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Project VeSElkA: results of abundance analysis I – HD 71030, HD 95608, HD 116235 and HD 186568

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ABSTRACT

A portion of main-sequence stars, called chemically peculiar (CP) stars, show important abundance anomalies mainly due to atomic diffusion of the species within these stars. Certain CP stars have hydrodynamically stable atmospheres where atomic diffusion may dominate and lead to vertical abundance stratification there. Recently, Project VeSElkA (a word meaning rainbow in Ukrainian and standing for 'Vertical Stratification of Element Abundances') was initiated with the goal to detect vertical stratification of chemical abundances in selected CP stars using high-resolution spectra with large signal-to-noise ratios. The first extensive and detailed series of results from atomic-line analysis is presented here for four stars of Project VeSElkA: HD 71030, HD 95608, HD 116235 and HD 186568. These stars were recently observed with ESPaDOnS at Canada–France–Hawaii Telescope. Strong evidence of iron stratification in the atmospheres of HD 95608 and HD 116235 was found. Chromium also shows a steep abundance gradient in the upper atmospheres of these two stars. No evidence of stratification is found for HD 71030 and HD 186568.

Key words: diffusion – stars: abundances – stars: atmospheres – stars: chemically peculiar.

1 INTRODUCTION

Chemical abundance peculiarities in main-sequence stars were first detected by Morgan (1931, 1932) through the analysis of abnormally strong absorption lines of various species. The terminology of chemically peculiar (CP) stars was first introduced by Preston (1974) who defined four groups of CP stars: AmFm, ApBp, HgMn and He-weak stars. Nowadays, the family of CP stars may be divided in eight distinct groups specified by Maitzen (1984) and Smith (1996). However, other type of stars outside the main sequence, such as blue horizontal-branch stars (Glaspey et al. 1989) for instance, also show chemical peculiarities.

In addition to abundance anomalies, certain CP stars have a relatively low rotational velocity (e.g. Abt 2000; Royer et al. 2002). This last property may render certain regions of a given star more hydrodynamically stable where the relatively slow process of atomic diffusion (Michaud 1970) may then dominate large-scale matter currents often present in fast rotating stars. Atomic diffusion is mainly due to the competition between local gravity and radiative acceleration (e.g. Gonzalez et al. 1995; Alecian & LeBlanc 2000) of atoms due to their absorption of photons from the stellar radiative field. Momentum from these photons is then transferred to the atoms which are pushed towards the surface of the star when the radiative acceleration produced is sufficient. Elements with weak radiative acceleration sink towards the centre of the star. The relative diffusion of the atomic species leads to abundance anomalies in various parts of certain stars, including at the surface of CP stars. These anomalies become visible in the spectra of CP stars where certain lines become stronger or weaker due to the respective overabundance or underabundance of the various species. Some stars, such as ApBp stars have large magnetic fields that in conjunction with atomic diffusion may lead to abundance patches at their surface (e.g. Kochukhov et al. 2002; Shavrina et al. 2010).

In CP stars, where the atmosphere is hydrodynamically stable, vertical abundance stratification may be present near the stellar surface for certain elements due to atomic diffusion. For instance, it is commonly believed that the presence of a large magnetic field may help to stabilize the atmospheric medium against convective motions, thus letting the effects of diffusion to take place.

In certain stars, such as AmFm stars, even though they have a low rotational velocity as compared to normal stars (Abt 2000), convective mixing takes place in their atmosphere (Richer, Michaud & Turcotte 2000; Richard, Michaud & Richer 2001). Therefore, no vertical stratification of the elements can exist there. The surface abundance anomalies of AmFm stars stem from deeper layers where diffusion is efficient and the local anomalies are brought up to the surface by convective mixing.

Vertical stratification of the elements in stellar atmospheres can affect the physical structure of certain stars (Hui-Bon-Hoa, LeBlanc & Hauschildt 2000; LeBlanc et al. 2009; Stift & Alecian 2012). Such structural changes can also have photometric

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manifestations (LeBlanc, Hui-Bon-Hoa & Khalack 2010; Krticka et al. 2012), such as observed in the case of blue horizontal-branch stars (Ferraro et al. 1998; Grundahl et al. 1999). It is therefore important to properly measure such vertical stratification profiles by spectral analysis in order to gauge their properties and importance in various types of stars showing abundance anomalies. Such results may also be useful in putting constraints on theoretical modelling of stellar atmospheres including vertical abundance stratification.

Project VeSElkA (a word meaning rainbow in Ukrainian and standing for 'Vertical Stratification of Element Abundances') aims to detect vertical stratification of elements in selected CP stars using high-resolution spectra with large signal-to-noise ratios. A number of slowly rotating, relatively bright and poorly studied probable CP stars have been selected from the peculiar star catalogue of Renson & Manfroid (2009). As discussed above, not all selected stars are expected to show vertical abundance stratification, but their analysis will none the less give estimates for the abundances of the detected elements at their surface. An analysis of Balmer lines of a first series of stars from the VeSElkA sample is presented in Khalack & LeBlanc (2015) where the fundamental parameters of these stars are evaluated.

This paper aims to present extensive abundance analysis of four stars of Project VeSElkA, namely HD 71030, HD 95608, HD 116235 and HD 186568 recently observed with ESPaDOnS at Canada–France–Hawaii Telescope (CFHT). Three of these stars were classified by Renson & Manfroid (2009) as Am or Fm stars and the fourth one (HD 186568) was judged to be a B9p star, while Hubrig & Castelli (2001) considered it to be a normal B-type star. However, it should be mentioned that the classification by Renson & Manfroid (2009) of HD 186568 and HD 71030 is, according to them, more doubtful. For the stars studied here, our analysis may shed some light on their exact CP-type.

The method used to probe for the possible presence of vertical abundance stratification was first presented in Khalack et al. (2007) and has been successfully applied to blue horizontal-branch stars (Khalack et al. 2007, 2008, 2010), to HgMn stars (Thiam et al. 2010) and recently to the post-horizontal-branch star HD 76431 (Khalack et al. 2014). This procedure calculates the abundance for individual atomic lines which enables to search for abundance variations with respect to depth assuming the lines are formed in different atmospheric layers. Therefore, high-resolution spectra with large signal-to-noise ratios are essential to obtain precise results from the analysis of individual atomic lines.

The stars chosen for Project VeSElkA have relatively low rotational velocities ($V \sin i < 40$ km s^{-1}) so that the lines are narrow and less blended. Also, as it was mentioned above, slow rotation is a prerequisite to have hydrodynamically stable atmospheres where diffusion may take place.

Preliminary results of the abundance analysis for some elements (Ti, Cr, Fe and Ni) for HD 71030, HD 95608 and HD 116235 were presented by Khalack et al. (2014). A more detailed analysis of these elements and others are presented here. The star HD 22920, which was observed in Project VeSElkA has also been analysed (Khalack & Poitras 2015). This star shows strong spectral variability relative to its rotational phase. It was also found that Si and Cr appear to be vertically stratified in its atmosphere.

In this paper, the observations undertaken for the four stars under consideration and the acquired spectra will be briefly described. The spectral analysis and the related numerical simulations will then be presented. Results for the radial and rotational velocities, the average abundance for the elements detected in each star and, when found, their vertical stratification profiles will be shown. A discussion follows.

Table 1. Physical parameters of programme stars taken from Khalack & LeBlanc (2015).

Star	$T_{\rm eff}$ (K)	log g
HD 71030	6780	4.04
HD 95608	9200	4.25
HD 116235	8900	4.33
HD 186568	11 070	3.44

2 OBSERVATIONS

The four stars studied here were observed with ESPaDOnS at CFHT. High-resolution ($R = 65\,000$) Stokes IV spectra with large signal-to-noise ratios were obtained in the spectral range 3700–10 500 Å and were reduced with the software package LIBRE-ESPRIT (Donati et al. 1997). Two or more spectra of each star were taken to verify for any spectral variability. For the four stars studied here, no such variability is detected. Also, no strong magnetic fields were found. More details about these observations are given in Khalack & LeBlanc (2015); for instance, the exposure times and the signal-to-noise ratios are given in their table 1 for each star studied here.

3 SPECTRAL ANALYSIS AND RESULTS

3.1 Analysis method

After identifying unblended spectral lines present in the spectrum of each star, the modified (Khalack & Wade 2006) ZEEMAN2 code developed by Landstreet (1988) was used to simulate the flux for each individual atomic line. The line data used for atomic-line identification and for these simulations come from NIST (Kramida et al. 2013) and VALD-3 (Kupka et al. 1999) data bases. The code also needs the stellar atmosphere model for the star under consideration in input. These models were calculated with version 15 of the PHOENIX (Hauschildt, Baron & Allard 1999) atmospheric code using solar abundances. The physical parameters used for the calculations of these models are given in Table 1 and are taken from the results of Khalack & LeBlanc (2015). They obtained the fundamental parameters of these stars by the analysis of nine Balmer lines.

For each identified line, the abundance of the ion associated to the line, the rotational velocity $V \sin i$ and the radial velocity $V_{\rm r}$ are estimated with the modified version of the ZEEMAN2 code. These values are obtained by fitting the synthetic spectrum to the observed one and by employing a downhill simplex method for finding the error minimum (Khalack & Wade 2006). The analysis of the values of these three variables may be used to reject atomic lines that are blended or misidentified.

The optical depth of the line core is calculated at each layer of the atmospheric model. In order to study the possible variation of the abundance with respect to depth, the abundance of each line for a given species is associated to the layer where its line-core optical depth is equal to unity. Therefore, for species with a large number of lines (approximately 10 or more) that are formed at sufficiently different optical depths, the slope of the abundance variation relative to optical depth may then be estimated (see Khalack et al. 2007 for more details). When this slope is statistically significant and the abundance varies strongly (by 0.5 dex or more) within the

Table 2. Radial and rotational velocities obtained for programme stars.

Star	V_r (km s^{-1})	$V \sin i$ (km s^{-1})
HD 71030	37.74 ± 0.55	9.22 ± 0.96
HD 95608	−10.4 ± 1.0	17.2 ± 2.0
HD 116235	−10.3 ± 0.9	20.0 ± 1.1
HD 186568	−9.33 ± 0.70	18.25 ± 0.96

layers probed, we may assume that stratification is detected. The last condition related to the strong variation of the abundance is employed to assure that the variation is not simply due to known possible sources of uncertainties (atomic data, models, etc.) present in any such simulations and that cannot be easily estimated.

3.2 Radial and rotational velocities

The radial (V_r) and rotational ($V \sin i$) velocities obtained via the analysis of the selected atomic lines for the stars under consideration are shown in Table 2. The radial velocity obtained by Wilson (1953) for HD 116235 and those obtained by Gontcharov (2006) for the other three stars of our sample are consistent with the values presented in Table 2. The rotational velocities found here are also consistent with previous studies: Balachandran (1990) for HD 71030, Takeda et al. (2012) for HD 95608, Ammler-von Eiff & Reiners (2012) for HD 116235 and Hubrig & Castelli (2001) for HD 186568.

3.3 Average abundances

Table 3 gives the average abundances (relative to their solar value) for the different species present in the spectra of the four stars studied obtained from averaging the results of individual atomic lines. The number of lines (N) selected for each ion is also given in Table 3. The error of the determined average abundances is estimated with the mean quadratic deviation of the values obtained for the individual lines. In this section, we present a summary of a comparison of our results to others published elsewhere.

Prugniel, Vauglin & Koleva (2011) estimated the abundance of iron at [Fe/H] = 0.15 ± 0.03 in HD 71030 which is consistent to the results found in Table 3. No large abundance anomalies are detected for this star, therefore its classification as an Fm star by Renson & Manfroid (2009) versus a normal-type star remains doubtful.

For HD 95608, Takeda et al. (2012) obtained the abundances of five elements, two of which (Na and Fe) are also estimated here. For Fe, both results are consistent with one another and this element is found to be moderately overabundant. For Na, the abundance found here is a bit larger than the one found by Takeda et al. (2012). However, only two lines of Na were selected in our study, so such a difference is not surprising. As shown in Table 3 and considering elements with several or more well-defined lines, this star shows moderate overabundances of Na, Al, Fe and a large overabundance of Cr and Ni. Such abundance anomalies seem to indicate that it is a CP star. More details concerning the possible type of CP star of this object are given in the next subsection.

Erspamer & North (2003) obtained abundances for several elements in HD 116235 using an automated spectroscopic analysis applied to 140 A- and F-type stars. These results are consistent with ours for the elements C, O, Na, Mg, Si, S, Ca, Ti, Fe and Ni. However, for Cr we find an overabundance larger than the one found by Erspamer & North (2003). This star shows a moderate overabundance of Fe and a large overabundance of Cr and Ni which seems to indicate that it is clearly a CP star (see Table 3).

For HD 186568, except for Ti, which is moderately underabundant, the abundances found here are near their solar value. The Fe abundance found here is consistent with Hubrig & Castelli (2001).

Table 3. Average abundances obtained for programme stars.

Element	HD 71030		HD 95608		HD 116235		HD 186568	
	N	[X/H]	N	[X/H]	N	[X/H]	N	[X/H]
He I	0	–	0	–	0	–	6	0.46 ± 0.19
C I	2	−0.384 ± 0.002	0	–	4	−0.43 ± 0.37	2	−0.34 ± 0.12
N I	2	−0.50 ± 0.18	2	−1.14 ± 0.29	0	–	10	0.12 ± 0.16
O I	2	0.45 ± 0.36	0	–	2	−0.12 ± 0.37	5	0.16 ± 1.64
Na I	2	0.58 ± 0.58	2	0.59 ± 0.22	2	1.08 ± 0.65	0	–
Mg I	9	−0.05 ± 0.22	0	–	4	0.03 ± 0.18	0	–
Mg II	2	−0.32 ± 0.04	1	0.34	0	–	8	−0.15 ± 0.28
Al I	0	–	2	1.42 ± 0.95	0	–	0	–
Al II	0	–	1	0.54	0	–	0	–
Si I	14	−0.20 ± 0.51	2	0.37 ± 0.02	3	0.60 ± 0.45	0	–
Si II	0	–	5	0.30 ± 0.20	0	–	15	0.16 ± 0.19
S I	2	−0.20 ± 0.51	2	0.38 ± 0.08	3	0.83 ± 0.50	0	–
S II	0	–	0	–	0	–	10	0.28 ± 0.16
Ca I	8	0.51 ± 0.63	4	−0.33 ± 0.41	7	−0.17 ± 0.14	0	–
Ca II	1	−0.25	1	−0.36	0	–	0	–
Ti I	15	0.16 ± 0.49	4	2.11 ± 0.74	2	1.63 ± 1.15	0	–
Ti II	2	−0.23 ± 0.05	15	0.00 ± 0.34	6	0.90 ± 0.83	9	−0.67 ± 0.12
Cr I	10	0.29 ± 0.45	12	1.84 ± 1.19	3	1.34 ± 0.89	0	–
Cr II	3	0.13 ± 0.09	14	1.14 ± 0.59	15	2.26 ± 0.61	11	−0.19 ± 0.14
Mn I	3	1.23 ± 1.16	0	–	0	–	0	–
Fe I	134	0.19 ± 0.33	138	0.59 ± 0.35	126	0.68 ± 0.39	6	−0.23 ± 0.42
Fe II	23	0.11 ± 0.34	31	0.72 ± 0.33	17	1.43 ± 0.60	77	−0.03 ± 0.13
Co I	0	–	1	0.56	0	–	0	–
Co II	0	–	2	0.96 ± 0.97	0	–	0	–
Ni I	35	0.05 ± 0.17	11	2.19 ± 0.39	9	0.80 ± 0.16	0	–

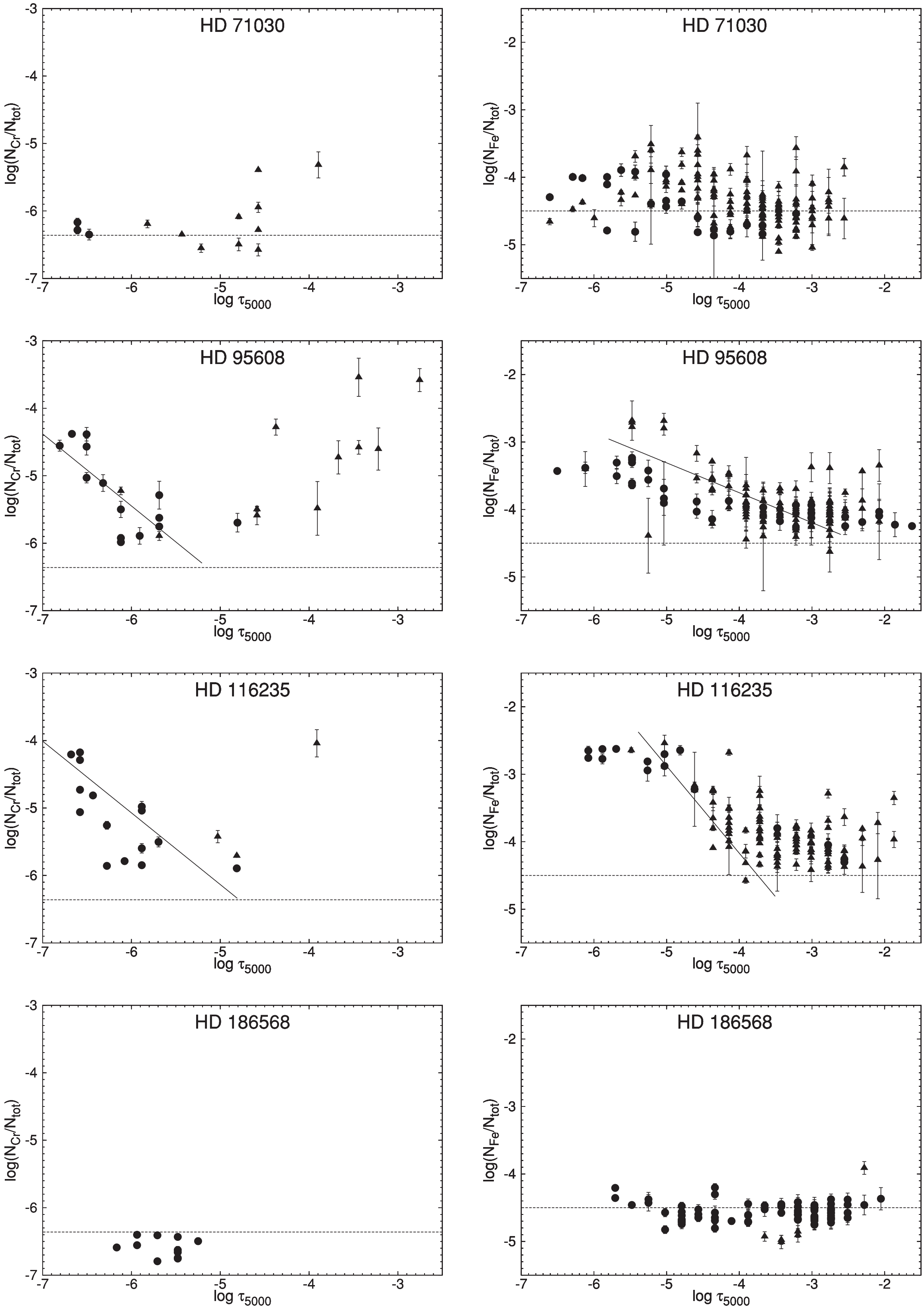

Figure 1. The abundance for Cr (left-hand panels) and Fe (right-hand panels) relative to the total number of atoms obtained from individual lines for the four stars under consideration as a function of optical depth at 5000 Å. The triangles represent lines of the neutral ion while the circles are those of the singly ionized species. The dashed line represents the solar abundance. Linear fits of the abundance stratification are shown where the abundance varies significantly, namely in certain parts of the atmospheres of HD 95608 and HD 116235.

Since no large abundances anomalies are detected, it is therefore unlikely a Bp star and is most probably a normal B-type star.

3.4 Vertical abundance stratification

Several species possess a sufficient number of detected atomic lines as to lead to an analysis of the possible dependence of the abundance relative to optical depth in the atmospheres of the stars under consideration. Since only Cr and Fe show some signs of stratification in these stars, only results for these two elements are illustrated here (see Fig. 1). A complete list of selected lines for each star is given in Tables 4a to 4d, which are presented exclusively in the electronic edition of the journal. Each data point in this figure represents a single line: lines of the neutral ions are designated by triangles while lines for singly ionized ions are represented by circles. The dashed lines found in Fig. 1 indicate the level of the solar abundance. The error bars found there have been multiplied by 10 in order to account for possible errors in atomic data.

It is clear with the results shown in Fig. 1 that no stratification of Cr or Fe exist in the stars HD 71030 and HD 186568. However, for Fe in both HD 95608 and HD 116235, a statistically significant abundance slope exists and the abundance varies strongly (by approximately 1 dex or more) in the layers where the lines are formed. Linear fits of the data points where the abundance varies strongly are also shown in Fig. 1. The slopes found for these fits are statistically significant (i.e. they are several times larger than the associated error). Also, both Fe I and Fe II show a similar dependence of the abundance relative to optical depth. Therefore, vertical stratification of iron is definitely present in the atmospheres of these two stars.

In HD 116235, Cr is dominated by mostly Cr II lines. This ion shows a strong vertical stratification in the outer atmospheric layers for which the slope is found to be statistically significant. Only three Cr I lines are visible in the spectra of this star, so this ion does not give any valuable information concerning the stratification of Cr. For HD 95608, Cr II shows a similar tendency as in HD 116235. However, the more numerous Cr I lines present (as compared to HD 116235), which are formed in deeper layers show the opposite tendency, namely an increase of the abundance relative to optical depth. It seems clear that Cr is stratified in the very shallow layers, but to reach a more confident conclusion about the vertical stratification of Cr deeper in these two stars, the analysis of lines in the near-infrared region of the spectrum could be useful in order to have more data points and measure the potential slope with higher confidence. None the less, it is clear that this element is strongly overabundant in both these stars. The overabundance of Cr is a well-known signature of Ap stars (Preston 1974). In addition, since at least Fe is vertically stratified in the atmospheres of HD 95608 and HD 116235, we would then classify these as Ap stars, albeit with weak magnetic fields since no clear signs of magnetic effects are detected in the spectra observed.

4 DISCUSSION AND CONCLUSIONS

In this paper, the first extensive series of results regarding abundance analysis from Project VeSElkA were presented for four stars (HD 71030, HD 95608, HD 116235 and HD 186568) found in the project's sample of more than 30 probable CP stars. This project aims to detect vertical abundance stratification of the elements in the atmospheres of CP stars. More than 150 lines were selected and analysed for each star studied here.

Clear evidence of vertical stratification of Fe in the atmospheres of HD 95608 and HD 116235 was found. The abundance of Cr also shows a steep gradient in the very shallow layers (i.e. in layers found above log $\tau_{5000} \sim -5.5$) of these two stars. The presence of stratification therefore seems to indicate that these two stars are most likely Ap-type stars.

No evidence of vertical stratification was found in the atmospheres of HD 71030 and HD 186568. Renson & Manfroid (2009) classified HD 71030 as a possible Fm star, although with some doubt remaining. Our results cannot confirm this classification. Meanwhile, Renson & Manfroid (2009) classified HD 186568 as a Bp star. Our abundance analysis rather shows that it is most likely a normal star.

The radial- and rotational-velocity estimates derived for the four stars under consideration through our spectral analysis were found to be consistent with the values found in previous studies.

Analysis of other stars included in Project VeSElkA's sample is ongoing. One of our aims is to verify if abundance gradients in the atmosphere depend on the effective temperature of stars, such as the dependency found for Fe stratification in blue horizontal-branch stars (Khalack et al. 2010; LeBlanc et al. 2010). Our results may also be useful to test theoretical models of stellar atmospheres including abundance stratification (i.e. LeBlanc et al. 2009; Stift & Alecian 2012) and to better understand the impact of the diffusion process in the atmospheres of CP stars.

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SUPPORTING INFORMATION

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

Table 4a.
Table 4b.
Table 4c.
Table 4d. (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stv1466/-/DC1).

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