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Testing the accretion scenario of λ Boo stars

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ABSTRACT

Context. The existence of a group of λ Boo stars has been known for years, however, the origin of its chemical peculiarity is still a matter of debate.

Aims. Our aim is to test the accretion scenario of λ Boo stars. This model predicts that in a binary system with two early-type stars passing through a diffuse cloud, both stars ought to display the same superficial peculiarity.

Methods. Via spectral synthesis, we carried out a detailed abundance determination of three multiple systems hosting a candidate λ Boo star: the remarkable triple system HD 15164/65/65C and the two binary systems HD 193256/281 and HD 198160/161. The stellar parameters were initially estimated using Strömgren photometry or literature values and then refined by requiring excitation and ionization balances for Fe lines. The abundances were determined iteratively for 24 different species by fitting synthetic spectra using the SYNTHE program together with local thermodynamic equilibrium (LTE) ATLAS12 model atmospheres. Specific opacities were calculated for each star, depending on its arbitrary composition and microturbulence velocity, $v_{\rm micro}$, through the opacity sampling method. The abundances of the light elements C and O were corrected by non-LTE effects. The complete chemical patterns of the stars were then compared to those of λ Boo stars.

Results. The abundance analysis of the triple system HD 15164/65/65C shows a clear λ Boo object (HD 15165) and two objects with a near-solar composition (HD 15164 and 15165C). Notably, the presence of a λ Boo star (HD 15165) together with a near-solar early-type object (HD 15164) is difficult to explain under the accretion scenario. Also, the solar-like composition derived for the late-type star of the system (HD 15165C) could be used, for the first time, as a proxy for the initial composition of the λ Boo stars. This could help to constrain any model of λ Boo stars formation – not only the accretion scenario. The abundance analysis of the binary system HD 193256/281 shows no clear λ Boo components, while the analysis of HD 198160/161 shows two mild-λ Boo stars. Then, by carefully reviewing the abundance analysis of all known binary systems with candidate λ Boo stars from literature and including the systems analyzed here, we find no binary or multiple system having two clear bona fide λ Boo stars, as would expected from the accretion scenario. The closest candidates to exhibiting two λ Boo-like stars are the binary systems HD 84948, HD 171948, and HD 198160; however we find that they show mild, rather than clear, λ Boo patterns.

Conclusions. We performed, for the first time, a complete analysis of a triple system that includes a λ Boo candidate. Our results brings little support to the accretion scenario of λ Boo stars. Furthermore, there is an urgent need for additional binary and multiple systems to be analyzed via a detailed abundance analysis in order to test the accretion model of λ Boo stars.

Key words. stars: abundances – binaries: visual – stars: chemically peculiar

1. Introduction

The main feature of λ Boo stars is a notable underabundance of most Fe-peak elements and near-solar abundances of lighter elements (C, N, O, and S). This class comprises main-sequence late-B to early-F stars, where a maximum of about 2% of all objects are believed to be λ Boo stars (Gray & Corbally 1998; Paunzen et al. 2001b). Classification-resolution spectroscopy has revealed promising λ Boo candidates (e.g., Murphy et al. 2015; Gray et al. 2017) and a more detailed abundance determination, especially including the lighter elements, is considered to be the ultimate test to confirm whether a candidate is indeed a bona fide member of the class (e.g., Andrievsky et al. 2002; Heiter et al. 2002).

The origin of the λ Boo peculiarity remains a challenge (see, e.g., the recent discussion from Murphy & Paunzen 2017, and references therein). Their rotational velocities do not necessarily point toward lower values, thus marking a difference with chemically peculiar Am and Ap stars (Abt & Morrell 1995; Murphy et al. 2015). A possible explanation focuses on the interaction of the star with a diffuse interstellar cloud (Kamp & Paunzen 2002; Martinez-Galarza et al. 2009). In this work, we refer to this model as the "accretion scenario," in which the underabundances are produced by different amounts of volatile accreted material and the more refractory species are possibly separated and repelled from the star. More recently, Jura (2015) proposed that this peculiar pattern possibly originates in the winds of

Table 1. Magnitudes and astrometric data for the stars studied in this work.

Star	V	α J2000	δ J2000	μ_α (mas yr^{-1})	μ_δ (mas yr^{-1})	π (mas)	Spectra
HD 15164	8.27	02 26 48.29	+10 34 57.59	36.552	–13.717	7.4185	MPG+FEROS
HD 15165	6.69	02 26 45.65	+10 33 55.07	36.680	–13.086	7.4414	MPG+FEROS
HD 15165C	11.78	02 26 47.40	+10 32 58.89	36.805	–13.131	7.5499	MPG+FEROS
HD 193256	7.53	20 20 26.57	–29 11 28.76	–1.991	–1.221	5.8675	CASLEO+REOSC
HD 193281	6.64	20 20 27.88	–29 11 49.97	–0.653	0.244	6.2644	CASLEO+REOSC
HD 198160	6.21	20 51 38.51	–62 25 45.59	82.697	–46.562	13.5137	MPG+FEROS
HD 198161	6.56	20 51 38.85	–62 25 45.26	82.077	–42.340	13.5315	MPG+FEROS

hot-Jupiter planets[1]. In this case, the planet acts as the source of gas poor in refractory species. However, Saffe et al. (2021) recently showed that eight early-type stars hosting hot-Jupiter planets do not display the λ Boo peculiarity. This would allow for the interaction of the star with a diffuse cloud to be considered as the more plausible scenario for explaining the λ Boo phenomena in main-sequence stars.

Under the accretion scenario, two early-type stars passing through a diffuse cloud should display, in principle, the same superficial peculiarity (e.g., Paunzen et al. 2012a,b). At the same time, hotter stars ($T_{\rm eff} > \sim$12 000 K) with strong winds and cooler stars ($T_{\rm eff} < \sim$6500 K) with larger convective zones should not notably change their composition. These predictions make the analysis of binary and multiple systems an important tool for testing the accretion scenario. However, the number of known candidate λ Boo stars in binary or multiple systems is limited to no more than a dozen objects (e.g., Paunzen et al. 2012a,b), where most of them are spectroscopic binary (SB) systems. To our knowledge, only five of these systems present a detailed chemical analysis of the two components (see the Appendix for a more detailed review). Notably, some stars of these binary systems were recently identified as non-members or uncertain members of the λ Boo class (see Gray et al. 2017). Based on literature data, we selected for this study three binary or multiple systems that possibly contest the accretion scenario. In addition, they are spatially resolved (in contrast to most candidate λ Boo stars that belong to SB systems, Paunzen et al. 2012a,b), allowing for an individual analysis without factoring in any strong contribution from the companion. We also review all known binary or multiple systems with candidate λ Boo stars, with data taken from the literature (see Appendix).

In this work, we present an analysis of the remarkable triple system HD 15165. It is composed of HD 15165, HD 15164, and HD 15165C (stars A, B, and C) with spectral types "F2 V kA2mA2 λ Boo?", "F1 V kA7mA6 (λ Boo)?", and "K2 V" (Murphy et al. 2015). Some previous works suggest that the A star belong to the λ Boo class (Andrievsky et al. 1995; Chernyshova et al. 1998), while the B star seem to display, notably, a solar composition (Andrievsky et al. 1995). If these abundances are confirmed, this could certainly defy the accretion scenario. In addition, there is no current analysis of the third star, the late-type component of the system. Therefore, we have taken the opportunity to perform a detailed abundance analysis that includes, for the first time, the three stars of the system, using a spectra with higher resolving power than previous works.

We also present an analysis of the binary systems HD 193256/281 and HD 198160/161. Both systems show solar values for C and subsolar Fe, similarly to other candidate λ Boo stars (Stürenburg 1993). However, more recent classification spectra suggest that only one star of the system belong to the λ Boo class (see Tables 1 and 4 of Murphy et al. 2015; Gray et al. 2017), which would be difficult to explain under the accretion scenario. This converts both systems in very interesting targets to study in detail and they are included in our analysis.

This work is organized as follows. In Sect. 2, we describe the observations and data reduction. In Sect. 3, we present the stellar parameters and chemical abundance analysis. In Sect. 4, we show the results and discussion. Finally, in Sect. 5, we highlight our main conclusions.

2. Observations

In Table 1, we present the visual magnitude V (from HIPPARCOS), coordinates, proper motions, and parallax (from *Gaia* DR2, Gaia Collaboration 2018) for the stars studied in this work. The spectral data of the triple system HD 15165 were obtained with the Max Planck Gesselschaft (MPG) 2.2 m telescope at the European Southern Observatory (ESO) in La Silla, Chile on October 10, 2021 (Program ID: 0108.A-9012, PI: Marcelo Jaque Arancibia). We used the Fiber-fed Extended Range Optical Spectrograph (FEROS), which provides a high-resolution ($R \sim 48.000$) spectra when illuminated via the 2.0 arcsec aperture on the sky in the unbinned mode. Three individual spectra for each object were obtained, followed by a ThAr lamp in order to obtain an appropriate wavelength solution. The data were reduced using the FEROS Data Reduction System[2] (DRS). The spectral coverage resulted between 3700 and 9000 Å, approximately, and the signal-to-noise ratio (S/N) per pixel measured at ~5000 Å resulted in ~300.

The spectra of the binary system HD 193256/281 were obtained at the Complejo Astrónomico El Leoncito (CASLEO) between May 9 and 11, 2009 (PI: Maria Eugenia Veramendi). We used the *Jorge Sahade* 2.15-m telescope equipped with a REOSC echelle spectrograph[3] and a TEK 1024×1024 CCD detector. The REOSC spectrograph uses gratings as cross-dispersers. We used a grating with 400 lines mm^{-1}, which provides a resolving power of ~12 500 covering the spectral range of $\lambda\lambda$3800–6500. Three individual spectra for each object were obtained and then combined, reaching a final S/N per pixel of ~300 measured at ~5000 Å. The data were reduced with Image Reduction

[1] Hot-Jupiter planets present short orbital periods (<10 d) and large masses (>0.1 $M_{\rm Jup}$).

[2] https://www.eso.org/sci/facilities/lasilla/instruments/feros/tools/DRS.html

[3] On loan from the Institute d'Astrophysique de Liege, Belgium.

Table 2. Fundamental parameters derived for the stars in this work.

Star	$T_{\rm eff}$ (K)	$\log g$ (dex)	$v_{\rm micro}$ (km s^{-1})	$v \sin i$ (km s^{-1})
HD 15164	7150 ± 70	3.74 ± 0.08	2.54 ± 0.63	17.9 ± 0.7
HD 15165	6950 ± 139	3.80 ± 0.19	2.21 ± 0.55	125.7 ± 5.4
HD 15165C	4960 ± 51	4.40 ± 0.03	0.46 ± 0.07	2.4 ± 0.3
HD 193256	7780 ± 146	3.97 ± 0.19	3.23 ± 0.81	257.0 ± 8.2
HD 193281	8700 ± 140	3.60 ± 0.15	2.99 ± 0.75	91.5 ± 3.9
HD 198160	8010 ± 130	4.09 ± 0.15	3.31 ± 0.83	190.0 ± 6.8
HD 198161	8010 ± 130	4.09 ± 0.15	3.31 ± 0.83	185.0 ± 7.2

and Analysis Facility (IRAF) following the standard recipe for echelle spectra (i.e., bias and flat corrections, order-by-order normalization, scattered light correction, etc.).

Finally, the FEROS spectra of the binary system HD 198160/161 were obtained from the ESO Science Archive Facility[4]. The stars were observed between April 4 and 7, 2017 (Program ID: 099-A-9029). The spectra were reduced using the FEROS DRS, obtaining a spectral coverage and S/N values that are similar to those obtained with HD 15165.

3. Stellar parameters and abundance analysis

The stellar parameters $T_{\rm eff}$ and $\log g$ were estimated iteratively, similarly to previous works (Saffe et al. 2021). They were first estimated by using the Strömgren uvbyβ mean photometry of Hauck & Mermilliod (1998) or considering previously published results. We used the calibration of Napiwotzki et al. (1993) and deredenned colors according to Domingo & Figueras (1999) within the program TempLogG (Kaiser 2006), in order to derive the fundamental parameters. These initial values were refined (when necessary and possible) by imposing excitation and ionization balances of the iron lines. A similar strategy was previously applied in the literature (e.g., Saffe & Levato 2014; Saffe et al. 2021). The values derived in this way are listed in the Table 2, with an average dispersion of ~115 K and ~0.13 dex for $T_{\rm eff}$ and $\log g$, respectively.

The projected rotational velocities, $v \sin i$, were estimated by fitting most Fe I and Fe II lines in the spectra. Synthetic spectra were calculated using the program SYNTHE (Kurucz & Avrett 1981) together with ATLAS12 (Kurucz 1993) model atmospheres. Microturbulence velocity $v_{\rm micro}$ was estimated as a function of $T_{\rm eff}$ following the formula of Gebran et al. (2014), which is valid for ~6000 K $< T_{\rm eff} <$ ~10 000 K; however, for the late-type star HD 15165C, we used the formula of Ramirez et al. (2013) for FGK stars. We adopt for $v_{\rm micro}$ an uncertainty of ~25%, as suggested by Gebran et al. (2014).

Chemical abundances were determined iteratively by fitting a synthetic spectra using the program SYNTHE (Kurucz 1993). In the first step, we used an ATLAS12 model atmosphere calculated with solar abundances. With the new abundance values, we derived a new model atmosphere and started the process again. In each step, opacities were calculated for an arbitrary composition and $v_{\rm micro}$ using the opacity sampling (OS) method, in a similar fashion to previous works (Saffe et al. 2020, 2021). Possible differences originating from the use of opacities with solar-scaled composition instead of an arbitrary composition were recently estimated for solar-type stars (Saffe et al. 2018, 2019). When necessary, $T_{\rm eff}$ and $\log g$ were refined to achieve the balance of Fe I and Fe II lines. In this way, abundances and parameters are consistently derived until reach the same input and output abundance values (for more details, see Saffe et al. 2021).

[4] http://archive.eso.org/cms.html

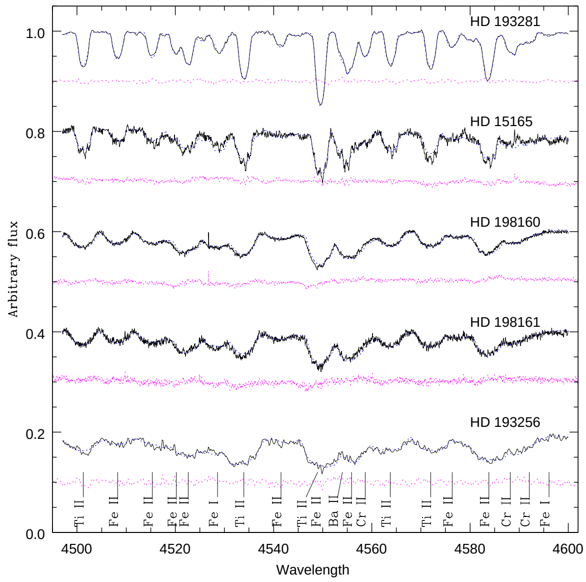

Fig. 1. Observed, synthetic, and difference spectra (black, blue dotted, and magenta lines) for the stars in our sample, sorted by $v \sin i$.

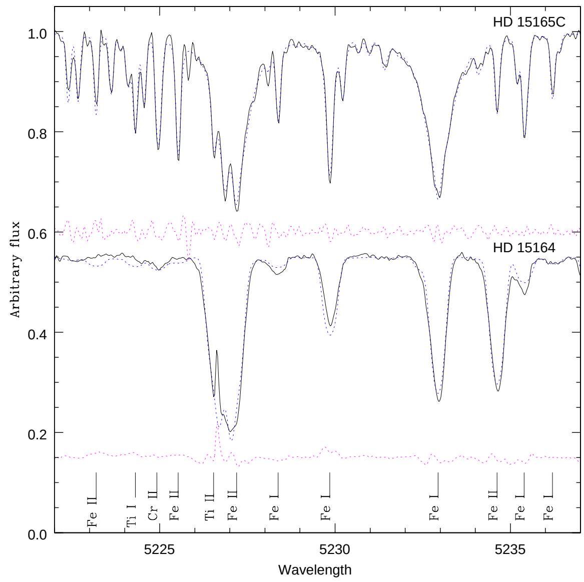

Fig. 2. Observed, synthetic, and difference spectra (black, blue dotted, and magenta lines) for the stars in our sample, sorted by $v \sin i$.

Chemical abundances were derived for 24 different species. The atomic line list and laboratory data used in this work are the same described in Saffe et al. (2021). In Figs. 1 and 2, we present an example of observed and synthetic spectra (black and blue dotted lines, almost superimposed) together with the difference spectra (magenta) for the stars in our sample. For clarity, Fig. 1 corresponds to stars with the higher $v \sin i$ values (>91 km s^{-1}), while Fig. 2 corresponds to stars with the lower $v \sin i$ values (<17.9 km s^{-1}). The stars are sorted in these plots by increasing $v \sin i$. There is a good agreement between the results of modeling and the observations for the lines of different chemical species. To determine the uncertainty in the abundance values, we considered different sources. The total error e_{tot} was derived as the quadratic sum of the line-to-line dispersion, e_1 (estimated as $\sigma/\sqrt{n}$, where σ is the standard deviation), and the error in the abundances (e_2, e_3, and e_4) when varying $T_{\rm eff}$, $\log g$ and $v_{\rm micro}$ by their corresponding uncertainties[5]. For chemical species with only one line, we adopt as σ the standard deviation of iron lines. The abundances, the total error, e_{tot}, and the individual errors, e_1 to e_4, are presented in Tables B.1 to B.7.

3.1. NLTE effects

Light-element non-local thermodynamic equilibrium (NLTE) abundances are particularly important in the case of λ Boo stars. For instance, Paunzen et al. (1999) derived for a sample of λ Boo stars an average O I correction of –0.5 dex; while for C I, they estimated an average correction of –0.1 dex. Rentzsch-Holm (1996) calculated carbon NLTE abundance corrections by using a multilevel model atom for stars with $T_{\rm eff}$ between 7000 K and 12 000 K, log g between 3.5 and 4.5 dex, and metallicities from –0.5 dex to +1.0 dex. She showed that C I NLTE effects are negative (calculated as NLTE-LTE) and depend basically on equivalent width $W_{\rm eq}$. Near ~7000 K, the three lower levels of C I are always in LTE; however, increasing the $T_{\rm eff}$ values increases the underpopulation of these levels respect to LTE by UV photoionization. Thus, we estimated NLTE abundance corrections of C I for the early-type stars in our sample by interpolating in their Figs. 7 and 8 as a function of $T_{\rm eff}$, $W_{\rm eq}$, and metallicity.

Sitnova et al. (2013) performed NLTE abundance corrections for O I for stars with spectral types from A to K ($T_{\rm eff}$ between 10 000 and 5000 K). These authors showed that NLTE effects lead to an strengthening of O I lines, producing a negative NLTE correction. We estimated NLTE abundance corrections of O I (IR triplet 7771 Å and 6158 Å) for the stars in this work, interpolating based on Table 11 of Sitnova et al. (2013), as a function of $T_{\rm eff}$. Other O I lines present corrections lower than ~–0.02 dex (see, e.g., Table 5 of Sitnova et al. 2013).

3.2. Comparisons with the literature

We present in Fig. 3 a comparison of [Fe/H] values derived in this work, with those taken from literature for the stars HD 15164 (Andrievsky et al. 1995), HD 15164 (Paunzen et al. 2002), HD 193256, HD 193281, HD 198160 and HD 198161 (Stürenburg 1993). In general, there is a reasonable agreement with literature, where the star HD 193281 present the larger difference (marked in the plot).

Stürenburg (1993) estimated for HD 193281 an iron abundance of [Fe/H] = –1.0 ± 0.2. However, we estimated for this star a somewhat higher value of [FeI/H] = –0.36 ± 0.13 ([FeII/H] = –0.48 ± 0.13). We explored the possible sources for this difference. They estimated a $T_{\rm eff}$ of 8080 K (without quoting uncertainties) by using the Strömgren photometry, while we estimated for this object a $T_{\rm eff}$ of 8700 ± 140 K, having a difference of 620 K. This could be one of the reasons for the different [Fe/H] that we obtained. Different works estimated for this star temperatures of 8700 K (Gray et al. 2017), 8623 K (Koleva & Vazdekis 2012) and, more recently, 8695 K (Arentsen et al. 2019). Then, our estimated $T_{\rm eff}$ is more in agreement with these works. We also note that this star has different metallicities published in the literature: –1.0 ± 0.2 dex (Stürenburg 1993), –0.68 dex (Koleva & Vazdekis 2012) and, more recently, –0.37 dex (Arentsen et al. 2019). Our estimated metallicity of [FeI/H] = –0.36 ± 0.13 is closer to the work of Arentsen et al. (2019).

[5] We adopt a minimum of 0.01 dex for the errors e_2, e_3 and e_4.

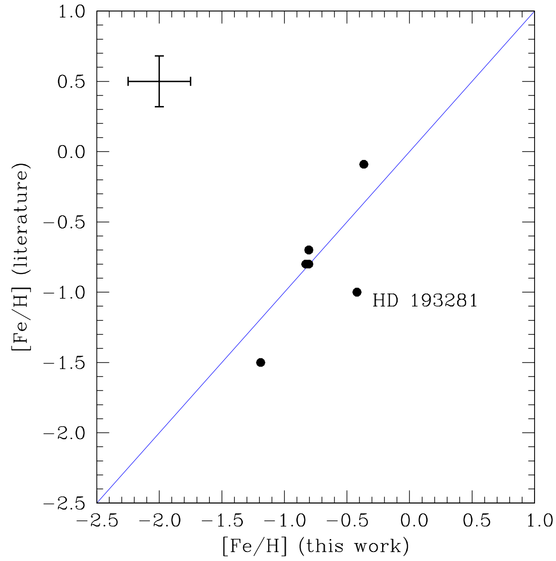

Fig. 3. Comparison of [Fe/H] values derived in this work with those from literature. Average dispersion bars are showed in the upper left corner.

In addition, there is evidence that HD 193281 could be contaminated by a nearby star. Simbad database reports that the star ADS 13702 B (= TYC 6918-1823-2) is located at ~3.5 arcsec from HD 193281, having spectral type “F5:V”. Ivanov et al. (2019) present a library of stellar spectra taken with the integral field spectrograph MUSE[6] at a low spectral resolution ($R \sim 2000$) but with a high spatial resolution (0.3–0.4 arcsec). They reported HD 193281 as a binary with ~3.8 arcsec separation and its components cross-contaminate each other. They identified the components as HD 193281 A and B, and estimated spectral types A2 III and K2 III, respectively (updating the spectral type F5:V reported by Simbad for the star HD 193281 B). This possible contamination could explain, at least in part, the different parameters and metallicities obtained from different works for this object. In this study, we estimated parameters and abundances of HD 193281 taken as single, for which the resulting values should then be considered with caution.

4. Discussion

In order to test the accretion scenario of λ Boo stars, we compared the chemical abundances of the stars in our sample with those of λ Boo stars. The three multiple systems with candidate λ Boo stars are discussed separately, while other binary or multiple systems with candidate λ Boo stars are discussed in the appendix.

4.1. Average pattern of λ Boo stars

To derive an average λ Boo pattern is not an easy task. Few works in the literature obtain homogeneous abundances of many species for λ Boo stars (e.g., Stürenburg 1993; Andrievsky et al. 2002; Heiter et al. 2002). Stürenburg (1993) derived abundances for 16 A-type stars classified, in principle, as λ Boo stars. They performed NLTE corrections for some elements including C.

[6] https://www.eso.org/sci/facilities/develop/instruments/muse.html

However, they included stars that were subsequently considered non-members or uncertain members, such as HD 38545 and HD 193281 (Murphy et al. 2015). Paunzen et al. (1999) and Kamp et al. (2001) derived light-element NLTE abundances for a sample of λ Boo stars. Then, Andrievsky et al. (2002) derived elemental abundances for 20 candidate λ Boo stars basically selected from classification-resolution spectroscopy. They performed (primarily) a LTE approach and included NLTE effects for Na. They were able to confirm the membership of only nine objects to the λ Boo class, while other stars were ruled out or present an unclear membership. Paunzen et al. (2002) collected abundance values for 26 candidate λ Boo stars (see their Table 5), using different literature sources. Also, Heiter et al. (2002) reported LTE abundance values for 12 candidate λ Boo stars, four of them belonging to SB systems. Thus, it would be highly desirable a homogeneous abundance determination that includes more candidate λ Boo stars and newer laboratory data for the lines, while encompassing NLTE effects, especially for the light elements.

In order to test the accretion scenario of λ Boo stars, we compared the chemical abundances of the stars in our sample with those of λ Boo stars. In this work, we used the data derived by Heiter et al. (2002), who homogeneously determined abundances for a number of λ Boo stars. From the average, we excluded those stars without CNO values and the stars analyzed here.

4.2. Triple system HD 15164/65/65C

This remarkable triple system is composed by two early-type stars (HD 15165 and HD 15164: stars A and B) and a late-type companion (HD 15165C). A number of studies suggest that the spectrum of HD 15165 resembles that of metal-deficient star, but the companion HD 15164 has a near-solar abundance (Mechler 1974, 1976; Abt 1980). Then, as explained in the introduction, some works suggest that the A star belongs to the λ Boo class (Andrievsky et al. 1995; Chernyshova et al. 1998), while the B star seems to display a solar composition (Andrievsky et al. 1995). To our knowledge, there is no abundance determination for the C component.

We present in Fig. 4 the chemical pattern of the stars HD 15164, HD 15165, and HD 15165C (black), compared to an average pattern of λ Boo stars (blue). For each star, we present two panels, corresponding to elements with atomic number $z <$ 32 and $z >$ 32. The error bars of the λ Boo pattern show the standard deviation derived from different stars, while the error bars for our stars correspond to the total error, $e_{\rm tot}$. As we can see in Fig. 4, the chemical pattern of the primary (HD 15165) is similar to the pattern of λ Boo stars, showing subsolar abundances of most metals (Mg, Al, Ca, Sc, Ti, Cr, Fe) together with near-solar values of C and O. The abundances of Sr and Ba present a less marked deficiency, while continuing to exhibit subsolar values. On the other hand, the chemical pattern of the secondary star (HD 15164) shows a slight deficiency in some metals (e.g., [Fe/H] = –0.36 ± 0.15 dex), although it is generally closer to the solar pattern than to the λ Boo stars. In this sense, a primary showing a λ Boo pattern and a secondary showing near-solar abundances verify the early result of Andrievsky et al. (1995): early-type stars A and B present different chemical compositions.

To our knowledge, there is no abundance determination of λ Boo stars that belong to a triple or multiple system. In particular, a late-type star that belongs to such a system could be used as a proxy for the initial composition of the material within which

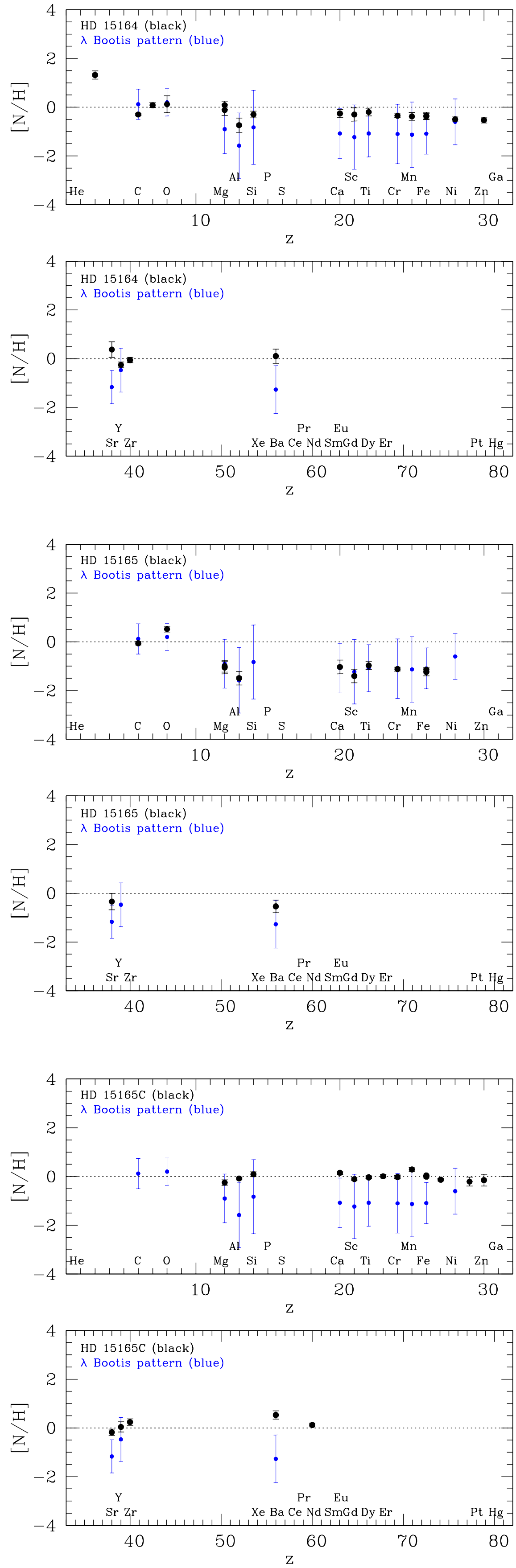

Fig. 4. Chemical pattern of the stars HD 15164, HD 15165 and HD 15165C (black), compared to an average pattern of λ Boo stars (blue).

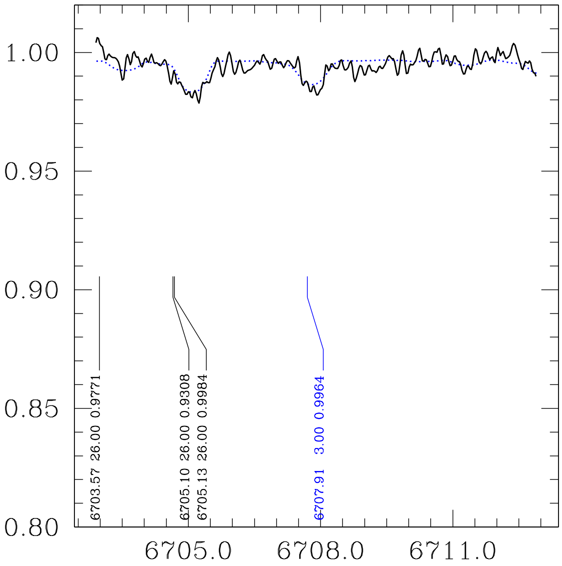

Fig. 5. Observed spectra (black line) and synthetic spectra (blue dotted line) near the Li line 6707.8 Å in the star HD 15164. Synthetic lines are indicated showing the wavelength, atomic number, and intensity.

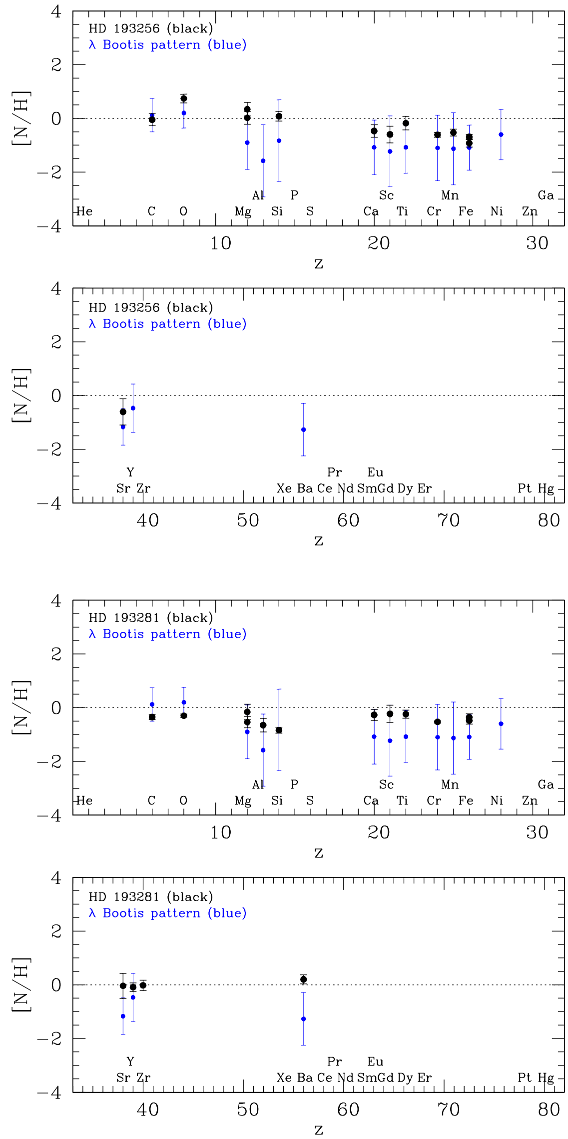

Fig. 6. Chemical pattern of the stars HD 193256 and HD 193281 (black), compared to an average pattern of λ Boo stars (blue).

the λ Boo star formed (under the hypothesis that they are born from the same molecular cloud). This could be important as an additional constraint for any model attempting to explain the λ Boo phenomena. We present in Fig. 4 the chemical pattern of HD 15165C, the late-type component of the triple system. The chemical pattern is compatible with a solar-like composition (for instance, [FeI/H] = 0.04 ± 0.02 dex). This is in agreement with the idea that λ Boo stars are Population I objects and originate (following any internal or external mechanism) from a solar-like composition.

Notably, the three stars that belong to the triple system present different chemical patterns. Star A presents a λ Boo pattern, while stars B and C present abundances closer to the Sun. However, stars B and C are also slightly different between them: the late-type star C present the closest abundances to the Sun, while the early-type star B shows a slightly deficiency. Most abundance values between stars B and C agree within ~0.30 dex, with a possible exception: the lithium content. The Li I 6707.8 Å line is clearly present in the spectra of the star B (HD 15164), as we can see in Fig. 5, while it is not detected in the spectra of stars A nor C. It is interesting to note that this line is commonly used as a proxy of recent accretion onto the atmosphere of the stars. For instance, Saffe et al. (2017) attributed a notable difference in the refractory abundances and in the Li content between the stars of the binary system HAT-P-4 to a possible accretion event of a rocky planet onto the primary. However, although HD 15164 shows clearly the Li line, its refractory content is slightly lower than the star HD 15165C, which would be difficult to explain with the accretion of refractory species.

We question whether it is possible for the supposed different abundances between stars A, B, and C to be due only to different values for $T_{\rm eff}$. The question makes sense because stars A and C present $T_{\rm eff}$ of 7150 K and 4960 K, with a difference of 2190 K. However, the total error, $e_{\rm tot}$, in abundances includes the error e_2, which measures the change in the abundances when varying $T_{\rm eff}$ by their corresponding uncertainty. Thus, we do not expect a strong change in the derived abundances due to $T_{\rm eff}$ (in any case, the possible change is contained within the total error, $e_{\rm tot}$).

4.3. Binary system HD 193256/281

HD 193256 was classified as λ Boo by Gray (1988) and then as uncertain λ Boo by Renson (1990). It is separated by ~27.5 arcsec from HD 193281, which was classified as λ Boo by Gray & Garrison (1987). Both stars HD 193256 and HD 193281 show approximately solar abundances of C and subsolar Fe in the study of Stürenburg (1993), who analyzed them separately. However, they also found near-solar values for other elements such as Mg and Si in both stars, which is different from what is found for average λ Boo stars. Kamp et al. (2001) found solar values in HD 193281 for N, O, and S, although for C they found –0.61 dex, similarly to Paunzen et al. (1999). However, more recent classification spectra suggest that only HD 193256 could belong to the λ Boo class (see Tables 1 and 4 of Murphy et al. 2015; Gray et al. 2017), while HD 193281 displays normal spectra.

In this work, we analyzed the spectra of HD 193256 and HD 193281 (both considered as single), for which the abundances of HD 193281 should be taken with caution. We present in Fig. 6 the chemical pattern of the stars HD 193256 and HD 193281 (black), compared to an average pattern of λ Boo stars (blue). The colors, panels, and error bars used are similar to those of Fig. 4. HD 193256 shows solar or suprasolar values for C and O, together with subsolar values (between 0.5–0.9 dex) of Ca, Cr, Fe, and Sr. However, we also found near-solar values of Mg, Si, and Ti, which is not common in λ Boo stars. Then, this object seem to present a mix of metals with solar and subsolar abundances. On the other hand, HD 193281 presents the chemical pattern of a slightly metal-deficient star in general, showing subsolar values for C and O (~0.3 dex) similar to Fe I (–0.36 ~ 0.13 dex). However, the results of HD 193281 should be taken with caution, due to a possible contamination of the nearby K2 III star.

In short, the solar abundances of some metals of HD 193256 (Mg, Si, and Ti) are different of λ Boo stars. The chemical pattern of HD 193281 (considered as single) shows a slightly metal deficient star. In addition, there is evidence for a possible contamination of HD 193281, where components A and B display spectral types A2 III and K2 III. Thus, the current evidence would not support the presence of two bona fide λ Boo stars in this binary (or triple) system. It would be desirable to carry out an analysis of HD 193281 separately for components A and B, in order to more properly determine the individual abundances.

4.4. Binary system HD 198160/161

HD 198160 form a visual binary system with HD 198161, separated by ~2.4 arcsec. HD 198160 was classified "A2 Vann wk4481" and "A2 Vn" (Gray 1988; Corbally & Garrison 1980), while HD 198161 was classified as "A3 Vn" (Corbally & Garrison 1980). Both stars were studied separately by Stürenburg (1993) considering them as twins (same $T_{\rm eff}$ and $\log g$). He derived near-solar values for C in both stars and subsolar values for Fe (–0.8 ± 0.2 dex), however, he also obtained solar values for Mg and Si (0.0 ± 0.1 dex and –0.2 ± 0.2 dex for both stars). Then, Paunzen et al. (1999) estimated near-solar NLTE values for C and O (quoted, however, for HD 198160/1 and not separated). More recently, Murphy et al. (2015) cautioned that individual NLTE volatile abundances for HD 198160 and HD 198161 have not been confirmed (such as those reported in this work) and for HD 198160, they tentatively adopted the classification "A2 Vann λ Boo." However, its companion HD 198161 was classified as a normal star, with spectral type "A3 V" and "A3 IV(n)" (Murphy et al. 2015; Gray et al. 2017).

We present in Fig. 7 the chemical pattern of the stars HD 198160 and HD 198161 (black), compared to an average pattern of λ Boo stars (blue). The colors, panels, and error bars used here are similar to those in Fig. 4. In both stars, most Fe-peak metals show a deficiency around 0.7–0.8 dex, similar to λ Boo stars. However, C and O also show subsolar values that might be quite low compared to other λ Boo stars. When comparing C with Fe abundances, the group of λ Boo stars present [C/Fe] ~ 1.21 ± 0.35 dex (excluding stars without CNO values and the stars analyzed here; Heiter et al. 2002) with minimum and maximum values of 0.70 and 1.74 dex. However, the stars HD 198160 and HD 198161 present [C/Fe] values of ~0.54 and ~0.48 dex, which are low compared to the average [C/Fe] and even lower than the minimum of 0.70 dex. Then, we considered that these low [C/Fe] values possibly correspond to mild-λ Boo stars, rather than to an average λ Boo object. It is important to note that our C and O abundances were corrected by NLTE, with average corrections of –0.15 dex and –0.81 dex for both stars. In other words, if we only adopt LTE values without correction, the C and O abundances would ultimately end up closer to those of λ Boo stars.

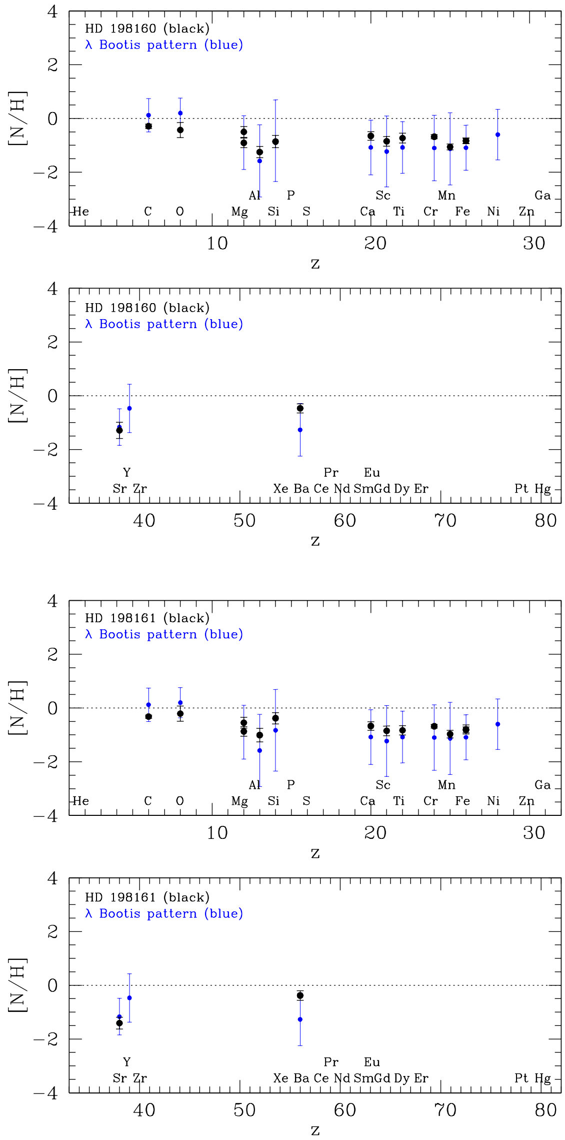

Fig. 7. Chemical pattern of the stars HD 198160 and HD 198161 (black), compared to an average pattern of λ Boo stars (blue).

4.5. Considering the physical association of the stars

The stars studied in this work were previously reported as (possible) members of binary or multiple systems, for the case of HD 15164/65/65C (Andrievsky et al. 1995; Chernyshova et al. 1998; Murphy et al. 2015), HD 193256/281 (Paunzen et al. 2012a; Murphy et al. 2015; Gray et al. 2017), and HD 198160/161 (Paunzen et al. 2012a; Murphy et al. 2015).

The coordinates, proper motions, and parallax of the stars (see Table 1) suggest that they are (at least) common proper-motion objects. We searched our targets stars in different binary catalogs from the literature (Shaya & Olling 2011; Tokovinin & Lepine 2012; Andrews et al. 2017). In particular, Andrews et al. (2017) performed a search of binaries through a Bayesian formulation in the *Tycho-Gaia* catalogs and derived likelihoods of Keplerian orbits. For HD 15164/65, they reported a probability greater than 99% that they form a physical system. Shaya & Olling (2011) developed a Bayesian method to discover non-random pairs using HIPPARCOS data. They include HD 198160/161 in their catalog of binaries, however there is no probability quoted for this pair. Finally, we find no record for HD 193256/181 in these binary catalogs.

In this work, we assume that the stars form physical binary or multiple systems. In the case where stars are not shown to be gravitationally bound, then these stars are not considered useful for testing the accretion scenario.

4.6. Considering whether there two bona fide λ Boo stars in binary systems

There is evidence in the literature supporting the accretion scenario in these cases. For example, we know there is an anti-correlation for C and O with Si (Paunzen et al. 1999), first noted by Holweger & Sturenburg (1993) for C. It is expected that refractory elements like Fe and Si are condensed in dust, while the more volatile CNO and S remain in the gaseous phase. Thus, the selective accretion of gas will produce ratios [C/Si] or [O/Si] larger than solar and reduced metallicity (Paunzen et al. 1999). Kamp et al. (2001) reached a similar conclusion comparing the volatile species N and S with the more refractory Ca. We should also expect that in stars with large values for $v \sin i$, the meridional circulation mixes material of solar composition from the stellar interior into the convection zone, so that any surface contamination due to accretion of circumstellar material should vanish. This observation seems to be weakly verified (see e.g., Solano et al. 2001) and would require a larger sample of λ Boo stars. As we can see, the accretion scenario could be tested by different methods.

In this work, we focus on the presence of λ Boo stars as members of binary systems (e.g., Stürenburg 1993; Paunzen et al. 2002, 2012a,b; Heiter et al. 2002); namely, the following 12 systems (see the appendix): HD 15164/65/65C, HD 38545, HD 64491, HD 84948, HD 111786, HD 141851, HD 148628/638, HD 171948, HD 174005, HD 193256/281, HD 198160/161, and HD 210111. Following the accretion scenario, two early-type stars in a binary system ought to display, in principle, a similar λ Boo pattern after passing through a diffuse cloud. However, a binary or multiple system having a λ Boo star together with a “normal” early-type component would be difficult to explain under the accretion scenario. This test of the accretion scenario would require a detailed analysis of both stars. As explained in the introduction, some stars that belong to these 12 systems were recently classified as non-members or uncertain members of the λ Boo class, such as HD 141851, HD 148638, and HD 193256 (see, e.g., Murphy et al. 2015; Gray et al. 2017). Thus, we are led to wonder whether any of these 12 systems really include two stars with bona fide λ Boo chemical patterns.

It would be desirable to carry out a detailed abundance analysis in order to verify the true λ Boo nature of a star, initially suggested (for instance) by its classification spectra (see, e.g., Andrievsky et al. 2002; Heiter et al. 2002). To our knowledge, only 5 out of the 12 systems present an abundance determination of both components: HD 15164/65, HD 84948, HD 171948, HD 193256/281, and HD 198160/161 (three of them were analyzed in this work). Some works present an abundance study only of the brighter component, such as in the case of HD 38545 (Stürenburg 1993) or HD 64491 (Kamp et al. 2001), while other systems only have a spectral classification, such as HD 174005 (Gray et al. 2017; Murphy et al. 2015).

An inspection of the abundance values reported in the literature (see the appendix) shows that, in our opinion, there is no binary system having two stars with bona fide λ Boo chemical patterns. The same is valid for the three systems analyzed in this work (HD 1564/65/65C, HD 193256/281, and HD 198160/161). In fact, we cannot find even one binary system where the two stars present bona fide λ Boo abundance patterns. We consider that the closest candidates to potentially exhibit both stars in a λ Boo pattern are the binary systems HD 84948, HD 171948, and HD 198160. These three systems show [C/Fe] values lower than 0.7 dex (the minimum [C/Fe] of λ Boo stars, see Sect. 4.4 and Appendix), as, perhaps, mild-λ Boo systems rather than clear λ Boo objects. Thus, we find no clear evidence for the presence of two λ Boo stars as members of binary systems. However, this fact (if confirmed) would not rule out the accretion scenario.

On the other hand, a challenge for the accretion scenario, would be the presence of a bona fide λ Boo star and a normal early-type object together in the same multiple system. By reviewing the 12 systems studied (including the stars of this work), we found only one candidate: the system HD 15164/65/65C analyzed here. The star A present a λ Boo pattern, while the stars B (early-type) and C (late-type) present abundances closer to the Sun. The different chemical composition between stars A and B was initially attributed to a possible stellar capture (Andrievsky et al. 1995). The probability of a binary capture depends on several factors, such as the number of stars per cubic parsec, the velocity dispersion, and the mass of the stars (e.g., Clarke & Pringle 1991; Boffin et al. 1998). The capture is not a dominant formation process for solar-mass (coeval) binaries in dense clusters (e.g., Clarke & Pringle 1991; Heller 1995; Boffin et al. 1998). To our knowledge, there is no known binary or triple system with an origin attributed to a capture. On the other hand, there are multiple observations of young binaries embedded in dense cores (e.g., Sadavoy & Stahler 2017), and even an image of a triple protostar formed via disk fragmentation (Tobin et al. 2016). Although the capture cannot be totally discarded, most observational evidence points toward the formation of binary and multiple systems from a common molecular cloud. Taking up the idea that the three stars are born together, it is difficult to explain the composition of the stars of HD 15165 under the accretion scenario. Furthermore, there is an urgent need for additional binary and multiple systems to be analyzed through a detailed abundance analysis in order to test the accretion model characterizing λ Boo stars.

5. Concluding remarks

In the present work, we performed a detailed abundance determination of select binary and multiple systems with candidate λ Boo stars in order to test the accretion scenario. Based on a review of the abundance values reported in the literature (see Appendix), we find that there are no binary systems featuring two stars with bona fide λ Boo chemical patterns. This assumption is valid for the three systems analyzed in this work (HD 15164/65/65C, HD 193256/281, and HD 198160/161). We consider that the closest possible candidates to feature both stars in a λ Boo pattern are the binary systems HD 84948, HD 171948, and HD 198160. However, these three binary systems are perhaps mild-λ Boo systems rather than clear λ Boo objects. Thus, in our opinion, the current evidence of binary and multiple systems does not give strong support to the accretion scenario for λ Boo stars.

On the other hand, a binary or multiple system formed by a λ Boo star and an early-type “normal” object would be difficult to explain under the accretion scenario. However, we did find one candidate: the remarkable triple system HD 15164/65/65C. It is composed by two early-type stars (A and B) and a late-type companion (C). In particular, the late-type component of the system could be used as a proxy for the initial composition of the system, constraining the formation models of λ Boo stars. We found a λ Boo pattern for the A star (HD 15165), while the stars B and C present abundances closer to the Sun. In conclusion, we find there is an urgent need for additional binary and multiple systems to be analyzed through a detailed abundance analysis in order to test the accretion model for λ Boo stars.

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Appendix A: Multiple systems with suspected λ Boo components

We reviewed the abundance determinations for binary or multiple systems with suspected λ Boo components from the literature, in order to determine if two bona fide λ Boo stars can be found. Spectral classification data is also included whenever available. The data have been updated to include the results from the present work.

HD 15164/65/65C: It is a visual triple system, where most works considered only the two brighter components. Andrievsky et al. (1995) studied spectra of the stars A and B (HD 15165 and HD 15164) using the LYNX (R∼24000) and AURELIE (R∼11000) spectrographs. They found subsolar values for two elements analyzed in the A star (-0.73 dex for [Ca/H] and -0.46 dex for [Fe/H]). Then, Chernyshova et al. (1998) re-analyzed the data for the A star and suggest that this object belongs to the λ Boo class, showing ∼solar values for C, O, and S (0.0 dex, -0.3 dex and 0.0 dex) together with subsolar values for refractory elements (for example, [Fe/H] = –1.6 dex). However, Andrievsky et al. (1995) also found solar values for several elements in the B star. They suggest that the different chemical composition of stars A and B is probably due to a stellar capture. Murphy et al. (2015) classified the spectra of the 3 stars as "F1 V kA7mA6 (λ Boo)?" (HD 15164), "F2 V kA2mA2 λ Boo?" (HD 15165) and "K2V" (HD 15165C). They also claim that the classification spectrum of HD 15165 does not match solar abundances, contrary to the result of Andrievsky et al. (1995).

In the present work, we find that star A presents a λ Boo pattern, while stars B and C present abundances closer to the Sun. In other words, we find different abundances for stars A and B, which are in agreement with Andrievsky et al. (1995). This is difficult to explain under the accretion scenario of λ Boo stars. Thus, we find that the current evidence does not support the presence of two bona fide λ Boo components in this system.

HD 38545: Stürenburg (1993) estimated solar abundances for C (-0.1±0.2 dex) and near-solar values for other metals such as Fe (-0.2±0.2 dex). However, it was analyzed as a single object and then considered not reliable by Heiter et al. (2002). This object was later mentioned as a possible visual binary with a small separation (<0.2", Heiter et al. 2002) and as a possible SB system (Paunzen et al. 2002). More recently, Prugniel et al. (2011) reported a low metallicity for this object ([Fe/H] = –0.48 dex) considered also as single. By inspecting IUE UV spectra, Murphy et al. (2015) suggest that it is a normal object rather than a λ Boo star ("non-member" of the class) and caution that its high $v \sin i$ (∼191 km/s) may also have had some role in early identifications as λ Boo. We note that this star is not included in the list of SB λ Boo stars of Paunzen et al. (2012a). To our knowledge, there is no spectral classification nor abundance determination for the secondary.

HD 64491: Kamp et al. (2001) identified this object as a SB system, namely, a previously undetected binary, showing high and low $v \sin i$ components. They estimated abundances for the star with higher $v \sin i$ (∼ 170 km/s) by directly fitting the composite spectra, obtaining [N/H] = –0.30 dex, [S/H] = –0.09 dex and [Ca/H] = –0.96 dex (using NLTE for C and S). Then, Iliev et al. (2001) reported that the orbital period of this SB system is between 230 and 760 days, and suggest that a new abundance analysis should be performed taking into account the binarity of the system. Faraggiana & Gerbaldi (2003) suggest that this object is composed by two slightly metal-poor objects (∼-0.5 dex) rather than a single object with [M/H]∼-1.5 dex. Murphy et al. (2015) classified the primary of the system as "F1 Vs kA3mA3 λ Boo." To our knowledge, there is no spectral classification nor abundance determination for the secondary (the object with lower $v \sin i$).

HD 84948: Paunzen et al. (1998) reported this object as a SB system and found subsolar abundances separately for the stars A and B ([Fe/H]= -1.2±0.3 dex and -1.0±0.2 dex, respectively). Then, Heiter et al. (2002) also performed a detailed abundance determination separately for components A and B. Both works reported that that the two stars are metal-poor, however CNO or S abundances were not reported. Then, Iliev et al. (2002) estimated NLTE abundances for C and O: they find subsolar values for C (-0.8±0.4 dex for both stars) while for O they found -0.6±0.3 dex and +0.2±0.3 for stars A and B. They also reported a period of 7.41 d for this SB2 system.

We present in Fig. A.1 a comparison of an average λ Boo pattern[7] taken from Heiter et al. (2002) and literature abundances for the stars A and B. This plot shows that C abundances seem to be low respect of λ Boo stars. When comparing C with Fe abundances, the group of λ Boo stars present [C/Fe]∼1.21±0.35 dex (excluding stars without CNO values and the stars analyzed here, Heiter et al. 2002) with minimum and maximum values of 0.70 and 1.74 dex. However, the stars A and B present [C/Fe] values of ∼0.4 and ∼0.2 dex[8], being low values compared to the average [C/Fe] and even lower than the minimum of 0.70 dex. These low [C/Fe] values possibly correspond to an extreme or mild-λ Boo star rather than to an average λ Boo object.

Paunzen et al. (2001a) classified HD 84948 as "kA7hF1mA6 V (LB)", while Murphy et al. (2015) classified HD 84948 as "F1.5 Vs kA5mA5 λ Boo?", a "probable member" of the λ Boo class using a newer spectra. Given the low values of [C/Fe] for both stars together with the "probable" spectral classification, we prefer to consider them as candidate λ Boo stars (perhaps mild-λ Boo stars) rather than bona fide members of the class. This binary system deserves a verification of the abundance values.

HD 111786 (= HR 4881): This star is considered as a classic λ Boo object by different works (e.g., Murphy et al. 2015). Stürenburg (1993) derived abundances in agreement with the λ Boo class (e.g., [C/H] = –0.2±0.2 dex and [Fe/H] = –1.5±0.3 dex). However, it was analyzed as a single object and then considered unreliable by Heiter et al. (2002). Furthermore, some authors proposed a SB nature for this system (Faraggiana et al. 1997; Paunzen et al. 2012b). We refer the reader to Murphy et al. (2015) for a more complete discussion about this object. The star was classified as "F0 V kA1mA1 λ Boo" (Murphy et al. 2015; Gray et al. 2017) and "F0 Vs kA1mA1 λ Boo" (Murphy et al. 2020). Notably, Faraggiana et al. (2001) proposed that HD 111786 is in fact a multiple system composed by five members: one broad-lined star and four narrow-lined stars with similar temperatures. Beyond the multiplicity of this system, to our knowledge, there is no spectral classification nor abundance determination for the secondary (or any other component) of the system.

HD 141851: Paunzen et al. (1999) found [C/H] and [O/H] NLTE abundances of -0.81 and -0.21 dex, respectively, showing $v \sin i$ in excess of 200 km s^{-}1. Kamp et al. (2001) derived LTE abundances of [Ca/H] = –1.30 dex, with typical errors of 0.2 dex. However, Heiter et al. (2002) mentioned that this object was analyzed as a single star and, thus, the abundances are not reliable. Later, different works laid claims that this object had

[7] We excluded from the average stars without CNO values and the stars analyzed here.

[8] Using Fe from Heiter et al. (2002) instead of Paunzen et al. (1998), the values are even lower: ∼0.3 and ∼0.1 dex for stars A and B.

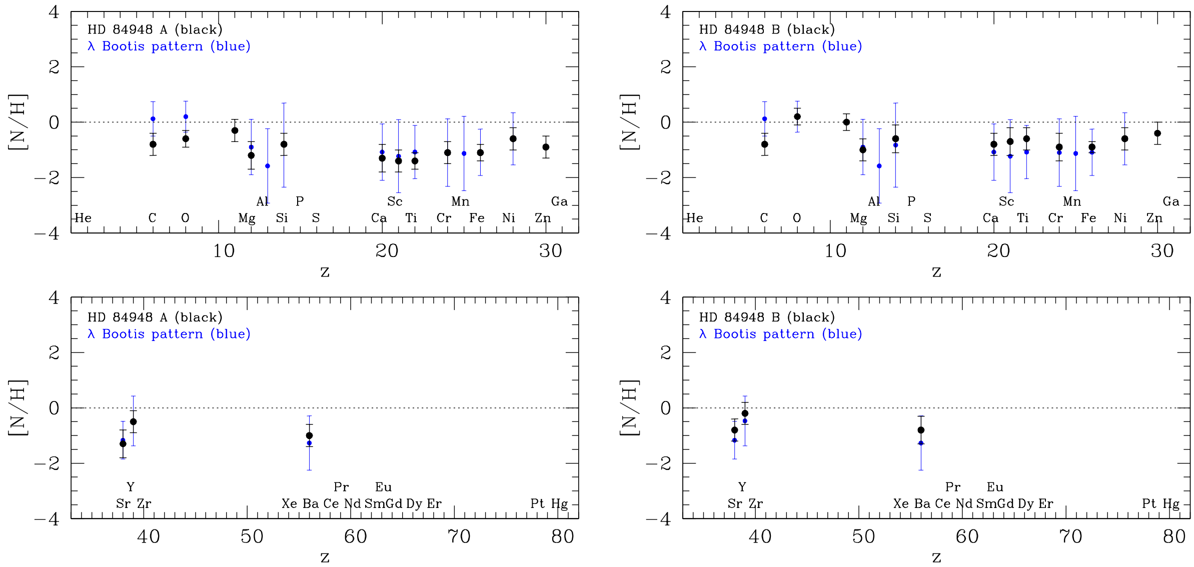

Fig. A.1. Comparison of an average λ Boo pattern (blue, Heiter et al. 2002) with the abundances from literature for the stars HD 84948 A and B (left and right panels, black).

been misclassified and did not belong to the λ Boo class (e.g., Paunzen et al. 2001a). Andrievsky et al. (2002) found [Fe/H] = -0.70, [Si/H] = -0.65, and [Na/H] = +0.60 dex; however, they did not decide whether this object could be named a λ Boo star. Murphy et al. (2015) classified this object as a normal "A2 IVn" star, while Gray et al. (2017) as "A2 IV-Vn", namely, a non-member of the λ Boo class. To our knowledge, there is no spectral classification nor abundance determination for the secondary.

HD 148628/638: The primary of this visual pair (HD 148638) was analyzed by Kamp et al. (2001) obtaining solar values of N and S together with subsolar Ca (-1.20 dex). However, Murphy et al. (2015, 2020) and Gray et al. (2017) classified this object as "A2 IV-n (4481-wk)" and "A2 IVn," rather than a member of the λ Boo class. To our knowledge, there is no spectral classification nor abundance study for the companion (HD 148628).

HD 171948: Together with HD 84948, Paunzen et al. (1998) identified this object as the first SB systems with λ Boo components. They reported very low abundances for Mg, Ti, Cr, and Fe separately for components A and B. Heiter et al. (2002) derived LTE abundances for this system, estimating the same values within the errors for both stars. For C, they obtained an upper limit ([C/H]<-0.5 dex), while O is considered for the same authors as deficient ([O/H] = –0.6±0.4 dex) – although it is high compared to heavy elements ([Fe/H] = –1.6±0.4 dex). Then, Iliev et al. (2002) reported NLTE abundances for C and O in this system, estimating the same values for both stars within the errors ([C/H] = –1.2~0.4 dex and [O/H]=+0.2~0.3). They also derived a period of 21.9 days for the SB system.

We present in Fig. A.2 a comparison of an average λ Boo pattern (Heiter et al. 2002) with the literature abundances of stars A and B, showing that C values seem to be low respect of λ Boo objects. Comparing C and Fe abundances, both stars A and B present [C/Fe] values of ~0.4 dex (taking NLTE C values from Iliev et al. 2002 and Fe from Heiter et al. 2002), which are lower than the average [C/Fe] of λ Boo stars (~1.21±0.35 dex excluding stars without CNO values and the stars analyzed here; Heiter et al. 2002) and lower than the minimum of 0.70 dex (Heiter et al. 2002). We consider that these low [C/Fe] values possibly correspond to an extreme or mild-λ Boo star rather than to an average λ Boo object.

Murphy et al. (2015) classified the primary of this binary system as "A3 Va- kB8.5 λ Boo," however, there is no spectral classification listed for the secondary (see their Table 1). Given the low values of [C/Fe] for both stars and the lack of a spectral classification for the secondary, we prefer to consider them as candidate λ Boo stars (perhaps mild-λ Boo stars) rather than bona fide members of the class. This binary system deserves a verification of the abundance values.

HD 174005: This object was mentioned as a possible SB system with a maximum separation of ~38 arcsec (Paunzen 2000; Solano et al. 2001; Paunzen et al. 2012a). Both Gray et al. (2001) and Murphy et al. (2015) classified this object as "A7 V kA2 mA2 λ Boo". To our knowledge, there is no abundance determination for the components of this system, nor any spectral classification for the secondary. This system would benefit from further analysis.

HD 193256/281: Studies of the star HD 193281 have resulted in near-solar C (-0.2±0.2 dex) and subsolar Fe (-1.0±0.2 dex), however, with near-solar values of Mg, Ti, Cr, and Sr as well, based on the study from Stürenburg (1993). Paunzen et al. (1999) estimated a NLTE oxygen abundance of -0.61 dex. Kamp et al. (2001) found solar values in HD 193281 for N, O, and S; however, for C they found -0.61 dex, similarly to Paunzen et al. (1999). Results for the star HD 193256 show near-solar C (0.0±0.2 dex) and subsolar Fe (-0.7±0.2 dex), but also near-solar values for Mg and Si (0.0±0.2 and 0.0±0.3 dex) in the study of Stürenburg (1993). Then, abundance values for both stars do not seem to agree with the general pattern of λ Boo stars. The spectra of HD 193256 were classified as "A9 Vn kA2mA2 λ Boo" (Murphy et al. 2015) and, similarly, as "A8 Vn kA3mA3 (λ Boo)" (Gray et al. 2017). However, the spectra of HD 193281 was classified as "A2IVn" (Murphy et al. 2015) and "A2 IV-V" (Gray et al. 2017). Given the spectral classification is in conflict with the abundances, Murphy et al. (2015) considered HD 193281 as an "uncertain member" of the λ Boo class.

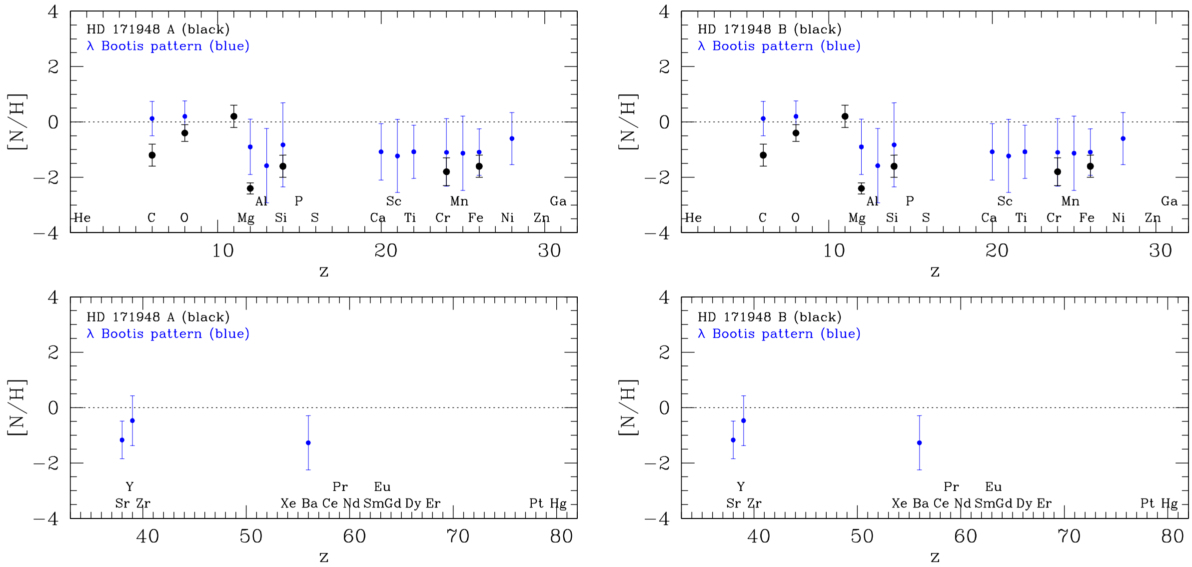

Fig. A.2. Comparison of an average λ Boo pattern (blue, Heiter et al. 2002) with the abundances from literature for the stars HD 171948 A and B (left and right panels, black).

In this work, we find that HD 193256 presents subsolar values of Cr, Mn, and Fe; however, it also exhibits near-solar values for Mg, Si, and Ti, which is different than in λ Boo stars. For HD 193281, we found a chemical pattern compatible with a a slightly metal-deficient star. However, we also caution that HD 193281 is possibly contaminated by a nearby star (see Sect. 3.2). Thus, the current evidence does not support the presence of two bona fide λ Boo objects in this system.

HD 198160/161: Both stars were studied separately by Stürenburg (1993), considering them to be twins (same $T_{\rm eff}$ and log g), although Gerbaldi et al. (2003) criticized this assumption based on their varied V and B values (0.35 and 0.39 mag). Stürenburg (1993) derived near-solar values for C in both stars (-0.2±0.3) and subsolar values for Fe (-0.8±0.2 dex), however he also obtained solar values for Mg and Si (0.0±0.1 dex and -0.2±0.2 dex for both stars). They also estimated suprasolar values for Na (+0.3±0.2 dex and +0.6±0.2 dex for both stars). Then, Paunzen et al. (1999) estimated near-solar NLTE values for C and O. Murphy et al. (2015) classified the spectra of both stars as "A2 Vann λ Boo" and "A3 V" (see their Table 1), respectively, while Gray et al. (2017) classified the spectra of HD 198160 as "A3 IV(n)".

In this work, we find a general deficiency of metals around 0.7–0.8 dex for both stars. However, we also found subsolar values for C and O, possibly low compared to other λ Boo stars. When comparing C with Fe abundances, we found that the stars HD 198160 and HD 198161 present [C/Fe] values of ~0.54 and ~0.48 dex, being low compared to the average [C/Fe] of λ Boo stars (~1.21±0.35 dex) and even lower than the minimum of 0.70 dex (see Sect. 4.3). Then, we consider that these low [C/Fe] values possibly correspond to mild-λ Boo stars, rather than to an average λ Boo object. In our opinion, current evidence does not support the presence of two bona fide λ Boo objects in the system.

HD 210111: Stürenburg (1993) analyzed this object as a single star, obtaining solar abundances for C (0.1~0.1 dex), a subsolar value for Fe (-1.1~0.2 dex), but also obtaining suprasolar and solar values for Sr and Ba (+0.45~0.2 and 0.05~0.2 dex). Solano et al. (2001) obtained subsolar values for Mg, Cr, Sc and Fe (between -0.8 dex and -1.3 dex), while Kamp et al. (2001) derived subsolar and near-solar abundances for C and O (-0.45 dex and -0.20 dex, with typical errors of 0.2 dex). Paunzen et al. (1999) estimated NLTE values for C and O of -0.45 dex and -0.20 dex. We suppose that the data presented in these abundance works correspond to the primary of the system, where its binary nature were not reported. This object was classified as "kA2hA7mA2 Vas λ Boo" with peculiar hydrogen lines by Gray (1988), and then as "A9 V kA2mA2 λ Boo" by Gray et al. (2017). A classification spectra for HD 210111 was presented by Paunzen et al. (2012b), who suggested the system was a SB2. They fitted the observed data using a composite spectrum with two equal components having [M/H] = –1.0 dex. For a more detailed abundance analysis, the authors suggested additional spectra for a large separation of the two components. In particular, for the secondary, there is no detailed abundance determination (including for the volatile species) nor spectral classification.

Appendix B: Chemical abundances

In this section, we present the chemical abundances derived in this work and their errors. The total error $e_{\rm tot}$ was derived as the quadratic sum of the line-to-line dispersion e_1 (estimated as $\sigma/\sqrt{n}$, where σ is the standard deviation) and the error in the abundances (e_2, e_3, and e_4) when varying $T_{\rm eff}$, $\log g$, and $v_{\rm micro}$ by their corresponding uncertainties[9]. For chemical species with only one line, we adopted as σ the standard deviation of iron lines. Abundance tables show the average abundance and the total error $e_{\rm tot}$, together with the errors e_1 to e_4.

[9] We adopt a minimum of 0.01 dex for the errors e_2, e_3, and e_4.

Table B.1. Chemical abundances for HD 15164.

Specie	[X/H] ± e_{tot}	e_1	e_2	e_3	e_4
Li I	1.32 ± 0.17	0.07	0.15	0.01	0.01
C I	-0.30 ± 0.05	0.02	0.04	0.02	0.01
N I	0.08 ± 0.10	0.07	0.05	0.01	0.04
O I	0.12 ± 0.35	0.07	0.30	0.04	0.16
Mg I	-0.12 ± 0.22	0.11	0.13	0.03	0.13
Mg II	0.08 ± 0.17	0.07	0.06	0.02	0.14
Al I	-0.74 ± 0.29	0.02	0.08	0.02	0.28
Si II	-0.30 ± 0.14	0.04	0.06	0.02	0.12
Ca II	-0.26 ± 0.17	0.07	0.15	0.01	0.02
Sc II	-0.30 ± 0.27	0.17	0.07	0.03	0.19
Ti II	-0.20 ± 0.16	0.02	0.08	0.02	0.14
Cr II	-0.35 ± 0.08	0.02	0.03	0.02	0.07
Mn I	-0.38 ± 0.16	0.04	0.14	0.01	0.06
Fe I	-0.36 ± 0.15	0.01	0.05	0.01	0.14
Fe II	-0.37 ± 0.11	0.01	0.03	0.01	0.11
Ni II	-0.50 ± 0.10	0.07	0.06	0.02	0.02
Zn I	-0.53 ± 0.12	0.02	0.12	0.01	0.01
Sr II	0.37 ± 0.32	0.02	0.16	0.01	0.27
Y II	-0.26 ± 0.12	0.03	0.11	0.02	0.04
Zr II	-0.06 ± 0.11	0.07	0.08	0.02	0.02
Ba II	0.10 ± 0.29	0.10	0.16	0.01	0.22

Table B.2. Chemical abundances for HD 15165.

Specie	[X/H] ± e_{tot}	e_1	e_2	e_3	e_4
C I	-0.06 ± 0.07	0.02	0.04	0.05	0.02
O I	0.52 ± 0.12	0.02	0.02	0.02	0.11
Mg I	-1.06 ± 0.25	0.21	0.08	0.06	0.09
Mg II	-1.00 ± 0.24	0.22	0.05	0.06	0.06
Al I	-1.49 ± 0.28	0.10	0.17	0.09	0.18
Ca II	-1.03 ± 0.28	0.26	0.09	0.01	0.04
Sc II	-1.40 ± 0.28	0.22	0.11	0.06	0.12
Ti II	-0.97 ± 0.16	0.06	0.04	0.06	0.13
Cr II	-1.12 ± 0.08	0.02	0.07	0.03	0.01
Fe I	-1.24 ± 0.16	0.06	0.09	0.01	0.12
Fe II	-1.14 ± 0.07	0.04	0.04	0.03	0.04
Sr II	-0.34 ± 0.34	0.07	0.13	0.01	0.31
Ba II	-0.54 ± 0.26	0.15	0.08	0.03	0.19

Table B.3. Chemical abundances for HD 15165C.

Specie	[X/H] ± e_{tot}	e_1	e_2	e_3	e_4
Mg I	-0.25 ± 0.11	0.10	0.01	0.01	0.01
Al I	-0.08 ± 0.03	0.02	0.01	0.01	0.01
Si I	0.09 ± 0.10	0.08	0.06	0.01	0.01
Ca I	0.15 ± 0.07	0.04	0.05	0.01	0.01
Sc II	-0.11 ± 0.06	0.06	0.01	0.01	0.01
Ti I	-0.03 ± 0.06	0.03	0.05	0.01	0.01
Ti II	-0.04 ± 0.05	0.05	0.01	0.01	0.01
V I	0.01 ± 0.07	0.04	0.06	0.01	0.01
Cr I	-0.02 ± 0.06	0.04	0.04	0.01	0.01
Cr II	-0.02 ± 0.08	0.08	0.01	0.01	0.01
Mn I	0.29 ± 0.09	0.09	0.02	0.01	0.01
Fe I	0.04 ± 0.02	0.01	0.01	0.01	0.01
Fe II	-0.01 ± 0.05	0.04	0.02	0.01	0.01
Co I	-0.13 ± 0.05	0.04	0.01	0.01	0.01
Cu I	-0.21 ± 0.18	0.18	0.01	0.01	0.01
Zn I	-0.15 ± 0.24	0.24	0.01	0.01	0.01
Sr II	-0.18 ± 0.13	0.13	0.01	0.01	0.01
Y II	0.04 ± 0.21	0.21	0.01	0.01	0.03
Zr II	0.24 ± 0.13	0.13	0.01	0.02	0.01
Ba II	0.53 ± 0.17	0.17	0.01	0.01	0.01
Nd II	0.12 ± 0.08	0.08	0.01	0.01	0.01

Table B.4. Chemical abundances for HD 193256.

Specie	[X/H] ± e_{tot}	e_1	e_2	e_3	e_4
C I	-0.05 ± 0.22	0.21	0.04	0.02	0.05
O I	0.74 ± 0.16	0.15	0.04	0.05	0.02
Mg I	0.34 ± 0.25	0.21	0.05	0.04	0.12
Mg II	0.02 ± 0.24	0.21	0.07	0.04	0.08
Si II	0.08 ± 0.18	0.07	0.16	0.04	0.02
Ca II	-0.47 ± 0.23	0.21	0.06	0.05	0.01
Sc II	-0.60 ± 0.31	0.21	0.08	0.03	0.21
Ti II	-0.18 ± 0.25	0.07	0.03	0.08	0.23
Cr II	-0.61 ± 0.09	0.02	0.02	0.07	0.06
Mn I	-0.53 ± 0.13	0.04	0.10	0.01	0.07
Fe I	-0.92 ± 0.15	0.07	0.06	0.02	0.12
Fe II	-0.69 ± 0.10	0.04	0.04	0.05	0.08
Sr II	-0.61 ± 0.49	0.27	0.10	0.10	0.38

Table B.5. Chemical abundances for HD 193281.

Specie	[X/H] ± e_{tot}	e_1	e_2	e_3	e_4
C I	-0.35 ± 0.10	0.07	0.07	0.01	0.01
O I	-0.30 ± 0.06	0.03	0.04	0.02	0.01
Mg I	-0.16 ± 0.29	0.20	0.10	0.06	0.18
Mg II	-0.54 ± 0.21	0.18	0.02	0.01	0.11
Al I	-0.65 ± 0.25	0.18	0.08	0.02	0.15
Si II	-0.84 ± 0.11	0.07	0.08	0.05	0.01
Ca II	-0.27 ± 0.21	0.18	0.11	0.01	0.01
Sc II	-0.23 ± 0.32	0.18	0.10	0.01	0.25
Ti II	-0.24 ± 0.15	0.05	0.05	0.04	0.13
Cr II	-0.53 ± 0.04	0.02	0.02	0.02	0.01
Fe I	-0.36 ± 0.13	0.05	0.09	0.02	0.07
Fe II	-0.48 ± 0.13	0.03	0.07	0.01	0.10
Sr II	-0.04 ± 0.47	0.01	0.16	0.01	0.44
Y II	-0.09 ± 0.16	0.13	0.09	0.04	0.01
Zr II	-0.02 ± 0.19	0.18	0.06	0.02	0.01
Ba II	0.20 ± 0.17	0.09	0.14	0.01	0.03

Table B.6. Chemical abundances for HD 198160.

Specie	[X/H] ± $e_{\rm tot}$	e_1	e_2	e_3	e_4
C I	-0.29 ± 0.08	0.07	0.01	0.04	0.03
O I	-0.43 ± 0.28	0.15	0.02	0.02	0.23
Mg I	-0.91 ± 0.18	0.08	0.03	0.01	0.15
Mg II	-0.50 ± 0.20	0.15	0.06	0.05	0.10
Al I	-1.25 ± 0.21	0.15	0.05	0.03	0.13
Si II	-0.86 ± 0.23	0.15	0.09	0.05	0.13
Ca II	-0.65 ± 0.16	0.15	0.05	0.03	0.01
Sc II	-0.85 ± 0.18	0.15	0.03	0.04	0.09
Ti II	-0.73 ± 0.18	0.02	0.02	0.06	0.17
Cr II	-0.68 ± 0.08	0.07	0.01	0.04	0.01
Mn I	-1.06 ± 0.11	0.01	0.11	0.01	0.02
Fe I	-0.83 ± 0.10	0.04	0.07	0.01	0.06
Fe II	-0.83 ± 0.10	0.03	0.04	0.04	0.08
Sr II	-1.29 ± 0.30	0.18	0.08	0.07	0.22
Ba II	-0.47 ± 0.17	0.15	0.08	0.01	0.02

Table B.7. Chemical abundances for HD 198161.

Specie	[X/H] ± $e_{\rm tot}$	e_1	e_2	e_3	e_4
C I	-0.32 ± 0.06	0.04	0.02	0.04	0.02
O I	-0.21 ± 0.28	0.15	0.02	0.02	0.23
Mg I	-0.87 ± 0.18	0.07	0.03	0.01	0.17
Mg II	-0.55 ± 0.20	0.15	0.06	0.05	0.10
Al I	-1.01 ± 0.25	0.15	0.06	0.04	0.18
Si II	-0.38 ± 0.21	0.15	0.08	0.05	0.10
Ca II	-0.67 ± 0.16	0.15	0.05	0.03	0.01
Sc II	-0.85 ± 0.18	0.15	0.03	0.04	0.09
Ti II	-0.83 ± 0.17	0.05	0.03	0.06	0.14
Cr II	-0.68 ± 0.07	0.06	0.01	0.04	0.01
Mn I	-0.97 ± 0.14	0.08	0.11	0.01	0.03
Fe I	-0.80 ± 0.17	0.03	0.07	0.01	0.15
Fe II	-0.81 ± 0.11	0.04	0.04	0.04	0.08
Sr II	-1.41 ± 0.22	0.04	0.08	0.07	0.19
Ba II	-0.38 ± 0.18	0.15	0.07	0.01	0.06