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λ Bootis stars with composite spectra★

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Abstract. We examine the large sample of λ Boo candidates collected in Table 1 of Gerbaldi et al. (2003) to see how many of them show composite spectra. Of the 132 λ Boo candidates we identify 22 which definitely show composite spectra and 15 more for which there are good reasons to suspect a composite spectrum. The percentage of λ Boo candidates with composite spectra is therefore >17% and possibly considerably higher. For such stars the λ Boo classification should be reconsidered taking into account the fact that their spectra are composite. We argue that some of the underabundances reported in the literature may simply be the result of the failure to consider the composite nature of the spectra. This leads to the legitimate suspicion that some, if not all, the λ Boo candidates are not chemically peculiar at all. A thorough analysis of even a single one of the λ Boo candidates with composite spectra, in which the composite nature of the spectrum is duly considered, which would demonstrate that the chemical peculiarities persist, would clear the doubt we presently have that the stars with composite spectra may not be λ Boo stars at all.

Key words. stars: atmospheres – stars: chemically peculiar – stars: binaries: spectroscopic – stars: fundamental parameters – binaries: visual – stars: abundances

1. Introduction

The λ Boo stars are a fascinating class of stars to which much attention has been devoted in recent years. It is the only class of A-type stars with abundances lower than solar, which however have all the kinematical and photometric properties of Pop I stars. It is widely accepted that their low metallicity cannot be ascribed to an age effect and is in fact unrelated to the chemical evolution of the Galaxy.

Several unsuccessful attempts have been made in the past to interpret this peculiar behaviour, from the first historical theory of spallation reactions (Sargent 1965) to the Michaud & Charland (1986) theory of diffusion/mass-loss, the weakness of which has been underlined by Baschek & Slettebak (1988) and examined in detail by Charbonneau (1993). These authors took up the critical problem of the thermally-driven meridional circulation generated by the relatively rapid rotation of these stars when compared to that of Am stars. In λ Boo stars a vigorous meridional circulation should prevent diffusion from operating efficiently.

The best theory, at present, is based on the diffusion-accretion model proposed by Venn & Lambert (1990) to explain the abundance anomalies of the three λ Boo stars studied by them. This hypothesis has been refined later on by Waters et al. (1992) and by Turcotte & Charbonneau (1993). The key point of these models is the existence of a surrounding disk of dust and gas which would be the remnant of the star formation material. The gaseous part would be accreted by the star, while the dust would be blown away by radiation pressure. According to this theory the λ Boo stars should be young objects, in the last phases of their pre-main sequence life or in the early phases of the main-sequence. In fact it has been shown that any remnant of the initial disk will be blown out in 10^6 yr upon termination of the accretion episode. It is in fact true that some λ Boo stars have IR excess or shell signatures or both which could be explained by circumstellar material still surrounding a very young star or system. Also λ Boo have been found to be non-radial pulsating objects, which would agree with the hypothesis that they lie in the zone of pulsation instability.

The hypothesis that the λ Boo stars may be young objects has been explored by several authors since the first study by Gerbaldi et al. (1993), but it has turned out not to be a general explanation. In fact it appears that the λ Boo stars occupy a very large domain of the HR diagram.

An essentially similar model in essence, but with an alternative scenario has been proposed by Kamp & Paunzen (2002)

★ Based on observations collected at ESO (Echelec spectrograph) and at TBL (Telescope Bernard Lyot) of the Pic du Midi Observatory (France).

where the surrounding disk is replaced by a diffuse IS cloud crossed by the star. In such a model it is however unclear why such effects should be limited to the λ Boo range of T_{eff}.

The objects classified as λ Boo display a large variety of properties and a remarkable lack of any relation between their physical parameters (T_{eff}, log g, $v \sin i$, age, Galactic coordinates) and measured abundance anomalies. Recently bright companions were detected near several λ Boo candidates by ground-based speckle and adaptive optics (AO) observations, as well as by the Hipparcos space experiment. This situation prompted us to explore a new hypothesis to explain the λ Boo phenomenon: a combination of two similar spectra can be confused with that of a single metal-poor star (Faraggiana & Bonifacio 1999).

In previous papers on this subject we showed that composite spectra due to undetected binary stars may be easily confused with those of a single peculiar star classified as λ Boo. In particular, from a detailed inspection of high resolution spectra of close binaries producing composite spectra, but classified as single peculiar stars belonging to the λ Boo class, we have selected some criteria that make it possible to distinguish composite spectra (Faraggiana et al. 2001a).

These criteria have been successfully used to demonstrate that other λ Boo stars are in fact binaries which give rise to composite spectra (Faraggiana et al. 2001a,b, 2003). More recently we have shown that a high percentage of λ Boo candidates have visual and UV photometric properties (Gerbaldi et al. 2003) that are incompatible with the λ Boo classification.

We are continuing our research aiming at selecting a group of spectra of metal-deficient Pop I A-type stars not contaminated by binarity.

In the present paper we recall in Sect. 2 the previously defined binary detection criteria and clarify how they are often complementary; we discuss, in Sect. 3, the new λ Boo candidates which appear to be binaries with the spectrum contaminated by that of a companion; in Sect. 4 we discuss the λ Boo candidates with composite spectra and in the conclusions we examine the possible relationship, if any, between duplicity and the λ Boo phenomenon.

2. Binary stars producing composite spectra

2.1. Duplicity detection by imaging: Hipparcos, speckle interferometry, adaptive optics

Binary systems detected by imaging are discussed in detail by Gerbaldi et al. (2003). The measure of separation and magnitude difference made it possible to recognize that 12 objects, corresponding to 9% of the total, classified as λ Boo, are in reality binaries that cannot be resolved at the spectrograph entrance. Their classification is based on the properties of the average spectrum of two stars of similar luminosity and spectral type; this combination in general produces a spectrum affected by veiling, so that the metal lines appear weak and may mimic those formed in a single metal deficient atmosphere.

2.2. Duplicity detection from spectroscopic and photometric data

The detection of duplicity is tricky since these objects do not show, in general, the classical double peaked narrow lines of most classical SB2. This is mainly due to the fact that one of the characteristics of λ Boo stars is the medium-high $v \sin i$ which produces broad and shallow lines. The detection of possible duplicity is therefore more promising in the visual-red wavelength range where the blending is less than at shorter wavelengths.

The OI triplet at 777.4 nm is not affected by any other line; the shape of the three components makes it possible to distinguish the presence of a secondary set of lines if a companion of similar brightness at this wavelength is present; however this is true only up to $v \sin i \simeq 100$ km s^{-1}, the value for which the 3 lines merge into one single broad featureless line. This very powerful criterion has been used to recognize spectroscopically known binaries among the lower rotating λ Boo candidates; an example is HD 47152 (Faraggiana et al. 2001a).

The presence of a secondary component of very similar brightness and similar atmospheric parameters may be easily detected by cross-correlation, using as template a sharp-lined synthetic spectrum (broadened to 5 km s^{-1}). An example is that of HD 11413 discussed in the next section. However, the cross-correlation does not always reveal the presence of the companion star; this is the case when:

1. the observed composite spectrum is detected by many lines showing the same asymmetry (as HD 196821 discussed in Sect. 3.4);
2. the lines of the brighter component are much stronger than those of the companion (as in HD 141851 discussed in Sect. 3.3);
3. the chosen spectral range includes a strong Balmer line whose behaviour dominates the cross-correlation[1].

The core of the Balmer lines should be deeper than that of the synthetic spectra computed with the LTE approximation, as are those computed with the SYNTHE code (Kurucz 1993) used by us; a flat and square inner core profile is a sign of probable duplicity (Faraggiana & Bonifacio 1999).

Other more subtle signatures of duplicity are the inconsistent results obtained when abundance analysis is attempted. This is what we have experienced, for example, with the known binary HD 47152, when we tried to fit its spectrum with that computed by using the model based on the parameters derived from the calibration of photometric colour indices. In this case the observed Balmer line wings are roughly fitted by LTE computations, but metal lines, in particular the many Fe I and Fe II lines do not respect the ionization equilibrium. Moreover the comparison with computations indicates that while some profiles are fitted by the computations, for others the computed lines appear to be either too strong or too weak.

In some cases, subtle duplicity signatures can be detected when several spectra are available, because the effect of the

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[1] This last limitation can be overcome by suppressing the Balmer line profile in both the observed and the template spectra, as has been done for HD 11413, HD 79108 and HD 210111 discussed below.

Table 1. The new composite spectra: observational data.

HD	HR	V	Tel	Spectr.	R	Date	Exp. time (mn)
11413	541	5.94	1.5 ESO	Echelec	28 000	16 Nov. 1992	50
						09 Sep. 1993	50
79108	3651	6.14	1.5 ESO	Echelec	28 000	15 Jan. 1995	55
141851	5895	5.09	1.5 ESO	Echelec	28 000	04 Apr. 1993	33
						07 Apr. 1993	30
			2.0 TBL	Musicos	32 000	20 Mar. 2000	60
196821	7903	6.08	2.0 TBL	Musicos	32 000	06 Oct. 2002	120
210111	8437	6.37	1.5 ESO	Echelec	28 000	07 Sep. 1993	120
						18 Sep. 1994	90
						14 Nov. 1994	55
149303	6162	5.65	2.0 TBL	Musicos	32 000	17 Feb. 2003	60

companion is different at different phases (e.g. HD 11413 and HD 210111 discussed in the following sections).

The presence of two sets of lines with different broadening as in the case of the visual spectrum of HD 111786 (Faraggiana et al. 1997) is also a sign of a composite spectrum. This, coupled with the absence of any narrow line component in the UV range (HR IUE spectra), allowed us to deduce that the narrow lines are due to a secondary source cooler than the primary. We point out that such narrow lines cannot be interpreted as due to a circumstellar shell, since shell lines have a different behaviour: the presence of a shell produces narrow components mainly of the resonance lines and of some low excitation lines and are not restricted to a limited wavelength range. This is the case for HD 38545 (Faraggiana et al. 2001a), for which strong shell lines are seen both in the visual and in the UV spectrum; the binary nature of this object was discovered by Hipparcos and, on the basis of the spectra at our disposal, we have been unable to decide if the shell surrounds one of the components of the binary system or the whole system. In fact the broad photospheric lines prevent the spectral detection of duplicity from inspection of the spectrum.

Large inconsistencies between the atmospheric parameters derived from the calibration of visual photometric colour indices and the UV flux distribution, discussed by Gerbaldi et al. (2003) for the stars observed by TD1, are also signs that the star is not a classical λ Boo.

3. Detected composite spectra

The target stars are extracted from the list of λ Boo stars compiled by Gerbaldi et al. (2003); this list contains all the stars that have been classified as members of this class and for each of them the reference to the classifier(s) is given.

In this section we describe the spectra of a few stars for which we have collected data supporting the interpretation as composite spectra. The basic data for these stars are given in Table 1, together with the observational data and some instrumental details.

The wavelength coverage of the spectra taken at ESO with the Echelec spectrograph is 421−450 nm since only the 9 central orders have been extracted. The nominal spectral resolution of 70 000 was degraded to 28 000 by using a slit width of 320 μm (1.5 arcsec on the sky). The reduction from the CCD images to the complete linear spectra (calibration frames, orders extraction, subtraction of background intensity and scattered light, wavelength calibration and connection of the orders) has been done with a package which runs under MIDAS and was developed expressly for the data from this spectrograph. The details of the procedure are described in Burnage & Gerbaldi (1990, 1992).

The spectra taken at TBL with the Musicos spectrograph cover the wavelength range 515−889 nm. The Musicos is a fiber-fed spectrograph and its resolution is determined by the 50 μm fiber corresponding to 2.1 arcsec on the sky which yields $R = 32\,000$. The photometric and wavelength reductions have been made by using ESpRIT (Echelle spectra Reduction: an Interactive Tool), a computer code for on-line processing developed by Donati et al. (1997) and made available at the TBL telescope of the Pic du Midi.

The atmospheric parameters derived from the Strömgren and Geneva colour indices, as described in Gerbaldi et al. (2003), are given in Table 2; these parameters are derived on the hypothesis that the objects are single stars, and cannot be used for a reliable abundance determination.

The validity of the calibrations of Moon & Dworetsky (1985) (MD) and Künzli et al. (1997) (Gen) for metal deficient stars may be questioned, however we believe that they are good enough for the present purpose.

The synthetic spectra used in the next sections have been computed using the Kurucz model atmosphere grid and SYNTHE code (Kurucz 1993).

3.1. HD 11413

This is one of the few stars unanimously classified as λ Boo (Abt & Morrell 1995; Gray 1988; Paunzen et al. 1997; Paunzen 2001). Abundances for this star have been discussed in several

Table 2. The new composite spectrum stars: atmospheric parameters derived from photometry.

HD	$E(b-y)$ MD	$T_{\rm eff}$ MD	$\log g$ MD	$T_{\rm eff}$ Gen	$\log g$ Gen	[M/H] Gen
11413	0.002	7950	3.84	7813	4.08	−2.03
79108	0.004	9830	4.07	9852	4.17	–
141851	−0.014	8080	3.86	8258	3.69	–
196821	0.002	10390	3.55	10260	3.63	–
210111	−0.023	7450	3.75	7545	4.26	−1.18
149303	−0.018	8120	3.80	8483	3.78	–

papers and are all based on the hypothesis that this is a single star. The star is an unresolved variable (U) according to the Hipparcos data and a δ Scuti-type variable according to Adelman et al. (2000). The spectra used in the present paper were used before by Grenier et al. (1999) for precise radial velocity (RV) measures and the star was classified in that paper as a probable double. We made a further check for duplicity correlating the spectra with the synthetic spectrum computed with the parameters obtained from *uvbyβ* photometry calibration and a low value of $v \sin i$ (5 km s^{-1}). Becase of the predominant rôle of the H_γ line in the 300 Å range covered by our spectra and of the possible inaccuracy of drawing the continuum through such a broad line, as present in dwarf A-type stars, which covers 3 orders of the echelle spectrograph, we artificially suppressed H_γ by normalization with a cubic spline through the line profile, both in the observed and computed spectra before performing the cross-correlation.

The cross-correlation program rebins the observed spectrum and the template in the velocity space, the rebinning is largely oversampled; the correlation index is normalized to 1 and in the abscissa the RV is given.

The cross-correlations (Fig. 1) indicate clearly that the spectrum is formed by more than one source. This is more evident for the HD 11413 spectrum taken on 1993, Sep. 9th, where a separation of about 48 km s^{-1} between the two components has been measured. The existence of a third body may be suspected from the shape of the cross-correlation of the spectrum taken on 1992, Nov. 16th (left wing).

To allow the reader to see what the cross-correlation of a star with a non-composite spectrum looks like, in the bottom panel of Fig. 1 we show the cross-correlation of an H_γ-suppressed spectrum of Sirius with an appropriate synthetic spectrum. The normalized peak is symmetric and its height is almost 0.8. Sirius is a known binary in which the secondary is a white dwarf and therefore much fainter, and its spectrum is not composite. The difference between this cross-correlation and those of HD 11413 is striking.

HD 11413 belongs to the group of pulsating λ Boo and a detailed analysis of its pulsation characteristics has been made by Koen et al. (2003); this makes it possible to study the impact of pulsations on the spectra analyzed here. These authors have shown that no line profile changes have been detected in the 3 days covered by their observations made with $R = 39\,000$, higher than that of the spectra used by us. Having taken a large series of spectra with very short exposures (240 to 500 s) these authors have been able to measure the RV variations connected with pulsations. Figure 2 of Koen et al. shows that the amplitude of these RV variations is 3 km s^{-1}.

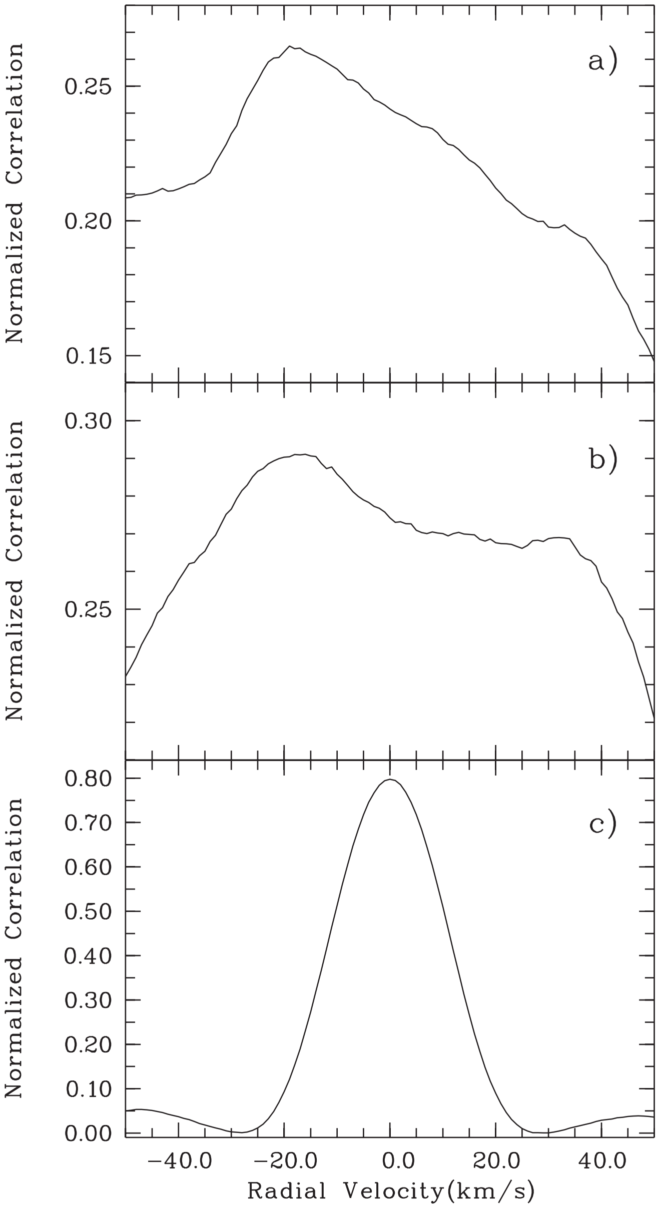

Fig. 1. Panel **a)**: the cross-correlation of the spectrum of HD 11413 taken on Nov. 16th, 1992 with a computed spectrum ($T_{\rm eff}$ = 7950 K, log g = 3.84, $v \sin i$ = 5 km s^{-1}) over the range 420–450 nm. In both spectra H_γ has been artificially suppressed (see text). Panel **b)**: the cross-correlation of the spectrum of HD 11413 taken on Sep. 9th, 1993 with the same computed spectrum as used in panel **a)**; also the spectral range is the same and H_γ has been likewise suppressed. Panel **c)**: the cross-correlation of the spectrum of Sirius; with a ($T_{\rm eff}$ = 9830 K, log g = 4.07, $v \sin i$ = 5 km s^{-1}) suitable synthetic spectrum, the spectral range is the same and H_γ has been suppressed as for HD 11413.

The RV difference between the two peaks found in the correlation of our spectrum of HD 11413 taken on September 9th 1993 is almost one order of magnitude higher. This cannot be due to the pulstion of the star; we also recall that our spectra, taken with 50 m of exposure, average the complex pulsation period (about 0.04 d), and so reduce the visibility of non-radial pulsations (NRP).

The comparison between observations and computations shows a poor agreement with the synthetic spectra computed with the parameters derived from either *uvbyβ* or Geneva photometries.

The $v \sin i$ derived by Royer et al. (2001) from the frequency of the first zero of the Fourier transform of 3 lines of these same spectra is 140 km s^{-1}, a value slightly higher than those measured by Stürenburg (1993) (125 km s^{-1}) and by Holweger & Rentzsch-Holm (1995) (122 km s^{-1}). These latter authors derived $v \sin i$ from the CaII K line profile; the discrepancy between this value and that derived from the metal lines in the 420−450 nm region is likely due to the fact that it is almost impossible to normalize correctly the observed spectrum in this region where the overlap of H_ϵ and H_8 broad wings makes it impossible to see the real continuum.

So HD 11413 is a new SB2 or multiple star, and it is another example of a peculiar hydrogen line star (PHL), common among λ Boo stars, which is explained by the duplicity of the object.

3.2. HD 79108

The star is a λ Boo candidate having a slightly negative Δa index (Maitzen & Pavlovski 1989; Vogt et al. 1998); it has also been classified λ Boo by Abt & Morrell (1995). King (1994) has derived an IR excess at 60 μm from IRAS data. Grenier et al. (1999) classified it as suspected double, but speckle interferometric observations (Ebersberger et al. 1986) gave a negative result. Its RV is variable according to the Bright Star Catalog in spite of the fact that the star does not belong to a known binary system. The H_γ profile is fitted by the spectrum computed with the MD parameters (Fig. 2); however the observed core is not deeper than the computed one, as expected (see Sect. 2.2). The metal lines have square and asymmetric profiles suggesting a composite spectrum. The cross-correlation made without H_γ, as for HD 11413, confirms that the object is in reality a complex system composed of at least two stars of similar luminosity and a third less luminous component (Fig. 3).

3.3. HD 141851

This star has been classified λ Boo candidate by Abt (1984) on the basis of the weak MgII 448.1 nm line; the colour indices in the Geneva photometric system support this classification (Hauck 1986). The star is included in the Paunzen et al. (1997) “consolidated catalogue of λ Boo stars”, but not in the list of “confirmed members” of this group by Paunzen (2001). The star is a known binary, first found by McAlister et al. (1987) through their speckle measures; the separation varies from 0.069 to 0.132 arcsec (Hartkopf et al. 2003), but no estimate of the magnitude difference is given by these authors. However, the orbital period seems to be very long, probably more than 60 yr, according to Iliev et al. (2001).

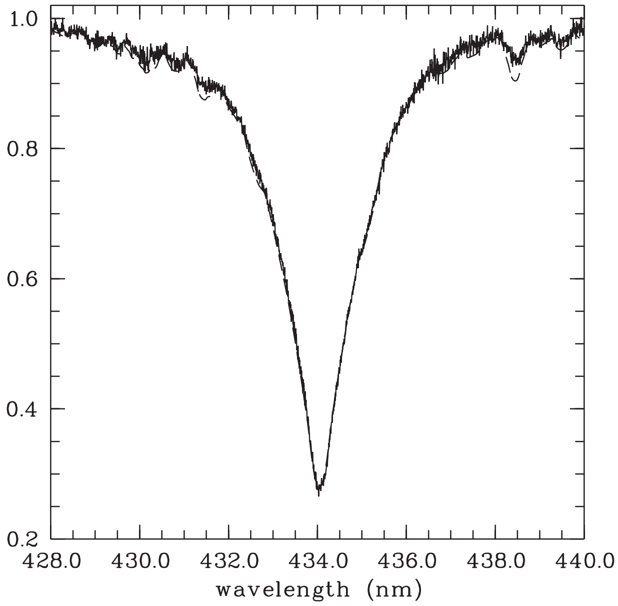

Fig. 2. The H_γ profile of HD 79108 compared with a spectrum computed with $T_{\rm eff}$ = 9830 K, log g = 4.07 and $v \sin i$ = 160 km s^{-1}.

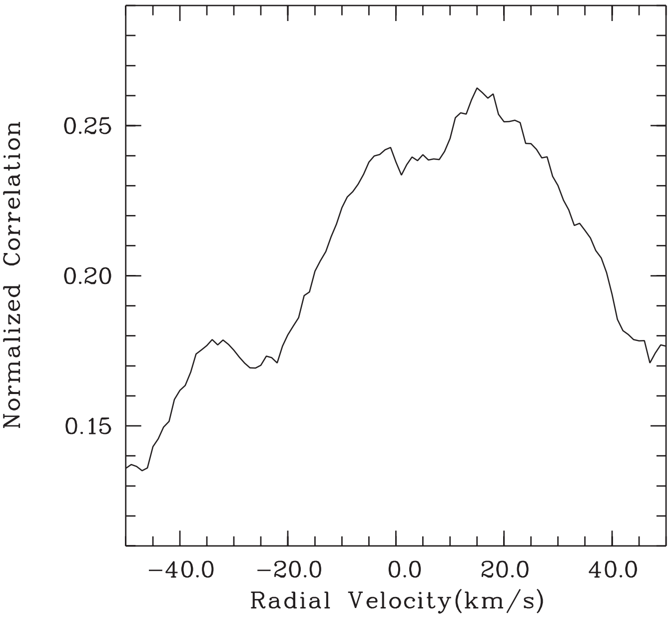

Fig. 3. The cross-correlation of the spectrum of HD 79108 with the synthetic spectrum computed with $T_{\rm eff}$ = 9830 K, log g = 4.07 and $v \sin i$ = 5 km s^{-1} and with H_γ suppressed (see text).

According to the spectrum analyzed by Grenier et al. (1999) the star belongs to the group of certain double A-F type with faint F-G component, i.e. the observed spectrum appears to be significantly contaminated by that of the fainter and cooler companion. AO observations (Gerbaldi et al. 2003) have demonstrated that the flux of the secondary star, is about 1/3 of that of the primary in the *H* filter and cannot be neglected.

The $v \sin i$ values found in the literature are quite diverse: 185 km s^{-1} (Abt & Morrell 1995), 230 km s^{-1} (Royer 2001), 200 km s^{-1} for C lines and 280 km s^{-1} for O lines (Paunzen et al. 1999a), 260 km s^{-1} (Andrievsky et al. 2002). None of

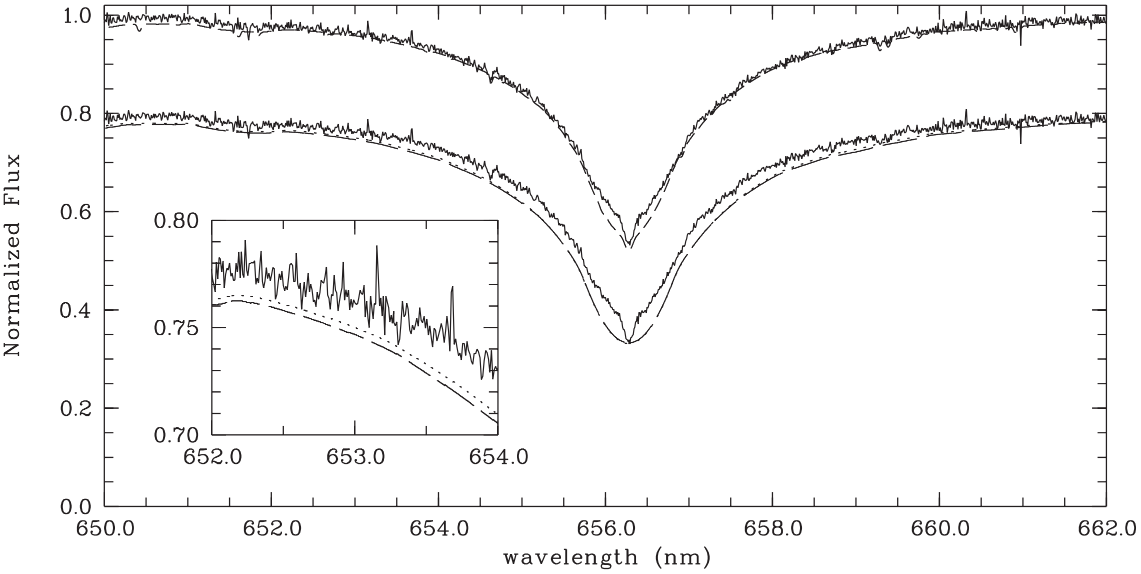

Fig. 4. The observed spectrum of HD 141851 (solid line) superimposed on the combined spectrum (short dashed line) obtained by combining two synthetic spectra as described in the text (*upper panel*). In the lower panel the same observed spectrum is compared with two synthetic spectra computed with solar abundances and parameters $T_{\rm eff}$ and log g derived from the photometry: 8080 K, 3.86 (long dashed line) and 8258 K, 3.69 (dotted line); the two computed spectra are almost identical as can be seen in the inset.

these authors mentions the presence of weak narrow lines all throughout the spectrum.

This star belongs to the sample of λ Boo for which Paunzen et al. (1999a) and Kamp et al. (2001) determined NLTE abundances of C, O and Ca in LTE respectively by using the average parameters of the two components of the system. In 2002 Andrievsky et al. made a new LTE abundance determination of C, O, Si and Fe; they adopted the same model as the previous authors. There are large differences in the abundances of C and O determined by the various authors: Paunzen et al. (1999a) give an LTE abundance of C of −0.73 (NLTE = −0.81) to be compared with the value by Andrievsky et al.: −0.20; in the same paper the LTE abundance of O is +0.25 (NLTE = −0.21) to be compared with the value by Andrievsky et al.: −0.38.

The LTE abundance difference of C is considerably larger than what a state of the art abundance analysis should provide; they are based on different lines, so probably differently affected by NLTE. The wavelength of the lines used by Andrievsky et al. is not specified so no abundance correction for NLTE can be estimated. Another possible interpretation of these different abundances is that the two groups used spectra taken at different dates, so probably at different phases of the binary system.

Hauck et al. (1998) measured the *EW* (2.3 mÅ) of a narrow component in the core of the K-line; they interpreted it as a signature of circumstellar matter around the star. This narrow feature may be interpreted more simply as spectral signature of the cooler companion.

X-ray emission, unexpected in early-, middle-A-type stars has been measured by ROSAT PSPC, and correctly ascribed to the companion star (Simon et al. 1995). In fact, if one component of this system has a $T_{\rm eff}$ lower than 8000 K, and thus a convective envelope from which X-rays may originate, the detection of the X-ray emission from the system does not present any peculiarity.

Note that what seems high noise of the spectrum of this star in reality consists of many weak lines of a component with a lower $T_{\rm eff}$ and a much lower v sin i ($\leq$20 km s^{-1}).

According to our spectra, the lines of the secondary component are weak, but definitely present in the blue region of the spectrum and more clearly from the Na I doublet.

The observed colour indices have been used in both photometries to derive the atmospheric parameters; in fact $E(b-y) = -0.010$ (computed by the program of Moon 1985). This slightly negative colour index may be considered as due both to the errors on the photometric measurements and to a distortion of the flux due to the composite spectrum. Penprase (1993) gives $E(B-V) = 0.07$ which corresponds to $E(b-y) = 0.05$. According to the distance of HD 141851 obtained from Hipparcos data, combined with the study of the high Galactic latitude molecular clouds by Penprase (1993), such a large reddening seems improbable. We recall that $E(B-V)$ has been derived by combining two photometric systems as well as the spectral classification of the star (Penprase 1992).

We computed two synthetic spectra with the parameters $T_{\rm eff}$ and log g derived from $uvby\beta$ and Geneva photometric colour indices as listed in Table 2, namely, (8080 K, 3.86), and (8258 K, 3.69). We assumed v sin i = 250 km s^{-1} from Royer (2001) and used solar abundance models.

In Fig. 4 the observations of the H_α region are overimposed on these two computed spectra. This comparison clearly shows that:

1. the difference of $T_{\rm eff}$ and log g computed by MD and Gen calibrations are such that the two different combinations produce the same Balmer line profiles;
2. the flat core of the observed H_α (and H_γ) profile, with respect to the computed one, is one of the binary signatures

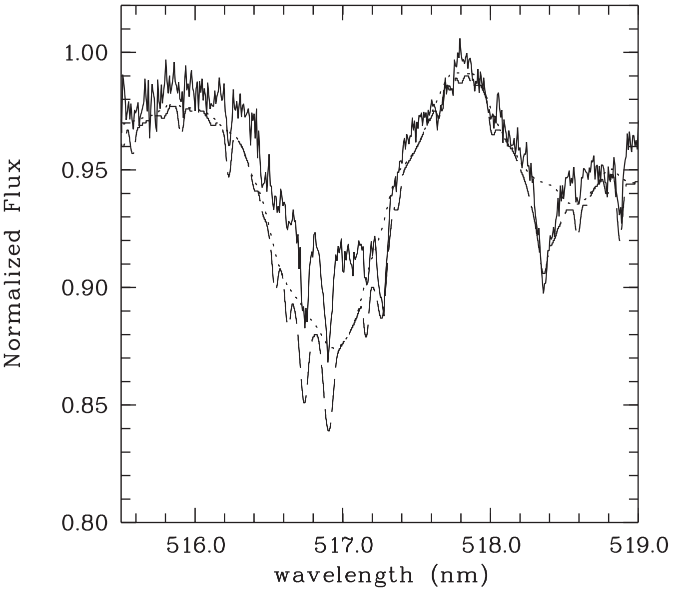

Fig. 5. The observed Mg I triplet of HD 141851 compared with two synthetic spectra: that computed with MD parameters (dotted line) and that obtained from the combination described in the text (long dashed line).

according to Faraggiana et al. (2001a), while the narrow inner core component belongs to the companion star.

The aspect of the observed spectrum, the value of $T_{\rm eff}$ obtained from the combined light, the magnitude difference in the H-band (Gerbaldi et al. 2003) and the analysis by Grenier et al. (1999) allow us to derive, as a starting guess, a combination of two spectra having $T_{\rm eff}$ = 8000 and 6000 K, log g = 4.0. The luminosity ratio in V has been computed from the absolute magnitudes M_H and M_V as given in Allen's astrophysical quantities (Cox 2000) for dwarf stars A7 and G0 which correspond to the two $T_{\rm eff}$ values. The M_H values of these spectral types are consistent with the luminosity ratio observed in AO. For the V magnitude, it follows that the ratio of the luminosity in this spectral domain is $L_1/L_{\rm tot} = 0.84$ and $L_2/L_{\rm tot} = 0.16$. This combined spectrum gives a better, but still not satisfactory, fit to the observation (Figs. 4 and 5).

We conclude that this is another star for which the claimed metal deficiency cannot be investigated if the duplicity of the system is not taken into account.

3.4. HD 196821

Various classifications of this star (classified as variable in the SIMBAD database) appear in the literature: magnetic star according to Wolff & Preston (1978) who measured $v \sin i = 20$ km s^{-1}; Ap of the Si-Cr group according to Heacox (1979); B9-HgMn in the Renson et al. (1991) catalogue of Ap stars, λ Boo according to Abt & Morrell (1995) who measured $v \sin i = 10$ km s^{-1}. A positive value of Δa (+0.014) is observed by Maitzen et al. (1998), contrary to what is expected in λ Boo stars (Maitzen & Pavlovski 1989).

The high blanketing, characteristic of CP stars and opposite to what is expected in λ Boo stars is the cause of the UV flux distribution shown in Fig. 6. In fact the UV flux observed by TD1 indicates that the blanketing is higher than that predicted for a star with solar abundances, thus excluding that HD 196821 is a λ Boo star.

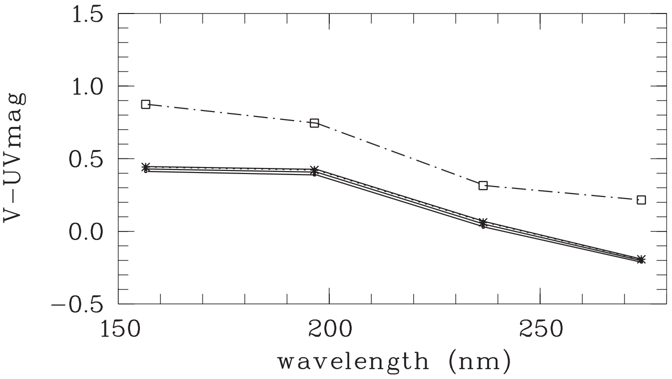

Fig. 6. The UV flux (and associated error bars) of HD 196821 measured by TD1 compared to the theoretical flux (dash-dot line) computed with solar abundances.

In this figure the 4 observed magnitudes are derived from the absolute fluxes in four passbands centered at 274.0, 236.5, 196.5 and 156.5 nm. The computed magnitudes are derived from the theoretical Kurucz fluxes integrated over the profile of the photometer channel passband (for the magnitude centered at 274.0) and over the response of each of the three spectrophotometer channels (135.0–175.0, 175.0–215.0, 215.0–255.0). These profiles are given in the Thompson et al. (1978) catalogue. The revised version of this catalogue, available at CDS, has been used to compute the UV magnitudes and their errors.

The only abundance analysis is that made by Heacox (1979) and it is based on $T_{\rm eff}$ = 10 400 K, log g = 3.7, $\xi = 3$ km s^{-1} and $v \sin i = 20$ km s^{-1}.

In his classification Bidelman (1988) notes "rather odd spectrum; Ap Cr?, SB?". In fact, inspection of the spectrum taken on 2002, Oct. 6 confirms that HD 196821 is an SB; the presence of a companion star is revealed by the fact that the strong lines all have the same kind of asymmetry; the profile of the O I triplet is given in Fig. 7 to illustrate the shape of the observed lines, which should be unblended in a single star.

3.5. HD 210111

In their RV program Grenier et al. (1999) classified the star as a probable double.

The duplicity of this star is suggested by the asymmetric and distorted profiles shown in Figs. 1 and 3 of Holweger & Stürenburg (1991) paper, especially for the Na I doublet, for the Mult. 4 Fe I lines 392.026, 392.2914, 392.7922 and 393.0299 nm and for Al I 394.4009 nm. The same double structure of Na I is evident in the averaged spectrum (of 5 spectra taken in 50 mn of observations) given by Bohlender et al. (1999) in their Fig. 9. Bohlender et al. (1999) in their study of non-radial pulsation (NRP) of λ Boo stars stress that this object has the largest amplitude NRP ever observed in dwarf stars of any class. Bohlender et al. report a peak to peak amplitude of 3% of the continuum in the mean-absolute-deviation

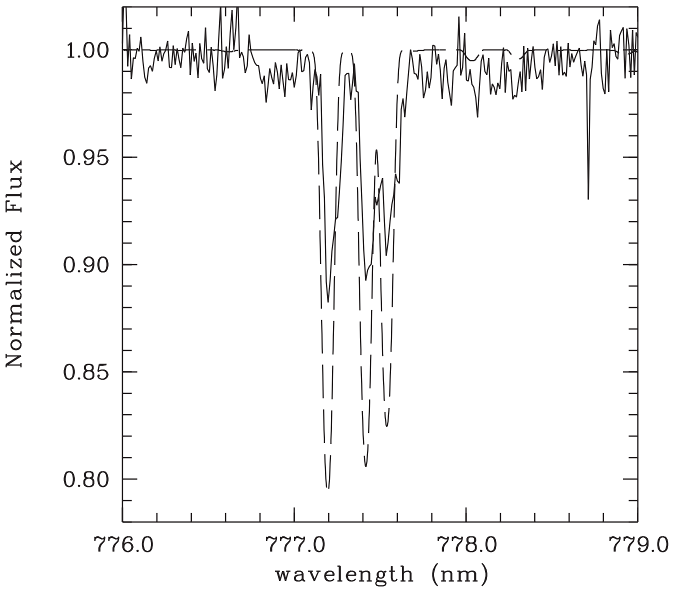

Fig. 7. The OI 777.4 triplet of HD 196821 compared with the theoretical spectrum computed by assuming solar abundances.

spectrum (MAD). These authors do not report any radial velocity variations, which, as in all non-radial modes, must be small. One may estimate the amplitude of the radial velocity variation in km s^{-1} by multiplying by a factor of 100 the amplitude in the MAD (Mantegazza, private communication), we thus expect radial velocity variations with an amplitude of the order of 3 km s^{-1}. The multiperiodic high amplitude NRP is amply documented by these authors. The cross-correlations computed with the 3 spectra obtained by us are shown in Fig. 8. The asymmetry of our correlation curves refers to spectra of 1h−2h of exposure; the largest amplitude of the NRP measured by Bohlender has a period of 49 min, so the effect of NRP has been averaged in these spectra. Nevertheless the RV between the two deformed peaks of the cross-correlation is more than 20 km s^{-1}, which cannot be confused with the radial velocity variations induced by the NRP, which are an order of magnitude smaller. Our results combined with the reamarks of Bohlender et al. (1999) suggest that HD 210111 is probably a combination of two similar NRP stars.

The TD1 observations suggest a flux deficiency in the band 156.5 nm compared with the other bands (Fig. 9) that, if confirmed, indicates that the companion star has a lower $T_{\rm eff}$.

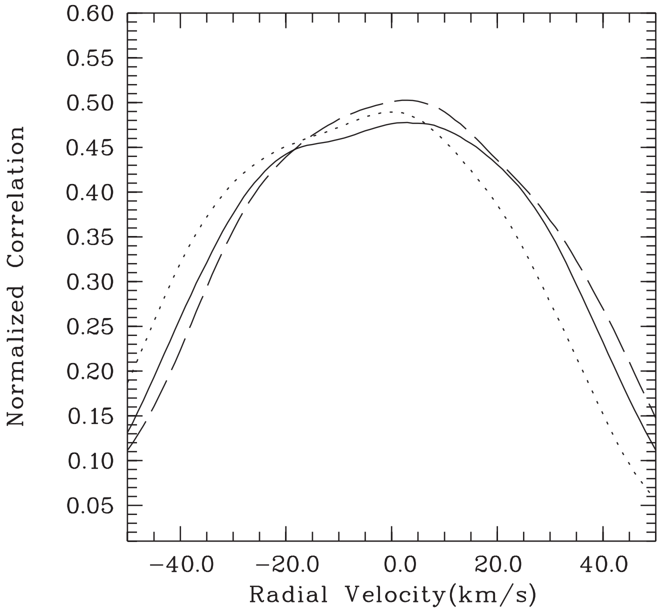

Fig. 8. The cross-correlations of the three spectra of HD 210111 (taken on Sep. 7th, 1993 (solid line), Sep. 18th, 1994 (long-dashed line) and on Nov. 14th, 1994 (dotted line)) with a computed spectrum ($T_{\rm eff}$ = 7500 K, log g = 4.0 $v \sin i$ = 5 km s^{-1}) over the range 420−450 nm. Both in the synthetic and observed spectra the H_γ has been artificially suppressed (see text).

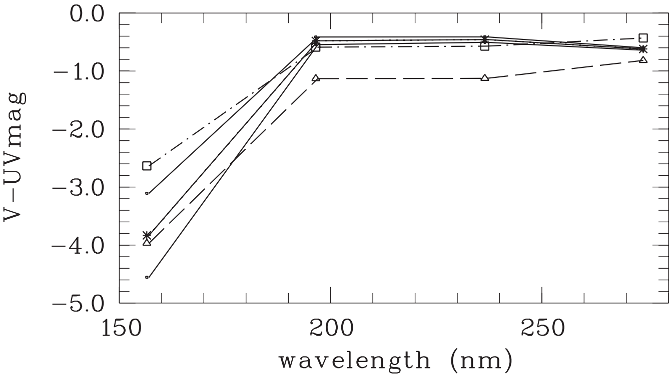

Fig. 9. The UV flux of HD 210111 and associated error bars (thick lines) compared to the theoretical flux ($T_{\rm eff}$ = 7500 K, log g = 4.00 abundances 1 dex lower than solar) (dash-dot line) and solar abundances (dashed line).

3.6. HD 149303: Wrong binary detection?

This star is a binary according to Paunzen et al. (1999a) from the profile of the O I triplet; one component being a slowly rotating star and the other one a fast rotator. In spite of this duplicity detection, the abundances of O, N, and S have been determined by these authors and by Kamp et al. (2001) in LTE and NLTE treating the star as single.

The values of $T_{\rm eff}$ (8000 K) and log g (3.8) used in these papers are those derived from Strömgren photometry through the calibration by Napiwotzki et al. (1993). The v sin i = 275 km s^{-1} has also been derived in the hypothesis that the spectrum is that of a single object.

In another paper Paunzen et al. (1999b) determined LTE abundances of Mg, Ti, Fe and Ni using totally different values for $T_{\rm eff}$ and log g (9000 K and 4.2) derived from another calibration of photometric data ($(b - y) - c_1$ by Kurucz 1991). The value of v sin i (200 km s^{-1}) derived in this paper is also very different from the previous one. We note here that the $(b - y)$ colour is inconsistent with the β value; in fact this latter predicted from the other stellar colours is 2.875 instead of the observed value of 2.848. It does seem a bit odd that abundances of different elements are derived using such different atmospheric parameters.

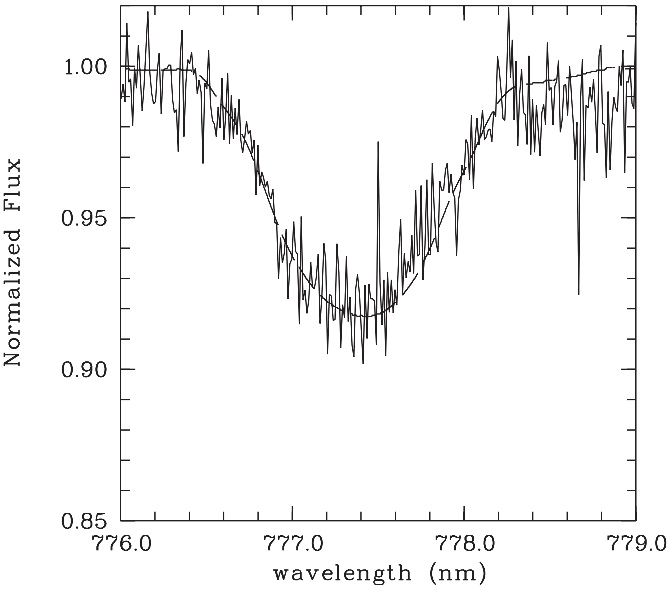

Fig. 10. The OI 777.4 profile of HD 149303 compared with that computed in the hypothesis that the star is a single object rotating at 275 km s^{-1}; the fictious fit has been obtained by adopting the MD parameters, but increasing the oxygen abundance by 1 dex to simulate the NLTE effect on this triplet.

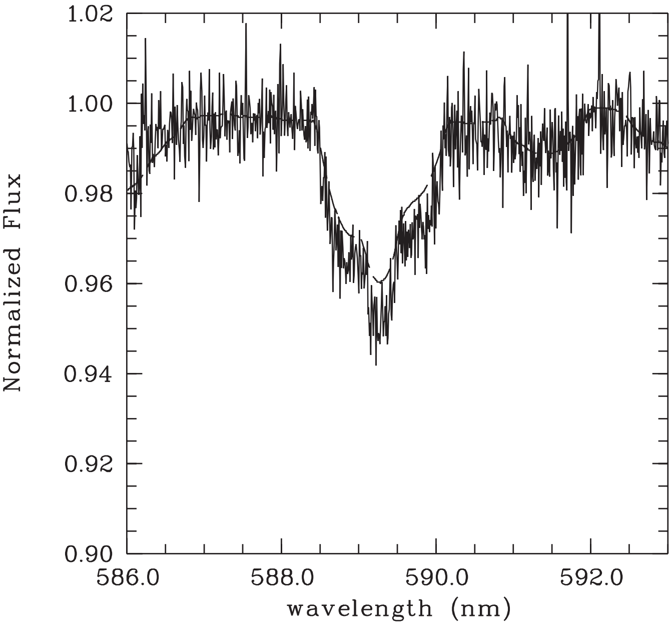

Fig. 11. The NaI doublet appears as a single very broad feature in the spectrum of HD 149303 (thick line); the synthetic spectrum has been computed by assuming that the star is a single object rotating at 275 km s^{-1}. The convolution of such broad lines produces the fictious central peak.

The $T_{\rm eff}$ values that we have derived from the $uvby\beta$ and Geneva colour indices are 8120 and 8483 K, and neither agrees with the H_α profile. The star is the A component of a visual binary system; the $E(b-y)$ computed for its B companion is 0.031, while $E(b-y) = -0.018$ has been derived for the primary. By forcing the star in another MD group (gr 5), a consistent value of $E(b-y) = 0.023$ is obtained for both; however the $T_{\rm eff}$ computed in that case is 9520 K ($\log g = 3.85$) which does not fit the observed H_α profile either and is in strong contradiction with the UV flux observed by IUE.

The complex structure of the OI 777.4 triplet claimed by Paunzen et al. (1999a) is not present on our spectrum, which simply indicates a very fast rotator (Fig. 10).

Even the Na I doublet (Fig. 11) is merged into a single feature with the central spurious "subrotational" peak due to the doublet convolution (see comments on this effect in Dravins et al. 1990).

It might be interesting to follow this star to recover the phase at which the low-rotating companion is detectable.

If this object, as one single star or as the fast rotating component of a binary system, is really rotating at $v \sin i = 275$ km s^{-1}, it should have lost its spherical shape and the gravity-darkening effect cannot be neglected. The effects of such a rotation on the stellar continuum and on the *EW* of the lines should be analyzed. Clearly this analysis cannot be done from a single spectrum of low S/N ratio such as the one at our disposal. We have only checked that the H_α profile is not fitted by either the profiles computed by adopting the models with the parameters derived by Strömgren and Geneva photometries; these models cannot be used for abundance analyses. According to our interpretation, it is highly probable that the extremely high $v \sin i$ value is in reality a combination of those of two medium-fast rotating stars whose average parameters do not reproduce the H_α profile because the stars are not equal.

The Referee suggested that the visual companion of HD 149303, whose separation has been measured by Hipparcos (parallax = 14.48 mas, sep = $16''\!.36$, $\Delta H_{\rm p} = 3.08$) may have been in the spectrograph slit during the Paunzen et al. observations and not during ours. The presence of the low $v \sin i$ component has been discovered by Paunzen et al. (1999a) in the OI triplet on spectra taken during 1996–1998 (no dates are given for these observations). The epoch of the Hipparcos catalogue is 1991.25, thus in order to be within the slit width of Paunzen et al. (which must have been of a few arcseconds, at most) the B component should have moved at least $15''$ in 7 years to be confused with its brighter companion; its tangent velocity would be 701.5 km s^{-1}. Whichever the orbit inclination the system cannot be bound and one should admit that the companion star is moving on an hyperbolic orbit, this is highly unlikely and can be dismissed. Therefore the hypothesis that this star was within the width of Paunzen's slit can be rejected. We have also checked on the DSS II IR image taken on 1997.35 that the B companion was, at that date, at a distance of about 17 arcsec and therefore could not be in the slit width of Paunzen et al.

An alternative hypothesis is that the companion star was within the height of the slit, which in fact may be quite long. However the spectra of the two stars should have been clearly separated in the focal plane, unless the instrument had a scale of $\sim 6''$ per pixel. Therefore Paunzen et al. should have been able to extract an uncontaminated spectrum of the primary star. Thus the secondary star seen by Paunzen cannot be the one seen by Hipparcos, but must be much closer.

We recall also that speckle measures by McAlister et al. (1997) gave a negative result for a nearby companion with an upper limit for the separation ≤ 0.038 arcsec.

Finally we recall that the known secondary with a magnitude difference of 3.08 corresponding to a flux ratio of less than 0.06 can hardly affect the spectrum of the primary star.

4. Discussion

The very diverse properties of the stars classified as λ Boo prompted us (Faraggiana & Bonifacio 1999) to consider the hypothesis that the peculiarities in many, if not all, λ Boo stars result from the fact that they are unresolved binary or multiple systems consisting of stars of similar luminosity. In this paper we have examined the extensive list of Gerbaldi et al. (2003) to see how many of the 136 objects classified as λ Boo stars show composite spectra which, if interpreted as spectra of a single star, may be responsible of the peculiarities which led to the λ Boo classification.

Four stars in Gerbaldi et al. (2003) are misclassified beyond any reasonable doubt: HD 34787 is a peculiar shell star with strong SrII 4077 and no shell core of Balmer lines (Gray et al. 2001), HD 37886 is an Hg-Mn star, HD 89353 (HR 4049) is an extremely iron deficient post-AGB star, HD 108283 is a shell star. Therefore the λ Boo candidates to be considered are 132.

One has to bear in mind the difference between binary systems in which one of the companions is several magnitudes fainter than the other (as is the case for, e.g., many Am stars) and binary systems which give rise to composite spectra. Let us summarize all the stars for which the presence of a composite spectrum is either certain or highly probable.

4.1. Stars classified as λ Boo with composite spectra

We consider as binaries which surely produce composite spectra those for which a separation between the components of less than 2 arcsec has been measured with a magnitude difference not larger than 2.2 mag. Twelve systems satisfy these criteria: 9 systems detected by Hipparcos (HD 22470, HD 36496, HD 38545, HD 47152, HD 97773, HD 118623, HD 170000, HD 217782 and HD 220278); 2 systems in the WDS (Washington Double Star) Catalog (Worley & Douglass 1997) (HD 160928 and HD 290492), and one star measured with adaptive optics (HD 141851) (Gerbaldi et al. 2003).

In addition to the stars for which high angular resolution observations have detected the duplicity and made it possible to measure the separation, we must consider those stars for which a detailed inspection of high resolution spectra revealed a composite spectrum: HD 64491 (Faraggiana & Gerbaldi 2003), HD 111786 (Faraggiana et al. 2001a), HD 153808 (Faraggiana et al. 2001a), HD 174005 (Faraggiana et al. 2001b), as well as the four stars discussed in the previous sections (HD 11413, HD 79108, HD 196821 and HD 210111).

To the list of stars with composite spectra two known binary systems should be added: the SB2 HD 210418 (Gray & Garrison 1987) and HD 98353; this latter star, better known as 55 UMa is a triple system formed by a close pair (A1V and A2V, both moderately Am) and a more distant component (A1V); it is discussed in detail by Liu et al. (1997).

It thus appears that the percentage of binaries in our sample, whose angular separation and magnitude difference produce composite spectra because they are not resolved in the spectrograph entrance, is 22 out of 132, i.e. of the order of 17%, therefore not as small as has been assumed in discussions on the origin of these stars.

4.2. Stars classified as λ Boo which likely display composite spectra

The above percentage could be higher, if a few of the stars listed below, for which a composite spectrum is suspected, can be confirmed as composite spectrum stars.

Stars for which speckle interferometry measured a separation less than 0.1 arcsec, but for which there are no indications of a magnitude difference (HD 21335, HD 98353, HD 225218) may be suspected of producing composite spectra, but require complementary observations to assess whether their spectra are indeed composite. HD 98353 = 55 UMa is a case for which such observations are available and it is in fact the triple system discussed above.

Other binary candidates which may produce composite spectra are the 14 stars with variable RV, not belonging to known visual or spectroscopic binary systems, already listed in Gerbaldi et al. (2003): HD 39283, HD 56405, HD 74873, HD 79108, HD 87696, HD 111604, HD 125489, HD 138527, HD 169009, HD 177756, HD 179791, HD 183324, HD 220061, HD 221756. A faint companion of HD 138527 has been detected by adaptive optics (Gerbaldi et al. 2003). Although other phenomena, such as, e.g., stellar pulsations, may be responsible for variable radial velocities, it is likely that several of these will turn out to be spectroscopic binaries. In fact among these HD 79108 is the new multiple system discussed in Sect. 3.2. For two others, HD 56405 and HD 125489, the UV flux (TD1 UV magnitudes), is lower than that computed with solar abundances, contrary to what is expected in the low-blanketed λ Boo stars (see Gerbaldi et al. 2003). We consider this an indication of a composite spectrum. In fact 5 out of the 8 stars showing this low UV flux are already known to be close binaries producing composite spectra, the remaining three are the two stars mentioned above and HD 212150. For 4 of the variable RV stars the UV flux is better fitted by theoretical fluxes computed assuming a solar abundance rather than lower than solar abundances, as should be the case for λ Boo stars (HD 39283, HD 74873, HD 87696 and HD 179791). Again this is a reason to suspect a composite spectrum.

A further reason to suspect the existence of composite spectra is the discrepancy between the absolute magnitude derived from the measured parallax and that derived from some calibration of photometric indices. From the comparison between the absolute magnitude derived from the Hipparcos parallax and the calibrations adopted by Moon (1985), a slight systematic difference exists, in the sense that, on average, the M_V derived from the Hipparcos parallax is brighter than that derived from the Moon (1985) calibrations. It is probably significant that the majority of the known binary stars appear over-luminous with respect to what is expected from the colours (see Fig. 4 in Gerbaldi et al. 2003). This is not always the case, for some stars the Hipparcos absolute magnitude is in excellent agreement with that derived from the Moon (1985) calibrations and in some it is even slightly fainter. Therefore the criterion of over-luminosity is neither necessary nor sufficient to establish the multiple nature of a star. However it certainly prompts further observations to ascertain its nature.

We add also that 16 λ Boo stars are included in the Grenier et al. (1999) catalogue of a sample of 610 southern B8-F2 stars. Radial velocities have been measured using a cross-correlation method (the templates are a grid of synthetic spectra). For 2 of them (HD 183324 and HD 223352) no RV is given because the cross-correlation with the adopted template produced a correlation peak that was too low and asymmetric; 2 others (HD 111786 and HD 141851) are certain doubles, 4 (HD 30422, HD 31295, HD 193281 and HD 210111) are probable and another 4 (HD 319, HD 75654, HD 79108 and HD 204041) suspected doubles, 1 (HD 142703) is a probable multiple system, 1 (HD 170680) showed the wide peak of B stars and only 1 (HD 39421) had a symmetric and Gaussian profile. We do not consider these remarks as a definite proof of the duplicity of these stars, but as an indication that a careful check for non-duplicity is required before elaborate analysis is carried out for them. The fact that 14 out of the 16 examined λ Boo stars gave problems in the RV measurements is a further indication of the high percentage of composite spectrum objects among λ Boo stars.

We finally note that for 19 stars the UV flux (TD1) cannot be reproduced by any LTE computation (groups 3a and 3b of Gerbaldi et al. 2003). Five of these stars are already known to produce composite spectra, two are classified D and one U by Hipparcos, while six have not been observed by this satellite. A distorted UV flux is not by itself evidence of duplicity; however, alternative explanations are more contrived. Therefore these stars ought to be further scrutinized in order to understand the reasons for this anomalous flux distribution.

5. Conclusions: Duplicity and λ Boo nature

From the above discussion we may conclude that the percentage of λ Boo stars with composite spectra is at least 17%, but could rise up to 28% if all the stars for which a composite spectrum is suspected were confirmed, and even more if we consider that for several stars, mainly the faintest ones, there are no data beyond classification dispersion spectra.

To understand the λ Boo phenomenon the list of λ Boo stars should be cleared of all the above stars for which the λ Boo classification is not confirmed when the duplicity is taken into account.

For example for the SB2 HD 84948 we have shown that the current λ Boo classification of the two components is based on an abundance analysis made by assuming incorrect atmospheric parameters (Faraggiana et al. 2001a). Therefore the λ Boo status of this star has still to be demonstrated.

The claim of Faraggiana & Bonifacio (1999) that undetected duplicity often results in *underabundances* when the spectrum is subject to a standard abundance analysis has recently found independent confirmation by the analysis of overluminous F-type stars by Griffin & Suchkov (2003). These authors analyzed F stars for which the absolute magnitude derived from *uvbyβ* photometry is over 0.5 mag greater than that derived from the Hipparcos parallax. In their sample of 77 stars they found 27 new binary systems from the radial velocity survey. The percentage of newly detected SB2 systems with positive [Fe/H] is 6%, while the same percentage for the whole sample is 21%, clearly showing that a composite spectrum may simulate metal underabundance more often than not.

At present the connection between the λ Boo nature and duplicity, if any, is not clear. The evidence we have presented here implies that a non-negligible fraction of λ Boo stars has composite spectra due to duplicity. Furthermore the effect of duplicity, when neglected, is such as to mimic underabundances, which is one of the main characteristics of λ Boo stars. Therefore for all the stars with composite spectra the λ Boo classification needs to be re-established (or rejected) taking into account the composite nature of the spectra. It would be tempting to conclude that the λ Boo phenomenon is *solely* due to undetected duplicity. However, on the one hand, there exists a majority of stars for which no sign of duplicity has been detected, although one should keep in mind that in some cases duplicity has not been searched for, or $v \sin i$ is too large for a spectroscopic detection or the stars are too faint and the angular separation too small to be resolved visually. On the other hand, it may well be that the λ Boo stars with composite spectra, when analyzed taking into account their binary or multiple nature, still show the underabundances typical of λ Boo stars.

If a significant number of λ Boo stars with composite spectra, when properly analysed, show “normal” (i.e. solar or solar-scaled) chemical abundances the very existence of λ Boo stars as a class of chemically peculiar stars may be called into question.

We believe that the most urgent thing to do, at present, in the study of λ Boo stars is to perform such a detailed analysis for as many λ Boo stars with composite spectra as possible. It is of paramount importance that such an analysis is based on many spectra, taken at different phases, with as large a spectral coverage as possible.

The other way to tackle the problem is to pursue observations at high angular resolution. Interferometric instrumentation on large telescopes, especially the VLTI should add valuable information, making it possible to explore effectively the problem of the λ Boo stars. If the λ Boo phenomenon is due to undetected duplicity one may expect the detection of new previously unknown binary systems.

What we now consider firmly established is:

1. the analysis of the abundances of the λ Boo-type binaries **must** be done by disentangling the observed composite spectra;
2. to know the position of the stars of a multiple system in the HR diagram one has to know the $T_{\rm eff}$ and L of all the components. Adopting average values of both parameters to speculate on the evolutionary stage of λ Boo stars does not have any physical meaning.

This paper concludes our series on the λ Boo candidates. We believe we have convincingly demonstrated the need for high resolution spectroscopy over a large wavelength interval and spectrum synthesis to determine the chemical composition of the λ Boo candidates with composite spectra. Such an analysis has not been performed for any of them yet. The current generation of echelle spectrographs on 4 m and 8 m class telescopes is well suited to tackle the problem.

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