Astron. Astrophys. 345, 597–604 (1999)

ASTRONOMY
AND
ASTROPHYSICS

Light element non-LTE abundances of λ Bootis stars

I. Carbon and oxygen[*]

E. Paunzen[1], I. Kamp[2], I.Kh. Iliev[3], U. Heiter[1], M. Hempel[2], W.W. Weiss[1], I.S. Barzova[3], F. Kerber[4], and P. Mittermayer[1]

[1] Institut für Astronomie der Universität Wien, Türkenschanzstrasse 17, A-1180 Wien, Austria (Ernst.Paunzen@univie.ac.at)
[2] Institut für Theoretische Physik und Astrophysik, Universität Kiel, D-24098 Kiel, Germany
[3] Institute of Astronomy, National Astronomical Observatory, P.O. Box 136, BG-4700 Smolyan, Bulgaria
[4] Institut für Astronomie der Universität Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria

Received 9 November 1998 / Accepted 21 January 1999

Abstract. Abundances for the light elements of λ Bootis stars are a main key to understand the astrophysical processes behind the so-called λ Bootis phenomenon. These stars are characterized by a typical abundance pattern (strong underabundances of the Fe-peak elements whereas the light elements have apparently solar abundances) which is still based mainly on LTE-calculations.

Therefore we started an investigation to derive accurate abundances of the light elements (C, N, O and S). For this purpose a new oxygen model atom was implemented in the Kiel non-LTE code. High resolution and high signal-to-noise spectra were used. For each element only a single wavelength region with lines of the specific element was selected and observed in order to avoid contamination from other elements.

In the first paper we present abundances for carbon and oxygen of a statistically significant number of well established λ Bootis stars. The second paper will deal with nitrogen and sulphur.

The most important result is that on average carbon is less abundant than oxygen but still both elements are significant more abundant than the Fe-peak elements. Furthermore the anticorrelation of carbon and oxygen with the silicon abundance is proven, which strongly supports the accretion/diffusion theory.

Key words: stars: abundances – stars: atmospheres – stars: chemically peculiar – stars: early-type

1. Introduction

Although normal A-type dwarfs, metal-rich Am and metal-poor λ Bootis stars share the same region in the HR-diagram and have nearly the same overall characteristics, they show an extremely large range – about 4 dex – of abundances in solar units in the stellar atmospheres. The theory of radiatively driven diffusion in the stellar atmosphere and accretion of depleted material onto the stellar surface can account for the observational facts. Still there are too many free parameters in theoretical models in order to unambiguously fit all observational data. The input from observations to models, on the other hand, is only of minor nature.

The group of λ Bootis stars might provide an input/output for the understanding of these astrophysical processes. The members of this group are characterized in the literature as Population I, A- to F-type stars with strong underabundances of Fe-peak elements and apparent solar abundances of light elements (C, N, O and S). This pattern should be explained by a theoretical model.

But especially the apparent solar abundance of the light elements is *not* based on solid grounds (Tables 1 and 2). Estimations found in the literature are mostly based on LTE calculations and have used strongly blended lines. We therefore have decided to derive abundances for the light elements for a statistically significant sample of well established members of the λ Bootis group. In order to get reliable and accurate results the following strategy was chosen:

- The model atmospheres and thus the abundance analysis were performed in non-LTE.
- Only two telescopes were used guaranteeing a homogeneous data set with a sufficient resolution and high signal-to-noise spectra.
- For each element a single wavelength region with lines from only one element was selected and observed to avoid contamination from other elements (Table 3).
- New and accurate $\log gf$-values (from Wiese et al. 1996) were used.

In the first paper we present the results of carbon (16 stars) and oxygen (22 stars). For the latter, a new oxygen model atom was implemented in the Kiel non-LTE code.

A statistical analysis of the derived results and a comparison with the literature will be discussed in the following.

Send offprint requests to: E. Paunzen

[*] Based on observations obtained at ESO-La Silla and BNAO Rozhen

Table 1. References for high-resolution spectroscopy of carbon and oxygen lines in λ Bootis stars

Num	Reference	Used lines	Resolution	$\#_{stars}$
1	BS69	O I 7771-5	20000	3
2	BS88	C I 1656-8	40000	7
		C II 1334-6		
		O I 1302		2
3	VL90	C I 7108-20	28000	3
		O I 6155-8		3
4	ST93	C I 4228	50000	12
		C I 4932		
		C I 5039-41		
		C I 5052		
5	AN98	C, O; optical	24000	4
6	HE98	C I 4269	25000	2
		C I 4762-75		
		C I 4817-27		
		C I 4932		
		C I 5052		
		C I 5380		
		O I 6158		3

BS69: Baschek & Searle (1969)
BS88: Baschek & Slettebak (1988)
VL90: Venn & Lambert (1990)
ST93: Stürenburg (1993)
AN98: Andrievsky et al. (1998)
HE98: Heiter et al. (1998)

2. Program stars and observations

The program stars were taken from the lists of Gray & Corbally (1993), Paunzen et al. (1997) and Paunzen & Gray (1997). All selected objects are well established members of the group taking into account various criteria which are based on optical classification as well as on IUE spectra (Solano & Paunzen 1998).

Most of the observations were made in 1997 and 1998 with the ESO 1.4m CAT/CES system. The Short and Very Long Camera (red channel) with CCD #38 were used. The spectra were taken in two different wavelength regions centered on 7120 Å and 7757 Å with a resolution of about 60000. The spectra were bias-subtracted, flat-fielded and normalized with standard IRAF routines. Special care was taken to remove fringes and telluric lines with the help of bright O and B-type stars.

Additional observations were carried out with the 2m RCC telescope of the Bulgarian Astronomical Observatory Rozhen during 1996–1998. The Third Camera of the coudé spectrograph and a virtual phase 580 × 520 ISTA CCD matrix with a pixel size of 24 μm × 18 μm were used. The slit-width was set to 300 μm which corresponds to $0.8''$ at the sky. With a 632 mm^{-1} Bausch & Lomb grating the spectral range of about 50 Å centered on 7120 Å was covered with a resolution of 35000. The range centered on 7770 Å was covered with a resolution of about 20000; in this case the spectra are twice as large. A hollow-cathode Fe-Ar lamp was used to produce a reference spectrum with a FWHM of about 2 pixels for the comparison lines. Flat field frames were made by using a tungsten projection lamp installed in front of the entrance slit of the spectrograph. The PC-based IPS software package (Smirnov et al. 1992) was used for bias subtraction, flat-fielding, spectrum extraction and wavelength calibration. The typical signal-to-noise ratio obtained for most of the spectra is between 100 and 250.

An abridged version of the observing log is available upon request from the first author.

Table 2. Carbon and oxygen abundances from the literature (Table 1) of well established members of the λ Bootis group; no error estimations are given in AN98(^{5}), all results except of ST93(^{3}) are based on LTE calculations

Star	[C]	[O]
HD 319	$+0.05(20)^4$	
HD 11413	$+0.05(20)^4$	
HD 31295		$-0.10(50)^1$
	$-0.50(20)^2$	$+0.20(20)^2$
	$-0.27(10)^3$	$-0.45(10)^3$
	$+0.05(20)^4$	
	-0.20^5	-0.05^5
HD 38545	$-0.15(20)^4$	
HD 84123	$-0.10(20)^6$	$-0.30(20)^6$
HD 111786	$-1.10(20)^2$	
	$-0.30(20)^4$	
HD 125162		$+0.60(50)^1$
	$-0.50(20)^2$	
	$-0.37(10)^3$	$-0.45(10)^3$
HD 170680	$-0.50(20)^2$	$+0.10(20)^2$
HD 183324	$-0.40(20)^2$	
	$+0.25(20)^4$	
	-0.40^6	-0.10^6
HD 192640		$+0.20(50)^1$
	$-0.50(20)^2$	
	$-0.24(15)^3$	$-0.46(15)^3$
	$-0.20(20)^4$	
	-0.10^5	-0.50^5
		-0.30^6
HD 193256	$-0.10(20)^4$	
HD 193281	$-0.25(20)^4$	
HD 198160/1	$-0.25(30)^4$	
HD 204041	$-0.40(10)^4$	
	-0.20^5	-0.50^5
HD 210111	$+0.00(10)^4$	
HD 221756	$-0.60(20)^2$	
	$+0.00^5$	-0.30^5

3. Model atmospheres and spectrum synthesis

All calculations were carried out with Kurucz's ATLAS9 code (Kurucz 1993) based on a microturbulence of 3 $\mathrm{km\,s^{-1}}$. The Strömgren $uvby\beta$ system and the calibration by Napiwotzki et al. (1993) were used to determine the effective temperature and surface gravity for our program stars (Table 6). A comparison of these values with spectroscopically (e.g. Heiter et al. 1998) and photometrically derived ones from the Geneva system (Künzli

Table 3. Line list and atomic parameters for Carbon (upper section) and Oxygen (lower section); the columns indicate the ionization state, the multiplet number according to the tables of Wiese et al. (1996), the wavelength, the excitation potential of the lower level, the oscillator strength (C: Wiese et al. 1996; O: VALD, Piskunov et al. 1995), van der Waals broadening (approximation of Unsöld 1968), Stark broadening (Griem 1968 for ions, Cowley 1971 for neutrals), and radiative damping (classical formula). The last two columns denote the lower and upper level numbers of the respective model atom (if the levels are not included in the carbon model atom, the line is treated in LTE; this is indicated by the level number 90)

Element	No.	Wavelength [Å]	X_i [eV]	log gf	log $C6$	log $C4$	$\gamma_{\rm rad}$ [10^8 s^{-1}]	i	j
C I	109	7100.12	8.64	−1.470	−29.61	−11.67	0.44	9	30
C II	131	7105.77	22.53	−1.733	−31.96	−6.76	0.44	90	90
C I	109	7108.93	8.64	−1.592	−29.61	−11.67	0.44	9	30
C I	108	7111.47	8.64	−1.086	−29.73	−11.68	0.44	9	31
C II	131	7112.48	22.53	−0.049	−31.96	−6.80	0.44	90	90
C II	131	7113.04	22.53	0.157	−31.96	−6.80	0.44	90	90
C I	108	7113.18	8.65	−0.774	−29.72	−11.66	0.44	9	31
C I	108	7115.17	8.64	−0.935	−29.73	−11.68	0.44	9	31
C I	109	7115.18	8.64	−1.473	−29.61	−11.68	0.44	9	30
C II	131	7115.63	22.53	0.339	−31.96	−6.82	0.44	90	90
C I	109	7116.99	8.65	−0.907	−29.60	−11.66	0.44	9	30
C I	109	7119.66	8.64	−1.149	−29.62	−11.68	0.44	9	30
C II	131	7119.76	22.53	−0.448	−31.96	−6.84	0.44	90	90
C II	131	7119.91	22.54	0.503	−31.96	−6.59	0.44	90	90
C I	108	7122.20	8.64	−2.116	−29.74	−11.68	0.44	9	31
C II	131	7125.72	22.53	−0.333	−31.96	−6.87	0.44	90	90
O I	56	7771.95	9.15	0.324	−31.08	−13.25	0.37	4	6
O I	56	7774.20	9.15	0.174	−31.08	−13.25	0.37	4	6
O I	56	7775.40	9.15	−0.046	−31.08	−13.25	0.37	4	6

et al. 1997) yields a good agreement within an estimated error of $\sigma(T_{\rm eff})$ = ±200 K and $\sigma(\log g)$ = ±0.2 dex.

Detailed non-LTE calculations were performed for each model atmosphere using the Kiel non-LTE code of Steenbock & Holweger (1984). The carbon model atom was taken from Stürenburg & Holweger (1990) whereas the oxygen model atom was newly implemented as is described in the next section.

3.1. The oxygen model atom

Baschek et al. (1977) and Takeda (1992) show the importance of non-LTE abundance corrections for the O I 7771-5 triplet in A-type stars. Following their approach we developed a model atom for neutral oxygen which comprises the lowest 15 terms of the singulet, triplet and quintet system (Table 4). The ground state of O II represents the continuum of the model atom. We take into account all line transitions between these levels except for the intercombination line at 6726 Å (Table 5). The level energies and their designations are from the tables of Moore (1971) whereas the line data are from the compilation of Wiese et al. (1996).

We use energy resolved photoionization cross sections for neutral oxygen from the Opacity Project provided by the CDS Strasbourg (Cunto et al. 1993; Seaton et al. 1992).

Electron and neutral hydrogen collision cross sections are calculated as outlined by Rentzsch-Holm (1996) using the f-values of Wiese et al. (1996).

Table 4. Levels of the oxygen model atom: their number (No.), the respective level number (Ref.) used by Baschek et al. (1977), the level designation and the level energies E (Moore 1971)

No.	Ref.	Designation	E [eV]
1	1	2p^{3}P	0.0097
2		2p^{1}D	1.9672
3		2p^{1}S	4.1896
4	2	3s^{5}S$^\circ$	9.1457
5		3s^{3}S$^\circ$	9.5210
6	3	3p^{5}P	10.7405
7		3p^{3}P	10.9888
8	4	4s^{5}S$^\circ$	11.8375
9		4s^{3}S$^\circ$	11.9304
10	5	3d^{5}D$^\circ$	12.0782
11		3d^{3}D$^\circ$	12.0866
12	6	4p^{5}P	12.2856
13		4p^{3}P	12.3583
14	7	5s^{5}S$^\circ$	12.6604
15	8	4d^{5}D$^\circ$	12.7532

In the previous studies of Baschek et al. (1977) and Takeda (1992) Vega serves as an example for non-LTE effects of O I in the atmospheres of A-type stars. Hence we present calculations of the non-LTE departure coefficients $b_i = n_i/n_i^*$ (the ratio of the non-LTE and LTE occupation numbers) for neutral oxygen

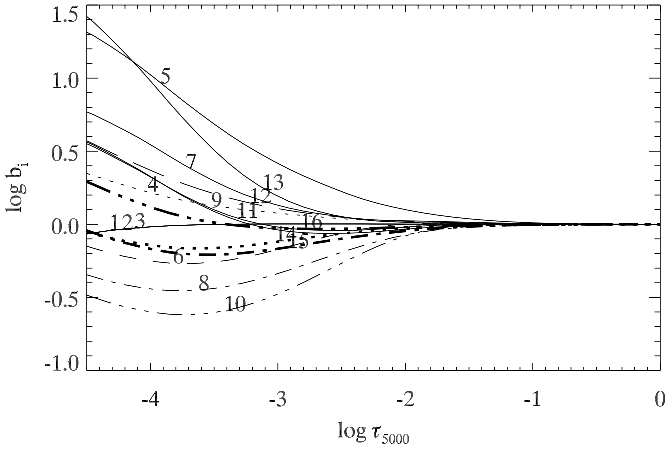

Fig. 1. Departure coefficients for neutral oxygen versus optical depth in a Vega ATLAS9(9500, 4.0, -0.5) model atmosphere; level numbers are according to Table 4, different line styles are used to enable a better distinction

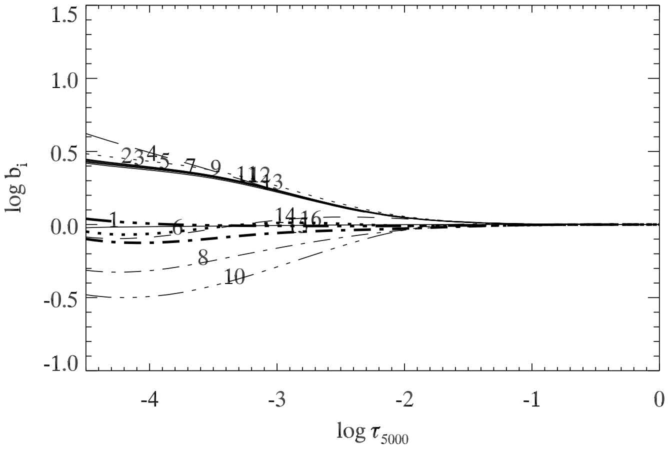

Fig. 2. Same as Fig. 1, but with strongly reduced collisional ionization cross sections of the triplet system

Table 5. Line transitions of the oxygen model atom: lower level number (Low), upper level number (Up), wavelength and $\log gf$-value (Wiese et al. 1996)

Low	Up	λ [Å]	$\log gf$
1	4	1355.6	−5.115
1	5	1303.5	−0.330
1	9	1040.1	−1.084
1	11	1026.6	−0.743
1	3	2972.3	−10.478
1	2	6333.8	−9.652
2	3	5577.3	−8.930
4	12	3947.4	−1.766
4	6	7773.4	0.700
5	13	4368.2	−1.709
5	7	8446.5	0.492
6	8	11299.0	0.407
6	14	6455.0	−0.589
6	15	6157.3	0.034
6	10	9263.9	1.156
7	9	13165.0	0.222
7	11	11299.0	0.407

based on the model atom described above and the Kiel non-LTE code (Steenbock & Holweger 1984).

Fig. 1 displays the departure coefficients as a function of optical depth τ_{5000} adopting a Vega ATLAS9 model atmosphere (Kurucz 1993) with $T_{\rm eff} = 9500$ K, $\log g = 3.90$, and a metallicity of [M/H]$= -0.5$ (Gigas 1986). Baschek et al. (1977) in their model atom account only for the excited quintet terms, because direct coupling by the forbidden line 6726 Å (3s^{5}S°-3p^{3}P) is very weak. However our model shows that collisional coupling between the two systems via collisional ionization to the continuum is not negligible. We can reproduce their non-LTE departure coefficients fairly well by neglecting collisional coupling of the triplet to the continuum (Fig. 2). Despite all efforts we are not able to reproduce the results of Takeda (1992). His departures are similar to those of Baschek et al. (1977) although he accounts for all three systems, singulet, triplet and quintet using an approach for the collisions similar to ours.

4. Non-LTE abundances

First of all we made an error estimation of the derived abundances based on two extreme (in $T_{\rm eff}$) program stars (HD 142703 and HD 170680).

To investigate the influence of an incorrectly chosen model atmosphere on the carbon and oxygen abundances, we determined these values for two grids of model atmospheres centered on the of the coolest and hottest star in our sample. These grids had a step width of 200 K and ranged from +600 K to −600 K relative to the $T_{\rm eff}$ adopted by us (see Table 6) and similarly for $\log g$ (± 0.6 dex with 0.2 dex step width). The maximum difference for any of the abundances relative to that one determined for the model atmosphere based on the adopted $T_{\rm eff}$ and $\log g$ (from Table 6) was 0.075 dex. Hence, the difference between our abundance values and those found in the literature cannot be accounted for by differences in the chosen atmospheres but are indeed due to non-LTE effects or differences in atomic parameters. A similar test with changed $v \sin i$ values results in even smaller abundance differences. We therefore adopted an error for our abundance determination of about 0.1 dex.

Figs. 3 and 4 show two carbon as well as oxygen spectra for a low and a high $v \sin i$ star. Included are the observations, LTE and non-LTE calculations using the same abundance.

A comparison of the non-LTE and LTE abundances shows the importance of the non-LTE approach. The abundance correction for oxygen is typically −0.5 dex (Table 6). For carbon the non-LTE correction is less significant, about −0.1 dex.

4.1. Comparison with previous work

A comparison of our results to the abundances from the literature seems to be rather inconclusive (Fig. 5). Nevertheless we

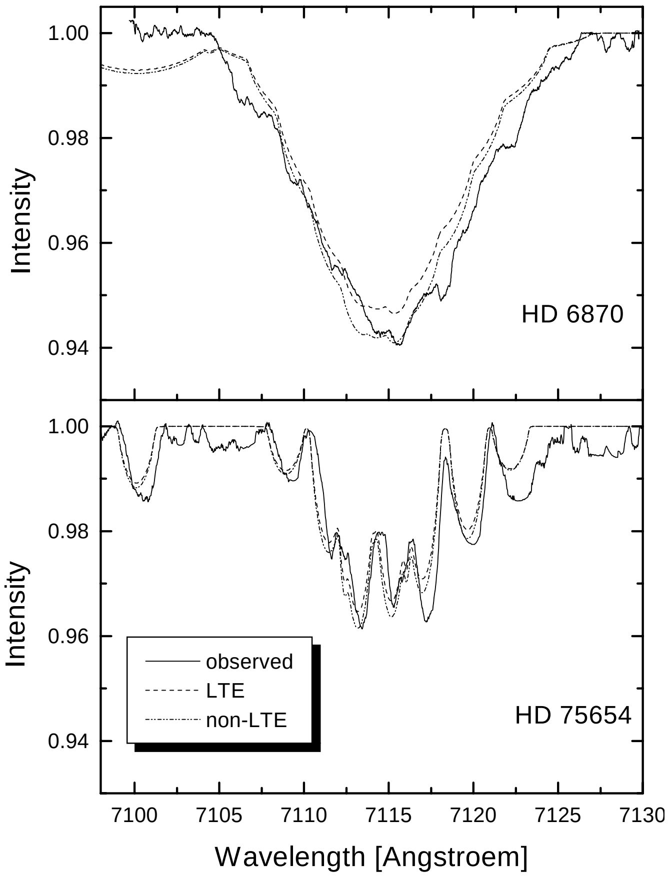

Fig. 3. Two selected carbon spectra with the abundances listed in Table 6

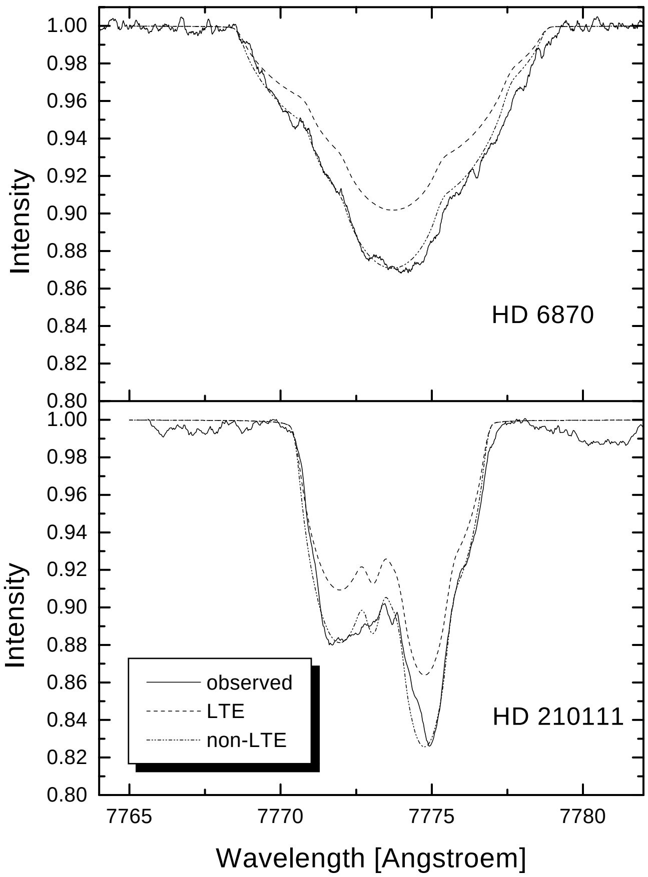

Fig. 4. Two selected oxygen spectra with the abundances listed in Table 6

note for the nine stars in common with Stürenburg (1993) that our carbon abundances show a typical offset of -0.4 dex to his values, except for two stars: for HD 11413 our line profile suggests a higher $v \sin i$, hence a larger carbon abundance; for HD 198160 Stürenburg's fit to the 4933 Å blend with barium may underestimate the carbon abundance. Taking these effects into account, the systematic offset of abundances derived from the optical lines (Stürenburg 1993) and the near infrared (this work) seems to be confirmed. We note that our carbon lines are weak but unblended whereas the optical lines of Stürenburg (1993) are all blended with barium, iron or chromium. All other determinations (Table 2) agree with carbon being typically slightly underabundant in λ Bootis stars.

We have three stars, HD 31295, HD 125162 and HD 192640 in common with Venn & Lambert (1990). From the oxygen 6155-8 Å blend they infer an underabundance of 0.45 dex for all three stars. Typical non-LTE abundance corrections for this blend are smaller than 0.1 dex. However the equivalent widths of their lines are rather weak, typically 80 mÅ, and the lines are strongly broadened due to high $v \sin i$ (80–130 km s^{-1}) which makes abundance analysis difficult. Our triplet lines are tenfold stronger and we account for non-LTE abundance corrections.

The results of Baschek & Searle (1969) are difficult to compare to ours because: 1) they use a different technique (curve-of-growth analysis); 2) they derive only abundances relative to the standard star Vega, which possibly also belongs to the group of λ Bootis stars; 3) they use the LTE approximation but the 7771-5 Å triplet is strongly affected by non-LTE effects. The oxygen abundances derived from the 1302 Å line (Baschek & Slettebak 1988) is in good agreement with our result, but lines in the visual region (Andrievsky et al. 1998; Heiter et al. 1998) yield systematically lower abundances by about 0.5 dex.

From Table 2 we conclude that there seems to be an inconsistency between the oxygen abundances derived from different wavelength regions: UV, optical and near infrared.

4.2. Remarks

Further comments to the following three stars are necessary:

HD 4158: This star was considered as λ Bootis type in the optical region by Graham & Slettebak (1973) because of its very weak metallic line spectrum (e.g. no Mg II 4481 line was detected). Faraggiana et al. (1990) confirmed its λ Bootis characteristics in the UV range. But the low effective temperature (6400 K) and surface gravity (3.0 dex) are outstanding for this group. If the membership of this star can be confirmed by a detailed abundance analysis it will be the coolest and most distant from the zero age main sequence λ Bootis star.

Table 6. Stellar parameters and derived abundances for our program stars

HD	HR	V [mag]	$b-y$ [mag]	m_1 [mag]	c_1 [mag]	β [mag]	$T_{\rm eff}$ [K]	$\log g$ [dex]	$v\sin i$ [km s^{-1}]	[C] LTE	[C] NLTE	[O] LTE	[O] NLTE
319	12	5.93	0.079	0.164	1.037	2.851	8100	3.8	60^1	−0.26	−0.36	+0.83	+0.22
4158		9.54	0.216	0.102	0.748	2.674	6400	3.0	85^3			+0.39	−0.16
6870		7.50	0.153	0.154	0.771	2.757	7400	4.0	$200/128^3$	+0.23	+0.14	+0.55	+0.05
11413	541	5.93	0.108	0.141	0.974	2.829	7900	3.8	122^1	−0.15	−0.25	+0.40	−0.10
30422	1525	6.18	0.101	0.185	0.871	2.832	8000	4.1	$150/120^3$	−0.19	−0.27	+0.15	−0.25
31295	1570	4.64	0.044	0.178	1.007	2.898	9100	4.1	120^3	−0.10	−0.19	+0.40	−0.08
75654	3517	6.38	0.161	0.140	0.816	2.753	7200	3.8	45^3	−0.38	−0.44	+0.75	+0.14
91130	4124	5.93	0.073	0.158	1.035	2.854	8000	3.8	135^3			+0.70	+0.14
120500		6.61	0.068	0.170	1.062	2.871	8200	3.9	125^3			+0.74	+0.19
125162	5351	4.18	0.051	0.182	1.000	2.894	8900	4.1	128^3			+0.52	+0.02
141851	5895	5.10	0.071	0.165	1.001	2.846	8100	3.8	$200/280^3$	−0.73	−0.81	+0.25	−0.21
142703	5930	6.12	0.180	0.118	0.725	2.743	7200	4.0	100^3	−0.47	−0.52	+0.24	−0.19
149303	6162	5.64	0.064	0.180	1.028	2.848	8000	3.8	275^3			+0.35	−0.14
168740	6871	6.14	0.136	0.139	0.881	2.798	7700	3.9	$150/145^3$	−0.35	−0.42	+0.48	−0.03
170680	6944	5.14	0.006	0.140	1.052	2.892	10000	4.1	215^3	+0.00	−0.06	+0.45	−0.07
183324	7400	5.77	0.051	0.165	1.003	2.890	9300	4.1	90^1	−0.05	−0.14		
192640	7736	4.95	0.101	0.157	0.927	2.833	8000	3.9	80^3			+0.33	−0.15
193256	7764C	7.70	0.115	0.165	0.984	2.819	7700	3.7	$240^1/260^3$	−0.55	−0.62	+0.25	−0.23
193281	7764A	6.61	0.098	0.152	1.109	2.844	8100	3.6	$83^1/95^3$	−0.52	−0.61	+0.53	−0.05
198160/1	7959	5.65	0.108	0.155	0.929	2.831	7800	3.9	$280/180^3$	−0.07	−0.16	+0.28	−0.18
204041	8203	6.45	0.093	0.167	0.940	2.845	8100	4.0	65^1	−0.75	−0.81	+0.00	−0.38
210111	8437	6.34	0.136	0.147	0.861	2.774	7400	3.8	55^1	−0.40	−0.45	+0.26	−0.20
221756	8947	5.59	0.056	0.166	1.072	2.878	8800	3.8	$100^2/112^3$			+0.70	+0.10

[1] Holweger & Rentzsch-Holm (1995)

[2] Gray & Corbally (1993)

[3] derived from our spectra, two different values indicate $v\sin i$ derived from the carbon and oxygen spectrum

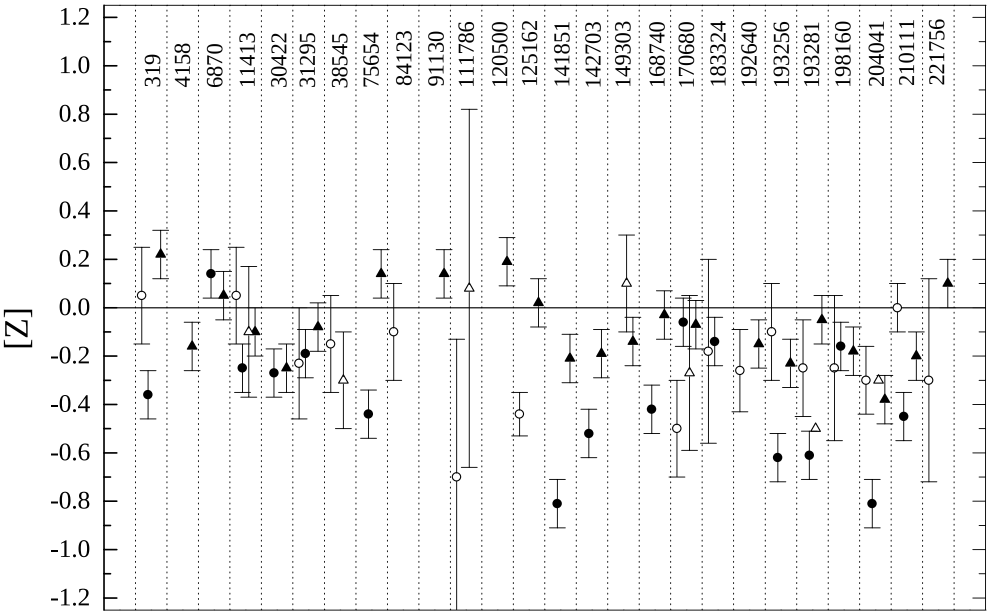

Fig. 5. Carbon (circles) and oxygen (triangles) abundances found in the literature (open) and from this work (filled)

HD 149303: Our oxygen spectrum indicates that this star is a so far not confirmed spectroscopic binary system with a high $v\sin i$ and a low $v\sin i$ component very similar to HD 111786 (Faraggiana et al. 1997).

HD 198160/1: As already pointed out by Stürenburg (1993) and Gray & Corbally (1993) both components of this very close visual binary system are members of the λ Bootis group. Since we were not able to resolve this system, our estimates are only an average for both components.

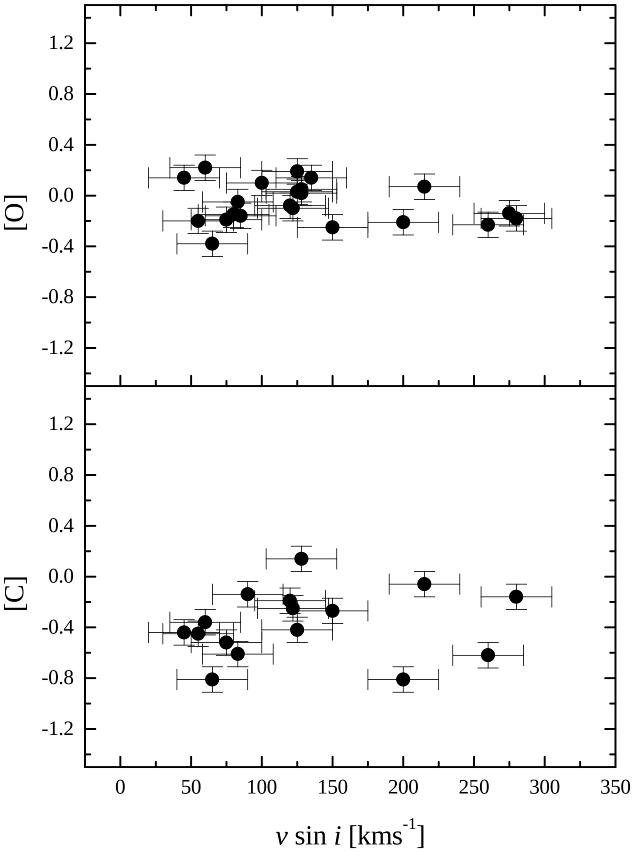

Fig. 6. No correlation between the projected rotational velocity and the carbon as well as oxygen abundance was found

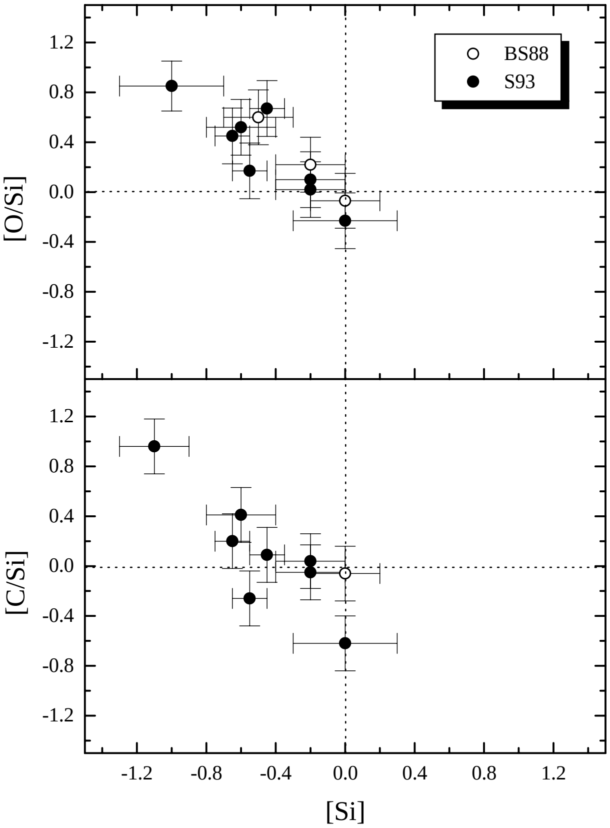

Fig. 7. The anticorrelation of the silicon and carbon as well as oxygen abundance is clearly visible. The silicon abundances were taken from Baschek & Slettebak (1988) and Stürenburg (1993)

5. Discussion

We find no correlation between the effective temperature and $\log g$ on the one hand and the carbon or oxygen abundances on the other hand. There is an indication of a marginal trend that with increasing $v \sin i$ the carbon abundance approaches the solar value (Fig. 6). A similar trend was already found for calcium by Holweger & Rentzsch-Holm (1995). For large $v \sin i$ the meridional circulation mixes material of solar composition from the stellar interior into the convection zone, so that any surface contamination due to diffusion processes or accretion of circumstellar material should vanish (Turcotte & Charbonneau 1993).

Carbon as well as oxygen reveal a strong anticorrelation with silicon (Fig. 7) which was first noted by Holweger & Stürenburg (1993) for carbon. The refractory elements Fe and Si are condensed in the dust phase of the circumstellar environment, while the volatile elements C, N, and O remain in the gaseous phase. Any preferential accretion of gas will hence lead to a [C/Si] or [O/Si] ratio larger than solar and to a reduced metallicity, [Si/H]<0 (see Fig. 7). The above noted results fit nicely in the accretion scenario for λ Bootis stars proposed by Venn & Lambert (1990). The fact that several of the λ Bootis stars have an infrared excess due to the presence of circumstellar dust and that about 50% of the λ Bootis stars reveal narrow absorption lines in Ca II K due to the presence of circumstellar gas, (Holweger & Rentzsch-Holm 1995; Hempel et al. 1998) additionally strengthens this hypothesis.

6. Conclusion

We have presented detailed non-LTE carbon and oxygen abundance determinations for a statistically significant number of well established λ Bootis stars. These abundances are based on unblended lines observed with high resolution and high signal-to-noise ratio.

The most important result is that on average carbon is *less* abundant than oxygen (Fig. 5). The mean carbon abundance is $-0.37(27)$ dex whereas the mean oxygen abundance is $-0.07(16)$ dex.

Furthermore, the anticorrelation of carbon and oxygen with the silicon abundance (first noted by Holweger & Stürenburg 1993) was proven, which strongly supports the accretion/diffusion hypothesis. As a future step, the abundances of nitrogen and sulphur (only hardly investigated in the literature) will be studied in order to check the predictions of the accretion/diffusion hypothesis.

It is also evident that abundances of Fe-peak elements for all well established λ Bootis stars are needed to provide better observational constraints for theoretical models.

Acknowledgements. This research was carried out within the working group *Asteroseismology-AMS* with funding from the Fonds zur Förderung der wissenschaftlichen Forschung, project *S7303-AST* and was partly supported by the Bulgarian National Science Foundation through grant F-603/96. Use was made of the Simbad and the Opacity Project database, operated at CDS, Strasbourg, France.

References

Andrievsky S.M., Chernyshova I.V., Klochkova V.G., Panchuk V.E., 1998, Contributions of the Astronomical Observatory Skalnaté Pleso, Vol. 27, No. 3, p. 446

Baschek B., Searle L., 1969, ApJ 155, 537

Baschek B., Slettebak A., 1988, A&A 207, 112

Baschek B., Scholz M., Sedlmayr E., 1977, A&A 55, 375

Cowley C.R., 1971, Observatory 91, 139

Cunto W., Mendoza C., Ochsenbein F., Zeippen C.J., 1993, Bull. Inform. CDS 42, p. 39

Faraggiana R., Gerbaldi M., Böhm C., 1990, A&A 235, 311

Faraggiana R., Gerbaldi M., Burnage R., 1997, A&A 318, L21

Gigas D., 1986, A&A 165, 170

Graham J.A., Slettebak A., 1973, AJ 78, 295

Gray R.O., Corbally C.J., 1993, AJ 106, 632

Griem H.R., 1968, Phys. Rev. 165, 258

Heiter U., Kupka F., Paunzen E., Weiss W.W., Gelbmann M., 1998, A&A 335, 1009

Hempel M., Holweger H., Kamp I., 1998, Contributions of the Astronomical Observatory Skalnaté Pleso, Vol. 27, No. 3, p. 246

Holweger H., Rentzsch-Holm I., 1995, A&A 303, 819

Holweger H., Stürenburg S., 1993, PASPC 44, 356

Künzli M., North P., Kurucz R.L., Nicolet B., 1997, A&AS 122, 51

Kurucz R.L., 1993, CD-ROM 1–23, Smithsonian Astrophysical Observatory

Moore C.E., 1971, Atomic Energy Levels, NSRDS-NBS 35

Napiwotzki R., Schönberner D., Wenske V., 1993, A&A 268, 653

Paunzen E., Gray R.O., 1997, A&AS 126, 407

Paunzen E., Weiss W.W., Heiter U., North P., 1997, A&AS 123, 93

Piskunov N.E., Kupka F., Ryabchikova T.A., Weiss W.W., Jeffery C.S., 1995, A&AS 112, 525

Rentzsch-Holm I., 1996, A&A 305, 275

Seaton M.J., Zeippen C.J., Tully J.A., et al., 1992, Rev. Mex. Astron. Astrofis. 23, 19

Smirnov O.M., Piskunov N.E., Afanasyev V.P., Morozov A.I., 1992, In: Worall D.M., Biemsdorfer C., Barnes J. (eds.) Astronomical Data Analysis Software and Systems. I, ASP Conf. Ser. 26, ASP, San Francisco, p. 344

Solano E., Paunzen E., 1998, A&A 331, 633

Steenbock W., Holweger H., 1984, A&A 130, 319

Stürenburg S., 1993, A&A 277, 139

Stürenburg S., Holweger H., 1990, A&A 237, 125

Takeda Y., 1992, PASJ 44, 309

Turcotte S., Charbonneau P., 1993, ApJ 413, 376

Unsöld A., 1968, Physik der Sternatmosphären. 2. Aufl., Springer Verlag, Heidelberg

Venn K.A., Lambert D.L., 1990, ApJ 363, 234

Wiese W.L., Fuhr J.R., Deters T.M., 1996, Journal of Physical and Chemical Reference Data, Monograph No.7: Atomic Transition Probabilities of Carbon, Nitrogen, and Oxygen