties could be found compared to globular-cluster BHB stars) and in order to further test the hypothesis related to diffusion. Abundances from each individual line is measured in spectra that we recently obtained with ESPaDOnS (at R = 81 000) at the Canada–France–Hawaii Telescope (CFHT) for the stars HD 128801, HD 143459, HD 213781, and HZ 27, as well as in the archival ESO spectrum (R = 80 000 to 110 000) for Feige 86 (or BD + 30°3431). This spectrum was studied by Cowley et al. (2007), where they confirmed that wavelength shifts in the Ca II infrared triplet of chemically peculiar (CP) stars are due to the heavy isotope ^{48}Ca. Four of the stars we have selected have been identified as field horizontal-branch stars by Behr (2003b). The fifth star of our sample, HD 213781, was marked as a probable one. The effective temperature of our stars is in the range from 9800 to 16 000 K, i.e. near and above the limit where atomic diffusion comes into play in hot globular-cluster BHB stars.

As opposed to BHB stars found in globular clusters, relatively few elaborated studies exist for corresponding stars found in the field. To study abundance anomalies in main-sequence A stars, including one of our stars HD 143459 (or HR 5959), Lemke (1989, 1990) used high-resolution spectra ($\Delta\lambda$ = 58.9 mÅ) taken with the ESO Coudé Echelle Spectrometer to observe lines of Fe, Ti, C, Si, Ca, Sr, and Ba. Adelman & Philip (1996) obtained the abundance of several elements for eight field horizontal-branch stars of spectral type A using medium resolution ($\Delta\lambda$ = 0.14 Å) spectra obtained at the Kitt Peak National Observatory (KPNO). One of these stars, namely HD 128801, is analysed here using higher resolution data. The work of Kinman et al. (2000) includes an analysis of the abundances of several tens of field BHB candidates, including again HD 128801. The abundance of Mg, Ti, and Fe of this star was determined with KPNO spectra with a resolution R = 15 000. Bonifacio, Castelli & Hack (1995) determined $T_{\rm eff}$ and log g of the field BHB star Feige 86, one of our sample stars. They used AURELIE spectra from the Observatoire de Haute-Provence with a resolution ranging from 31 000 to 60 000 and spectra from the *International Ultraviolet Explorer* (*IUE*) to estimate the abundance of several elements. Behr (2003b) also studied many red and blue horizontal-branch stars using echelle data from the McDonald Observatory at R = 60 000 along with HIRES data from Keck I at R = 45 000. He obtained $T_{\rm eff}$, log g, V sin i and the abundance of Mg and Fe for the stars of his sample. In addition, he also determined the abundance of He, Si, and P for five possible hot BHB stars. He studied all the sample stars presented here. As mentioned above, Khalack et al. (2007) studied the field BHB star HD 135485 with high-resolution data (R = 60 000 and 80 000). They found that the chemical elements N and S are stratified in the atmosphere of this star. More recently, For & Sneden (2010) analysed spectra obtained with the McDonald Observatory (R = 60 000) of 12 field BHB stars with $T_{\rm eff}$ between 7650 and 9000 K and found an underabundance of Fe.

Table 1. Physical parameters of the stars studied from Behr (2003b).

Star	$T_{\rm eff}$ (K)	log g (cm s^{-2})	[M/H]
Feige 86	$16\,111^{+413}_{-581}$	$3.78^{+0.65}_{-0.63}$	0.00
HD 128801	$10\,162^{+291}_{-327}$	$3.54^{+0.36}_{-1.03}$	−1.50
HD 143459	9990^{+174}_{-250}	$3.57^{+0.19}_{-0.29}$	−1.00
HD 213781	$13\,332^{+347}_{-374}$	$3.38^{+0.57}_{-0.49}$	0.00
HZ 27	9882^{+206}_{-371}	$3.38^{+0.40}_{-0.58}$	−1.50

This study is another step towards the ultimate goal to compare the properties of field BHB stars, in particular those related to the abundances and their stratification, with those of similar stars found in globular clusters. In this paper, we first describe the physical properties of the stars in our sample. Details concerning the observations and the spectra used are given next. Sections outlining the methods employed for the spectral analysis and presenting the results obtained as well as concluding remarks follow.

2 STARS STUDIED

The five stars studied here were identified as field BHB stars (or as a probable one in the case of HD 213781) by Behr (2003b). This author determined the basic physical parameters of these stars, effective temperature and surface gravity, as well as their rotational and radial velocities, along with their Fe and Mg abundances. For two of these stars (Feige 86 and HD 213781), he also determined the abundance of He, Si, and P. The basic physical parameters found by Behr (2003b) have been adopted here (see Table 1) to calculate model atmospheres needed for our simulations. The metallicity [M/H] employed for the preparation of the model atmospheres are estimated using the Fe abundance of each star found by Behr (2003b).

The five stars selected were chosen because of their relative brightness in the aim of obtaining high signal-to-noise spectra in a reasonable exposure time. This factor considerably restricted our choices of field BHB stars. Due to the scarcity of bright targets, the effective temperature of only two of the five stars chosen (see Table 1; Feige 86 and HD 213781) is above the threshold where diffusion is present in the atmospheres of globular-cluster BHB stars. Also, according to the results of Behr (2003b), only three of the selected stars have a low rotational velocity (V sin i < 10 km s^{-1}). The two others, namely HD 143459 and HD 213781, have V sin i >30 km s^{-1}. Moreover, Behr (2003b) also found that only two of these stars (Feige 86 and HD 213781) show an Fe abundance greater than the solar value.

3 OBSERVATIONS

Four of the selected objects were observed at the CFHT; we obtained high-resolution spectra of HD 143459, HD 128801, HD 213781, and HZ 27 with the echelle spectrograph ESPaDOnS (see Table 2 for the observational information). ESPaDOnS offered the complete spectrum in the visible region, covering the wavelength range from 3700 to 10 500 Å, in a single exposure with a high spectral

Table 2. Observational information for the five stars studied.

Star	Date	t_{exp}	Instrument	SNR (per pixel)
Feige 86	19-03-2006	1600	UVES	241
HD 128801	19-09-2013	2100	ESPaDOnS	424
HD 143459	19-09-2013	180	ESPaDOnS	512
HD 143459	14-08-2013	180	ESPaDOnS	512
HD 213781	19-09-2013	2940	ESPaDOnS	387
HD 213781	13-06-2014	1500	ESPaDOnS	261
HZ 27	15-04-2014	2394	ESPaDOnS	190

resolution R = 81 000 in the 'star only' mode. One or two exposures were obtained between 2013 and 2014 for these four stars. The total exposure time varies between 360 s and almost 4400 s. The peak signal-to-noise ratio (SNR) per pixel for these CFHT stars is between 190 and 720. The CFHT spectra were reduced with the ESPaDOnS software LIBRE-ESPRIT, developed by Donati et al. (1997).

The spectrum for a fifth object, Feige 86, was taken from the ESO archive (see Table 2). It was obtained in 2006 with the Ultraviolet and Visual Echelle Spectrograph (UVES) at UT2 of the VLT. It covers the wavelength range from 3300 to 9300 Å. The red and blue portions of the spectrum correspond to a resolving power R = 110 000 and 80 000, respectively. An SNR of 240 per pixel was achieved with a 1600 s exposure. The spectrum reduction was done with the UVES pipeline Data Reduction Software (version 2.5).

4 ABUNDANCE ANALYSIS

4.1 Procedure used for the spectral analysis

After identifying the atomic lines present in the observed spectra using the VALD-3 (Kupka et al. 1999) and NIST (Kramida, Ralchenko & Reader 2013) data bases, the ZEEMAN2 code (Landstreet 1998) was used to simulate each chosen line profile individually. Each line profile analysed has been cut and normalized individually prior to using ZEEMAN2. The model atmospheres used in our study were calculated with version 15 of the PHOENIX atmosphere code (Hauschildt, Allard & Baron 1999) in the local thermodynamic equilibrium (LTE) mode. The atmospheric parameters used for each model were adapted for each star (as given in Table 1).

Through the line fitting procedure (see Fig. 1 for examples of fits), ZEEMAN2 calculates the ion abundance $\log(N_{\rm ion}/N_{\rm tot})$, the radial velocity, and the projected rotational velocity, as well as the optical depth $\log(\tau_{5000})$ of the line centre at each layer of the chosen underlying model atmosphere. The ZEEMAN2 code has been modified by Khalack & Wade (2006) using the *downhill simplex method* (Press et al. 1992) to find the proper minimum for the error of the fit. In our work, only lines with a profile quality fit $\chi^2 \leq 3$ were used.

During our spectral analysis, we have done several tests with different continuum normalizations. We ended up rejecting a line when the normalization was influenced by the presence of multiple nearby lines in the continuum region as it gave a strong deviation ($>3\sigma$) of the stellar radial velocity. Furthermore, we only kept the lines that are not blended with another species, otherwise the number of free parameters (for all the ions responsible for the line profile) becomes too large. Blended lines of the same species are treated in our work as a single line profile (or data point); the optical depth ($\log(\tau_{5000})$) associated with this profile is the one related to its strongest component. Also, a few lines have been rejected on the basis of a large deviation of their radial and/or rotational velocity, as it suggested a bad identification of the ion. Finally, to take into account other sources of uncertainties related to the model (i.e. uncertainty for $T_{\rm eff}$, $\log g$, and metallicity) or potential non-LTE (NLTE) effects and uncertainties related to the atomic data, we arbitrarily multiplied the abundance uncertainties given by ZEEMAN2 by a factor 10. The final list of the atomic lines analysed for each star studied here is presented in Table 3, along with their wavelength λ, $\log gf$-values, lower energy level $E_{\rm low}$, and values obtained for their abundance and their line formation depth (the complete version of this table is found exclusively in the online version of the paper).

By associating the abundance obtained for each individual line to the layer of the model atmosphere where the optical depth of the line centre equals unity, possible variations of the abundance relative to depth may then be studied. A sufficient number of lines formed at different depths is however needed for such an analysis. All lines observed for an element, considering all its ions, must also be taken into account to study the vertical stratification of an element. This also assumes that the wavelength domain considered here covers the most important lines of an element and sample a broad physical domain in the atmosphere. This method, presented in Khalack et al. (2007, 2008, 2010) considering lines in a similar wavelength domain in the visible and with a similar high spectral resolution than our data, has been successfully used to detect abundance stratification in several globular-cluster BHB stars and in the field BHB star HD 135485. These stars cover a broad range of effective temperature. It has also been used to detect the abundance stratification in main-sequence CP stars (Khalack & LeBlanc 2015; LeBlanc et al. 2015).

The average abundance for each ion is also estimated here considering the results for the individual lines studied for the ion. The radial and rotational velocities for each star are also evaluated by calculating the mean of the values obtained for all the star's selected lines. An uncertainty for these parameters is calculated from the mean quadratic deviation of the individual line values considered.

4.2 Vertical abundance stratification

In order to verify for the presence of vertical abundance stratification for a given element, we consider that at least 10 lines must be visible over a broad range of optical depth. For each of the stars under consideration, up to five elements had enough lines for such an analysis (Table 4–8 give for each star the number of lines N studied for each ion identified in their spectrum). Because of the richness of its absorption spectrum, iron is presented for all our stars in Fig. 2. In this figure, showing the abundance as a function of the optical depth, each data point is associated with a studied line profile. Depending on the star temperature, the visible domain contains ions of Fe I and Fe II, Fe II only, or Fe II and Fe III. A linear fit was calculated through these data for each star, the resulting slope along with its uncertainty are also shown in Fig. 2. To declare an element as stratified, we adopted two rules: (1) the slope of the variation of the abundance as a function of the optical depth must be statistically significant, i.e. larger than 3σ; and (2) the overall abundance variation must be larger than 0.5 dex, an arbitrary criteria but rather safe considering all the other sources of uncertainties. With these rules, there is no strong evidence of iron stratification in our stars, except for only a weak indication that Fe may be stratified in Feige 86 (the overall abundance variation being a bit below our 0.5 dex criteria).

However, a more significant indication of vertical stratification is observed for phosphorus in HD 213781 as shown in Fig. 3. This figure also presents the phosphorus abundance of Feige 86, for which enough lines have also been observed to undertake a stratification

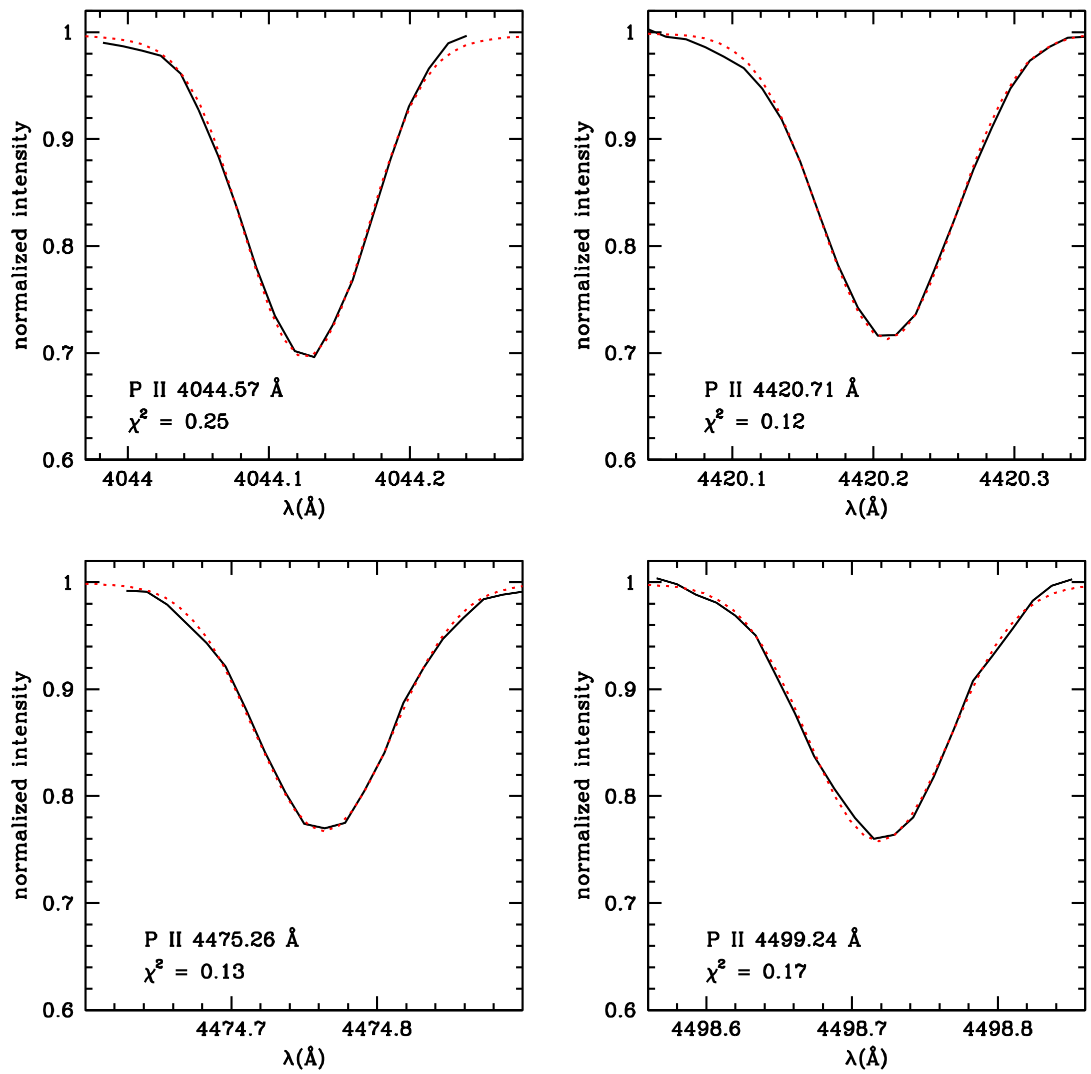

Figure 1. Examples of ZEEMAN2 profile fitting results for four P II lines in Feige 86. The observed profiles (solid curves) are compared to the simulated ones (dotted curves).

Table 3. An excerpt of the list of spectral lines used for each star studied.

		(a) Feige 86		
λ (Å)	log(*gf*)	log ($N_{\rm ion}/N_{\rm tot}$)	log(τ_{5000})	$E_{\rm low}$(cm^{-1})
		C II		
4267.261	0.716	−5.9623 ± 0.049	−2.275	145550.70
		Mg II		
4384.637	−0.790	−5.2674 ± 0.044	−2.504	80619.50
4390.514	−1.478	−5.3928 ± 0.029	–	80650.02
4390.564	−0.523	−5.3928 ± 0.029	−2.733	80650.02
4427.994	−1.210	−5.1224 ± 0.072	−2.275	80619.50
–	–	–	–	–

Notes. (1) The complete version of this table is found exclusively in the online version of the paper.
(2) The lines with no values for the optical depth of line formation shown were treated within a single profile with a stronger line of the same species.

Table 4. Average chemical abundances [X/H] of Feige 86.

Ion	*N*	This study	Behr (2003b)	Bonifacio et al. (1995)
C II	1	−2.36	–	−2.39
Mg II	6	−0.74 ± 0.14	<−2.00 ± 1.36	−0.90
Si II	17	−0.49 ± 0.33	$-2.85^{+0.63}_{-0.52}$	−0.54 ± 0.10
P II	33	+1.72 ± 0.20	$+1.73^{+0.09}_{-0.09}$	+1.60 ± 0.40
P III	5	+1.19 ± 0.29	–	+1.42
Ar II	2	+0.94 ± 0.47	–	+0.66
Ca II	4	+0.14 ± 0.24	–	+0.16
Ti II	17	+0.52 ± 0.19	–	+0.69
Cr II	2	+0.18 ± 0.27	–	+0.14
Mn II	17	+1.12 ± 0.20	–	+0.61
Fe II	223	+0.32 ± 0.22	$+0.38^{+0.19}_{-0.20}$	+0.34 ± 0.40
Fe III	7	+0.01 ± 0.16	–	+0.27
Ni II	1	−0.13	–	+0.03
Cu II	4	+2.65 ± 0.93	–	+2.02

analysis. In the case of HD 213781, phosphorus shows a statistically significant slope for the linear fit of the abundance. The overall abundance variation is slightly above 0.5 dex. However, it is clear that phosphorous is not stratified in Feige 86.

In order to verify the robustness of the slope found for phosphorous in HD 213781, several simulations are done while varying $T_{\rm eff}$ and log *g* according to their uncertainties (see Table 1), and [M/H] by ± 0.2 dex as inspired by the [Fe/H] uncertainties obtained by Behr

Table 5. Average chemical abundances [X/H] of HD 128801.

Ion	N	This study	Behr (2003b)	Kinman et al. (2000)	Adelman & Philip (1996)
N I	2	-0.41 ± 0.01	–	–	–
O I	7	-0.67 ± 0.12	–	–	-0.71
Mg II	5	-1.11 ± 0.08	-1.01 ± 0.08	-1.15	-0.81
Si II	10	-1.07 ± 0.16	–	–	-1.28
Ca II	2	-2.01 ± 0.96	–	–	-2.28
Ti II	18	-1.35 ± 0.15	–	-1.18 ± 0.10	-1.26
Cr II	5	-1.43 ± 0.04	–	-1.41	-1.50
Fe I	9	-1.30 ± 0.11	–	-1.51 ± 0.05	-1.19
Fe II	37	-1.36 ± 0.16	-1.38 ± 0.09	-1.47 ± 0.08	-1.33

Table 6. Average chemical abundances [X/H] of HD 143459.

Ion	N	This study	Behr (2003b)	Lemke (1989, 1990)
C I	2	-0.34 ± 0.09	–	-0.71 ± 0.07
N I	10	$+0.01 \pm 0.13$	–	–
O I	4	$+0.04 \pm 0.18$	–	–
Mg II	4	-0.59 ± 0.07	-0.34 ± 0.27	–
Si II	9	-0.44 ± 0.16	–	-0.37 ± 0.28
Ca II	4	-0.98 ± 0.14	–	–
Ti II	31	-0.45 ± 0.17	–	-0.94 ± 0.31
Cr II	11	-0.45 ± 0.14	–	–
Fe I	17	-0.66 ± 0.15	–	-1.07 ± 0.29
Fe II	51	-0.55 ± 0.23	-0.84 ± 0.10	-1.14 ± 0.20

Table 7. Average chemical abundances [X/H] of HD 213781.

Ion	N	This study	Behr (2003b)
C II	3	-0.43 ± 0.19	–
Mg II	6	-0.64 ± 0.14	$-0.76^{+0.26}_{-0.29}$
Si II	16	-0.18 ± 0.20	$-0.68^{+0.50}_{-0.65}$
P II	22	$+1.29 \pm 0.22$	$+0.77^{+0.35}_{-0.62}$
S II	2	-0.49 ± 0.66	–
Ca II	1	$+0.04$	–
Ti II	15	$+0.38 \pm 0.14$	–
Mn II	10	$+0.85 \pm 0.17$	–
Fe II	135	$+0.14 \pm 0.15$	$+0.08^{+0.15}_{-0.15}$

Table 8. Average chemical abundances [X/H] of HZ 27.

Ion	N	This study	Behr (2003b)
N I	5	-0.38 ± 0.18	–
O I	9	-0.02 ± 0.31	–
Mg I	2	-0.77 ± 0.06	–
Mg II	2	-0.89 ± 0.04	-0.72 ± 0.60
Si II	5	-1.14 ± 0.29	–
Ca II	4	-1.71 ± 0.45	–
Ti II	9	-1.08 ± 0.31	–
Fe I	3	-0.90 ± 0.18	–
Fe II	21	-1.30 ± 0.38	-1.39 ± 0.35

(2003b). We find that the slope remains statistically significant in all these simulations, and therefore our results are relatively robust with regards to uncertainties surrounding the model atmospheres used.

The study of the variation of the abundance as a function of the line optical depth for other ions (e.g. Si II, Ti II, Mn II, Cr II, N I), depending on the stars in our sample, did not reveal any significant stratification.

4.3 Average abundances

Fig. 2 already shows that iron is clearly underabundant (relative to solar values as given by Asplund et al. 2009) in HD 128801, HD 143459, and HZ 27, while it is near or above solar in Feige 86 and HD 213781. We present here the average abundances found for each species studied in the five field BHB stars of our sample along with a comparison with previous studies. Depending on the stars, these studies are those of Lemke (1989, 1990), Adelman & Philip (1996), Kinman et al. (2000), Bonifacio et al. (1995), and Behr (2003b). Behr (2003b) studied all stars presented in this article. To estimate the average abundance of each species for these stars, he employed the spectral synthesis code LINFOR (the version provided by Lemke, private communication), with the ATLAS9 model atmosphere of Kurucz (1993a), and atomic parameters from the VALD data base. He fitted line profiles. Although he used high spectral resolution data (R = 60 000 from the echelle instrument at the McDonald Observatory and R = 45 000 with HIRES at Keck I) the SNR was not very high (38, 49, 84, 49, and 15 for Feige 86, HD 128801, HD 143459, HD 213781, and HZ 27, respectively).

Feige 86. Our spectral analysis allows us to obtain the average abundance of 14 ions for Feige 86. The number N of line profiles selected for each ion is given in Table 4, along with our results (the method used to obtain the errors for our abundances is described in Section 4.1) and the results from other authors for comparison. Our average abundances are consistent with those of Behr (2003b), except for Si II for which he obtained a relatively large uncertainty. However, the abundance obtained here for this ion is consistent with the one found by Bonifacio et al. (1995). In the study of Bonifacio et al. (1995, using AURELIE data at R = 31 000 to 60 000 and *IUE* spectra), the visible and ultraviolet regions were explored. Average abundances of the species in the visible region were obtained both from the equivalent widths and from the line profiles. For the ultraviolet region, abundances were found from the line profiles only. These authors used the code SYNTHE (Kurucz 1993b) to calculate the synthetic spectrum with ATLAS9 model atmospheres and the code WIDTH (Kurucz 1993a) to obtained the line equivalent widths. Our average abundances for all the elements studied generally compare well with those of Bonifacio et al. (1995), and also Castelli, Parthasarathy & Hack (1997; not shown in Table 4) both using UV data. We find small differences for Mn II, Fe III, and Ni II, but since Bonifacio et al. (1995) do not give error bars for their abundances, it is difficult to draw a firm conclusion about the veracity of these differences. Our results show that P, Ar, Mn, and Cu are clearly overabundant (relative to solar values) while C, and Mg show moderate to strong underabundances, as summarized in Fig. 4.

HD 128801. We obtained the average abundances for nine ions of HD 128801 (see Table 5). Our results are generally consistent with those found by Behr (2003b), Kinman et al. (2000), and Adelman & Philip (1996). Only Fe I and Mg II show, respectively, a slight difference with the value of Kinman et al. (2000) and Adelman & Philip (1996). In their work, using KPNO spectra with a resolution R = 15 000 and synthetic spectra computed with the SYNTHE code, Kinman et al. (2000) used ATLAS9 model atmospheres and the WIDTH code to estimate the abundance of the elements of this star from the equivalent widths with the atomic line lists from Kurucz & Bell (1995). Adelman & Philip (1996, with KPNO spectra at 0.14 Å) performed a correlation analysis of the abundance of 10 elements in HD 128801, using the code SYNSPEC of Hubeny, Lanz & Jeffrey (1994) for the calculation of the synthetic spectra with ATLAS9 model atmospheres of Kurucz (1995). All elements

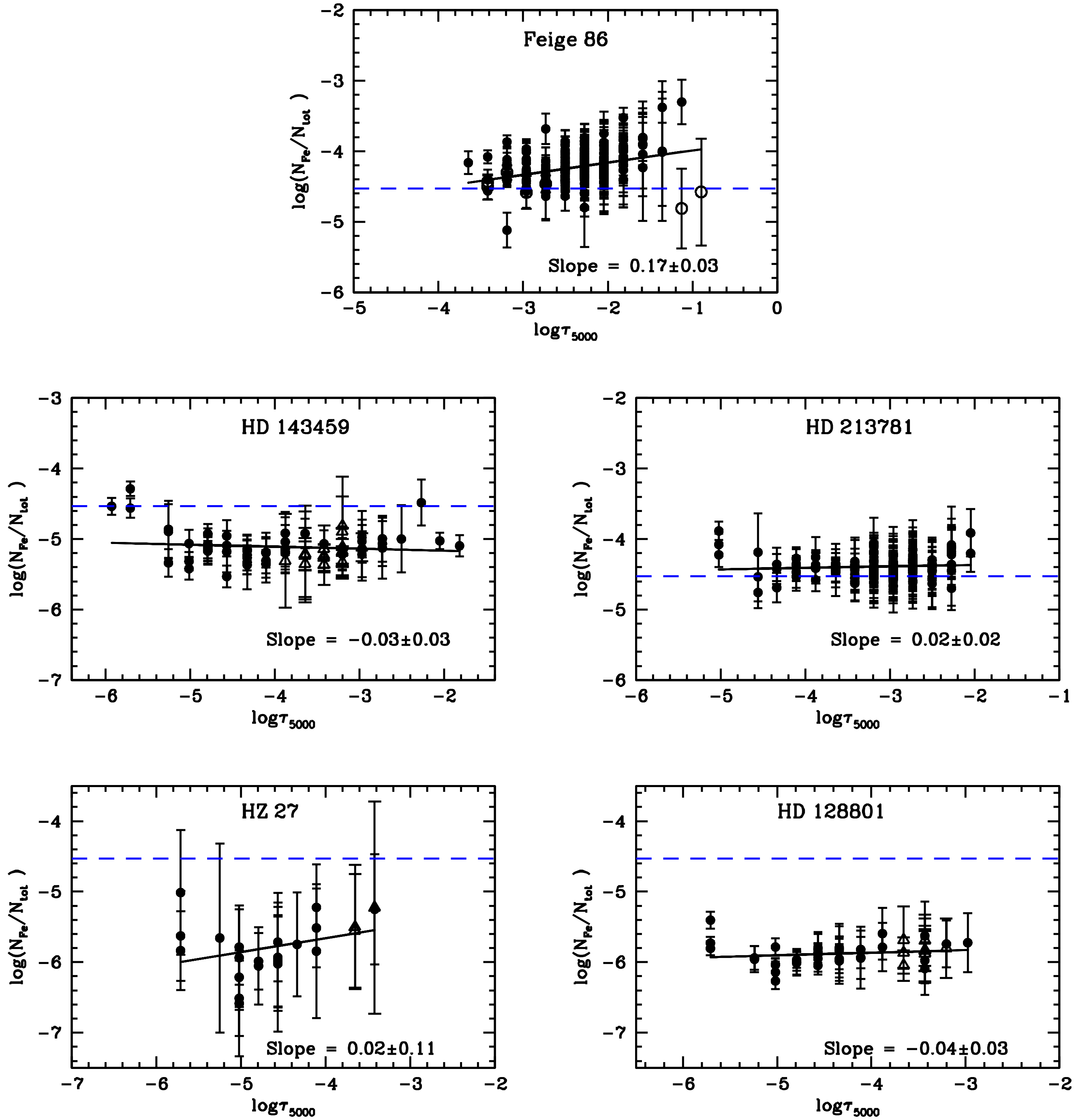

Figure 2. The iron abundance relative to the total number of atoms obtained from individual lines for the five field BHB stars studied as a function of the optical depth at 5000 Å. Fe I lines are represented by open triangles, Fe II lines by filled circles, and Fe III lines by open circles. The dashed line represents the solar abundance. Linear fits of the abundance are also shown (solid lines) along with their slope.

studied here show a weak to moderately strong underabundance (see Fig. 4).

HD 143459. Atomic lines from a total of 10 ions were identified for HD 143459 (see Table 6). The average abundance obtained for Mg II and Fe II by Behr (2003b) are consistent with ours. Meanwhile, for the five ions in common with the work of Lemke (1989, 1990), C I and Fe II show slight differences in their abundance as compared to ours. To study this field BHB star, Lemke (1989, 1990) used ESO spectra (with a resolution 58.9 mÅ) and LINFOR (the version developed by Holweger, Steffen & Steenbock) to compute the synthetic spectra with ATLAS6 model atmospheres of Kurucz (1979). He estimated the abundance of the elements from equivalent widths. Lemke (1989) calculated iron abundances for HD 143459 in LTE and NLTE. He found that the abundances for Fe I lines are approximately 0.3 dex larger in NLTE, while Fe II lines are not sensitive to NLTE effects, at least pertaining the abundance analysis. Lemke (1990) found that in A-type stars, the NLTE abundance of Ca I is approximately 0.3–0.8 dex larger in NLTE. However, no result is

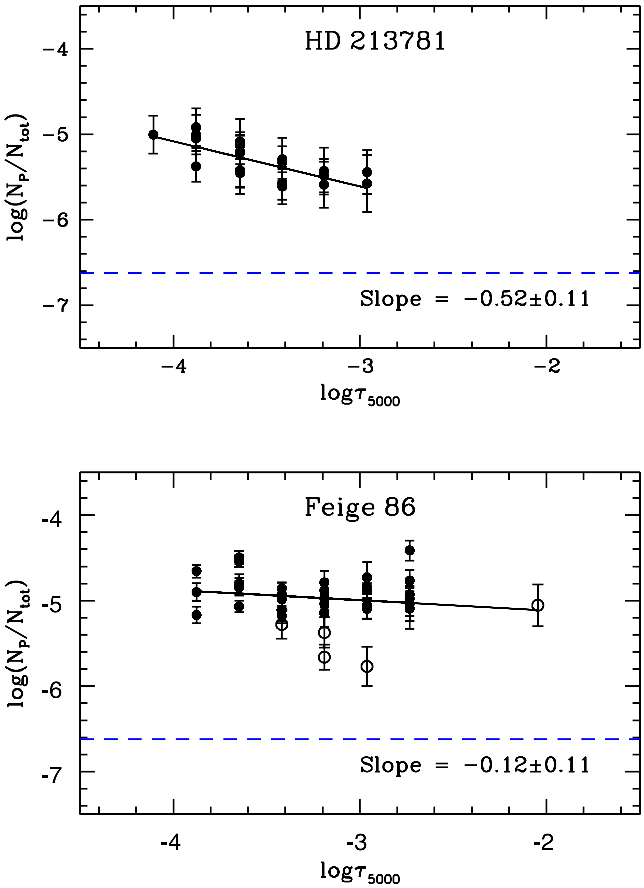

Figure 3. The phosphorus abundance in HD 213781 and Feige 86, relative to the total number of atoms obtained from individual lines as a function of optical depth at 5000 Å. See caption of Fig. 2 for more details.

given for Ca II and it is therefore unclear if the low abundances found here with Ca II lines in HD 143459 (and also HD 128801 and HZ 27; see Tables 5, 6 and 8) are due to our LTE treatment. The abundances found here for most elements show moderate to weak underabundances (see Fig. 4).

HD 213781. Nine ions were studied for HD 213781 (see Table 7). For the four ions in common with Behr (2003b), there is a good agreement. We find that only P and Mn show a clear overabundance, while Mg is the only element that has a significant underabundance (see Fig. 4).

HZ 27. Finally, Table 8 presents our results for nine ions in the atmosphere of HZ 27. Two of these ions (Mg II and Fe II) were also studied by Behr (2003b) and his results are in agreement with ours. All elements, except O, show a moderate to strong underabundance (see Fig. 4).

4.4 Rotational and radial velocities

The rotational and radial velocities ($V \sin i$ and V_r, respectively) determined via the analysis of all the selected atomic lines for each of the five field BHB stars studied here are presented in Table 9. This table also gives the velocities computed by Behr (2003b). Our uncertainties are smaller than those of Behr (2003b) mainly because our data have a larger SNR and because we are considering more lines and more ions (see Table 3). Nevertheless, the velocities obtained here are in agreement with those found by Behr (2003b), except for the value of V_r for Feige 86, which is only barely inconsistent with the result of Behr (2003b).

5 DISCUSSION AND CONCLUSION

In our study, we analysed the spectrum of HD 128801, HD 143459, HD 213781, and H7 27, that we obtained with the echelle spectrographe ESPaDOnS at the CFHT, and the spectrum of Feige 86 observed with UVES at ESO by Cowley et al. (2007). Along with confirming the stellar rotational and radial velocities and the abundance of several elements identified in the spectrum of these stars as compared to previous studies (even if we used different data, models, atomic data, and analysis techniques), such high-quality spectra permits us to search for a possible vertical stratification of the element abundance in five field BHB stars. For our work, we used the ZEEMAN2 code and PHOENIX model atmospheres. A large number of line profiles (from 60 to 339, according to the star) for up to 12 different species have been selected and analysed individually.

The analysis of the spectrum of the three cooler stars HD 128801, HD 143459, and HZ 27 reveal that most chemical elements studied are underabundant. No overabundance of any metal was found for these stars. In addition, no vertical stratification of any chemical element was detected in the atmospheres of these cooler stars. As for BHB stars cooler than 11 500 K observed in globular clusters, we may conclude that diffusion is not at play in the atmospheres of HD 128801, HD 143459, and HZ 27.

However, in the hot BHB stars of our sample, Feige 86 and HD 213781, the abundance found for most elements are near or above their solar value. No vertical stratification of iron was detected in the atmosphere of the hot field BHB stars studied here, except maybe for Feige 86 where indications of a weak stratification is seen. We have however found strong evidence of vertical stratification of phosphorus in HD 213781 despite its large projected rotational velocity (35 km s^{-1}). In globulars clusters, previous studied shown that vertical stratification is detectable in the atmosphere of hot BHB stars ($T_{\rm eff} \geq$ 11 500 K) which typically have low projected rotational velocity ($\lesssim$ 10 km s^{-1}). This is the first study, which reveals a vertical stratification detected in a BHB star with such a large projected rotational velocity. Since several elements identified in HD 213781 have an abundance at or above solar and since vertical stratification of phosphorus is detected, atomic diffusion is confirmed in the atmosphere of this star. Feige 86 shows definite overabundances of P, Ar, Mn and Cu. In addition Fe is near but above its solar abundance. Atomic diffusion is also likely at play in the atmosphere of this hot field BHB star.

HD 213781 was actually classified as a *possible* BHB star by Behr (2003b). On the other hand, Silva & Napiwotzki (2011) suggested, from a kinematics study, that it is on the main sequence. Renson & Manfroid (2009) also classified it as a main-sequence star of type Bp. Since no Si or Cr lines are detected in the spectrum of HD 213781, it is most likely not a Bp star. The overabundance of P and Mn (see Table 7) are characteristics typical of HgMn stars. However, no strong lines of Be, Ga, Pt or Hg, which are also often seen in HgMn stars (Smith 1996), are detected here. As seen in Feige 86 (Table 4), an overabundance of P and Mn may also be present in BHB stars. A phosphorous overabundance was also found in the BHB stars HD 135485 (Khalack et al. 2007) and WF4-3085 (Khalack et al. 2008). We conclude that from its spectral characteristics, HD 213781 is therefore most probably a BHB star. However, the reason for its large rotational velocity as compared to other similar BHB stars remains a mystery.

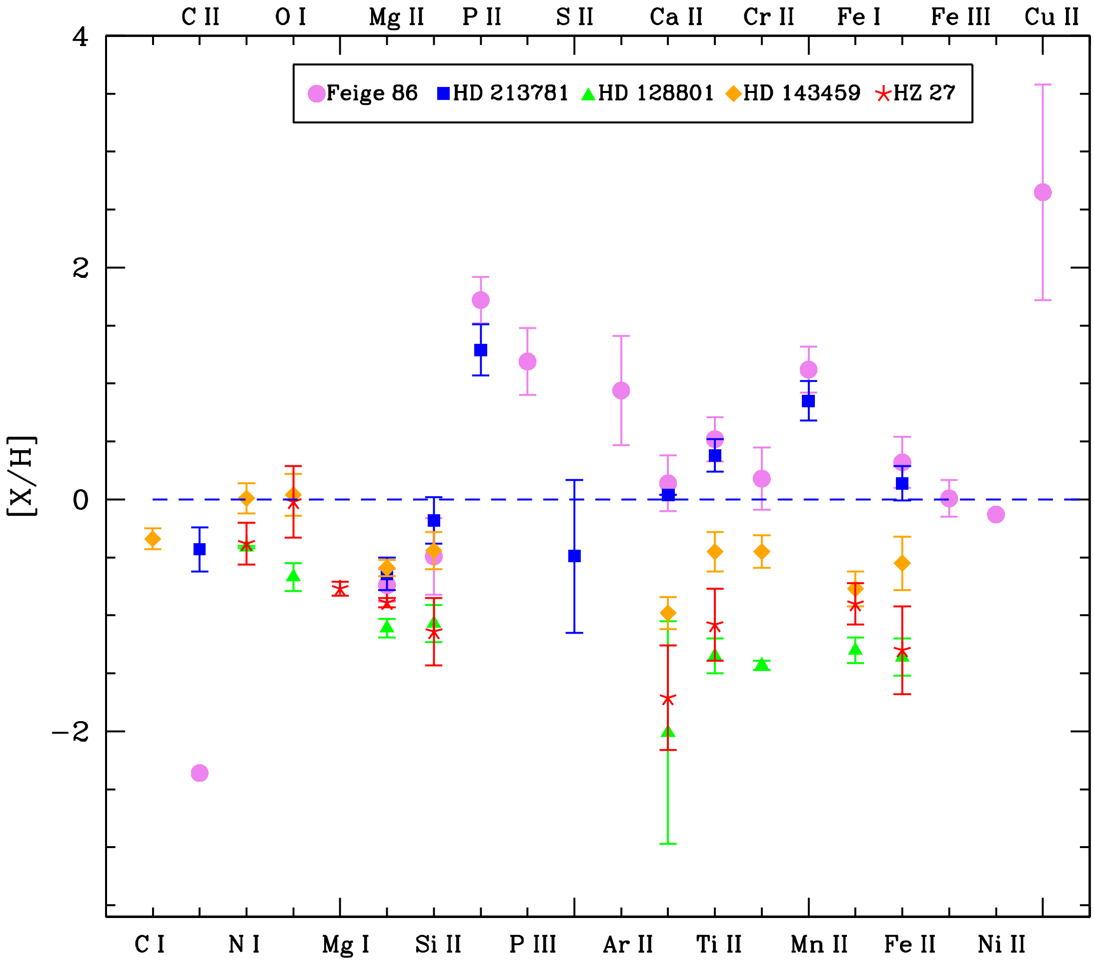

Figure 4. The average abundances obtained relative to the solar abundance for the five field BHB stars studied in this paper.

Table 9. Rotational and radial velocities measured.

Star	$V \sin i$ (km s^{-1}) This study	$V \sin i$ (km s^{-1}) Behr (2003b)	V_r (km s^{-1}) This study	V_r (km s^{-1}) Behr (2003b)
Feige 86	1.56 ± 0.50	$0.0^{+4.2}_{-0.0}$	−28.34 ± 0.69	−26.54 ± 0.80
HD 128801	9.29 ± 0.93	$8.6^{+1.6}_{-0.7}$	−81.23 ± 0.90	−79.62 ± 2.11
HD 143459	36.59 ± 0.93	$36.8^{+2.8}_{-3.0}$	−21.77 ± 1.18	−19.71 ± 2.51
HD 213781	34.71 ± 1.03	$34.5^{+4.5}_{-3.9}$	−31.31 ± 1.44	−30.00 ± 3.49
HZ 27	6.83 ± 1.35	$6.6^{+5.0}_{-6.6}$	−18.90 ± 1.83	−17.72 ± 2.04

In summary, the three cooler stars do not show overabundances while the two hot ones, found above the usual $T_{\rm eff} \simeq 11\,500$ K threshold, have overabundances. Therefore, from the limited sample of field BHB stars studied here, they seem to possess similar chemical properties as their globular-cluster counterparts.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 3a. - Feige 86
Table 3b. - HD 128801
Table 3c. - HD 143459
Table 3d. - HD 213781
Table 3e. - HZ 27 (http://www.mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stw653/-/DC1).

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