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How many λ Bootis stars are binaries?*

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Abstract. In the attempt to shed new light on the λ Boo phenomenon we analyzed the astrometric, photometric and spectroscopic characteristics of stars out of a list of recently selected λ Boo candidates.

We show that the class is still ill-defined and discuss the possibility that some, if not most stars presently classified as λ Boo, are in fact binary pairs and that peculiar abundances may not correspond to actual values if the average values of the atmospheric parameters $T_{\rm eff}$ and log g are assumed and the effect of veiling is not taken into account.

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

1. Introduction

The class of λ Boo stars still presents poorly defined characteristics, and this more than 50 years after the discovery of the prototype member λ Boo by Morgan et al. (1943) who noted the abnormally weak metal lines of this A0 dwarf star.

The properties that should define a λ Boo star are not clearly established; the proposed spectroscopic criteria are usually based on the weakness of metal lines, especially of the Mg II 4481, compared with what is expected from the hydrogen line type, while C, N, O and S have nearly solar abundances. The kinematic behaviour should allow to distinguish these stars from the metal poor A-type Horizontal Branch stars. Moderate to high projected rotational velocities are usually found among λ Boo stars, although some exceptions have been recently identified (e.g. HD 64491 and HD 74873 selected by Paunzen & Gray 1997).

The result of the vague definitions of these non-evolved metal underabundant stars is well reflected by the variety of opinions existing at present about the members of this class. The metal abundances obtained up to now reveal a high scatter from star to star.

Details on the evolution with time of the λ Boo definition are summarized in Faraggiana & Gerbaldi (1998); the not clearly defined properties of these stars are, at least partially, responsible of the various hypotheses proposed to explain the λ Boo phenomenon as well as of the uncertainty on the age attributed to these objects, which spans from that of stars not yet on the Main Sequence to that of old objects descending from contact binary systems.

The present paper reviews the characteristics of the members of this class according to recent compilations and discusses the effect of duplicity on a composite spectrum as source of misclassification for some of these candidates.

In a modern astrophysical perspective, age, position in the HR diagram and chemical abundances are the key quantities which describe a class of stars. The purpose of introducing a class of stars is to help identify a common underlying phenomenology. For λ Boo stars the aim is to find the common factor which can explain the observed chemical peculiarities; to be meaningful this must explain a statistically significant sample of stars. Bearing this in mind, it is clear that any classification scheme which does not rely on abundance criteria is unlikely to be helpful. It is probable that as high accuracy abundance data accumulate, we will have to revise our concept of λ Boo stars and probably reach a more physical definition.

2. The λ Boo candidates

Many stars were classified as λ Boo in the past. The catalogue of Renson et al. (1990) includes over 100 candidates. Many of these turned out to be misclassified and the whole sample results too heterogeneous. We selected stars classified as λ Boo in recent papers based on modern data, hoping to extract a more homogeneous sample. They should be considered λ Boo candidates, since for many of them further analysis to check whether they match any given λ Boo definition is still required. The candidates we selected, with the exception of three of them, have been listed in at least one of the following papers: Abt & Morrell(1995; hereafter AM), Paunzen et al. (1997; hereafter CC), Gray (1997; hereafter G). The exceptions are: HD 290492 and HD 90821 which were classified as λ Boo by Paunzen & Gray (1997); HD 105759 for which the G classification is unpublished.

Both methods and scope differ among the three papers (i.e. AM,CC,G). However, the degree of reliability of each of them

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is difficult to define. Promising candidates are found in all lists, although Gray is probably the most reliable source, because the author (Gray & Garrison 1987, 1989a, 1989b; Garrison & Gray 1994; GG in Table 1) has classified a large sample of "normal" and "standard" stars using the same methods.

AM is a study of stellar v $\sin i$ of 1700 A-type stars of the Bright Star Catalogue (Hoffleit & Warren 1994) (BSC). On the basis of their available spectra (photographic spectra of dispersion 39 $\text{Å}\text{mm}^{-1}$) they give a classification for each star. Some are classified as λ Boo. [1]

CC, on the contrary, is a paper specifically aimed at λ Boo stars. Their working definition is "Pop I hydrogen burning A-type stars, which are, except of C, N, O and S, metal poor". The catalogue contains 45 objects and includes stars with a $T_{\rm eff}$ as low as 6500 K. The stars should have the same characteristics of those of λ Boo itself and establish a homogeneous group of λ Boo stars. According to the criteria adopted by the authors, the log g must be consistent with a Main Sequence evolutionary status, but the photometrically derived log g is less than 3.6 for 9 of the 45 selected objects. Accurate abundances for some elements are available for less than half of these stars and the abundances of the key elements C,N,O and S for an even smaller number of objects. Keeping in mind our remarks on the importance of abundances in establishing the λ Boo status, this status still has to be confirmed for over one half of the stars in CC.

G is also specifically devoted to λ Boo stars. It is based on his own accurate classification for all but one star (for which the abundance analysis has been performed by Stürenburg (1993; hereafter St93)). This classification is based on the comparison with a set of a previously selected sample of standard stars with various v$\sin i$ values. This list must be considered as the most reliable source of λ Boo candidates because it is based on a large set of homogeneous data.

Since the λ Boo nature rests ultimately on a peculiar abundance pattern, only an accurate abundance analysis based on high quality data and covering a broad spectral range can allow to either retain or reject these candidates.

The list assembled in such a way comprises 89 objects, 9 of which are in common with CC, G and AM; further 7 further objects are in common between CC and G, but were not observed by AM. Thus out of 89 candidates there is concordance among different classificators at most in 16 cases, i.e. less than 20%. We interpret this poor agreement as evidence of the subjective classification criteria adopted by each author.

We intend to examine the properties of these stars with the aim at investigating:

i) if a homogeneous group can be selected;

ii) if one of the hitherto proposed theories about the origin of the λ Boo phenomenon is able to explain *all* the observed peculiarities of these stars.

[1] AM classification has been criticized by the referee (Dr. E. Paunzen) because the standards of Morgan et al. (1978) defined for a dispersion of 125 A mm^{-1} are used, in spite of the higher dispersion available. In fact since most of the λ Boo stars have $v \sin i > 150$ km/s a higher dispersion does not improve the results. However, AM note that, even if this procedure may in fact lead to an inaccuracy in the spectral type of 0.27 subclasses they could see faint lines better.

3. Spectral characteristics

Abundance analyses have been performed only for a few λ Boo stars. Baschek & Searle (1969) analyzed 5 stars through the curve of growth method and rejected 2 of them from the λ Boo class. Venn & Lambert (1990) made a new modern analysis of the 3 stars retained as λ Boo by the previous authors. St93 determined the metal abundances for 15 stars, 2 of which were in common with those considered in the two previous papers. Heiter et al. (1998) analyzed 3 stars, 2 of which are in common with previous authors. Paunzen et al. (1999) derived non-LTE abundances of C and O for 16 and 22 stars, respectively. To these analyses of the visual spectra we can add the semiquantitative study of the UV spectra of 10 λ Boo candidates (3 of which are not included in our Table 1) made by Baschek & Slettebak (1988).

The comparison of the abundances obtained so far shows the erratic behaviour of the abundance anomalies in different stars: an emblematic example is the peculiarly slight *over-abundance* of Mg found by St93 in HD 38545 and the almost solar Mg abundance found in HD 193281.

Solar abundances of the elements C,N,O and S is a property that requires to be further proved; in fact it is essentially based on the Venn & Lambert (1990) study of 3 stars, but we stress that the measured lines of these elements refer to the neutral stage and lie in the red or near infrared spectral range so that a possible contamination by a cool companion star would increase the abundances of C, N, O and S. The other semiquantitative studies by Baschek & Slettebak (1988) and by Andrillat et al. (1995) are not conclusive, since opposite conclusions are drawn in these two papers for what concerns the C,O and S elements (N does not appear in the Andrillat et al. paper).

The Paunzen et al. (1999) paper strengthens our remarks on C, N, O and S abundance pattern. In fact, the mean [C/H] abundance results -0.37 $\pm$ 0.27, and the comparison of O abundances derived previously, show the inconsistency of those derived from lines in UV, optical and near-IR regions. The extreme cases of HD 141851 and HD 204041 with [C/H]$= -0.81$ pose some doubts on the notion that C is solar in λ Boo stars. Moreover, for HD 204041 even the LTE [C/H]$= -0.75$ is not far from the [Fe/H]$= -0.95$ found by St93, but we recall that a conclusive abundance pattern can be obtained only by analyzing all elements with the same model, i.e. with the same parameters $T_{\rm eff}$, log g, microturbulence, vsini and abundances.

The large survey by St93 does not include any abundance determination of N, O and S; an almost solar abundance is derived for C, but no details on the measured lines are given; considering the paucity of C lines in the spectral ranges analyzed by St93, quite possibly most of the results rely mainly on the CI 4932 Å line. We note also that a similar, almost solar abundance is derived for the Mg, which is usually the key element for the λ Boo classification, in one third of his sample stars. Another

Table 1. The λ Boo candidates.

HD	CC	G	G+GG classif.	AM	AM classif.	AM vsin i	Sep $''$ HIP	Δm mag HIP	Sep $''$ WDS	Δm mag WDS	Rem.
3				x	A0Vn(λBoo)	210:					D
319	x	x	A1mA2 Vb λBoo PHL		A2Vp(4481wk)	45			2.1	5.1	
2904				x	A0Vnn(λBoo)	225:					
4158[1]	x				–						
5789				x	B9.5Vnn (λBoo)	230:			7.8	0.8	
6870	x				–						
11413	x	x	A1 Va λBoo PHL	x	A1Vp(λBoo)	...					U
11503			B9.5 IV$^+$n	x	A0Vp(λBoo)n	185			8.6	0.0	
22470				x	B9.5p (λBoo)	65	0.152	1.36			
23258				x	A0Vp(λBoo)	110					
23392		x	A0 Va- (λBoo) NHL		–						
30422	x	x	A3 Vb λBoo PHL		A3Vp(4481wk)	100					
30739			A0.5 IVn	x	A0Vp(λBoo)	195					
31295	x	x	A0 Va λBoo NHL	x	A0Vp(λBoo)	105					
34787				x	B9.5Vp(λBoo)	200:					
36726		x	kA0hA5mA0 λBoo NHL		–						
290492[2]									0.6	1.4	
294253	x	x	B9.5 Va (λBoo) NHL		–						
290799	x	x	A2 Vb λBoo PHL		–						
38545	x	x	A2 Va$^+$ λBoo PHL		A2IVn+shell (TiII,CaK,HI)	175	0.155	0.64	0.1	–	
39421	x		A1 Van		A2Vp(4481wk)	215:					
47152[3]				x	A2Vp(λBoo)	25	0.212	0.77	0.1	-	
64491		x	kA3hF0mA3 V λBoo (PHL)	x	A9Vp(λBoo)	15					
66684A			B9 Va	x	B9.5Vp(λBoo)	65	3.527	0.73	3.5	0.9	
74873		x	kA0.5hA5mA0.5 V λBoo NHL		A1Vp(4481wk)	10					
75654	x				–						
79108				x	A0Vp(λBoo)	160					
81290	x				–						
83041	x				–						
84123	x				–						
84948	x				–						
87696			A7 V	x	A9Vp(λBoo;met:A5)	150					
89239				x	A2Vp(λBoo;met:B9.5)	135					
90821			kA2hA7mA2 Vn λBoo								
91130A		x	A0 Va$^-$ λBoo (PHL)	x	A0Vp(λBoo)	190					M
98772	x			x	A1IVn	230:					
101108	x				–		6.7	3.2			
105058	x	x	kA1hA7mA1 V λBoo (PHL)		–						U
105759			kA2hF0mA2 V (λBoo)								
106223	x				–						
107233	x	x	kA1hF0mA1 Va λBoo PHL		–						U
108283			A9 IVnp SrII	x	A9Vp(λBoo)	185					
109738	x				–						
109980				x	A6Vp(λBoo)	255:					M
110377				x	A6Vp(λBoo)	160					
110411	x	x	A0 Va (λBoo) NHL		A0Vp(4481wk)	140					
111604				x	A5Vp(λBoo)	180					U
111786	x	x	A1.5 Va$^-$ λBoo PHL	x	F0Vp(λBoo;met:A1)	135					
112097				x	F0Vp(λBoo,met:A7)	61					
118623AB			A7 Vn	x	F0Vp(λBoo)n	190			1.1	1.9	
120500		x	kA1.5hA5mA1.5 V (λBoo) NHL								
125162	x	x	A0 Va λBoo NHL	x	A0Vp(λBoo,met:v.wk)	110					
125489				x	F0 Vp(λBoo,met:A5)	145					
130158				x	A0IIIp(λBoo)	55					U
138527				x	B9.5Vp(λBoo: Ca,4481 wk)	...					D

Table 1. The λ Boo candidates (continued).

HD	CC	G	G+GG classif.	AM	AM classif.	AM vsin i	Sep $''$ HIP	Δm mag HIP	Sep $''$ WDS	Δm mag WDS	Rem.
141851	x				A3 Vp(4481wk)n	185			0.1	-	
142703	x	x	kA1hF0mA1 Va λBoo PHL	x	A9Vp(λBoo)	95					
142994	x	x	A3 Va λBoo PHL		–						
144708[4]				x	B9Vp(λBoo)nn	255:			3.4	3.5	
149303	x				–						
153808			A0 IV$^+$	x	A0IVp(λBoo)	50			0.2	-	
156954	x				–						
159082[5]				x	A0IVp(λBoo)	30			0.2	-	
160928	x				–				0.1	0.0	
168740	x				–						M
169009				x	A1V p(λBoo)	35					U
170000[6]			kB9hB9HeA0V(Si)+Note	x	A0IIIp(λBoo)	65	0.382	1.45	0.6	1.5	
170680	x	x	A0 Van (λBoo) NHL	x	A0Vp(λBoo)	200:					
171948	x	x	A0 Vb λBoo NHL		–						
177120	x				–				8.0	1.5	U
177756			kB8HeA0IV wk4481+Note	x	B9.5p(λBoo)n	...					
183324	x	x	A0 Vb λBoo NHL	x	A0IVp(λBoo)	105					
184190	x				–						
184779	x				–						
192424	x				–				6.2	0.0	
192640	x	x	A0.5 Va- λBoo PHL	x	A7Vp(λBoo, met A1,4481 wk)	35					U
193256	x	x	A2 Va λBoo PHL		–						D
193281[7]	x	x	A3mA2 Vb λBoo PHL		A2.5V	75			4.7	3.0	
196821				x	A0III(λBoo)s	10					
198160[8]	x	x	A2 Vann λBoo PHL:		–				2.7	0.31	
198161		x	A2		–						
204041	x	x	A1 Vb λBoo PHL	x	A3Vp(λBoo)	55					
210111	x	x	kA2hA7mA2 Vas λBoo PHL		–						
212150				x	A0Vp(λBoo)	180					
214454			A7 IV-V	x	F0Vp(λBoo;met:A6)	93					
220061			A5 V	x	A5Vp(λBoo)	135					
221756	x	x	A1 Va+ (λBoo) P/NHL		A1Vp(4481wk)	75					
223352			A0Va$^+$n	x	A0Vp(λBoo)n	280:			3.3	7.04	S
225218[9]				x	A3IVp(λBoo)s	20					

[1]both A and B are SB, [2]different from Paunzen & Gray 1997,[3]occultation and interferometric binary P=22.3yr, [4]A=SB P=4.02d, [5]A=SB P.6.8d, [6]A=SB and αCVn, [7]A of a quintuple system C= HD 193256, [8]B=HD 198161, [9] HIP note: ambiguous double star solution, WDS gives Aa sep=$0.1''$ Aa-B sep= $5.2''$ $\Delta m = 2.6$; B=SB hence the system is quadruple. Remarks from ESA Hipparcos Catalogue (1997) D=duplicity-induced variability, M=possibly microvariable, S=suspected non-single, U=unsolved variable.

peculiar element behaviour is that of Na whose abundance is found to be lower than the solar one in 5 stars, almost solar in 2 stars and higher than the solar one in 6 stars.

The present knowledge of the Balmer line profiles of the λ Boo stars is based on the studies by Gray (1988) and by Iliev & Barzova (1993a, 1993b, 1998). Gray pointed out peculiar Balmer profiles in some λ Boo stars from classification dispersion spectra. In the spectra of some stars he noted Balmer lines with broad wings and weak core, and an inconsistency of the β index with the luminosity class based on the extent of the hydrogen-line wings. These problems were not present in other λ Boo stars. Thus, according to the appearence of the Balmer lines, he divided the λ Boo stars into two distinct classes: NHL (Normal Hydrogen-Line profile) and PHL (Peculiar Hydrogen-Line profile). Subsequent studies by Iliev and Barzova based on high dispersion photographic spectra confirmed and quantified this peculiarity. This dicothomy is therefore observationally well established, but we still lack a theoretical interpretation for it.

4. Kinematics

Given the metal-weakness of λ Boo stars, it is proper to wonder whether some of them are truly metal-poor stars with halo kinematics. The kinematics of the stars in Table 1 observed by Hipparcos and with known RV has been computed from proper motions and radial velocity as described in Johnson & Soderblom (1987). A left-handed system was used in which U

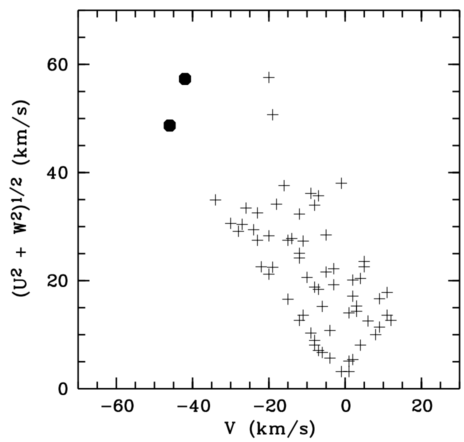

Fig. 1. Kinematics of λ Boo stars. HIP 5321 (HD 6870) and HIP 47752 (HD 84123) are shown as black dots.

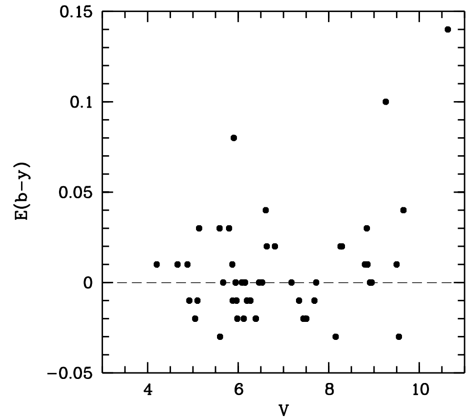

Fig. 2. The colour excess E(b-y) of λ Boo stars as a function of their apparent magnitude.

is directed towards the Galactic anticenter, V in the direction of Galactic rotation and W towards the north Galactic pole. In Fig. 1 we plot the rotational velocity V versus $\sqrt{(U^2+W^2)}$, which may be taken as a measure of kinetic energy not associated to rotation. All velocities are heliocentric, so that stars with V around 0 kms^{-1} and small $\sqrt{(U^2+W^2)}$ are qualified as disk members. All the λ Boo stars pass this test, in agreement with Gómez et al. (1998). This outcome was expected as a consequence of the brightness of the stars for which velocity data are available; out of the 14 sample stars weaker than V=8, eight were not observed by Hipparcos and 5 lack a measured RV. Thus, among the faint stars of our sample, we could compute the space velocities only for HD 101108. In Fig. 2 we note that HIP 5321 (HD 6870) and HIP 47752 (HD 84123), shown as black dots, present a marginal deviation from disklike kinematics.

The first star has been classified as Population II blue straggler (Bond & MacConnell, 1971) and has been identified as a member of the σ Pup group, which is similar to the globular cluster 47 Tuc (Rodgers, 1968, Eggen 1970a, 1970b), which has metallicity [Fe/H]= -0.71 (Da Costa & Armandroff 1990). This star also presents a UV excess in the (U-B) colour, similar to that of Pop II stars, which is not found in other λ Boo candidates. However, the nature of this star is still matter of debate. Paunzen et al. (1999) consider it a λ Boo star. Their O abundance of [O/H]= $+0.05$ could be reconciled with an extreme case of α element enhancement as found in Pop II stars. However, their C value [C/H]=+0.14 prompt interpretation as Pop I. Clearly an elucidation of its nature must rely on the determination of the abundaces of C,N,O, α elements and iron-peak elements using the same stellar atmospheric parameters. We note here that the abundances of C and O have been obtained by Paunzen et al. (1999) by assuming very different values of $v\sin i$ (128 and 200 $\mathrm{km\,s}^{-1}$, respectively).

HD 84123 belongs to the cooler ($T_{\rm eff}$ = 6900 K) λ Boo candidates selected only by CC and has peculiar characteristics. The UBV colours indicate that it does not belong to the MS, as confirmed by the photometrically derived log g=3.5; the UV magnitudes measured by the TD1 experiment (Thompson et al. 1978) do not fit those computed with these parameters at 2365 and 2740 Å.

5. Atmospheric parameters

Photometric indices of the $uvby\beta$ system are examined in order to determine the atmospheric parameters $T_{\rm eff}$ and log g from the calibration of the colour indices by Moon & Dworetsky (1985) (MD).

5.1. Colour excess

The observed indices are taken from the catalogue of Mermilliod et al. (1997). For 5 stars (HD 5789, HD 171948, HD 177120, HD 192424 and HD 198161) they are not available and for HD 184190 only the β index was measured; for the remaining 82 stars the colour were dereddened using the UVBYLIST code of Moon (1985). In fact, 30 stars in Table 1 have a visual magnitude weaker than 6.5 so that we cannot neglect a possible influence of reddenning. In 36% of the stars the colour excess has a negative value, which is twice the occurrence found in the sample of 71 bright dwarf A0 stars recently analyzed by Gerbaldi et al. (1999) with the same procedure. The most negative colour excess among this latter sample was of -0.02, found for one star only, while for the other stars with negative colour eexcess it was equal to -0.01. Among the objects of the present sample the stars with negative colour excess equal to or less than -0.02 are at least 10. The UVBYLIST code requires that the stars are assigned to one of six possible groups, depending on spectral type and colours; for several stars the choice of the appropriate group is ambiguous owing to inconsistencies of the colour indices and spectral type. We decided to give less importance to the spectral type and rely more on the unreddened β index. For the still remaining doubtful cases an unambiguous choice between the parameters derived with different choices cannot be performed without further information; for the most doubtful cases the various possible choices have been retained.

Since the MD procedure has been established for solar abundance stars, we investigated if the derived colour excess is related to the lower than solar abundances, attributed to these stars by analyzing, with the same procedure, the theoretical colour indices computed for [M/H] = - 0.5 and - 1.0 (Castelli 1998). The colour indices computed for abundances 10 times lower than solar produce a spurious colour excess up to 0.03 for $T_{\rm eff}$ =8000 K, but never a negative value. We thus conclude that a negative value of E(b-y) cannot be directly related to metal underabundances.

Strange enough the value of E(b-y) is not correlated to the V magnitude which, for these non evolved stars, is expected to be roughly related to their distance (Fig. 2).

A high value of v sin i is expected to affect the photometric (Collins & Smith 1985) and spectroscopic (Cranmer & Collins 1993; Collins & Truax 1995) characteristics of A-type stars. The inspection of the stars for which AM measured the v sin i has not revealed any correlation between the anomalous negative colour excess and the v sin i value.

We observe also that for 12 stars the photometric measures refer to two components of a binary system and thus require some sort of disentangling from the influence of the companion.

5.2. $T_{\rm eff}$ and log g

The parameters $T_{\rm eff}$ and log g have been derived from the MD TEFFLOGG code according to the above described choice of colour excess. The table of these parameters is available from the authors.

The stars cover a broad domain of the HR diagram around the prototype λ Boo; in fact $T_{\rm eff}$ spans from 6500 (HD 4158 and HD 106223) to 14500 K (HD 22470) and log g from 2.87 (HD 108283) to 4.50 (HD 294253). We note that the 8 stars with $T_{\rm eff}$ lower than 7100 K belong to the CC list and the 5 stars with $T_{\rm eff}$ higher than 10500 K are from AM; a systematic shift in $T_{\rm eff}$ probably exists between these two sources. However, the bulk of the stars in the two papers lies in the temperature range they share.

We conclude that before proceeding further with the discussion of the region of the HR diagram covered by these stars it is necessary to examine their photometric properties and their peculiarities.

5.3. Colour-magnitude diagram

For the stars with a Hipparcos measured parallax we may readily build a colour-magnitude diagram. Undereddened colours are used, the only "faint" star being HD 105058, which is expected to be unreddened (Faraggiana et al. 1990). This is displayed in Fig. 3, where the isochrones of solar composition and ages of 200 Myr and 500 Myr of the Padova group (Bertelli et al. 1994) are also shown. We note the inconsistency between the position in the HR diagram and the log g values derived from $uvby\beta$ photometry and by using the MD procedure; this point deserves further analysis. Two facts are clear from this comparison: 1) most of the λ Boo stars lie outside the main sequence; 2) a range in ages between 0.2 and 1 Gyr is necessary to explain the observed dispersion in the colour magnitude diagram,

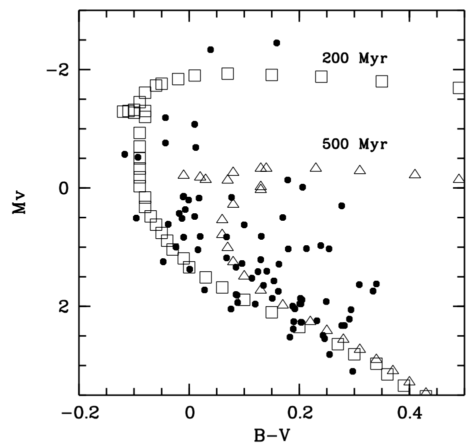

Fig. 3. The colour magnitude diagram: dots indicate the λ Boo stars; squares and triangles the isochrones of Bertelli et al. (1994) for 200 and 500 Myr respectively.

if we consider these stars in post-main sequence phase. The alternative hypothesis that *all* these stars are very young objects in the late phase of their pre-main sequence evolution is highly improbable; in fact, according to the scenario proposed by Turcotte and Charbonneau (1993) the accretion of gas, but not of dust, should occur in less than 10^6 years and the number of bright λ Boo candidates would imply that the star formation process is still very active in the solar neighbourhood, which would imply a large number of MS B stars in a similar volume. A fraction of pre-main sequence stars cannot either be excluded or demonstrated on the basis of only these data.

6. Peculiarities of λ Boo candidates

We performed a systematic search of known binaries among the λ Boo candidates of Table 1.

HD 38545 and HD 141851 are visual binaries whose speckle interferometric measurements are given by McAlister et al. (1993). Given the small separation of the pairs, ground-based spectra will always be the combined spectrum of these binaries; for the first star, Hipparcos data demonstrate that the effect of the companion is surely not negligible. Starting from the analysis of the H_γ profile, Faraggiana et al. (1997) were able to show that a third star, HD 111786, is indeed a binary system and this finding was supported by the identification of the lines (in the visual, but not in the UV range below 2000 Å) of the cooler companion, which are narrow if compared to those of the primary star, this happens quite likely because the companion is seen pole on. In order to determine abundances, the spectra of the two components must be disentangled.

Twelve out of 89 stars of our sample are known to be visual binaries according to the Mermilliod et al. (1997) catalogue. For these binaries only the combined colour indices have been measured and therefore they cannot be safely used to derive the atmospheric parameters of the primary component. In order to evaluate the influence of the companion star, we extracted the angular separation and the magnitudes for the components A and B from the Washington Visual Double Star Catalog (Worley & Douglass 1997; hereafter WDS); these data are given in Columns 10 and 11 of Table 1 for the objects with an angular separation of less than 10 arcsec. The contamination on the observed spectra depends on the luminosity difference of the components and on the slit width of the spectrograph on the sky; for several stars the observed spectra are expected to be affected by the companion star and, in some cases (HD 290492, HD 38545, HD 47152, HD 141851, HD 153808, HD 159082, HD 160928, HD 170000 and HD 225218), a composite spectrum cannot be avoided with observations from ground instruments unless it can be demonstrated that the companion luminosity is much weaker.

The effect of the secondary star should underlie the discordant classifications proposed for HD 225218, either B9 III or A3 Vs; moreover its UV magnitudes, as determined by the TD1 experiment (Thompson et al. 1978), would suggest a much lower reddening than that derived from the Strömgren photometry, i.e. E(b-y)=0.03, a value more coherent with the stellar visual magnitude.

The two stars HD 141851 and HD 149303, being X-ray sources (Hünsch et al. 1998), are expected to have cool companions.

Significant discrepancies in the magnitude and photometric colours of the AB system HD 193281 are reported in the literature (BSC).

The ESA Hipparcos Catalogue (1997) allowed to complete information on some stars and to add new binaries; these data are collected in Columns 8 and 9 of Table 1.

Further known binaries are:

• The already quoted spectroscopic binary HD 111786 and HD 84948 and HD 171948. The 4 components of the last two binaries are all λ Boo stars, according to Paunzen et al. (1998); however, we note that the Mg does not show underabundance higher than the other metals and that the abundances of the key elements C,N,O and S are not given.

• HD 142703 is a suspected occultation double (BSC).

• HD 79108 is a suspected SB (BSC), but we could not retrive any further information on the possible influence of the companion on photometric and spectroscopic data.

• The oxygen spectrum indicates that HD 149303 is an SB system (Paunzen et al. 1999).

We also note the inconsistent classifications assigned to HD 22470 i.e. a λ Boo star (AM) or He-weak with variable intensity of the SiII 4128-30 doublet (Gray 1988). The explanation of the peculiarities has been given by the Hipparcos detection of its duplicity (see Columns 8 and 9 of Table 1). Similar remarks apply to two other binaries, HD 47152 and HD 170000, which have been both classified, as single objects, either Ap or λ Boo.

Two more spurious λ Boo candidates are HD 130158 which is in reality an Ap Si-λ4200 star (Gray 1988) and HD 159082 which is a B9 Hg-Mn (see, for example, Hubrig & Mathys 1996).

The peculiarity of HD 108283, which has a very high c_1 value and therefore a derived log g which is the lowest of our sample stars, but also a very high v sini value, deserves further analysis before being assigned to the λ Boo class; Hauck et al. (1998) rejected it from the λ Boo class.

We conclude that from ground and space observations close duplicity which is able to affect the observed spectrum, has been already observed or suspected for 24 % or 33 % (if the stars classified U by Hipparcos are included) of the stars of Table 1 and that some spurious λ Boo candidates are present.

7. Predicted composite spectra

In the abundance analyses λ Boo stars have been generally considered as single stars. The exception is the analysis of the two SB2 stars HD 84948 and HD 171948 by Paunzen et al. (1998). In the present section we consider the influence of a possible companion on model parameters and on derived abundances and discuss the ability to pick out the already known binaries on the basis of spectra. This has a direct bearing on the issue whether binarity may lead to significant systematic errors in the abundance analysis and classification of λ Boo stars.

In a binary system, if the angular separation of the two components is too small to be detected, and the two stars have a similar mean to high projected rotational velocity, the spectral lines of the components are not resolved in the observed spectrum and duplicity is not easily detected spectroscopically. If the two components have significantly different parameters, the duplicity should appear when a large spectral range is covered by observations, the contribution of each star being different at different wavelengths. This implies that there are doubts on binarity, the analysis of spectral ranges of only a few hundred Å may not be sufficient to establish or reject the binarity.

If a binary star is analyzed in the classical 3500-5500 Å range, the average values of $T_{\rm eff}$ and $\log g$ are derived from the combined light; synthetic spectra are computed from the adopted model atmosphere and the best fit with observations is obtained by adjusting the microturbulence value and the chemical abundances.

In Fig. 4 we illustrate the result of the comparison of a composite spectrum with two single-star spectra. We note that in these spectra the H_γ profile is practically the same, but most of the metal lines simulate a metal underabundance in the composite spectrum. The hydrogen profile, in this case, would be considered as NHL. Metal underabundances would be obtained from the combined spectrum if analyzed by disregarding its binary nature. A similar result on the apparent metal underabundances of the Am triple system, π Sgr, if analyzed as a single object, has been obtained by Lyubimkov & Samedov (1987).

To illustrate how a PHL profile can be produced by the combination of 2 single profiles, we constructed the composite H_γ line given in Fig. 5 and compared it with the single spectra computed with $T_{\rm eff}$ =7000 K, log g=4.0, which fits the wings, and with $T_{\rm eff}$ =9750 K, log g=3.0, which fits the core of the composite spectrum. All these profiles refer to solar abundance models. The example has been constructed in such a way as to enhance at most the effect which is observed in PHL stars and is not intended to simulate any really observed object.

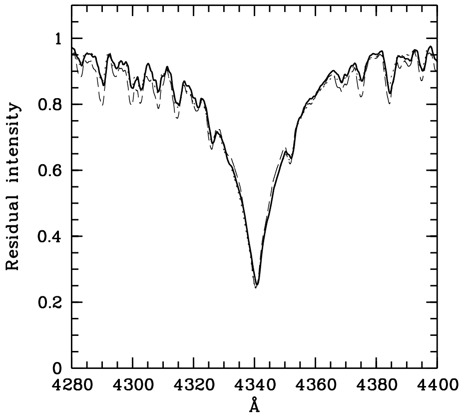

Fig. 4. The comparison between a computed composite spectrum and a single one in the region of H_γ. The composite (thick line) consists of two spectra corresponding to $T_{\rm eff}$ = 7200 and 9000 K, log g =4.0, vsini=50 km s^{-1}, luminosities L/L$_{tot}$ =0.2 and 0.8 respectively, and solar abundances; the two spectra have been slightly shifted with respect to each other. The two single spectra with which the composite is compared correspond to $T_{\rm eff}$ = 8000 K, log g =4.0, solar abundances and $T_{\rm eff}$ = 8250 K log g =4.0 and [M/H]=-0.5, both with vsini=100 km s^{-1}.

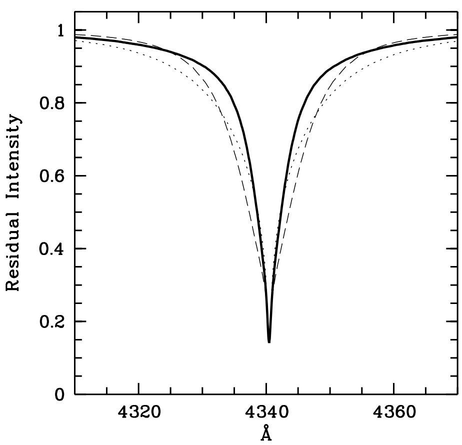

Fig. 5. Example of how a PHL profile (thick line) may be created by combining two single spectra of $T_{\rm eff}$ = 9500 K, log g = 2.0 and $T_{\rm eff}$ = 8500 K, log g =4.0, and luminosity ratios L/L_{tot} of 0.8 and 0.2 respectively with a single one in the region of H_γ. The dashed profile corresponds to $T_{\rm eff}$ = 7000 K, log g =4.0 and fits the wings. The dotted profile corresponds to $T_{\rm eff}$ = 9750 K, log g = 3.0 and fits the core. This is an example to illustrate the effect which is much larger than what is actually observed in λ Boo PHL stars.

8. Discussion

In the previous sections we stressed the fact that the λ Boo candidates of Table 1 constitute a non homogeneous group. By adding the informations spread in the literature, we summarize that among λ Boo stars:

- some but not all show PHL profiles (Gray 1988, 1997);
- some but not all have an IR excess (2 stars in Sadakane & Nishida 1986; 2 stars in Cheng et al. 1992; 1 star in Grady et al. 1996; 2 more in King, 1994);
- some but not all have a shell surrounding the star which is detected by the presence of narrow circumstellar components of Ca II K line (Holweger & Rentzsch-Holm 1995) and of metal lines (Hauck et al. 1995 and 1998; Andrillat et al. 1995);
- some but not all show the UV broad absorption feature centered on λ1600 Å (Baschek et al. 1984; Faraggiana et al. 1990; Holweger et al. 1994). We recall that the combined effect of the stellar flux drop and the lowering IUE sensitivity is responsible for the mostly underexposed IUE spectra of the middle and late A-type stars, so that the λ1600 Å could be searched only among the hottest λ Boo candidates;
- for three of them an abundance pattern similar to that of the ISM has been derived (Venn & Lambert 1990).

On the basis of the few abundance coherent analyses available, several hypotheses have been made on the age of these stars:

i) very young stars which have not reached the main sequence (Waters et al. 1992; Gerbaldi et al. 1993; Holweger & Rentzsch-Holm 1995).
ii) dwarfs in the middle of their life on the main sequence, with an age of 10^7-10^9 years (Iliev & Barzova, 1995);
iii) quite old objects representing a merger of binaries of W UMa type (Andrievsky 1997).

The only property common to all λ Boo stars of Table 1 is the weakness of most metal lines, which is also confirmed by the negative Δa values (a photometric index measuring the blanketing in the region λ5200 Å) measured by Maitzen & Pavlovski (1989a and 1989b) for the stars they observed.

Taking this common characteristic of the group as a starting point, we inspect the possible causes that may produce a weak-lined spectrum.

The classical explanation of metal underabundances, for stars belonging to Population I, is related to the existence of single stars with peculiar atmospheres in which some elements are depleted by different amounts.

Disturbing is that the abundance pattern is not the same in the λ Boo candidates analyzed up to now; one particular element shows different abundance peculiarities in different stars, so that it is difficult, at present, to establish the average chemical composition of λ Boo stars and thus to elaborate a theory explaining the phenomenon.

Venn & Lambert (1990) formulated the hypothesis that the λ Boo phenomenon could be the result of accretion of gas but not of dust from circumstellar or interstellar material. The only modern and detailed analyses available at present are the two papers by Venn & Lambert (1990) and by St93. We compared the metal abundances derived for the λ Boo stars by these authors with those of the ISM as given by Savage & Sembach (1996). This comparison shows that the similarity is only marginal; in the first place there is a large difference from star to star in the abundance of any given element, unlike what happens in the ISM, in the second place the highest underabundances in the ISM are those of Ca and Ti while in most λ Boo candidates it is that of Mg.

Among possible explanations of the λ Boo phenomenon one should also take into account the possibility that these stars indeed belong to a metal-weak population. The kinematic data imply that λ Boo stars belong to the disk population, which has indeed a metal-poor population in the range -0.5<[Fe/H]<-1.0 and possibly the thick disk has a metal-weak tail at much lower metallicities (Beers & Sommer-Larsen 1995). We must examine the two possible cases that λ Boo stars are either Main Sequence (MS) and therefore relatively young, or on the Horizontal Branch and therefore old.

The main argument to reject the hypothesis that λ Boo stars are metal-poor MS stars is that while in λ Boo stars Mg, Si, Ca and Ti are among the most underabundant elements, in metal-poor stars the even-Z light elements, synthesized by α capture processes, show an increasing enhancement over iron with decreasing metallicity, reaching a 0.4 - 0.5 dex enhancement at [Fe/H]= -1.0.

To distinguish Blue Horizontal Branch (BHB) stars from λ Boo stars on the basis of spectroscopic properties alone, is not trivial. However, the BHB population in the solar neighbourhood would be uncomfortably large if most λ Boo belonged to this class. A further argument against the BHB hypothesis is that most λ Boo stars are characterized by mean to high projected rotational velocities, while BHB stars are all slow rotators. All fast rotators may be thus rejected as BHB stars. Although the possibility could be still considered open for slowly rotating λ Boo stars (e.g. HD 64491 and HD 74873 (Paunzen & Gray (1997) and a few others proposed by AM), their number is very small. We recall that low $v\sin i$ stars may be either intrinsically slow rotators or fast rotators seen at high inclination.

From the foregoing discussion we reject the hypothesis of membership of the class to a metal-poor population and do not discuss it any further.

A completely different origin of weak metal lines is that produced by stellar duplicity. Examples of how a composite spectrum, which is the average of two actual components of not very dissimilar spectral type, can be classified as Mg-weak is given by Corbally (1987) for HD 27657 and HD 53921. Corbally remarks also that the AB spectrum of HD 41628 "is close to imitating a λ Boo star, but the A5 Balmer line class is a compromise between A7 V strength and A3 V wings... example of two normal parent spectra producing a peculiar composite".

The effect of veiling in the spectrum of a binary with components not very dissimilar from one another (M=2 and 1.4 solar masses) has been investigated in detail by Lyubimkov (1992). Most of his analysis, devoted to Am stars, refers to composite spectra (computed for 4 selected evolutionary phases) obtained by combining two spectra for which solar abundances are adopted only for elements lighter than Ti. A general apparent underabundance of these elements is derived by his computations when the original duplicity is neglected, in agreement with the weak metal lines obtained by our example plotted in Fig. 4.

According to the data collected in the previous sections, 11 stars of our original sample are doubles with an angular separation smaller than 1.2 arcsec, 3 stars are SB2 and 4 are probably non-single, according to the Hipparcos data. In conclusion, for 18/89= 20 % of our sample stars duplicity must be examined in further detail before determining atmospheric abundances.

Grenier et al. (1999) in their radial velocity study of a sample of B to F stars, included in the Hipparcos catalogue, obtained spectra for 16 stars of our sample. Of these 12 are suspected, probable or established binaries, only 4 of these are among the 18 known binaries previously mentioned. If all of them will be confirmed to be binaries the percentage will raise to 29%. We note also that 11 of these stars are in common with the G list and 8 are classified as PHL by him.

If we apply the present knowledge to the 15 stars analyzed by St93, we see that 2 of them are SB2 (HD 38545 and HD 111786), for HD 198160 and HD 198161 the atmospheric parameters, derived from the combined photometric indices, require the hypothesis that the two stars are strictly the same so that the same $T_{\rm eff}$ and log g can be adopted. The duplicity of these stars requires to be further examined in order to determine accurate single elements abundances. Furthermore, the variability of the 5 variable stars must be examined to assess that its amplitude does not affect the photometrically derived atmospheric parameters.

High S/N spectroscopic data of spectral regions in which not severely blended features are present are necessary to discriminate between "veiling" (spectral lines when they retain the breadth of their temperature type, but are shallower than normal (Corbally 1987)) which indicates a composite spectrum and normal profiles with weak intensities, which are sign of real metal underabundances. Such discrimination, however, becomes extremely difficult when the observed spectrum is characterized by broad and weak metal lines as in most λ Boo candidates.

What we can expect in a composite spectrum of two similar A-type stars are Balmer lines broader than those of the single components by an amount which depends on the relative RV of the components, so simulating a star with a higher log g value when compared to computed spectra or intrinsically very high for an early A-type star as it may be the case of HD 294253 (the parameters derived by MD programs are $T_{\rm eff}$ =10370 K log g=4.50). Moreover, the composite Balmer line profile will present a flat inner core which depends on the difference of the two radial velocities as well as a global profile which may be different from what is expected from the dominating broadenings: Doppler core and linear Stark wings.

For the stars recognized to be double by speckle observations, and not observed by the Hipparcos satellite, the extraction of luminosity ratios from speckle data will be fundamental to better define the character of the two components. Algorithms to extract luminosity ratios from speckle data have been developed, but these techniques are still limited (Sowell & Wilson 1993). If the luminosity of the companion is large enough (of the order of 25% of the total luminosity), the veiling may not be neglected; in fact the metallic lines will appear weaker, thus leading to an underestimate of the metallicity.

The IR colours could also prove to be powerful diagnostic tool for the presence of cooler companions. A cool companion of HD 111786 was predicted by its photometry in the J,H and K bands by Gerbaldi (1990) on the basis of the discrepancy with the (B-V) value and was ascribed to a probable cool companion.

The foregoing discussion leads us to formulate the hypothesis that a considerable fraction of λ Boo candidates are in fact binaries. This is supported by the large fraction of binaries recently discovered among λ Boo stars either through the speckle technique or by the Hipparcos experiment. Also the high number of stars with a "blue" colour excess supports that our binarity hypothesis is at the origin of distorted energy distributions and of not coherent uvbyβ indices of several λ Boo candidates. The PHL phenomenon cannot be easily explained if the stars are single, however its explanation becomes trivial if the stars are binary, as has been demonstrated in the case of the stars HD 38545 and HD 111786, classified PHL by Gray (1988, 1997), which indeed turned out to be binaries. The apparently erratic abundance patterns pose serious problems to the accretion hypothesis, but again it may be easily reconciled in the case of binary stars.

The fact that some of the stars are binaries does not exclude the possibility that chemical peculiarities are actually present in their atmospheres. However their quantification requires that the binarity is properly accounted for.

9. Conclusion

We have shown that each author has his own definition and list of λ Boo candidates and these lists only partly overlap. Until all the classification schemes converge into a single with a physical basis there is little hope of understanding the λ Boo phenomenon.

Recent observations, mainly by speckle interferometry and by the Hipparcos satellite, have detected the binary nature of several λ Boo candidates and other candidates have been recognized on the basis of high resolution spectra.

We make the hypothesis that abundance anomalies are, at least partly, due to the effect of veiling in a composite spectrum and that other still undetected binaries are likely to be present among the objects collected in Table 1. Distorted and uncertain colours (e.g. stars with negative colour excess and reddened bright stars) and peculiar Balmer line profiles are reasons for suspecting duplicity.

The photometrically derived atmospheric parameters of close visual binaries refer to the average photometric indices of the components and an abundance analysis based on them requires that the two components form a twin pair or have very different luminosities. Moreover, for some of these binaries the angular separation is such that a composite spectrum cannot be avoided.

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