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Research Note

Accurate LTE abundances of seven well established λ Bootis stars*

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Abstract. High resolution and high signal-to-noise CCD spectra were analyzed to determine accurate LTE abundances for seven well established λ Bootis stars (a group of A to F-type stars with strong underabundances of Fe-peak elements whereas the C, N, O and S appear to be solar abundant): HD 31295, HD 125162, HD 142994, HD 149303, HD 192640, HD 204041 and HD 221756. In general, 13 elements were investigated. The effective temperatures of our program stars range from 7200 to 9000 K.

The main results are the following: C, O, *Na* and S seem to be nearly solar abundant for *all* investigated stars. A wide range of underabundances within the individual stars exists for all other elements.

No correlation of the individual abundances with astrophysical parameters such as $T_{\rm eff}$, log g and $v \sin i$ was found.

These results are consistent with the accretion/diffusion model which is currently adopted for the explanation of the λ Bootis phenomenon.

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

1. Introduction

λ Bootis stars are chemically peculiar (strong underabundances of Fe-peak elements whereas C, N, O and S appear to be solar abundant) Pop. I, A to F-type stars of the upper main sequence. This abundance pattern seems to be restricted to the stellar surface only.

To explain the so-called λ Bootis phenomenon, Venn & Lambert (1990) adopted an accretion hypothesis. According to this theory, the chemical peculiarity of λ Bootis stars originates from the presence of a circumstellar shell (most likely a remnant of the star formation). The circumstellar shell consists of two phases: gas and dust grains. The dust grains accumulate metals with a rather high condensation temperature (e.g. Si and Fe) whereas elements with a significant lower condensation temperature remain in the gaseous phase (e.g. C, N and O). Depleted gas from the circumstellar envelope is accreted by the star while dust grains drift out of the shell due to radiative pressure.

Further studies of the proposed accretion scenario were made by Charbonneau (1991) and Turcotte & Charbonneau (1993). They combined it with the theory of diffusion in the outer layers of the stellar atmosphere.

Since then only a few publications (e.g. Stürenburg 1993; Heiter et al. 1998) were devoted to the derivation of accurate abundances for well established members of the λ Bootis group. Because it is very important to know the apparent abundance pattern of these stars in order to put constraints on theories, we have analyzed high resolution spectra of seven well established λ Bootis stars. This should help to clarify if a typical abundance pattern exists for these stars and to derive possible correlations with other astrophysical parameters.

2. Program stars, observation and reduction

We have chosen to observe seven well established members (according to Gray & Corbally 1993) of the λ Bootis group (e.g. λ Bootis itself) in order to extend the list of known abundances for elements.

HR 6162 is not included in Gray & Corbally (1993) but we believe that this object is also a member of the λ Bootis group. This star was classified as A2Vp (λ Bootis) by Abt (1985) and as A3IV-V (wk 4481) by Paunzen & Gray (1997); Paunzen et al. (1999) derived [O] = -0.14 dex. With the abundances reported in this work, this star resembles the typical abundance pattern of the λ Bootis group.

CCD spectra for five of our program stars were obtained with the Echelle spectrometer LYNX on the 6m telescope (Special Astrophysical Observatory of the Russian Academy of Sciences, Russia, Northern Caucasus). A detailed description of this instrument is given by Panchuk et al. (1993). The resolving power is about 24000 and the obtained signal-to-noise ratio

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* Based on observations from the Special Astrophysical Observatory of the Russian Academy of Sciences, Russia, Northern Caucasus and the McDonald Observatory

Table 1. Observation log of the program stars.

HD	HR	Name	JD 2400000+	Region [Å]
31295	1570	π^1 Ori	51080.611	4700–8600
125162	5351	λ Boo	48849.330	4260–5885
142994		IN Lup	50172.917	4290–4730
149303	6162		50174.984	4290–4730
192640	7736	29 Cyg	48854.490	4985–7220
204041	8203		48857.460	4985–7110
221756	8947	15 And	48854.551	4985–7220

Table 2. The characteristics of our program stars with the estimated errors: $\sigma(v \sin i) = 10\,\mathrm{km\,s^{-1}}$; $\sigma(T_{\mathrm{eff}}) = 200$ K and $\sigma(\log g) = 0.2$ dex

HR/HD	$b-y$ [mag]	c_1 [mag]	$v \sin i$ [km s^{-1}]	T_{eff} [K]	$\log g$ [dex]
1570	0.044	1.007	105	8750	4.2
5351	0.051	1.000	100	8650	4.0
142994	0.199	0.870	120	7200	3.4
6162	0.064	1.028	200	9000	4.2
7736	0.101	0.927	80	8000	4.2
8203	0.093	0.940	65	8300	4.2
8947	0.056	1.072	100	9000	4.1

is about 100. Two program stars (HD 142994 and HR 6162) were observed with the 2.1m telescope at the McDonald Observatory using the Sandiford Cassegrain Echelle spectrograph. These spectra have a resolution of 0.035 Åpixel^{-1} and cover the spectral range of 4290 to 4730 Å with a signal-to-noise ratio of about 150. The detailed observing log is listed in Table 1.

3. Atmospheric parameters and abundance analysis

We have estimated the atmospheric parameters (effective temperature and surface gravity) by using the $(b-y) - c_1$ grid by Kurucz (1991). The Strömgren colours (Table 2) were taken from Paunzen et al. (1997). The derived values are in good agreement with other calibrations of the Strömgren (Napiwotzki et al. 1993) as well as of the Geneva (Künzli et al. 1997) system. Comparing all results we derive an error for the effective temperature of ± 200 K whereas the errors for the surface gravity is ± 0.2 dex.

The atmospheric models from Kurucz (1993) based on a microturbulence of $3\,\mathrm{km\,s^{-1}}$ were used for the calculations. Such a microturbulence was also used in the papers by Stürenburg (1993) and Heiter et al. (1998) for a temperature range of 6800 to 9300 K. These models were convolved with $v \sin i$ values (taken from Paunzen et al. 1997 and/or derived directly by matching the synthetic to the observed spectrum) for each individual star.

The STARSP code (Tsymbal 1996) was applied for the spectral synthesis. Oscillator strengths for the investigated lines were taken from the list of Kurucz (1993). For all lines we have compared the solar synthetic spectrum (solar model from Kurucz's grid, $\zeta = 1\,\mathrm{km\,s^{-1}}$, abundances from Grevesse & Noels 1993) with the observed solar flux spectrum (Kurucz et al. 1984) in order to correct the individual $\log gf$ values.

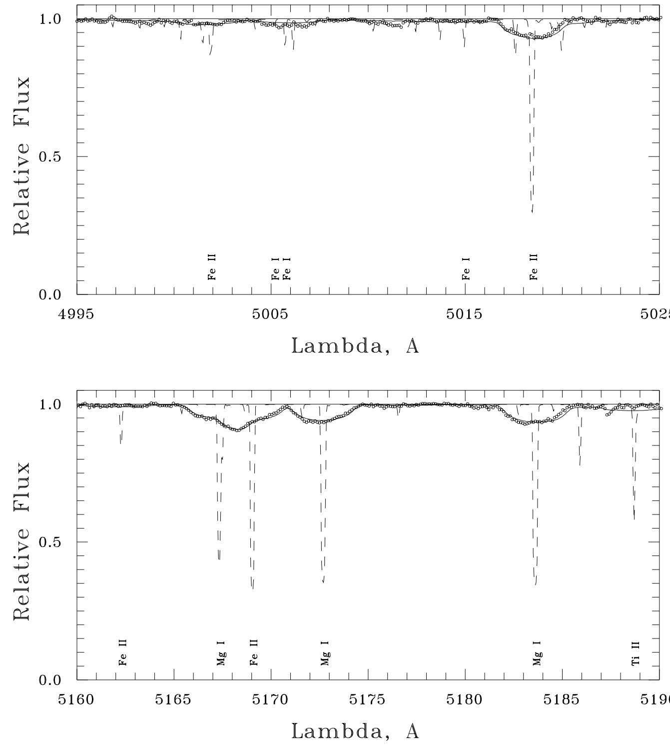

Fig. 1. Observed and synthetic spectra for HR 8947. The dashed line represents the synthetic spectrum without rotational broadening.

Table 3. Lines used for the analyis of HR 8947.

Element	lines
C I	5052.15, 5380.34
O I	6155.97, 6155.99, 6156.75, 6156.78, 6158.17, 6158.19
Mg I	5172.68, 5183.60, 5528.40
Si II	5055.98, 6347.11
Ca I	6162.17
Sc II	5526.81
Ti II	5129.15, 5188.70
Cr I	5206.04, 5208.43
Cr II	4990.44
Fe I	5139.46, 5269.54, 5324.19, 5369.97, 5404.13, 5415.20, 5586.76
Fe II	5001.96, 5018.44, 5276.00

We have not used very strong lines in order to avoid effects such as partial saturation and/or significant non-LTE corrections. For example, the Mg II 4481 Å blend was not used for the analysis. Table 3 lists the lines used for the analysis of HR 8947 (Fig. 1).

The error of the derived abundances is therefore mainly introduced by the comparison of the theoretical and observed solar flux. The uncertainties of modeling the synthetic and observed spectra of the program stars is negligible. We adopt an individual error of ± 0.2 dex for the derived abundances.

We note that for the program stars in common with the works of Venn & Lambert (1990), Stürenburg (1993) and Heiter et al.

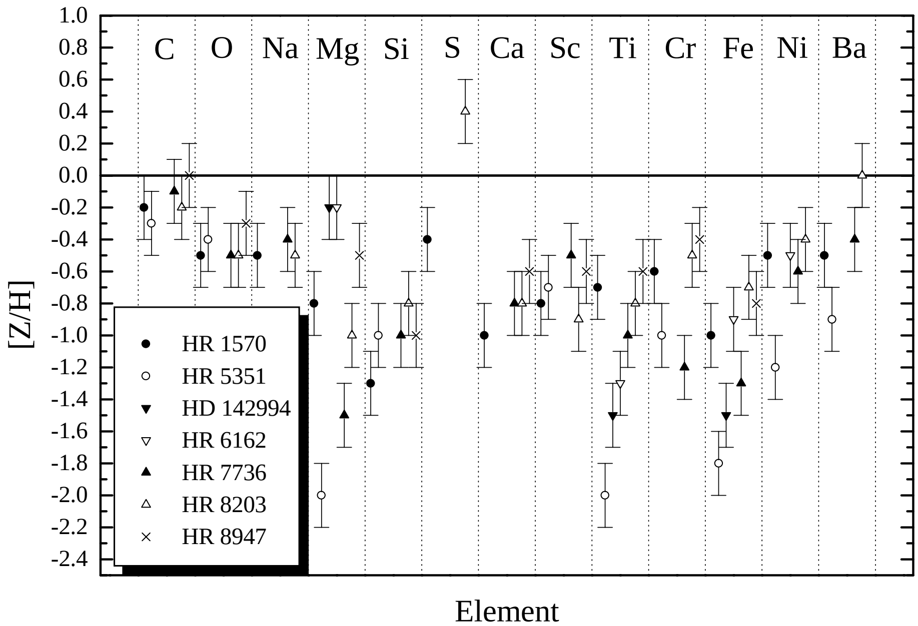

Fig. 2. The abundances from Table 4 for the seven program stars.

Table 4. Abundances of the program stars, the error of the individual abundances is ±0.2 dex. In brackets is the number of used lines for two ionization stages.

Element	HR 1570	HR 5351	HD 142994	HR 6162	HR 7736	HR 8203	HR 8947
C	−0.2 (2/0)	−0.3 (2/0)			−0.1 (3/0)	−0.2 (4/0)	+0.0 (2/0)
O	−0.5 (6/0)	−0.4 (2/0)			−0.5 (6/0)	−0.5 (6/0)	−0.3 (6/0)
Na	−0.5 (2/0)				−0.4 (4/0)	−0.5 (1/0)	
Mg	−0.8 (4/0)	−2.0 (2/0)	−0.2 (3/0)	−0.2 (3/0)	−1.5 (3/0)	−1.0 (3/0)	−0.5 (3/0)
Si	−1.3 (4/2)	−1.0 (0/1)			−1.0 (4/2)	−0.8 (0/3)	−1.0 (0/2)
S	−0.4 (4/0)					+0.4 (4/0)	
Ca	−1.0 (1/0)				−0.8 (3/0)	−0.8 (3/0)	−0.6 (1/0)
Sc	−0.8 (0/1)	−0.7 (0/2)			−0.5 (0/2)	−0.9 (0/1)	−0.6 (0/1)
Ti	−0.7 (0/2)	−2.0 (0/1)	−1.5 (2/0)	−1.3 (2/0)	−1.0 (0/2)	−0.8 (0/2)	−0.6 (0/2)
Cr	−0.6 (2/0)	−1.0 (0/3)			−1.2 (0/2)	−0.5 (3/0)	−0.4 (2/1)
Fe	−1.0 (8/8)	−1.8 (2/8)	−1.5 (3/4)	−0.9 (3/4)	−1.3 (8/6)	−0.7 (21/6)	−0.8 (7/3)
Ni	−0.5 (0/3)	−1.2 (0/1)		−0.5 (2/0)	−0.6 (6/0)	−0.4 (5/0)	
Ba	−0.5 (0/1)	−0.9 (0/1)			−0.4 (0/1)	+0.0 (0/1)	

(1998) a good agreement was achieved supporting our analysis technique. Taking for example the abundances of HR 7736 (included in all three references) one derives a typical error of about 0.25 dex for the mean differences which is in the range of our estimated error.

4. Results

Table 4 lists the result of our analysis whereas Fig. 2 shows it graphically. From the figure we are able to draw some remarkable conclusions:

– C, O, Na and S seem to be nearly solar abundant for *all* investigated stars.
– A wide range of underabundances within the individual stars exists for all other elements.

The fact that sodium shows the same abundance as C, O and S was found before (Stürenburg 1993) but was widely neglected so far. In the framework of the accretion/diffusion hypothesis this result seems not very surprising. The condensation temperature of sodium (≈1000 K) is still significantly lower than those of iron or silicon (≈1300 K). This means that the alkali silicates are more likely formed than metallic grains (Field 1974).

The fact that a wide range of underabundances within the individual stars was detected is not easy to understand. It could mean that observational parameters such as the inclination manifest if we believe that something like a disk exists around these stars. But according to the accretion/diffusion hypothesis, a migration over the entire stellar surface takes place. Note that no correlation of the abundances with $v \sin i$, $T_{\rm eff}$ or $\log g$ was found.

If we compare this result with the group of Am stars (also non-magnetic with diffusion as main process), then we find similarities. According to Wolff (1983) the abundances found within the Am group show also widely different absolute values. This was interpreted as a manifestation of the different stages of the diffusion process itself.

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