A&A 396, 641–648 (2002)
DOI: 10.1051/0004-6361:20021423
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Astronomy & Astrophysics

The elemental abundance pattern of twenty λ Bootis candidate stars*

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Received 23 July 2002 / Accepted 12 September 2002

Abstract. Detailed elemental abundances were derived for twenty bona fide λ Bootis as well as two MK standard stars. Other than LTE abundances for ten elements (including C and O), NLTE values for Na were determined. The group of λ Bootis stars consists of non-magnetic, Population I, late B to early F-type dwarfs with a typical abundance pattern (Fe-peak elements being underabundant whereas C, N, O and S being almost solar abundant). Since classification resolution spectroscopy in the optical domain is not capable of determining the abundance of the light elements, a detailed abundance analysis is the ultimate test for the membership of an object to this group. Another important point is the detection of apparent spectroscopic binary systems in which two solar abundance objects mimic one metal-weak star, as proposed as a working hypothesis by Faraggiana & Bonifacio (1999). From twenty program stars we are able to confirm or establish the membership for nine objects (HD 23258, HD 36726, HD 40588, HD 74911, HD 84123, HD 91130, HD 106223, HD 111604 and HD 290799). Five stars (HD 90821, HD 98772, HD 103483, HD 108765 and HD 261904) can be definitely ruled out as being members of the λ Bootis group whereas no unambiguous decision can be drawn for another six stars (HD 66684, HD 105058, HD 120500, HD 141851, HD 201184 and HD 294253). One very important result is the apparent overabundances found for Na which cannot be explained by accretion or mass-loss alone.

Key words. stars: chemically peculiar – stars: early type

1. Introduction

The main feature of the stars belonging to the λ Bootis group is a remarkable underabundance of many elements heavier than oxygen (with the exception of sulphur). During the last decades several studies of the chemical composition of bona-fide λ Bootis stars have been performed. The analysis of high resolution spectra helps to unambiguously establish membership of the λ Bootis group and to find undetected spectroscopic binary systems among bona-fide candidates.

1.1. Abundance anomalies

More than ten years ago Venn & Lambert (1990) performed an investigation of three λ Bootis stars and showed that these objects have near-to-solar abundances of C, N, O and S, while for elements such as Mg, Ca, Ti, Fe, Sr, relative-to-solar abundances were found to range from -1 to -2 dex. Soon after that, Stürenburg (1993) analyzed 15 suspected λ Bootis stars, and confirmed the previous results of Venn & Lambert (1990) for two stars common in both samples, namely HD 31295 and HD 192640. For the whole sample of investigated stars, Stürenburg obtained the following elemental distribution: the mean carbon abundance appeared to be solar with all studied elements heavier than sodium (Mg−Ba) 0.5−1.5 dex below the solar values.

Recently, Andrievsky et al. (1998), Paunzen et al. (1999b), Heiter (2002) and Solano et al. (2001) determined accurate LTE abundances mainly for Fe-peak elements of newly discovered λ Bootis stars. These values were completed by Paunzen et al. (1999a) and Kamp et al. (2001) who performed a detailed NLTE abundance analysis for the light elements C, N, O and S.

From the latter references it is clear that the elemental distribution is subsolar with the exception of carbon, nitrogen, oxygen and sulphur. Such a distribution cannot be explained

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* Based on observations from the Osservatorio Astronomico di Padova-Asiago, McDonald Observatory, Kitt Peak National Observatory and Observatório do Pico dos Dias-LNA/CNPq/MCT.

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:20021423

Table 1. Observations used in this work.

Observatory	Tel. [m]	Spect.	Date	Observer	Wavelength range [Å]	Resolution
Asiago (Italy)	1.8	Echelle	02/1997	U. Heiter E. Paunzen	4600–7110	30 000
OPD/LNA (Brazil)	1.6	Coudé	06/1995	E. Paunzen	3900–4900 4165–5685	30 000
KPNO (Arizona)	0.9	Coudé	04/1998	M. Weber	4240–4570	30 000

by the atomic diffusion in the atmospheres of λ Bootis stars, because 1) the general prediction of the diffusion – based hypothesis is an overabundance of the iron-group elements and the heavier species. An attempt of Michaud & Charland (1986) to apply the diffusion mechanism with mass loss to explain the λ Bootis phenomenon has led only to modest underabundances of about a factor of three, 2) λ Bootis stars rotate rather rapidly (characteristic value is about of 100 km s^{-1}) which does not favor elemental segregation.

1.2. Possible origin of the λ Bootis chemical peculiarity

Cowley et al. (1982) were the first who pointed out that the λ Bootis stars can originate from the interstellar gaseous component with non-solar chemical composition, or with some kind of gas–dust separation. Venn & Lambert (1990) were the first to realize that the main source of the discussed anomalies was very unlikely to be the interstellar medium but was rather the circumstellar envelope. These authors noticed that there is an obvious similarity between the elemental distribution in λ Bootis and that of post-AGB stars. Both kinds of stars have infrared excesses indicating the presence of a circumstellar shell, although these excesses were only detected for some very bright λ Bootis stars.

One can make a reasonable conclusion that some physical processes operating in the circumstellar envelope may modify its chemical content, and after the contamination of the atmospheric gas with such a modified material from the envelope, the atmosphere can take on a non-solar elemental composition. If this mechanism is indeed in effect, a direct link between the envelope and atmosphere has to exist. Such a link can be provided through accretion, while the required physical process in the envelope can be reconciled with dust formation in the rather cool gas. At a certain temperature T and gas pressure, the dust grains will be preferably formed from the elements having the condensation temperatures $T_c \geq T$, while the elements with lower condensation temperatures remain in the gaseous phase. It is quite possible that the atoms of elements such as Ca, Ti, Fe, etc. are locked into grains first because their condensation temperature is higher than 1000 K. For C, N, O and S, T_c is much lower than this value, and they are not incorporated into grains even at the predicted envelope temperatures. If the gas of the circumstellar shell, which is depleted in the refractory elements and contains normal abundances of the CNO-S elements, is accreted by the central star, then upon being mixed with the atmospheric gas it can alter an initial photospheric abundance pattern leading to the observed phenomenon. Andrievsky & Paunzen (2000) showed that the necessary conditions for gas–dust separation can indeed take place in the stellar envelope.

Although this hypothesis seems to explain qualitatively the observed phenomenon, there are still several unresolved problems attributed to it. For further tests and constraints of this hypothesis one has to obtain reliable LTE/NLTE elemental abundances for a large sample of λ Bootis candidate stars. This paper presents the results of a comprehensive investigation of the elemental abundances for twenty program as well as two "standard" stars.

2. Program stars

The program stars were chosen from the lists of Gray & Corbally (1993) and Paunzen & Gray (1997). Additional objects were taken from preliminary results of a spectroscopic survey for λ Bootis stars as described in Paunzen & Gray (1997). The two standard stars HD 110379 and HD 135379 are from Gray (private communication).

High resolution and high signal-to-noise (normally more than 150) spectra have been obtained at four sites as listed in Table 1.

The spectroscopic material was reduced using the DECH20 code (Galazutdinov 1992). This code enables one to perform all the necessary manipulations of the spectra (continuum placement, wavelength calibration, equivalent width measurement, etc.).

3. Stellar parameters for modelling the atmospheres

The effective temperatures and surface gravities were estimated using the Strömgren photometric indices (available for the program stars through the SIMBAD data base) by means of the Moon's numerical code based on the grid published by Moon & Dworetsky (1985) and modified by Napiwotzki (1994). The derived values were checked with additional calibrations in the Geneva system (Künzli et al. 1997) resulting in an excellent agreement. Comparing all results we derive an error of the effective temperature of ±250 K whereas the errors of the surface gravities are ±0.2 dex.

For all the program stars we adopted the microturbulence velocity $V_t = 2.5$ km s^{-1}. For the sharp-lined star HD 84123 this value was specified using Fe I lines.

The atmosphere models of Kurucz (1991) and oscillator strengths for the lines of interest from the VALD data

Table 2. Parameters of the program (upper panel) and two "normal" type (lower panel) stars, $\sigma(v \sin i) = 10\,\mathrm{km\,s^{-1}}$, $\sigma(T_{\rm eff}) = 250\,\mathrm{K}$ and $\sigma(\log g) = 0.2$ dex, in the last column we indicate with asterisks the stars showing strong emission in the Na I D_1, D_2 lines

HD	$T_{\rm eff}$ [K]	$\log g$ [dex]	$v \sin i$ [km s^{-1}]	[Z]	Obs.	Rem.
23258	9500	4.3	125	−0.5	Asiago	
36726	9800	4.5	80	−0.5	Asiago	*
40588	8750	4.0	115	−1.0	Asiago	
66684	10000	4.0	105	−1.0	Asiago,KPNO	
74911	7950	3.8	190	−1.0	Asiago,KPNO	
84123	6925	3.5	28	−0.5	Asiago,OPD/LNA	
90821	8300	3.7	150	+0.0	Asiago	*
91130	8170	4.0	150	−0.5	Asiago,KPNO	
98772	8400	3.8	230	+0.0	Asiago	
103483	8350	3.9	85	−0.5	Asiago	
105058	7630	3.9	140	−0.5	KPNO	
106223	6500	3.9	80	−1.0	KPNO	
108765	8750	3.9	125	+0.0	Asiago	
111604	7600	3.8	180	−1.0	Asiago	
120500	8400	3.8	130	−0.5	Asiago,KPNO	
141851	8100	3.8	260	−0.5	Asiago,OPD/LNA	
201184	9970	4.2	200	+0.0	OPD/LNA	
261904	9670	4.2	150	+0.0	Asiago	*
290799	8000	4.1	70	−1.0	Asiago	*
294253	10900	4.5	70	+0.0	Asiago	*
110379	7720	3.8	25	+0.0	OPD/LNA	
135379	8670	4.2	65	+0.0	OPD/LNA	

base (Kupka et al. 1999) were used to determine individual elemental abundances. The LTE spectrum synthesis method (SYNSPEC, Hubeny et al. 1994) was used for all but one of the program stars with rotationally broadened spectra. In case of the sharp-lined star HD 84123 we performed the equivalent widths analysis with the WIDTH9 code (Kurucz 1992).

Projected rotational velocities were determined by matching observed and calculated profiles of the least blended metallic lines (mainly Mg II and Fe II).

The determined atmospheric parameters for all program stars are given in Table 2. In Table 2 we indicate with asterisks the stars showing strong emission in D_1, D_2 Na I lines.

4. Abundance determinations

Our analysis was based primarily on a LTE approach, but we investigate also the influence of NLTE effects on Na. As the present investigation is part of a larger project on λ Bootis stars we also discuss problems which may emerge when combining abundances from different references.

4.1. LTE abundances

Note that our implementation of the SYNSPEC code enables one to calculate the abundances only for chemical elements with $Z \leq 28$, therefore, to derive values of elements such as Y and Ba we used the STARSP code (Tsymbal 1996). The solar abundances have been taken from Grevesse & Noels (1993). The abundances determined for program stars and two MK standard stars HD 110379 (F0 V) and HD 135379 (A3 Vb) are given in Table 3. MK standard stars have, within the errors, solar values, which lends confidence to our analysis. The results for the λ Bootis star HD 84123 are discussed in detail in the following section and are compared with an earlier investigation of Heiter et al. (1998).

4.2. Consistency checks with HD 84123

The λ Bootis star HD 84123 provided an excellent test for abundance determinations obtained from identical data, but performed independently by two different teams. The abundances derived within the present investigation mainly by the team from Odessa are compared in Table 4 with the values from Heiter et al. (1998). This comparison illustrates problems which may occur if abundances obtained by different research groups are merged for a statistical analysis without paying sufficient attention to the homogeneity of such a data base.

Heiter et al. (1998) used different stellar parameters ($T_{\rm eff}$ = 6800 K, $\log g$ = 3.5 dex, $V_{\rm t}$ = 3.0 km s^{-1} and $v \sin i$ = 15 km s^{-1}) to those in the present investigation, as well as a different source of element abundances for the Sun (Anders & Grevesse 1989). Differences in solar reference abundances are a sometimes neglected, but significant, source of error as is illustrated in Fig. 1. This figure shows the abundance differences for the Sun for the elements up to Ba from five different references frequently used in the literature: Anders & Grevesse (1989), Grevesse & Noels (1993), Grevesse et al. (1996), Grevesse & Sauval (1998) and Holweger (2001). The differences can reach values of up to 0.3 dex and frequently are about 0.15 dex for the elements discussed in the present investigation. The reference to Anders & Grevesse (1989) was used by Heiter et al. (1998).

Table 3. LTE abundances for program stars: $[M/H] = \log(N/N_H) - \log(N/N_H)_\odot$.

	HD 23258				HD 36726				HD 40588			
Element	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)
C	+0.25	–	1	8.80	+0.15	–	1	8.70	+0.31	0.13	5	8.86
O	+0.08	0.00	2	8.95	+0.03	–	1	8.90	−0.22	0.05	2	8.65
Mg	−0.58	0.07	3	7.00	−0.73	0.00	2	6.85	−0.68	0.00	3	6.90
Si	−0.72	0.05	3	6.83	−0.98	0.09	3	6.57	−1.05	0.17	4	6.50
Cr	−0.57	–	1	5.10	–	–	–	–	–	–	–	–
Fe	−0.67	0.03	4	6.83	−0.58	0.09	3	6.92	−1.03	0.07	6	6.47
	HD 66684				HD 74911				HD 90821			
Element	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)
C	–	–	–	–	−0.25	–	1	8.30	–	–	–	–
Mg	−0.28	0.00	2	7.30	−0.78	0.00	3	6.80	+0.00	–	1	7.58
Ca	–	–	–	–	–	–	–	–	+0.10	0.12	4	6.46
Si	−0.85	0.10	2	6.70	−0.85	–	1	6.70	+0.38	0.03	3	7.93
Cr	–	–	–	–	–	–	–	–	+0.00	–	2	5.67
Fe	−1.05	0.11	3	6.45	−0.83	0.12	3	6.67	−0.03	0.14	12	7.47
Ni	–	–	–	–	–	–	–	–	−0.10	–	1	6.15
Ba	–	–	–	–	–	–	–	–	+0.00	–	1	2.13
	HD 91130				HD 98772				HD 103483			
Element	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)
C	−0.30	–	1	8.25	+0.00	–	1	8.55	–	–	–	–
O	−0.50	–	1	8.37	+0.20	–	1	8.67	−0.67	–	1	8.20
Mg	−1.19	0.06	4	6.39	+0.00	–	1	7.58	−1.03	0.15	2	6.55
Si	−1.00	0	2	6.55	+0.00	–	2	7.55	−0.62	0.03	2	6.93
Ti	−1.17	0.08	7	3.85	–	–	–	–	–	–	–	–
Cr	−0.98	0.03	3	4.69	−0.37	0.03	3	5.30	–	–	–	–
Fe	−1.69	0.05	7	5.81	−0.50	0.06	7	7.00	−0.62	0.13	3	6.88
	HD 105058				HD 106223				HD 108765			
Element	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)
Mg	−0.90	–	1	6.68	−1.60	–	1	5.98	+0.10	0.12	3	7.68
Si	–	–	–	–	–	–	–	–	−0.35	0.05	2	7.20
Ca	−1.10	–	2	5.26	−2.42	0	2	3.94	–	–	–	–
Sc	−1.05	–	1	2.12	−1.80	–	1	1.37	–	–	–	–
Ti	−0.95	0.04	5	4.07	−1.84	0.09	9	3.18	+0.03	0.35	2	5.05
Cr	−1.15	0.08	3	4.52	−2.17	0.12	3	3.50	–	–	–	–
Fe	−1.20	0.14	6	6.30	−2.03	0.05	12	5.47	−0.24	0.10	6	7.26
Ni	–	–	–	–	−1.30	–	1	4.95	–	–	–	–
Y	–	–	–	–	−1.20	–	1	1.04	–	–	–	–
Ba	−0.99	–	1	1.14	−2.00	–	1	0.13	–	–	–	–
	HD 111604				HD 120500				HD 141851			
Element	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)
C	−0.25	0.00	2	8.30	+0.20	0.20	2	8.75	−0.20	–	1	8.35
O	–	–	–	–	−0.22	0.15	2	8.65	−0.38	0.00	2	7.20
Mg	−0.98	0.00	3	6.60	−0.23	0.07	3	7.35	–	–	–	–
Si	−0.85	–	1	6.70	−0.95	0.00	2	6.60	−0.65	0.10	2	6.90
Cr	−1.07	–	1	4.60	–	–	–	–	–	–	–	–
Fe	−1.08	0.04	6	6.42	−0.67	0.06	3	6.83	−0.70	–	1	6.80
	HD 201184				HD 261904				HD 290799			
Element	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)
C	–	–	–	–	–	–	–	–	−0.13	0.18	2	8.43
O	–	–	–	–	+0.00	–	1	8.87	+0.00	–	1	8.87
Mg	−0.05	0	2	7.53	+0.37	0.06	3	7.95	−0.46	0.02	3	7.12
Si	–	–	–	–	+0.00	–	2	7.55	−1.35	–	1	6.20
Ca	−0.30	–	1	6.06	–	–	–	–	–	–	–	–
Ti	−0.35	0.07	4	4.67	–	–	–	–	–	–	–	–
Cr	−0.30	–	1	5.37	+0.00	–	1	5.67	–	–	–	–
Fe	−0.41	0.06	4	7.09	+0.10	0.23	10	7.60	−0.97	0.16	10	6.53
	HD 294253				HD 110379				HD 135379			
Element	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)	[M/H]	σ	N	(M/H)
C	–	–	–	–	+0.20	–	1	8.75	+0.00	–	1	8.55
O	+0.00	–	1	8.87	–	–	–	–	–	–	–	–
Mg	−0.40	–	2	7.18	+0.05	0.07	2	7.63	+0.10	0.14	2	7.68
Si	−0.60	–	1	6.95	–	–	–	–	–	–	–	–
Sc	–	–	–	–	–	–	–	–	+0.20	–	1	3.37
Ti	–	–	–	–	−0.13	0.05	5	4.89	+0.17	0.17	5	5.19
Cr	−0.20	–	1	5.47	−0.17	0.12	2	5.51	+0.01	0.20	5	5.68
Mn	–	–	–	–	+0.25	0.07	2	5.64	–	–	–	–
Fe	−0.54	0.06	5	6.96	+0.03	0.10	14	7.53	+0.12	0.19	11	7.62
Ni	–	–	–	–	+0.17	0.08	4	6.42	+0.00	–	1	6.25

Another important and well–known error source is the position of continuum level for stars even with a very low $v \sin i$ value (Hill 1995). We have determined the Fe abundance with the same software tools and model atmosphere, but once using the spectrum of HD 84123 as was normalized to continuum for the present investigation and a second time using the normalized spectrum from Heiter et al. (1998). For the first analysis, based on 23 lines, we obtained [Fe] = −0.86, for the other normalized spectrum [Fe] = −1.00. It is important to stress that everything else in the abundance determination procedure was the

Table 4. LTE abundances for HD 84123 from this work and Heiter et al. (1998). Values with an asterisk were derived for both ionization levels. Convection models are Mixing Length Theory (MLT) or from Canuto & Mazzitelli (1991, CM), the solar reference abundances were taken from Grevesse & Noels (1993, GN) or from Anders & Grevesse (1989, AG)

	This work			Heiter et al. (1998)		
Ion	[M/H]	σ	N	[M/H]	σ	N
C I	+0.10	0.17	18	−0.10	0.20	9
Na I	−0.82	0.09	2	−0.70	0.40	10
Mg I	−0.77	0.10	3	−1.00*	0.20	8
Si I	−0.42	0.17	7	−1.00*	0.20	6
Si II	−0.68	0.08	2	–	–	–
S I	−0.32	0.07	5	–	–	–
Ca I	−0.56	0.13	20	−0.90*	0.20	37
Ca II	−0.49	0.39	2	–	–	–
Sc II	−0.71	0.10	8	−1.10	0.20	10
Ti I	−0.75	0.09	4	−1.00*	0.10	37
Ti II	−0.86	0.10	28	–	–	–
Cr I	−0.84	0.20	7	–	–	–
Cr II	−0.86	0.10	14	−1.10*	0.20	28
Mn I	−0.65	0.15	6	−1.10	0.30	14
Fe I	−0.75	0.09	104	−1.20*	0.20	211
Fe II	−0.77	0.08	20	–	–	–
Ni I	−0.69	0.12	17	−1.00	0.20	20
Cu I	−0.71	–	1	−1.20	0.30	2
Zn I	–	–	–	−1.30	0.20	3
Zn II	−0.88	0.05	3	–	–	–
Y II	−0.50	0.08	4	−0.80	0.10	7
Zr II	−0.36	0.24	3	–	–	–
Ba II	−0.45	0.16	5	−1.00	0.20	6
$T_{\rm eff}$	6925 K			6800 K		
Conv.	MLT			CM		
Sun	GN			AG		

same, except for the normalization of the observed spectrum. In Fig. 2 we show a comparison between our determination of equivalent widths in the HD 84123 spectrum, and that of Heiter et al. (1998).

Further abundance differences originate in different models of atmospheres used for the analyses. Heiter et al. (1998) used Kurucz–based model atmospheres with the Canuto & Mazzitelli (1991) treatment of convection. At the temperature of about 7000 K a difference for the abundances of such an atmosphere relative to the standard Kurucz MLT atmospheres (or equivalent) was derived to be of the order of 0.1 dex (Heiter et al. 1998, their Sect. 5.2).

Another prominent difference of the present analysis and that of Heiter et al. (1998) is the temperature used for the model atmosphere, which is 6925 K and 6800 K, respectively. An uncertainty of the effective temperature of 250 K is not unusual, in particular for the analysis of stars with large $v \sin i$ and weak lines. A trend analysis of the line-abundances versus excitation energy (sensitive to the choice of $T_{\rm eff}$) gives a slope for the linear regression of −0.017 (Fe I 108 lines, see Fig. 3) and of −0.005 (Fe II 31 lines) for the hotter temperature and of +0.013 and +0.014 for the cooler. All values of the slopes are considerably smaller than the errors, however, they indicate that a temperature between 6800 K and 6925 K formally might be the best choice. However, one has to keep in mind that a similar analysis of several different elements (as was the case for Heiter et al. 1998) will give again an interval for optimum effective temperatures of about 100–200 K. With an adopted effective temperature and surface gravity for HD 84123, a visible dependence between the derived iron abundance and equivalent width vanishes if $V_{\rm t}$ = 2.7 km s^{-1} (Fig. 4).

Finally, we have to mention another possible source for discrepancies, which is the choice of atomic parameters. The quality and quantity of oscillator strengths, Stark and van der Waals broadening parameters, etc., has increased significantly over the last decades. A spectrum analysis produced for a given star 30 years ago can differ from a modern determination by 40% and more, just because different atomic parameters were used, and usually a much larger spectrum range extended to the red is nowadays available. However, this source

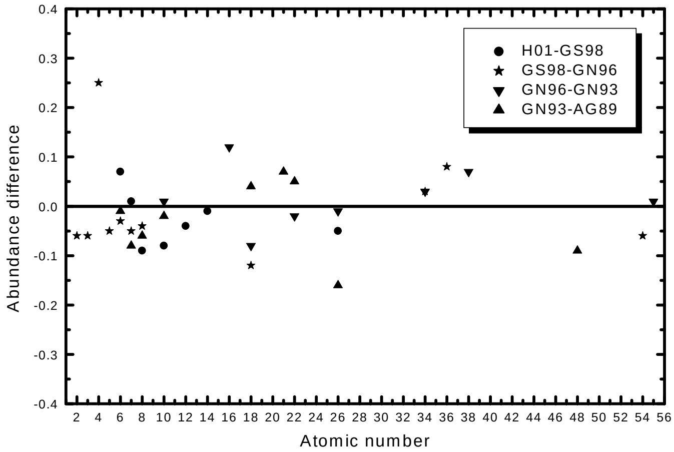

Fig. 1. Abundance differences for the elements up to barium for the Sun from five different references: Anders & Grevesse (1989, AG89), Grevesse & Noels (1993, GN93), Grevesse et al. (1996, GN96), Grevesse & Sauval (1998, GS98) and Holweger (2001, H01).

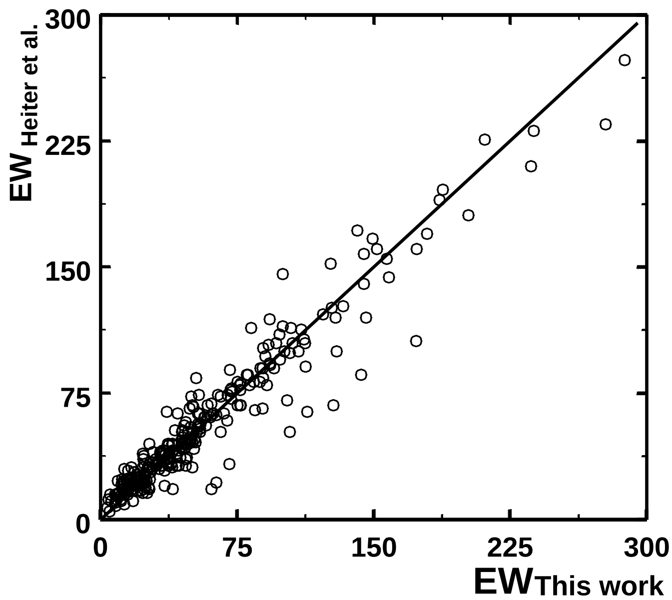

Fig. 2. Comparison between our determination of equivalent widths in HD 84123 spectrum, and that of Heiter et al. (1998).

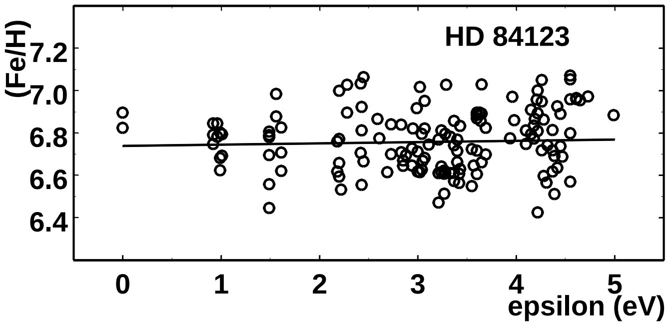

Fig. 3. Iron abundance from individual Fe I lines vs. their excitation potentials: determination of the effective temperature.

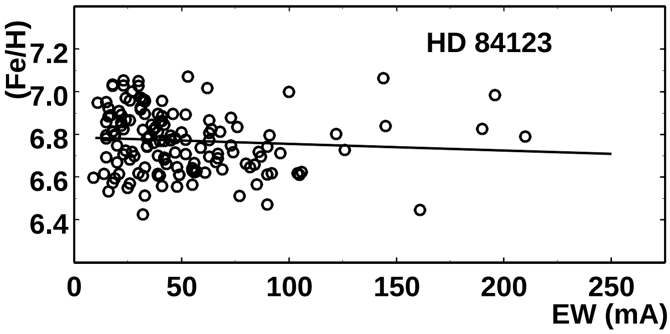

Fig. 4. Iron abundance from individual Fe I lines vs. their equivalent widths: determination of the microturbulent velocity.

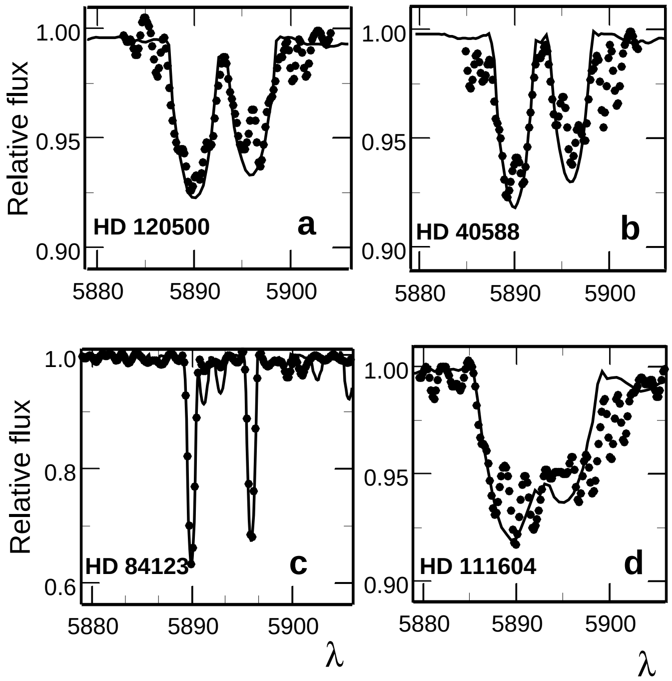

Fig. 5. Synthetic (**solid line**) and observed (**dots**) profiles in the vicinity of sodium line.

of discrepancies is not relevant for the present comparison, because the VALD data base has been used since 1996 by all groups involved.

In conclusion, we found for HD 84123 upper limits for the differences of the iron abundances (present determination vs. Heiter et al. 1998).

- Temperature difference of 125 K: +0.10 dex;
- Continuum placement: +0.14 dex;
- Convection model: +0.10 dex;
- Standard Sun values: +0.17 dex;
- Atomic parameters: +0.0 dex.

The various contributions add up to +0.5 dex which corresponds well within the errors quoted for the Fe abundance determinations to the difference given in Table 4 of +0.45 dex. We cannot decide which analysis, the present one or that of Heiter et al. (1998), is the "correct" one. However, we want to emphasize the importance of a critical assessment of the different parameters used when comparing published results.

4.3. NLTE calculations for sodium

One of the elements whose abundance can be measured in λ Bootis stars is sodium. Nevertheless, it should be noted that only the strong D_1, D_2 doublet is detectable in the spectra of our program stars. One can expect that the sodium abundances derived from D_1 and D_2 lines under the LTE approximation should be strongly overestimated. To derive an accurate sodium abundance we have performed an NLTE analysis.

The sodium atomic model (Sakhibullin 1987; Korotin & Mishenina 1999) adopted for the NLTE calculations is based on the use of the modified version of the MULTI code (Carlsson 1986; Korotin et al. 1999). It consists of 27 levels for Na I and the ground level of Na II. The radiative transitions between the first 20 levels of Na I and the ground level of Na II were considered. Transitions between the remaining levels were used only in the equations of particle number conservation. Finally, 46 $(b-b)$ and 20 $(b-f)$ transitions were included in the linearization procedure. For 34 transitions the radiative rates were fixed.

In Table 5 we present the mean sodium abundances of the program stars obtained in the NLTE approximations from D_1, D_2 Na I lines. In Fig. 5 we show graphically the results of the spectrum synthesis in the vicinity of the sodium doublet.

We also redetermined the NLTE abundances for HD 192640, HD 204041 and HD 221756 previously investigated by Andrievsky et al. (1998) in a purely LTE approximation.

Although the NLTE abundances from the sodium resonance doublet are lower than the LTE ones in the considered temperature domain, they nevertheless appear to be significantly higher than the abundances for the other heavy elements. Some objects exhibit values even higher than the solar abundance. This result is rather surprising but was already suspected and discussed by the LTE analysis of Stürenburg (1993) and Paunzen et al. (1999b). If an accretion–based hypothesis is able to explain the λ Bootis phenomenon, then one should expect that Na with its rather high condensation temperature ($T_c \approx 1000$ K, a value which is just on the edge for grains to build) be less abundant than C, N and O ($T_c \approx 150$ K) but more abundant than elements like Ca, Ti and Fe ($T_c > 1250$ K). However, our result indicates that Na is even *more* abundant

Table 5. NLTE sodium abundances for the program stars from the D_1 and D_2 doublet, $(Na/H)_\odot$ = 6.33. For objects with only one value listed, both lines are well fitted, σ([Na/H]) = 0.15 dex.

HD	[Na/H]	σ
23258	+0.75	±0.25
40588	+0.20	±0.25
66684	−0.10	±0.15
84123	−0.45	±0.15
90821	+0.45	±0.25
103483	−0.55	±0.15
111604	+0.45	±0.25
120500	+0.30	±0.15
141851	+0.60	±0.15
290799	+0.45	±0.25
192640	−0.60	±0.25
204041	+0.80	±0.25
221756	+1.15	±0.25

than C and O, which cannot be easily explained by any theory based only on accretion or mass-loss.

5. Comparison with classification spectroscopy and results

A main criterion for the membership of the λ Bootis group is the existence of a typical abundance pattern with the most crucial elements being C, N, O and S showing solar values. These elements do not show any prominent lines in the optical range normally used for classification spectroscopy (Gray 1988). This method is therefore only capable of finding metal–weak (morphology of the Ca K as well as the overall metallic lines), Population I (shape of the hydrogen lines), late B to early F-type objects. Such objects are only good λ Bootis candidates with the final decision on their membership having to be made via a detailed abundance analysis. Several other groups of objects (Field-Blue-Stragglers, Field-Horizontal-Branch and intermediate Population II type stars, Gray 1989) are mainly distinct from the λ Bootis group by the apparent solar abundances of C, N, O and S (Heiter 2000).

Another important aspect in analyzing high resolution spectra is the detection of spectroscopic binary systems among the bona-fide λ Bootis candidates. According to Faraggiana & Bonifacio (1999) some λ Bootis stars are undetected (at least at classification resolution) binary systems where two solar abundance objects mimic one metal-weak star.

The following objects have been described in the literature (Paunzen & Gray 1997; Gray & Corbally 1998) as true λ Bootis stars, which is confirmed by our analysis: HD 36726, HD 84123, HD 91130, HD 106223, HD 111604 and HD 290799. For HD 91130 and HD 106223 we have taken into account the abundance of the light elements from Paunzen et al. (1999a) and Heiter (2002).

Three stars were found in the literature (Paunzen & Gray 1997; Paunzen et al. 2001) to be λ Bootis candidate stars. These objects were confirmed as being members of this group:

- **HD 23258**: classified as A0 Vp (λ Boo) in Abt & Morrell (1995) and as A0 Vb (slightly metal weak) in Paunzen & Gray (1997). Our analysis found the typical abundance pattern (C and O solar whereas Mg, Si, Cr and Fe are moderately underabundant).
- **HD 40588**: classified as A1 Vp (wk 4481 MgII) in Abt & Morrell (1995) and as A1 Va (wk 4481 MgII) in Paunzen et al. (2001), again the typical pattern was found.
- **HD 74911**: the derived abundances establish this star as being a member of this group, classified as A2 IV (wk 4481 MgII) in Paunzen & Gray (1997).

We are not able to decide if HD 66684, HD 105058, HD 120500, HD 141851 and HD 294253 are true members of the λ Bootis group or not. For two objects (HD 66684 and HD 105058) no abundances for the light elements were determined whereas for the other stars doubts about the typical abundance pattern arose. We also note that HD 141851 was announced as being a spectroscopic binary system by Faraggiana & Bonifacio (1999).

From our detailed abundance analysis we are able to *reject* the following stars as being members of the λ Bootis group:

- **HD 90821**: classified as kA2hA7mA2 Vn λ Boo in Paunzen & Gray (1997), the abundances derived for seven elements do not show any significant deviation from solar values.
- **HD 98772**: Abt (1984) classified this star as A1 Vnp (4481 MgII weak), Abt & Morrell (1995) as A1 IVn and Paunzen et al. (2001) as A1 Va. C, O, Mg and Si exhibit solar abundances whereas Cr and Fe show small underabundances. This might indicate a peculiar nature of this object.
- **HD 103483**: the classification (kA2hA5mA3 V) given in Paunzen et al. (2001) is in contradiction with the one (A2 Vn) by Abt & Morrell (1995). This object is clearly metal-weak (on the average −0.65 dex). Since oxygen behaves like the heavier elements, this star was rejected as being member of the λ Bootis group.
- **HD 108765**: the abundances for this star are (within the errors) solar which contradicts the classification as kA3hA3mA0 V given in Paunzen et al. (2001).
- **HD 261904**: Member of the young open cluster NGC 2264 # 138 in the notation of Walker (1956). First listed as a probable λ Bootis star (A0.5 V wk 4481 MgII) in Paunzen & Gray (1997), confirmed as a mild λ Bootis star in Gray & Corbally (1998) and Paunzen (2001). From our analysis we derive solar abundances for O, Mg, Si, Cr and Fe. With its rejection as being a true λ Bootis star, only a few members of this group within the young Orion OBI association remain that have well determined ages.

With only two stars (HD 90821 and HD 261904) misclassified as members of the λ Bootis group, the capability of classification resolution spectroscopy to make a first selection of promising λ Bootis candidates is proven. However, in order to establish a homogenous group of objects with the same astrophysical characteristics, a detailed abundance analysis, including especially at least one of the light elements (C, N, O or S) is necessary.

Acknowledgements. This work benefitted from the Fonds zur Förderung der wissenschaftlichen Forschung, project *P14984*.

We would like to thank R. O. Gray for his help during the preparation of this project. The authors are indebted to the referee, Dr. S. Turcotte, for important comments which allowed us to improve the first version of this paper.

Use was made of the SIMBAD database, operated at CDS, Strasbourg, France.

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