Project VeSElkA: a search for the vertical stratification of element abundances in HD 157087

V. Khalack

Département de Physique et d’Astronomie, Université de Moncton, Moncton, NB, Canada E1A 3E9

Accepted 2018 February 24. Received 2018 February 23; in original form 2017 December 31

ABSTRACT

The new spectropolarimetric spectra of HD 157087 obtained recently with ESPaDOnS (Echelle SpectroPolarimetric Device for Observations of Stars) at the Canada–France–Hawaii Telescope are analysed to verify the nature of this object. The fundamental stellar parameters $T_{\text{eff}} = 8882$ K, $\log g = 3.57$ were obtained for HD 157087 from the analysis of nine Balmer line profiles in two available spectra. A comparison of the results of our abundance analysis with previously published data shows a variability of the average abundance with time for some chemical species, while the abundances of other elements remain almost constant. The abundance analysis also reveals evidence of a significant abundance increase towards the deeper atmospheric layers for C, S, Ca, Sc, V, Cr, Mn, Co, Ni and Zr. Together with the discovered enhanced abundance of Ca and Sc, this finding contradicts the classification of HD 157087 as a marginal Am star. An analysis of the available measurements of radial velocity revealed long- and short-period variations. The long-period variation supports the idea that HD 157087 is an astrometric binary system with a period longer than 6 yr. The presence of the short-period variation of $V_r$, as well as the detection of the temporal variation of the average abundance, suggests that HD 157087 may be a triple system, in which a short-period binary rotates around a third star. In this case, the short-period binary may consist of slowly rotating Am and A (or Ap with a weak magnetic field) stars that have similar effective temperatures and surface gravities, but different abundance peculiarities.

Key words: atomic processes – line: profiles – stars: atmospheres – binaries: general – stars: chemically peculiar – stars: individual: HD 157087.

1 INTRODUCTION

A significant number of main sequence stars within the range of spectral classes B2–F4 show peculiar chemical abundances of various elements with respect to solar values. These stars have been termed chemically peculiar (CP) stars and were initially classified by Preston (1974) into four distinct groups depending on the type of chemical peculiarity. A more detailed classification of CP stars has recently been proposed by Maitzen (1984) and Smith (1996). The classification of Preston (1974) is widely used by authors to compile catalogues of known CP stars in both hemispheres (Renson, Gerbaldi & Catalano 1991; Bychkov, Bychkova & Madej 2003). The most complete catalogue of known and suspected Ap, HgMn and Am stars has recently been published by Renson & Manfroid (2009).

The observed chemical peculiarity of CP stars can be explained in terms of the atomic diffusion mechanism (Michaud 1970). In a hydrodynamically stable stellar atmosphere, competition between gravitational and radiative forces can lead to the accumulation or depletion of chemical elements at certain optical depths. Effective atomic diffusion can result in a vertical stratification of the abundance of chemical species (Hui-Bon-Hoa, LeBlanc & Hauschildt 2000; LeBlanc et al. 2009). The direct detection of a vertical stratification of element abundances in the stellar atmospheres of CP stars suggests the effective work of the atomic diffusion mechanism and will lead to a better understanding of the evolution of CP stars and how this results in the observed peculiarities of chemical abundance (Khalack & LeBlanc 2015a).

In order to search for the signs and to study the vertical stratification of element abundances in stellar atmospheres of CP stars of various types, our group initiated project VeSElkA (Khalack & LeBlanc 2015a,b), which stands for Vertical Stratification of Element Abundances. A hydrodynamically stable atmosphere may be present in main sequence stars of intermediate mass with a slow axial rotation. For this reason, only slowly rotating CP stars with $V \sin i < 40$ km s$^{-1}$ were selected for the VeSElkA project, using the catalogue of Renson & Manfroid (2009). CP stars with a small value
of $V\sin i$ usually exhibit a number of sharp and mostly unblended line profiles well suited for abundance analysis and for the search for signs of vertical abundance stratification (Khalack et al. 2013, 2014; Khalack, Gallant & Thibeault 2017). Object HD 157087 (HR 6455, HIP 84821, BD +25° 3246) is mentioned by Renson & Manfroid (2009) as a candidate CP star of spectral class A2. On account of its relatively low rotational velocity of $V\sin i = 15$ km s$^{-1}$ (Royer et al. 2002), it was selected for project VeSElKA. The first remark about the chemical peculiarity of HD 157087 was published by Morgan (1932), who detected the spectral presence of a relatively strong line of Eu II 4205.05 Å.

Until recently, HD 157087 was considered to be a poorly studied Am star that shows some variability of radial velocity. The variability of HD 157087 was published by Morgan (1932), who detected a relatively good approximation of the observed Balmer line profiles (thick lines) for HD 157087. At the bottom of the figure, the differences between the observed and synthetic spectra are shown and shifted by 0.1 for clarity. The Balmer line profiles are shifted by 0.5 for the same reason.

Relative flux

$\Delta \lambda_{A}$ Å

Table 1. Journal of spectropolarimetric observations and respective estimates of the mean longitudinal magnetic field in HD 157087.

| Date (UTC) | HJD (2400000+) | $t_{exp}$ (s) | S/N | $<B_z>$ (G) | $<N_z>$ (G) |
|------------|----------------|--------------|-----|-------------|-------------|
| 2014 Feb 10 | 56699.11730 | 764 | 820/650 | $+40 \pm 36$ | $-20 \pm 36$ |
| 2014 Feb 15 | 56704.08525 | 764 | 900/700 | $-11 \pm 33$ | $-4 \pm 33$ |

Figure 1. The synthetic profiles (thin dotted lines) obtained with the rrsn2 code for $T_{\text{eff}} = 8882$ K, log $g = 3.57$, [M/H] = 0.0 ($\chi^{2}/v = 0.5758$) represent a relatively good approximation of the observed Balmer line profiles (thick lines) for HD 157087. The effective temperature, surface gravity and metallicity were described in Section 4, while the results of the abundance analysis are presented in Section 5. The binary nature of HD 157087 is considered in Section 6, and the discussion follows in Section 7.

2 OBSERVATIONS AND DATA REDUCTION

HD 157087 was observed on 2014 February 10 and 15 with the spectropolarimeter ESPaDOnS, which works in the spectral domain from 3700 to 10 000 Å employing the deep-depletion e2v device called Olapa (see Table 1). The instrument performances and optical characteristics of the spectropolarimetry are described in detail in Donati et al. (2006). The high-resolution ($R = 65,000$) Stokes $I$ and $V$ spectra with signal-to-noise (S/N) ratio > 500 were acquired with ESPaDOnS and reduced employing the specially designed software LIBRE-ESPRIT (Donati et al. 1997), which yields the circular polarization spectrum (Stokes $V$) and the normal spectrum (Stokes $I$). Table 1 presents a journal of spectropolarimetric observations of HD 157087, where the first and second columns show the UTC date and the HJD of spectral acquisition. The exposure duration and the S/N ratio (in Stokes $I$ and $V$ spectra) are given in the third and fourth columns, respectively. Estimates of the mean longitudinal magnetic field and the null field for this star are given in the fifth and sixth columns, respectively (see Subsection 3.4).

The effective temperature, surface gravity and metallicity were determined from the best fit to the Balmer line profiles observed in the non-normalized spectra (see Section 3 and Fig. 1). The reduced
spectra were normalized to the continuum to study line profiles that belong to helium and metals (see Section 5).

3 ESTIMATION OF FUNDAMENTAL STELLAR PARAMETERS

The effective temperature and the surface gravity of HD 157087 were determined using two methods for photometric temperature calibration and by fitting non-normalized profiles of Balmer lines (except for $H_\alpha$) visible in the three available spectra of this star (see Fig. 1).

3.1 Analysis of Balmer line profiles

The Balmer line profiles of HD 157087 were fitted with the help of the FITSB2 code (Napiwotzki et al. 2004), using grids of synthetic fluxes calculated for different values of $T_{\text{eff}}$, log $g$ and metallicity obtained with the code PHOENIX (Hauschildt, Baron & Allard 1997). In order to derive the best-fitting parameters ($T_{\text{eff}}$, log $g$ and metallicity) of the stellar atmosphere model, the code FITSB2 performs fitting only the Balmer line profiles. Nevertheless, during this procedure it takes into account some strong metallic lines that are present in the Balmer wings. The FITSB2 code does not perform an abundance analysis for each chemical element, but it results in an estimate of metallicity that serves as an average measure of the abundance of metals. For this reason, the spectral lines of most metals are not well fitted in Fig. 1 (see the curves representing the differences between the synthetic and observed spectra presented at the bottom of this image).

In this study we used grids of synthetic fluxes calculated by Khalack & LeBlanc (2015a) with spectral resolution $R = 60,000$ for models with different metallicities using version 15 of the code PHOENIX, and grids of synthetic fluxes$^2$ simulated by Husser et al. (2013) for models with different metallicities and abundances of $\alpha$-elements (O, Ne, Mg, Si, S, Ar, Ca and Ti) employing version 16 of the code PHOENIX (Hauschildt & Baron 1999). Husser et al. (2013) calculated the grids of synthetic fluxes with spectral resolution $R = 500,000$, which we reduced to $R = 50,000$ when compiling those grids to the format read by the FITSB2 code. Compared with the PHOENIX15 code, the new version 16, employs an updated list of atomic and molecular lines and uses a new equation of state to simulate a model of the stellar atmosphere and the respective synthetic flux (Husser et al. 2013).

The fitting results obtained for the three available spectra (see Table 1) of HD 157087 are shown in Table 2. In all cases, the fitting procedure was carried out assuming a rotational velocity $V \sin i = 10 \text{ km s}^{-1}$ derived for HD 157087 from a preliminary analysis of Si II line profiles. For the three available spectra, the fitting procedure that employs the same type of grids of synthetic fluxes (for example, calculated with the PHOENIX15 code) results in almost the same values of $T_{\text{eff}}$, log $g$ and metallicity (see Table 2). The effective temperatures provided by the use of the PHOENIX16 grids of synthetic fluxes (Husser et al. 2013) appear to be always significantly smaller than the $T_{\text{eff}}$ obtained employing the PHOENIX15 grids of synthetic fluxes (Khalack & LeBlanc 2015a). However, both types of grids result in the same values of the surface gravity and metallicity and in similar values of the radial velocity. Fig. 1 presents an example of the best fit of Balmer line profiles obtained using the grids of synthetic fluxes simulated with the PHOENIX15 code (Khalack & LeBlanc 2015a). The differences between the synthetic and observed spectra presented at the bottom of this image show that the obtained best fit approximates the analysed Balmer line profiles relatively well, even taking into account the contamination of Balmer wings by some metal lines.

3.2 Photometric temperature calibrations

The effective temperature $T_{\text{eff}} = 8897 \pm 51 \text{ K}$ was derived for HD 157087 from the photometric temperature ($c_1$)-calibration introduced by Napiwotzki, Schönberner & Wenske (1993) for Ap stars. For this procedure, we used the photometric index $[c_1] = 1.177 \pm 0.012$ determined according to Strömgren (1966) from the $uvby$% photometric photometry of this star (Napiwotzki et al. 1993).

Taking into account the parallax measured by Hipparcos (ESA 1997; van Leeuwen 2007), the distance to HD 157087 is approximately 137 pc. The service for 3D dust-mapping$^3$ provides for this object an interstellar reddening $E(B-V)_{\text{KSI}} \approx 0.006$ mag (Schlafly et al. 2014; Green et al. 2014, 2015), which according to Schlafly & Finkbeiner (2011) corresponds to $E(B-V) \approx 0.0053$ mag. The colour $B-V \approx 0.063$ mag provided for HD 157087 by Hipparcos (ESA 1997) is thus reduced to $(B-V)_0 \approx 0.058$ mag, and the employed photometric temperature calibration (Netopil et al. 2008) results for this star in the effective temperature $T_{\text{eff}} = 8930 \pm 165$ K.

The final results for $T_{\text{eff}}$ are presented in Table 3, in which all three methods result in similar values for the effective temperature, taking into account their estimation errors.

---

$^2$The grids of synthetic spectra are available at http://phoenix.astro.physik.uni-goettingen.de/

$^3$A 3D mapping of dust distribution in the solar neighbourhood is available at http://argonaut.rc.fas.harvard.edu/query
metallicity $[M/H]$ is between isochrones calculated by Bressan et al. (2012) for the determination of its age, mass and surface gravity through interpolation of HD 157087 on the Hertzsprung–Russell (HR) diagram and to estimate its luminosity and absolute magnitude based on the analysis of Balmer line profiles, taking into account the estimation errors (see Tables 2 and 3).

Unfortunately, the data calculated by Bressan et al. (2012) for the various isochrones do not include direct information on the size of the stellar radius. Nevertheless, its maximal value can be estimated from the known stellar mass and surface gravity, assuming a uniform distribution of mass in a sphere of stellar radius (see Table 3). If we use the masses obtained from the interpolation of isochrones and the log $g$ derived from the simulation of Balmer line profiles, the estimates of stellar radius will be smaller by a few per cent.

### 3.4 Magnetic field measurement

An estimate of the mean longitudinal magnetic field (averaged over the visible stellar disc) was deduced from an analysis of Stokes $I$ and $V$ profiles of the $H_\alpha$ line core using an approach that was initially developed by Landstreet et al. (2015). It was tested employing the spectropolarimetric observations (Stokes $I$ and $V$ spectra) of HD 16605 and HD 49299, and the derived measurements of the mean longitudinal magnetic field are similar to the results obtained by Landstreet et al. (2015) for these stars employing the least-squares deconvolution method (Landstreet et al. 2008). The estimates of the mean longitudinal magnetic field ($B_\alpha$) and of the null field $\langle N_\alpha \rangle$ derived for HD 157087 are shown in Table 1.

### 3.5 Model of the stellar atmosphere

In order to carry out an abundance analysis, we simulated a model of the stellar atmosphere for HD 157087 with the help of the PHOENIX15 code (Hauschildt et al. 1997) using the values $T_{\text{eff}} = 8882$ K and $\log g = 3.57$ derived from the fitting of Balmer line profiles. The stellar radius $R_* = 4.5 R_\odot$ provided for this star by the Catalogue of Apparent Diameters and Absolute Radii (Pasinetti Fracassini et al. 2001) and measured by Wesselink, Paranya & De Vorkin (1972) was also used to calculate a model of the stellar atmosphere. This radius is slightly smaller than the radii obtained using the log $g$ derived from the interpolation of isochrones, but it is similar to those radii obtained using the log $g$ derived from the simulation of Balmer line profiles (see Table 3).

All the derived values of stellar radius indicate that HD 157087 is of luminosity class III (Wesselink et al. 1972; Pasinetti Fracassini et al. 2001). In the procedure to calculate the stellar atmosphere model, we employed an approach in which the surface gravity depends on the optical depth of the modelled

### Table 3. Stellar parameters of HD 157087 derived from the spectral and photometric data.

| Parameter                  | Value       |
|----------------------------|-------------|
| Distance$^a$ (pc)          | 136.99 ± 0.08 |
| Age: log $t$               | 8.64 ± 0.03  |
| $M_V$ (mag)                | −0.34 ± 0.18 |
| log $(L/\text{L}_\odot)$   | 2.07 ± 0.07  |
| $T_{\text{eff}}$ (K)       | 8882 ± 100   |
| $R'_{K}/R_\odot$           | 4.63 ± 0.09  |
| $R'_{I}/R_\odot$           | 4.53 ± 0.09  |
| $M_{\ast}/M_\odot$         | 2.78 ± 0.10  |
| log $(g)$                  | 3.55 ± 0.10  |
| $T_{\text{eff}}$ (K)       | 8930 ± 51    |
| $T_{\text{eff}}^\star$ (K) | 8930 ± 165   |

Notes: $^a$Data from Hipparcos (van Leeuwen 2007); $^b$results derived from the fitting of Balmer lines using the grid of synthetic fluxes calculated with PHOENIX15 (Hauschildt et al. 1997); $^c$results derived from the $[\text{Fe}/\text{H}]$-photometric temperature calibrations (Napiwotzki et al. 1993); $^d$results obtained from the $(B-V)_\odot$ photometric temperature calibrations (Netopil et al. 2008); $^e$radii derived from mass and log $g$ known from the interpolation of isochrones (Bressan et al. 2012); $^f$radii obtained from known mass and log $g$ derived from the fitting of Balmer lines.

3.3 Age, mass, log $g$ and radius

Using the the known value of $E(B-V)_{\text{SED}}$, we can determine the interstellar extinction for HD 157087 (Schlafly & Finkbeiner 2011) and estimate its luminosity and absolute magnitude based on the visual magnitude and parallax provided for this object in the Hipparcos catalogue (ESA 1997; van Leeuwen 2007). The distance, absolute magnitude and luminosity derived in this way are given in Table 3. Taking into account the effective temperature obtained from the analysis of Balmer line profiles, the aforementioned luminosity and their estimation errors, it is possible to locate the position of HD 157087 on the Hertzsprung–Russell (HR) diagram and to determine its age, mass and surface gravity through interpolation between isochrones calculated by Bressan et al. (2012) for the metallicity $[M/H] = 0.0$ (see Fig. 2). In this case, the same values of $T_{\text{eff}}$ and luminosity correspond to two different ages, for which the proper stellar mass and surface gravity were estimated from the interpolation of isochrones (see Table 3). The surface gravity derived for the two ages is in good agreement with the log $g$ obtained for HD 157087 from the fitting of Balmer line profiles, taking into account the estimation errors (see Tables 2 and 3).

An estimate of the mean longitudinal magnetic field (averaged over the visible stellar disc) was deduced from an analysis of Stokes $I$ and $V$ profiles of the $H_\alpha$ line core using an approach that was initially developed by Landstreet et al. (2015). It was tested employing the spectropolarimetric observations (Stokes $I$ and $V$ spectra) of HD 16605 and HD 49299, and the derived measurements of the mean longitudinal magnetic field are similar to the results obtained by Landstreet et al. (2015) for these stars employing the least-squares deconvolution method (Landstreet et al. 2008). The estimates of the mean longitudinal magnetic field ($B_\alpha$) and of the null field $\langle N_\alpha \rangle$ derived for HD 157087 are shown in Table 1.

### 3.5 Model of the stellar atmosphere

In order to carry out an abundance analysis, we simulated a model of the stellar atmosphere for HD 157087 with the help of the PHOENIX15 code (Hauschildt et al. 1997) using the values $T_{\text{eff}} = 8882$ K and $\log g = 3.57$ derived from the fitting of Balmer line profiles. The stellar radius $R_* = 4.5 R_\odot$ provided for this star by the Catalogue of Apparent Diameters and Absolute Radii (Pasinetti Fracassini et al. 2001) and measured by Wesselink, Paranya & De Vorkin (1972) was also used to calculate a model of the stellar atmosphere. This radius is slightly smaller than the radii obtained using the log $g$ derived from the interpolation of isochrones, but it is similar to those radii obtained using the log $g$ derived from the simulation of Balmer line profiles (see Table 3).

All the derived values of stellar radius indicate that HD 157087 is of luminosity class III (Wesselink et al. 1972; Pasinetti Fracassini et al. 2001). In the procedure to calculate the stellar atmosphere model, we employed an approach in which the surface gravity depends on the optical depth of the modelled

4 Isochrones for stars with different metallicities can be downloaded at stev.oapd.inaf.it/cgi-bin/cmd
4 FITTING PROCEDURE

During a preliminary check of normalized spectra, we selected for analysis those spectral regions with a clearly visible continuum and a good S/N ratio, and that are clean from telluric lines and outside the wings of Balmer lines. An automatic procedure then scanned these regions for spectral line profiles (blended or unblended with a width less than 4 Å) that are deep enough for abundance analysis, taking into account the local S/N ratio. Observational data for each selected line profile were stored in a separate file. This file was linked to a list of spectral lines (and respective atomic data) that belong to different ions of specified chemical species and contribute to the formation of the selected profile. This automatic procedure also creates a file with the input data for the ZEEMAN2 code (Landstreet 1988) and an HTML file with the images of all line profiles selected for analysis. A user can easily verify the quality of all selected line profiles by looking at their images in any HTML browser, and then make corrections and rerun the automatic procedure if necessary.

A modified version of the ZEEMAN2 code (Khalack & Wade 2006; Khalack et al. 2007) was used to automatically treat a list of 1000 line profiles in consecutive mode. From the analysis of each line profile, the user can determine the abundances of chemical elements that contribute to it, V sin i and the radial velocity of the studied star (see Fig. 3). If a line profile is caused by the contribution from only one spectral line of a certain ion, we can assume that the core of the line profile is formed mainly at the line optical depth \( \tau_c = 1 \), which corresponds to a particular layer of the stellar atmosphere specified by a particular value of optical depth \( \tau_{5000} \). Taking into account that the different spectral lines usually have different oscillator strengths and lower energetic levels, their cores are generally formed at different optical depths \( \tau_{5000} \). An analysis of a number of line profiles that belong to the same ion results in a certain distribution of ion abundance with optical depth.

In the case of a well-mixed stellar atmosphere, a uniform distribution of ion abundance will be apparent for all studied optical depths. However, in a hydromagnetically stable atmosphere atomic diffusion may lead to a vertical stratification of ion abundance (Michaud 1970), and from an analysis of line profiles it is possible to detect a certain pattern in the abundance change with optical depth. This method has been previously employed by Khalack et al. (2007, 2008), Khalack, LeBlanc & Behr (2010), Khalack et al. (2013, 2014, 2017), Thiam et al. (2010), LeBlanc et al. (2015), Khalack & Poitras (2015) and Ndiaye, LeBlanc & Khalack (2017) to search for proof of vertical abundance stratification of chemical elements in the stellar atmospheres of some blue horizontal-branch (BHB), post-HB and CP stars. A similar approach was used recently by Castelli et al. (2017) to study the abundance peculiarities in HR 6000 (a non-magnetic Bp star), but employing instead the average optical depth of line profile formation (Castelli 2005) to determine the respective value of \( \tau_{5000} \).

The observed line profiles even in sharp-lined (because of a small value of V sin i) CP stars can be blended to different degrees owing to the contribution from ions of different chemical species (see, for example, Fig. 3). In the approach used in this study, for each selected line profile we have compiled a list of spectral lines that contribute to the studied profile. If the contribution of a particular ion to the formation of this profile is done through only one blend (line), we determine the optical depth of core formation for this line \( \tau_c = 1 \) and then derive the respective value of \( \tau_{5000} \). In the case that several blends (lines) that belong to the same ion are present in the line list, we determine the optical depth of core formation of the strongest component and then derive the respective optical depth \( \tau_{5000} \). This procedure is repeated for all the ions that contribute to the studied profile and whose abundance is determined from the fitting procedure. An analysis of 1000 line profiles will result in a pattern of abundance distribution with optical depth for all studied ions if they are represented by a number of spectral lines in the observed stellar spectra.

In order to carry out the abundance analysis of the available spectra of HD 157087 we employed lines and the respective atomic data of Kramida et al. (2015; Kupka et al. 2000; Ryabchikova et al. 2015) of the first two ionization states of 39 chemical species to properly fit the selected line profiles with the help of the ZEEMAN2 code (Landstreet 1988; Khalack & Wade 2006; Khalack et al. 2007). An example of the list of spectral lines used for the abundance analysis is shown in Table 4: the full version of the table is available online for both studied spectra (see Subsection 5.1). Taking into account the high resolution of the HD 157087 spectra obtained with ESPaDOnS (see Section 2.1), the number of spectral measurements (data at certain wavelengths) in a studied line profile always exceeds the number of free model parameters used to fit this profile with a synthetic one (see, for example, Fig. 3). Therefore it is possible to estimate the values of the radial \( V \) and rotational \( V \sin i \) velocities, and of an element’s abundance with relatively good precision. Taking into account the given S/N ratio of the analysed spectra (see Table 1), the precision of abundance estimates is not high for the elements whose lines contribute to the formation of weak line profiles or of weak blends in strong profiles. In both these cases,

| Ion | \( \lambda \) (Å) | \( \log N_{\text{ion}}/N_{\text{tot}} \) | \( \log g f \) | \( E_1 \) (cm\(^{-1}\)) |
|-----|----------------|------------------|------------|----------------|
| C1  | 4932.049       | -4.314 ± 0.012   | -1.658     | 61981.82       |
| C1  | 5380.337       | -4.452 ± 0.002   | -1.616     | 61981.82       |
| C1  | 9061.440       | -3.734 ± 0.004   | -0.347     | 60352.63       |
| C1  | 9088.510       | -4.414 ± 0.005   | -0.430     | 60352.64       |
the lines under consideration are formed in the deep layers of the stellar atmosphere and it is necessary to pay special attention to the derived abundance estimates. Nevertheless, a combination of these estimates with the results derived for the same ion from the analysis of other line profiles helps to recreate the general tendency of the abundance variation with optical depth. For this reason, the spectra obtained with a high spectral resolution and a high S/N ratio are the most suitable for an abundance analysis that employs the aforementioned approach to search for signatures of the vertical stratification of an element’s abundance.

5 ABUNDANCE ANALYSIS

Taking into account that the derived estimates of the longitudinal magnetic field are negligibly small for all analysed spectra (see Subsection 3.4 and Table 1), only Stokes I spectra have been used in this study to carry out an abundance analysis for HD 157087. A model of the stellar atmosphere calculated for \( T_{\text{eff}} = 8882 \) K, \( \log g = 3.57 \), \([\text{M}/\text{H}] = 0.0\) and microturbulence velocity \( \xi = 2.1 \) km\( s^{-1}\) (Yüce et al. 2011) with the help of the PHOENIX15 code (Hauschildt et al. 1997) was employed to simulate the synthetic line profiles.

Each line profile selected for analysis was fitted 4–5 times with the ZEEMAN2 code (Landstreet 1988; Khalack & Wade 2006; Khalack et al. 2007), using a different set of initial values for the average abundance of chemical elements, \( V \sin i \) and radial velocity, which were fed into the fitting routine. This approach allows one to verify if the absolute minimum of the \( \chi^2 \)-function is reached and the best-fitting results are obtained. A post-simulation automatic procedure compares the ‘best-fitting data’ from the different simulations of the same line profile and selects the best results with the smallest derived value of the \( \chi^2 \)-function.

Following the procedure developed by Khalack et al. (2017), an upper cut-off limit was imposed for the \( \chi^2 \)-function that corresponds to a relatively ‘good fit’. This limit depends on the S/N ratio in the studied spectrum and is required to exclude from the abundance analysis data gathered from the line profiles with a low fit quality. The same procedure verifies each well-fitted profile (with an acceptable value of the \( \chi^2 \)-function) if the obtained data for the abundance estimates, the radial velocity and \( V \sin i \) are significantly different from their average values, those data are removed from the abundance analysis.

5.1 Average abundance estimates

A post-simulation automatic procedure used the profiles with a ‘good’ fit obtained from the separate analysis of two spectra to estimate the average abundance for each ion. We then compared our estimates of average abundance derived for different ions with previously published data (Yüce et al. 2011) to ascertain if the chemical peculiarity of the studied star is variable in time. Table 5 contains the average estimates of ion abundance derived for HD 157087 (HD 6455) in this study and by Yüce et al. (2011). The first column specifies the studied ion, the second and third columns present respectively the average abundance with estimation errors and the number of analysed profiles (N) selected from the combined spectra observed on 2014 February 10 (see Table 1), while the fourth and fifth columns provide the same information for the line profiles selected from the spectrum observed on 2014 February 15. The sixth and seventh columns show similar data for the average abundance estimates obtained recently for this star by Yüce et al. (2011), taking into account the new estimates of solar abundance (Grevesse et al. 2010, 2015; Scott et al. 2015a,b). The error bars were calculated taking into account the estimation errors of the stellar average abundance and the precision of solar abundance estimates.

Among the analysed chemical species, only C I, Mg II and Mo I (February 15) appear to be slightly under-abundant (\( \sim -0.2 \) to \( -0.3 \) dex), while C II and Mg I seem to have solar abundance in the stellar atmosphere of HD 157087. However, Yüce et al. (2011) found a solar abundance for Cr I and Mg II, and an abundance deficit for Mg I. These authors also reported an under-abundance of O I (\( \sim -1.0 \) dex), Sc II and Co I (\( \sim -0.4 \) dex), while we found solar abundances of O I and O II, and enhanced abundances for Sc I, Sc II (February 15) and Co I.

Our analysis has shown that the abundances of Na I (February 10), Si I, Si II, Ar II, Sc II (February 15), Ti II, V I (February 10), V II, Cr II, Mn I, Mn II, Fe I, Fe II, Ni I and Zn I are significantly enhanced (\( \sim +0.2 \) to \( +0.7 \) dex), while Al II, P I, P II (February 15), Sc II, Ti I, V I (February 15), Cr II, Co I, Co II, Ni II, Sr II, Y I (February 10), Y II and rare earth elements (REEs) (La, Ce, Pr II, Nd II, Sm, Eu II, Gd, Dy) are strongly overabundant (\( \sim +0.8 \) to \( +1.7 \) dex) in the stellar atmosphere of HD 157087 (see Table 5). In the present study, extremely high abundances of Zr II (\( \geq +2.1 \) to \( +2.3 \) dex) and Ba I (February 10: \( \sim +3.0 \) dex) have also been found for this star, while Zr II and Ba II are strongly overabundant (\( \sim +1.0 \) to \( +1.5 \) dex) in the two analysed spectra. The derived abundance of Yb II is solar in the spectra obtained on February 10 but enhanced in the spectrum obtained on February 15. Yüce et al. (2011) reported similar abundance estimates for Si I, V II, Ni I, Ni II, Zn I, Y II, Zr II, La II, Ce II, Nd II, Eu II and Gd II, but, in general, we have found higher abundance estimates for the other ions (see Fig. 4).

Fig. 4 shows the derived average abundances of neutral and once-ionized ions in the stellar atmosphere of HD 157087 with respect to their solar abundance. It can clearly be seen that there are significant discrepancies between the abundance estimates derived in this study and those found by Yüce et al. (2011). Taking into account the time difference between when the reported spectra and the spectra of Yüce et al. (2011) were obtained, the detected time variation of abundance estimates for different ions could indicate that this star is a member of a binary system (see Section 6).

5.2 Analysis of the vertical stratification of element abundance

An analysis of the variation of element abundance with atmospheric depth (taking into account neutral and singly ionized ions) reveals evidence of a vertical stratification of some chemical species in the stellar atmosphere of HD 157087 (see Fig. 5). Table 6 presents the slopes derived from the linear regression of abundance change with optical depth found in the spectra obtained on February 10 (third column) and on February 15 (fourth column). The slopes of linear regression were calculated for different regions of the optical depth, as shown in the second column. If the abundance estimates for a given chemical element are obtained for a very narrow range of optical depth, it is not possible to determine the abundance change with optical depth accurately. Therefore, in Table 6 the data for He, Ne, Na, Al, Ar, K, Cu, Zn, Sr, Mo and Eu are not shown because all their abundance estimates occupy a very narrow range of optical depth.

Some elements, such as C, S, Ca, Sc, V, Cr, Mn, Co, Ni and Zr, show significant trends of abundance increase towards deeper atmospheric depths. For some of them, the abundance increase reaches up to 2 dex (see Fig. 5). The abundances of titanium, iron and probably barium reach their minimum at optical depths log \( \tau_{5000} \) = \(-6.5\) to \(-6.0\), log \( \tau_{5000} \) = \(-3.5\) to \(-2.8\), log \( \tau_{5000} \) = \(-6.8\) to
Table 5. Comparison of the average abundances derived for HD 157087.

| Ion | Feb 10° | Feb 15° | Yüce et al. (2011) |
|-----|---------|---------|-------------------|
|     | [X/H]   | N       | [X/H]             | N       |
| He I | −0.08 ± 0.13 | 4       | −0.15 ± 0.09     | 7       |
| C I  | −0.33 ± 0.08 | 26      | −0.25 ± 0.08     | 19      | −0.14 ± 0.13 | 3 |
| C II | +0.09 ± 0.12 | 4       | −0.04 ± 0.11     | 10      |
| N I  | −0.15 ± 0.08 | 6       | −0.09 ± 0.10     | 8       |
| O I  | +0.02 ± 0.07 | 16      | −0.06 ± 0.09     | 13      | −0.87 ± 0.12 | 1 |
| O II | +0.02 ± 0.07 | 14      | +0.01 ± 0.12     | 9       |
| Ne II | +0.02 ± 0.11 | 52      | +0.05 ± 0.11     | 39      |
| Na I | +0.73 ± 0.12 | 7       | +0.25 ± 0.50     | 1       |
| Mg I | +0.12 ± 0.09 | 6       | −0.04 ± 0.04     | 4       | −0.47 ± 0.24 | 2 |
| Mg II | −0.20 ± 0.06 | 9       | −0.22 ± 0.07     | 9       | −0.07 ± 0.23 | 4 |
| Al II | +1.38 ± 0.41 | 4       | +1.11 ± 0.21     | 7       | +0.27 ± 0.12 | 1 |
| Si I | +0.12 ± 0.10 | 20      | +0.19 ± 0.12     | 19      |
| Si II | +0.17 ± 0.11 | 18      | +0.24 ± 0.09     | 19      | −0.01 ± 0.19 | 9 |
| P I  | +1.10 ± 0.37 | 2       | +1.19 ± 0.44     | 3       |
| P II | +0.33 ± 0.19 | 10      | +1.39 ± 0.12     | 4       |
| S I  | +0.37 ± 0.06 | 12      | +0.30 ± 0.10     | 9       | +0.38 ± 0.12 | 3 |
| S II | +0.79 ± 0.10 | 9       | +0.70 ± 0.12     | 12      |
| Ar I | +0.38 ± 0.14 | 42      | +0.38 ± 0.15     | 25      |
| Ca I | +0.47 ± 0.52 | 2       | +0.84 ± 0.59     | 2       |
| Ca II | +0.22 ± 0.08 | 38      | +0.12 ± 0.07     | 29      | −0.12 ± 0.16 | 8 |
| Sc I | +0.12 ± 0.10 | 15      | −0.01 ± 0.06     | 10      |
| Sc II | +0.90 ± 0.23 | 7       | +1.78 ± 0.19     | 13      |
| Nb I | +0.00 ± 0.09 | 17      | +0.74 ± 0.26     | 9       | −0.35 ± 0.19 | 9 |
| Ti I | +0.09 ± 0.10 | 38      | +0.90 ± 0.10     | 36      | +0.30 ± 0.08 | 6 |
| Ti II | +0.39 ± 0.06 | 109     | +0.34 ± 0.06     | 96      | −0.14 ± 0.20 | 51 |
| V I  | +0.62 ± 0.14 | 24      | +1.00 ± 0.14     | 22      | +0.18 ± 0.12 | 1 |
| V II | +0.40 ± 0.10 | 49      | +0.52 ± 0.10     | 48      | +0.45 ± 0.22 | 28 |
| Cr I | +0.86 ± 0.07 | 131     | +0.83 ± 0.07     | 116     | +0.31 ± 0.20 | 13 |
| Cr II | +0.53 ± 0.07 | 131     | +0.47 ± 0.07     | 108     | +0.10 ± 0.21 | 40 |
| Mn I | +0.75 ± 0.10 | 62      | +0.70 ± 0.08     | 74      | +0.11 ± 0.16 | 20 |
| Mn II | +0.63 ± 0.10 | 55      | +0.52 ± 0.09     | 55      | +0.29 ± 0.21 | 14 |
| Fe I | +0.20 ± 0.04 | 440     | +0.17 ± 0.04     | 366     | +0.14 ± 0.18 | 247 |
| Fe II | +0.41 ± 0.05 | 252     | +0.38 ± 0.05     | 195     | +0.15 ± 0.20 | 73 |
| Co I | +1.53 ± 0.09 | 91      | +1.52 ± 0.10     | 74      | +0.44 ± 0.21 | 7 |
| Co II | +1.74 ± 0.12 | 36      | +1.36 ± 0.16     | 26      |
| Ni I | +0.59 ± 0.05 | 127     | +0.60 ± 0.05     | 104     | +0.55 ± 0.19 | 34 |
| Ni II | +0.91 ± 0.10 | 33      | +0.80 ± 0.08     | 28      | +0.65 ± 0.16 | 6 |
| Zr I | +0.04 ± 0.08 | 3       | −0.15 ± 0.08     | 4       | +0.67 ± 0.08 | 3 |
| Zr II | +0.75 ± 0.10 | 127     | +0.82 ± 0.07     | 28      | +0.79 ± 0.20 | 14 |
| Zn I | +0.10 ± 0.08 | 3       | +0.28 ± 0.04     | 2       |
| Zn II | +0.10 ± 0.08 | 3       | +0.12 ± 0.05     | 44      | +0.95 ± 0.18 | 32 |
| Mo I | −0.12 ± 0.11 | 20      | −0.30 ± 0.10     | 12      |
| Ba I | +3.00 ± 0.09 | 2       | +1.49 ± 0.23     | 9       | +1.24 ± 0.46 | 2 |
| Ba II | +1.49 ± 0.23 | 9       | +1.24 ± 0.14     | 7       | +0.46 ± 0.08 | 2 |
| La I | +1.06 ± 0.11 | 30      | +0.98 ± 0.11     | 20      | +0.93 ± 0.11 | 10 |
| La II | +1.67 ± 0.06 | 4       | +1.44 ± 0.50     | 1       |
| Ce I | +1.67 ± 0.06 | 199     | +1.58 ± 0.07     | 162     | +0.97 ± 0.18 | 31 |
| Ce II | +2.30 ± 0.10 | 49      | +2.13 ± 0.13     | 32      |
| Nd I | +1.69 ± 0.08 | 77      | +1.52 ± 0.08     | 84      | +0.84 ± 0.07 | 3 |
| Sm I | +1.27 ± 0.34 | 6       | +1.46 ± 1.22     | 2       |
| Sm II | +1.87 ± 0.13 | 36      | +1.53 ± 0.12     | 43      |
| Eu I | +1.06 ± 0.26 | 4       | +0.79 ± 0.18     | 5       | +0.83 ± 0.05 | 2 |
| Gd I | +0.86 ± 0.33 | 5       | +1.31 ± 1.01     | 2       |
| Gd II | +1.48 ± 0.11 | 39      | +1.47 ± 0.11     | 37      | +1.08 ± 0.17 | 3 |
| Dy I | +1.25 ± 0.06 | 3       | +1.10 ± 0.50     | 1       |
| Dy II | +1.54 ± 0.13 | 21      | +1.48 ± 0.15     | 23      | +0.81 ± 0.15 | 6 |
| Yb I | +0.17 ± 0.18 | 8       | +0.71 ± 0.24     | 7       |

Notes: *results for two spectra observed on different nights (see Table 1).
−6.3, respectively, and have a tendency to increase towards the upper and deeper atmospheric layers. For barium, this picture is less convincing because of the much smaller number of abundance estimates that indicate this behaviour (see Fig. 5).

Other elements, such as N, O, Si, P (February 15) and Y, do not show any significant stratification of their vertical abundance. In addition, the results of the abundance analysis of spectra obtained on February 10 indicate that phosphorus increases its abundance towards the upper levels of the stellar atmosphere. Magnesium (February 10) seems to slightly increase its abundance towards the upper atmospheric layers in HD 157087, but the derived slope of abundance change with optical depths is not significant (see Table 6).

REEs (Ce, Dy, Gd, La, Nd, Pr, Sm and Yb) are significantly enhanced in the layers close to the stellar surface and show almost the same increase of their abundance towards the deeper atmospheric layers. Nevertheless, the range of optical depths where one can trace an abundance increase is narrow. Usually the range is \( \log \tau_{\text{9000}} = -7.5 \) to \(-5.0\) (see Fig. 5 and Table 6). In the deeper layers of the stellar atmosphere, some REEs (for example, cerium) do show an abundance similar to (or smaller than) that found in the layers close to the stellar surface.

We find a similar situation for the vertical stratification of the zirconium abundance based on the analysis of only \( \text{Zr}\) ii line profiles, taking into account the narrow range of optical depths of their formation. However, the analysis of \( \text{Zr}\) i line profiles results in even higher abundance estimates for the deeper atmospheric layers (see Fig. 5). Therefore, in this case we have stronger evidence for the vertical abundance stratification of zirconium.

### 6 BINARY SYSTEM

The detection of vertical abundance stratification for some metals whose average abundance changes with time (see Tables 5, 6) does not agree well with the hypothesis that HD 157087 is a singular star of Am type. The detected change of average abundance can be explained in terms of the binary nature of this star, as reported by Bidelman (1988). In a binary system, the secondary component may contribute significantly to the strength of the observed line profiles and cause a variability in chemical abundance with orbital phase (Lyubimkov 1989). The analysis of line profiles in the available spectra of HD 157087 does not show clear signatures (line profiles) that can be attributed to the secondary component. Furthermore, Makarov & Kaplan (2005) have reported HD 157087 as an astrometric binary system that shows some changes in its short-term proper motion. Usually such changes can be detected only in long-period binaries with the periods longer than 6 yr (Makarov & Kaplan 2005).

The estimates of radial velocity derived in this study are shown in Table 7, together with the previously published data of Plaskett et al. (1922) and Yüce et al. (2011). These data were analysed with the help of version 1.2 of the code PERIOD04 developed by Lenz & Breger (2005), which was specifically designed to carry out a statistical analysis of large astronomical data sets with significant gaps. The Fourier transformation of the available data on radial velocity results in spurious peaks in the frequency diagram. The most significant peaks are found one by one and pre-whitened from the observed data using the least-squares fitting procedure (Lenz & Breger 2005). The analysis results in the detection of five periods, with the amplitudes having a significant S/N ratio at the detected frequency (see Table 8). Finally, the available radial velocity data were fitted taking into account all five frequencies using the least-squares procedure, and the obtained periods, amplitudes and phases are shown respectively in the first, second and third columns of Table 8. The presented uncertainties are the highest ones obtained from the error-matrix produced by the Levenberg–Marquardt non-linear least-squares fitting procedure and from the Monte Carlo simulation of a signal with the detected frequencies (Lenz & Breger 2005). They do not take into account the estimation errors reported for the \( V_r\) measurements. In this approach, the uncorrelated uncertainties for the frequency and the phase are derived (Montgomery & Odonoghue 1999). The fourth column of Table 8 contains the S/N ratio calculated for each derived frequency from the simulation of the white noise using the dispersion of residual data left after the pre-whitening procedure (Lenz & Breger 2005). Taking into account the high uncertainties for the detected periods and their amplitudes and phases (see Table 8), the derived results can be considered only as indicators of the long-term and the short-term periodic variations of \( V_r\). To determine these periods with a higher precision it would be necessary to acquire additional spectra of HD 157087 and to derive new data for the radial velocity.

Considering that the previous measurements of radial velocity have large estimation errors and are not well folded in the time
Figure 5. Distribution of titanium, manganese, chromium, iron, zirconium, barium, cerium and neodymium abundances with optical depth in the stellar atmosphere of HD 157087. The filled symbols present results derived from an analysis of the combined spectra observed on 2014 February 10 (see Table 1), while the open symbols denote the data obtained from an analysis of the spectrum observed on 2014 February 15. The triangles and circles represent the data obtained for neutral and singly ionized atoms, respectively. For each studied element, its solar abundance with respect to the total number of atoms in 1 cm$^{-2}$ is specified by a horizontal dashed line.
domain (Plaskett et al. 1922; Yüce et al. 2011), the derived periods may differ significantly from the real ones. Nevertheless, in Table 8 it is possible to identify the presence of a long-period (several years) variability of radial velocity that can be explained by orbital motion in a binary system. This fact supports the hypothesis of Makarov & Kaplan (2005) that HD 157087 is an astrometric binary system with a period longer than 6 yr. On the other hand, short-period variations (3–6 d) of radial velocity are also evident and could be caused by an axial rotation of the star with abundance inhomogeneities on its surface or by a short-period binary that rotates around a third star (assuming that HD 157087 is a triple system). In any case, to measure the short-period radial velocity variability in HD 157087 with higher precision it is necessary to acquire additional spectra of this star that are well folded over the period of 3–6 d.

### 7 DISCUSSION

Renson & Manfroid (2009) considered HD 157087 as a candidate CP star of spectral class A2, while Yüce et al. (2011) reported HD 157087 as a marginal Am star, based on their abundance analysis. Bidelman (1988) also identified HD 157087 as a marginal Am star that is probably a member of a binary system, while Makarov & Kaplan (2005) showed that HD 157087 is a member of an astrometric binary system. The present paper has aimed to study the abundance stratification of chemical elements in the stellar atmosphere of HD 157087 and to analyse the change of its average abundance with time in order to verify the nature of this object.

The effective temperature derived in this study from the fitting of Balmer line profiles (Khalack & LeBlanc 2015a) is in good accordance with the estimate of \( T_{\text{eff}} \) obtained from two photometric temperature calibrations (Napiwotzki et al. 1993; Netopil et al. 2008). Taking into account the estimation errors, the values of \( T_{\text{eff}} \) and \( \log g \) (see Table 3) derived here agree relatively well with \( T_{\text{eff}} = 8700 \pm 150 \, \text{K} \) and \( \log g = 3.25 \pm 0.20 \) obtained for HD 157087 by Yüce et al. (2011). Based on the visual magnitude and parallax provided for this object in the Hipparcos catalogue (ESA 1997; van Leeuwen 2007), we derived its luminosity and found its position on the HR diagram (see Fig. 2). For the derived effective temperature and luminosity, the interpolation of isochrones calculated by Bressan et al. (2012) for the metallicity [M/H] = 0.0 results in two sets of age, mass, surface gravity and stellar radius (see Table 3). The estimates of stellar age (mass, surface gravity and radius) obtained for HD 157087 in the two sets are similar to one another, taking into account their uncertainties. The value of \( \log g \) obtained from the interpolation of isochrones is very close to the one derived from the fitting of Balmer line profiles. Our estimate of the stellar radius also agrees well with the \( R_{\ast} = 4.5 \, R_{\odot} \) provided for this object in the Catalogue of Apparent Diameters and Absolute Radii (Pasinetti Fracassini et al. 2001). It is found that HD 157087 does not possess a detectable magnetic field (see Table 1).
The stellar atmosphere model was calculated with the help of the PHOENIX15 code (Hauschildt et al. 1997) for \( T_{\text{eff}} = 8882 \) K, \( \log g = 3.57 \), [M/H] = 0.0, assuming a microturbulence velocity \( \xi = 2.1 \) km s\(^{-1}\) (Yüce et al. 2011). The model was used to carry out an abundance analysis using the code ZEEMAN2 (Landstreet 1988; Khalack & Wade 2006; Khalack et al. 2007), under the assumption that HD 157087 is a single star with no magnetic field. From the analysis of 929 profiles in the combined spectrum obtained on 2014 February 10 and of 746 line profiles in the spectrum obtained on 2014 February 15, we estimated its radial velocity (see Table 7) and \( V \sin(i) = 10.35 \pm 0.05 \) km s\(^{-1}\) (February 10) and \( 10.18 \pm 0.05 \) km s\(^{-1}\) (February 15), and the average abundance of chemical elements (see Table 5). The average abundances of chemical elements derived here are usually higher (especially for the REEs) than the values reported by Yüce et al. (2011) for the studied star (see Fig. 4). This fact argues in favour of the binary nature of HD 157087. Our analysis of the available measurements of radial velocity results in the detection of long-period (5–23 yr) and short-period (3–6 d) variations (see Table 8). The long-period variation agrees well with the idea that HD 157087 is an astrometric binary system with a period longer than 6 yr (Makarov & Kaplan 2005). Meanwhile, the presence of the short-period variation of \( V \) and the changes of average abundance with time suggest that HD 157087 may in reality be a triple system in which a short-period binary rotates around a third star.

The convective stellar atmosphere of an Am star should possess a more or less uniform abundance everywhere at the stellar surface and at different optical depths, owing to the turbulent motions that rapidly smooth out any abundance inhomogeneities (Michaud et al. 1983). According to Preston (1974) and Adelman (1987), the stellar atmospheres of classical Am stars are usually rich in heavy elements and show a deficit in calcium and scandium. The results of the abundance analysis in this study argue against the classification of HD 157087 as even a marginal Am star (Bidelman 1988; Yüce et al. 2011), because the stellar atmosphere of this star shows a solar calcium abundance (Ca i seems to be enhanced in the spectrum obtained on February 10), and scandium appears to be significantly overabundant. An analysis of the vertical abundance stratification of elements in the stellar atmosphere of HD 157087 reveals that C, S, Ca, Sc, V, Cr, Mn, Co, Ni and Zr show significant trends of abundance increase towards the deeper atmospheric layers (see Table 6). This fact does not support the classification of HD 157087 as an Am star either, because Am stars should not possess a vertical abundance stratification of chemical elements in their atmosphere (Michaud et al. 1983). However, taking into account the hypothesis of a triple system with a short-period binary as a member, the reported facts can be explained in terms of the assumption that this short-period binary consists of slowly rotating Am and A stars (or even an Ap star with a weak magnetic field) that have a similar \( T_{\text{eff}} \) and \( \log g \) but different abundance peculiarities. According to Lyubimkov (1989), the orbital motion in the short-period binary can explain the observed variation of average abundance with time. This hypothesis also explains the detection of the vertical abundance stratification for several chemical species in HD 157087 at certain orbital phases.

The spectra analysed here were acquired with ESPaDOnS over a time span of 5 d. The estimates of average abundance for the studied chemical species (see Table 5) and the profiles of vertical abundance stratification (see Table 6) do not change significantly during this period of time, although the value of \( N_{\text{obs}} \) obtained for HD 157087 decreases by 0.008 dex. Therefore, the short-period variation of radial velocity might also be attributed to the period of axial rotation of HD 157087. Taking into account that HD 157087 is a member of an astrometric binary system (Makarov & Kaplan 2005) whose components should be visually separated, it would be difficult to explain under an assumption of only one rotating star the detected long-term change of the average abundance over 5 d (see Table 5) and over a longer period of time (see Section 6).

In order to confirm or reject these hypotheses, it is necessary to perform a thorough abundance analysis of additional high-resolution and high S/N spectra of HD 157087 that densely cover a time span of 3–6 d or an even longer period. This would provide more measurements of radial velocity that could contribute to the estimation of short-variability periods with higher precision. The variability of the average abundance estimates and probably of the vertical abundance stratification of chemical species with time could also be studied in more detail.

ACKNOWLEDGEMENTS

This work is based on observations obtained at the Canada–France–Hawaii Telescope (CFHT), which is operated by the National Research Council of Canada, the Institut National des Sciences de l’Univers of the Centre National de la Recherche Scientifique of France, and the University of Hawaii. The operations at CFHT are conducted with care and respect from the summit of Maunakea, which is a significant cultural and historic site. I am grateful to Professor F. Castelly for useful comments and helpful advice that led to a significant improvement in this study. I acknowledge support from the Natural Sciences and Engineering Research Council of Canada and thank the Faculté des Études Supérieures et de la Recherche and the Faculté des Sciences de l’Université de Moncton for financial support of this research. Some of the calculations were carried out on the supercomputer brierree of the University of Montreal, under the guidance of Calcul Québec and Calcul Canada. The use of this supercomputer is funded by the Canadian Foundation for Innovation (CFI), NanoQuébec, RMGA and Research Fund of Québec – Nature and Technology (FRQNT).

REFERENCES

Abt H. A., Morell N. I., 1995, ApJS, 99, 135
Adelman S. J., 1987, A&AS, 67, 353
Bidelman W. P., 1988, PASP, 100, 1084
Bressan M. P., Marigo P., Girardi L., Salasnich B., Dal Cero C., Rubele S., Nanni A., 2012, MNRAS, 427, 127
Bychkov V. D., Bychkova L. V., Madej J., 2003, A&A, 407, 631
Castelli F., 2005, Mem. Soc. Astron. Ital. Suppl., 8, 44
Castelli F., Cowley C. R., Ayers T. R., Catanzaro G., Leone F., 2017, A&A, 601, A119
Donati J.-F., Semel M., Carter B. D., Rees D. E., Cameron A. C., 1997, MNRAS, 291, 658
Donati J.-F., Catala C., Landstreet J. D., Petit P., 2006, in Casini R., Lites B. W., eds, Astronomy Society of the Pacific Conference Series Vol. 358, Solar Polarization 4. Astron. Soc. Pac., San Francisco, p. 362
ESA, 1997, The Hipparcos and Tycho Catalogues, ESA, SP Series 1200.
ESA, Noordwijk
Green G. M. et al., 2014, ApJ, 783, 114
Green G. M. et al., 2015, ApJ, 810, 25
Grevesse N., Asplund M., Sauval A. J., Scott P., 2010, Ap&SS, 328, 179
Grevesse N., Scott P., Asplund M., Sauval A. J., 2015, A&A, 573, 27
Hauschildt P. H., Baron E., 1999, J. Comput. Appl. Math., 109, 41
Hauschildt P. H., Baron E., Allard F., 1997, ApJ, 483, 390
Hui-Bon-Hoa A., LeBlanc F., Hauschildt P. H., 2000, ApJ, 535, L43
Husser T.-O. et al., 2013, A&A, 553, 6
Khalack V., LeBlanc F., 2015a, AJ, 150, 1

Downloaded from https://academic.oup.com/mnras/article-abstract/477/1/882/4975808 by guest on 16 March 2020
Supporting Information

Supplementary data are available at MNRAS online.

Table 4. List of spectral lines and respective atomic data used to study the abundance peculiarities in HD 157087.

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

This paper has been typeset from a TeX/LaTeX file prepared by the author.