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A spectroscopic survey for λ Bootis stars

III. Final results*

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Abstract. In the third paper of a series dedicated to the spectroscopic survey for new λ Bootis stars, we present all new and confirmed members of the group as well as a detailed analysis of the observed sample. The nature of this small group of chemically peculiar stars of the upper main sequence still challenges our understanding of processes like diffusion, mass-loss and accretion. The typical abundances pattern (nearly solar values for C, N, O and S whereas the Fe-peak elements are moderate to strong underabundant) can still not be explained by any proposed theory. Hence, the significant increase of new members gives the opportunity to investigate the group properties in more detail. We report the discovery of 26 new members of the group and the confirmation of 18 candidates from the literature. This almost triples the number of known λ Bootis stars. The existence of one member in the young open cluster NGC 2264 and four members in the Orion OB1 association proves that the λ Bootis phenomenon already works at very early stages of stellar evolution. Recent results from the Hipparcos mission have shown that the well established λ Bootis stars of the Galactic field comprise the whole area from the Zero Age Main Sequence to the Terminal Age Main Sequence ($\approx 10^9$ yr for an A-type star). There is a continuous transition between very young and rather evolved evolutionary stages. We find that the overall percentage of λ Bootis type among all normal type stars in the spectral range from B8 to F4 is 2% in the Galactic field as well as in open clusters. Furthermore, 44 metal-weak objects are listed which might be connected with the λ Bootis phenomenon. Our biased sample (chosen by photometric boxes) is not distinguished from all A-type stars in the corresponding spectral region by the rotational velocity distribution. Only for the luminosity classes IV and III (especially for the cooler program stars) the determined mean $v \sin i$ values are very high compared to those of the literature.

Key words. astronomical data bases – surveys – stars: chemically peculiar – stars: early type – stars: fundamental parameters

1. Introduction

The classification of bona-fide λ Bootis stars is a difficult and sometimes misleading task. Since the work of Gray (1988) an increasing amount of interest was spent in order to find new members of this group. Gray & Corbally (1993) and Abt & Morrell (1995) announced candidates and members based on classification resolution spectra.

In total, not more than 40 "true" λ Bootis stars remained after a critical assessment of the literature (Paunzen et al. 1997). We will show in this paper that further candidates from this list had to be discarded.

The small number of known λ Bootis stars was the motivation for a whole sky spectroscopic survey for new members in the Galactic field as well as in open clusters.

In the first two papers of this series (Paunzen & Gray 1997; Paunzen et al. 2001, hereafter Papers I and II, respectively) the selection of candidates via photometric boxes, the requirements of spectroscopic observations and all individual spectral classifications were presented.

In total, 708 objects in six open clusters (NGC 2232, NGC 2264, NGC 2301, NGC 3532, NGC 6025 and NGC 6475), the Orion OB1 association and the Galactic field were observed and classified.

In Paper I we have already presented six new (HD 23392, HD 36726, HD 74873, HD 90821, HD 120500 and HD 290492) and confirmed another six (HD 64491, HD 91130, HD 105058, HD 170680, HD 171948 and HD 294253) candidates of the λ Bootis group. Furthermore, eleven good candidates have been listed.

* Based on observations from the Observatoire de Haute-Provence, Osservatorio Astronomico di Padova-Asiago, Observatório do Pico dos Dias-LNA/CNPq/MCT, Chews Ridge Observatory (MIRA) and University of Toronto Southern Observatory (Las Campanas).

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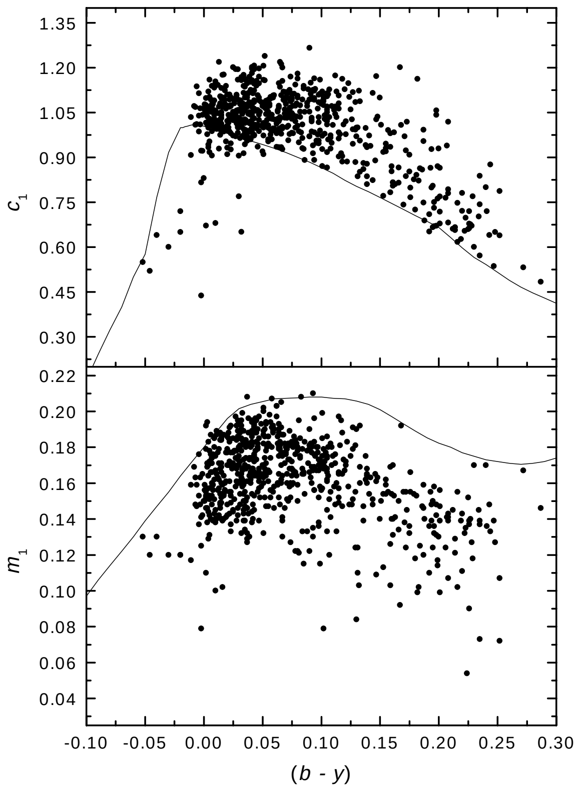

Fig. 1. c_1 versus $(b-y)$, upper panel and m_1 versus $(b-y)$, lower panel for all observed stars from Paper II. The solid lines are the standard relations from Philip & Egret (1980).

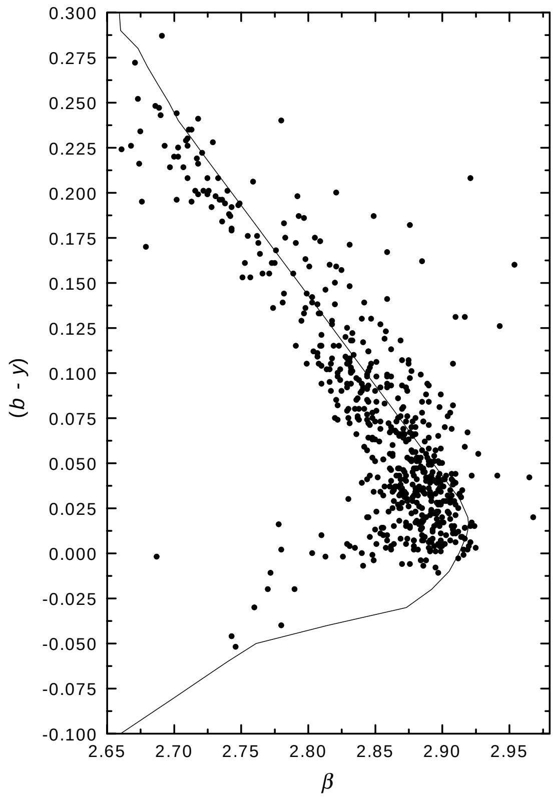

Fig. 2. $(b-y)$ versus β for all observed stars from Paper II. The solid line is the standard relation from Philip & Egret (1980).

The detailed spectral classification and a statistical investigation of the whole observed sample is given in Paper II. A comparison of our classifications with those objects in common with the work of Abt & Morrell (1995) shows an excellent agreement.

In this paper, a detailed statistical investigation of the observed sample is presented including Strömgren $uvby\beta$ photometry as well as projected rotational velocity values from the literature.

We have identified 26 new members of the group and are able to confirm 18 candidates from the literature. Furthermore, many metal-weak objects were found which might be closely connected to this group.

2. The observed sample and its properties

Since the observed candidates are selected via their photometric properties in the Strömgren $uvby\beta$ system, the sample is not bias free. As it is shown in Paper II, the distribution on the sky is uniform with lack of suitable objects between $+75^{\circ} < b < +90^{\circ}$ and $-75^{\circ} < b < -90^{\circ}$. Most of the stars lie in the magnitude range $6 < V < 7$ mag.

In total, 708 candidates are included in our sample. Observations were obtained in six open clusters (NGC 2232, NGC 2264, NGC 2301, NGC 3532, NGC 6025 and NGC 6475), the Orion OB1 association and the Galactic field.

Table 1. Rotational velocity distribution of the observed sample (Paper II) and of all "normal" stars from Abt & Morrell (1995), AM95.

	this work			AM95		
	A0–A1			A0–A1		
	V	IV	III	V	IV	III
n	79	27	4	188	60	45
$<v \sin i>$	121	99	80	142	62	52
s.e.	66	74	76	65	48	55
	A2–A4			A2–A4		
	V	IV	III	V	IV	III
n	60	17	3	242	84	25
$<v \sin i>$	118	104	158	131	62	68
s.e.	64	85	129	62	51	68
	A5–F0			A5–F0		
	V	IV	III	V	IV	III
n	17	7	2	234	79	54
$<v \sin i>$	118	155	198	125	89	73
s.e.	57	68	74	50	44	36

Figure 1 shows the c_1 versus $(b-y)$ and m_1 versus $(b-y)$ diagrams for the program stars. The majority of apparent normal type stars between $-0.050 < (b-y) < +0.100$ mag is obvious. There is also a group of objects with $(b-y) > +0.100$ mag lying just on the edge to the normal type stars. However, a large number of stars

Table 2. New and confirmed λ Bootis stars from the spectroscopic survey. Classifications in parentheses indicate stars in which the λ Bootis characteristics are mild.

HD	HR	HIP	ADS	Spectral Type	V	$b-y$	m_1	c_1	β	$v \sin i$	Status
6870		5321		hF0mA1 V λ Boo	7.48	0.153	0.154	0.771	2.757	165	C
7908		6108		hF0mA3 V λ Boo	7.30	0.192	0.136	0.652	2.728		N
13755		10304		hF2mA5 V λ Boo	7.84	0.181	0.153	0.841			N
23392		17462		A0 Va λ Boo	8.26	0.014	0.154	0.975	2.917		N
24472		18153		hF2mA7 V (λ Boo)	7.09	0.214	0.129	0.666	2.697		N
35242	1777	25205		hA3mA1 Va λ Boo	6.34	0.067	0.175	0.999	2.866	90	N
36726			4156	kA0hA5mA0 V λ Boo	8.81	0.043	0.164	0.975	2.922	80	N
54272				kA5hF2mA5 V λ Boo	8.80	0.214	0.121	0.657	2.707		N
64491	3083	38723		kA3hF0mA3 V λ Boo	6.23	0.196	0.132	0.669	2.734	45	C
74873	3481	43121		kA0.5hA5mA0.5 V λ Boo	5.89	0.064	0.188	0.934	2.890	130	N
75654	3517	43354		hF0mA5 V λ Boo	6.38	0.161	0.140	0.816	2.753	45	C
81290		46011		kA5hF3mA5 V (λ Boo)	8.86	0.252	0.107	0.639	2.673	55	C
83041		47018		kA2hF2mA2 V (λ Boo)	8.80	0.230	0.104	0.725	2.705	95	C
83277		47155		kA3hF2mA3 V (λ Boo)	8.30	0.220	0.111	0.721	2.700		N
84123		47752		kA6hF1mA6 V (λ Boo)	6.84	0.235	0.073	0.743	2.713	15	C
84948		48126		kA6hF1mA6 V (λ Boo)	8.14	0.196	0.136	0.750	2.702	45	C
90821				hA2hA7mA2 Vn λ Boo	9.20	0.068	0.176	1.092	2.865	135	N
91130	4124	51556	7813	A0 V λ Boo	5.90	0.073	0.158	1.035	2.854	135	C
101108		56768	8246	A3 IV-V (λ Boo)	8.83	0.115	0.157	0.963		90	C
102541		57567		kA5hF0mA5 V λ Boo	7.94	0.163	0.141	0.810	2.798		N
105058		58992		A1hA5mA1 V λ Boo	8.89	0.129	0.124	0.993		130	C
106223		59594		kA3hF3mA3 V (λ Boo)	7.42	0.226	0.090	0.678	2.668	100	C
109738				kA1hA9mA1 V λ Boo	6.35	0.165	0.129	0.864	2.778	165	N
111005		62318	8662	hF0mA3 V λ Boo	7.95	0.223	0.135	0.698		140	N
120500		67481		kA2hA5mA2 V λ Boo	6.60	0.069	0.171	1.060	2.871	125	N
120896		67705		kA6hF0mA6 V λ Boo	8.50	0.166	0.150	0.815	2.764		N
125889				kA4hF2mA4 V (λ Boo)	9.82	0.206	0.124	0.765	2.759		N
130767		72505		A0 Va λ Boo	6.91	0.002	0.179	1.064	2.919		N
148638		81039		hA7mA2 V λ Boo	7.90	0.129	0.155	1.085	2.818		N
149130		81329		kA7hF0mA7 V λ Boo	8.49	0.229	0.118	0.770	2.709		N
153747		83410		hA7mA0 V λ Boo	7.41	0.098	0.136	1.034	2.859		N
154153	6338	83650		hF0mA5 V (λ Boo)	6.18	0.199	0.114	0.762	2.718		C
156954		84895		hF1mA5 V (λ Boo)	7.67	0.201	0.139	0.679	2.726	50	C
168740	6871	90304		hA7mA2 V λ Boo	6.13	0.136	0.139	0.881	2.798	150	C
168947				kA3hF0mA3 V λ Boo	8.10	0.172	0.124	0.923	2.791		N
170680	6944	90806	11411	A0 Van (λ Boo)	5.12	0.006	0.140	1.052	2.892	215	C
171948		91234	11498	A0 Vb λ Boo	6.76					15	C
175445		92884		hA5mA2 V λ Boo	7.79	0.055	0.167	1.052			N
184779				kA4hF1mA4 V (λ Boo)	8.90	0.184	0.125	0.863	2.736		C
191850				kA4hF0mA4 V λ Boo	9.62	0.166	0.134	0.866			N
216847		113351		hF0mA3 Vn λ Boo	7.06	0.155	0.154	0.946	2.766		N
261904				A0.5 V (λ Boo)	10.20	0.040	0.160	0.960	2.890		N
290492			4211	A0.5 Vb (λ Boo)	9.27	0.084	0.133	0.931	2.851	70	N
294253				B9.5 Va (λ Boo)	9.69	0.023	0.133	0.926	2.904		C

between $+0.100 < (b-y) < +0.250$ mag should be definitely metal-weak. But with the exception of some rapid rotators with a higher luminosity (Table 1), almost no star shows any detectable metal-weakness at all. The reason for this is not clear at first sight, but one tends to give some (heuristic) answers:

- Measurement errors for the Strömgren $uvby\beta$ colors;
- Influence of rapid rotation on the Strömgren $uvby\beta$ colors;
- Significant reddening influences this domain;
- Classification resolution spectroscopy is not able to detect only mild metal-weakness;
- There is a continuous transition of λ Bootis to normal type stars in this domain;
- Undetected spectroscopic binary systems.

Taking $(b-y) = +0.100$ mag as limit, then 22 λ Bootis stars are redder and 45 are bluer. If we assume that reddening does not significantly affect the program stars then the λ Bootis group comprises only about 4% of all stars in the selected photometric box at $(b-y) < +0.100$ mag, but more than 30% in the same domain at $+0.100 < (b-y) < +0.250$ mag. If reddening severely affects the program stars, this percentage gets even higher because the estimated reddening for the λ Bootis stars in this domain is

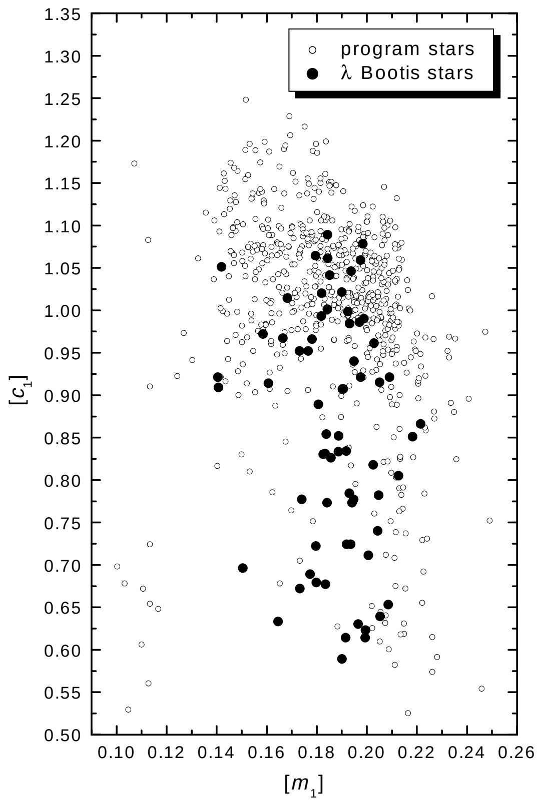

Fig. 3. $[c_1]$ versus $[m_1]$ for all program (open circles) and well established λ Bootis stars (filled circles).

almost negligible (Faraggiana & Bonifacio 1999). This is also support by Fig. 2 which shows the $(b-y)$ versus β diagram for the program stars.

In order to test if reddening has a significant effect upon the candidate selection and classification, the reddening free parameters $[c_1] = c_1 - 0.20(b-y)$ and $[m_1] = m_1 + 0.33(b-y)$ were used. Figure 3 shows the $[c_1]$ versus $[m_1]$ diagram for all program and well established λ Bootis stars. For the domain with $[c_1] < +0.85$ mag the λ Bootis stars still comprise about 30% of all objects. This clearly suggests that reddening does *not* affect the statistics in this photometric range.

Since the rotational velocity was often used to distinguish λ Bootis from other stars (Gray 1988), the rotational velocity distribution of the observed sample to that of "normal" type stars from Abt & Morrell (1995) was compared. This should help to decide if λ Bootis stars form a separate group among high-$v \sin i$ stars (Gray 1988). Thus yielding a connection between "normal" type high-$v \sin i$ and peculiar λ Bootis stars.

Table 1 lists the results for different luminosity classes. The mean values for the luminosity class V are in good agreement with that of all normal stars from Abt & Morrell (1995). The biased sample (chosen by photometric boxes) is therefore not distinguished from all A-type stars by the rotational velocity distribution. This seems not true for the luminosity classes IV and III (especially for the cooler program stars). The determined mean $v \sin i$ values are very high (compared to the mean derived for all A-type stars from Abt & Morrell 1995) indicating that the evolved stars in the given box exhibit all high-$v \sin i$ values. However, it cannot be proved if this is an intrinsic effect due to rotation itself.

Table 3. Investigated clusters and associations in order to find new λ Bootis stars from Gray & Corbally (1998, 1999) and this survey. The ages are taken from Lyngå (1987).

Cluster	$\log t$	λ Boo	Cluster	$\log t$	λ Boo
NGC 2264	7.00	1	NGC 2301	8.19	no
Orion OB1	7.00	4	Stock 2	8.23	no
IC 1396	7.23	no	NGC 1039	8.26	no
IC 348	7.26	no	NGC 7039	8.38	no
NGC 7160	7.36	no	NGC 3532	8.40	no
NGC 2232	7.58	no	NGC 7063	8.42	no
IC 4665	7.58	no	NGC 7092	8.61	no
NGC 6025	7.75	no	NGC 6633	8.66	no
NGC 7243	7.90	no	NGC 7209	8.69	no
α Per	7.90	no	IC 4756	8.78	no
Pleiades	7.92	no	Hyades	8.80	no
NGC 6475	8.11	no	Praesepe	8.84	no

3. New and confirmed λ Bootis stars

The main result of the spectroscopic survey are, of course, the new and confirmed members of the λ Bootis group. Besides the paper of Gray & Corbally (1993), all candidates in the literature were reobserved in order to establish a membership to this group. Based on the observations, we were able to identify 26 new λ Bootis stars and confirm the membership of 18 stars (Table 2). This yields an overall detection rate of about 6% in the chosen photometric boxes. A rather surprising low percentage compared to the total number of other peculiar stars in this spectral domain.

In the following paragraphs, the new and confirmed λ Bootis stars have been discussed in more detail. The following objects have been already described in Paper I: HD 23392, HD 36726, HD 64491, HD 74873, HD 90821, HD 91130, HD 101108, HD 105058, HD 120500, HD 170680, HD 171948, HD 290492 and HD 294253.

HD 6870: This δ Scuti type pulsator was found as photometric candidate by Hauck (1986).

HD 7908: Lance (1988a,b) had this star in her sample of high-velocity A stars. Her parameters given for this star are: $T_{\rm eff} = 7300$ K, $\log g = 4.11$ dex, $M_V = 2.39$ mag and $\log t = 8.80$. She addresses this object as being Population I.

HD 13755: The hydrogen lines and metallic-line morphology match the F2 V standard very well. However, metals are clearly weak.

HD 24472: Gray (1989) classified this star as F3 V m−2; the actual classification is hF2mA7 V (λ Boo).

HD 35242: Abt & Morrell (1995) classified this star as A1 Vp (wk 4481).

HD 54272: Very metal-weak star, no other quotations in the literature were found.

HD 75654: Discovered as as photometric candidate by Hauck (1986).
HD 81290: Clearly metal-weak, photometry does not support a possible intermediate Population II nature.
HD 83041: Very similar to HD 81290.
HD 83277: A very cool λ Bootis star similar to HD 107233. No other quotations in the literature were found.
HD 84123: The classification of this star is kA6hF1mA6 V (λ Boo). It was found as a photometric candidate by Hauck (1986). Heiter (2001) confirms abundances typical for most of the λ Bootis stars.
HD 84948: This spectroscopic binary system (Paunzen et al. 1998) was classified as F0 V wl (λ Boo) by Abt (1984).
HD 102541: Very weak metallic-line spectrum for the hydrogen line type.
HD 106223: A long list of controversial spectral types in the literature can be found (see Gray 1989). Neither photometric nor kinematic data support a possible intermediate Population II nature. It was therefore taken as member of the λ Bootis group with a classification as kA3hF3mA3 V (λ Boo).
HD 109738: An extreme metal-weak λ Bootis star.
HD 111005: Classified as kA4hF0mF1 by Abt (1981) and as hF0mA3 V λ Boo in this work.
HD 120896: Only mildly metal-weak.
HD 125889: Cool λ Bootis star classified as kA4hF2mA4 V (λ Boo).
HD 130767: Very similar to λ Bootis itself.
HD 148638: This rather bright visual binary system is wide separated ($23''$).
HD 149130: Only mildly metal-weak. The Michigan catalogue lists A8wl as spectral type.
HD 153747: Desikachary & McInally (1979) classified this δ Scuti pulsator as A1 IV (the HD spectral type is B9). Photometry supports the estimated spectral classification as hA7mA0 V λ Boo.
HD 154153: Gray (1989) lists F1 V m-2.5, again a borderline case between intermediate Population II and λ Bootis nature: hF0mA5 V (λ Boo).
HD 156954: Abt et al. (1979) list F0 Vwl as spectral type. Hauck (1986) confirmed a possible membership via Geneva photometry, the derived classification is hF1mA5 V (λ Boo).
HD 168740: Hauck (1986) found it as a photometric candidate, the derived classification is hA7mA2 V λ Boo.
HD 168947: Eggen (1982) suggested that this visual binary system (B-type companion; $d = 5.5'$) has not yet arrived at the Zero Age Main Sequence.
HD 175445: This star is very similar to HD 120500.
HD 184779: A very cool λ Bootis star similar to HD 107233.
HD 191850: The spectral type given in the Michigan catalogue is A2 II/III, already an indication for a probable membership to the λ Bootis group, the derived classification: kA4hF0mA4 V λ Boo.
HD 216847: The hydrogen lines agree very well with F0, although it is a very rapid rotator, it is clearly metal-weak: hF0mA3 Vn λ Boo.
HD 261904: NGC 2264 #138, confirmed as mild λ Bootis star by Gray & Corbally (1998).
Besides the list of well established λ Bootis stars from Gray & Corbally (1993) the following five stars are also considered as members of this group: HD 15165, HD 87271, HD 105759, HD 110377, HD 111604. A detailed description of their properties and references found in the literature are given in Paunzen (2000).

Among our sample several stars showing a weak Mg II 4481Å line and/or an abnormal metallic line spectrum were found. Such a peculiarity is ambiguous (Paper I) and not the main criterion for a λ Bootis type. These stars deserve therefore further attention. Additional observations with a higher resolution are needed for an unambiguous spectral classification, but, mainly due to the otherwise normal metallic-line spectrum, one is definitely able to rule out a membership to the λ Bootis group. The following objects have been already described in Paper I: HD 23258, HD 39421, HD 66684, HD 74911, HD 105199, HD 149303 and NGC 2264 #87. The other objects showing this peculiarity are:
BD +33 2070: *kA0hA3IVpn (wk 4481)*, very unusual spectrum showing metal-weakness but also a very strange overall metallic-line spectrum.
BD +33 2171: *kA1hF2mA1 V:*, classified as intermediate Population II type star.
HD 4158: *hF3mF0 V (wk met)*, this very cool star is clearly metal-weak.
HD 5524: *A3 V (wk met)*, this star is only marginally metal-weak.
HD 7804: *A3 V (wk met)*.
HD 8511: *F0 IVn (wk met)*, this rapid rotator is only marginally metal-weak.
HD 23728: *F0 IV (wk met)*.
HD 35860: *A1 Va (wk 4881)*, besides only a weak Mg II 4481Å line, the metallic line spectrum seems normal.
HD 39551: *A3 IIIn (wk 4481)*, this subgiant is clearly metal-weak.
HD 40588: *A1 Va (sl wk 4481)*, besides only a marginally weak Mg II 4481Å line, the metal-line spectrum seems normal.
HD 42533: *A1 V (wk 4481)*.
HD 43950: *F0 IV (wk met)*.
HD 44125: *A3 V (wk met)*.
HD 51693: *A3 V (wk met)*.
HD 57133: *F0 IV (wk met)*.
HD 57514: *A7 III (wk 4481)*, this subgiant shows only a marginally weak Mg II 4481 line.
HD 58666: *A5 IV (wk met)*, this subgiant is only marginally metal-weak.
HD 67262: *F5 V (wk met)*, this star is probable an intermediate Population II object.
HD 70549: *A7 V (wk met)*, this star is only marginally metal-weak.

HD 74558: *A7IV (wk met)*, this subgiant is only marginally metal-weak.
HD 83965: *kA2hA4mA3 IV*, proto Am star.
HD 86986: *A1 V (wk 4481)*.
HD 90816: *A5IV (wk met)*.
HD 94479: *F0 V (wk met)*, this star is only marginally metal-weak.
HD 100311: *A3 V (wk 4481)*, besides only a weak Mg II 4481Å line, the metallic line spectrum seems normal.
HD 100740: *kA4hA8mA5 V*, the Mg II 4481Å line seems normal, otherwise metal-weak.
HD 103483: *kA2hA5mA3 V*, this star is only marginally metal-weak.
HD 107740: *A6 V (sl wk 4481)*, besides only a marginally weak Mg II 4481Å line, the metal-line spectrum seems normal.
HD 108765: *kA3hA3mA0 V*, this star is only marginally metal-weak. HD 126441: *F1 V (wk met)*.
HD 126969: *A6 V (sl wk 4481)*, besides only a marginally weak Mg II 4481Å line, the metallic line spectrum seems normal.
HD 129231: *A3 V (wk 4481)*.
HD 131752: *A2 V (sl wk met)*, this star is only marginally metal-weak.
HD 131777: *A1 V (wk met)*, this star is only marginally metal-weak.
HD 133716: *A2 V (sl wk met)*.
HD 159441: *F5 V (wk met)*.
HD 160928: *A2IV (wk met)*, this subgiant is only marginally metal-weak.
HD 167231: *A2IV (wk met)*.
HD 177406: *A2IV (wk met)*.
HD 181998: *hF2mA3 V*, this suspected γ Dor variable seems to be evolved.
HD 182490: *hF2mA3 V*, this star is probable an intermediate Population II object.
HD 185905: *A5 V (wk met)*, this star is only marginally metal-weak.
HD 214172: *A1 V (wk met) PHL*, the metallic line spectrum is only marginally weak. The hydrogen lines are very broad.
HD 217498: *A3 V (wk met)*.
HD 218108: *A3 V (wk 4481)*.
HD 224213: *F0 IVn (wk met)*, this rapid rotating subgiant is only marginally metal-weak.

4. Incidence and time scale of the λ Bootis phenomenon

In order to establish upper and lower limits for a time scale of the λ Bootis phenomenon, members of open clusters for our spectroscopic survey were selected. All given parameters for the open clusters and associations are from Lyngå (1987). Stars were observed in NGC 2232 ($\log t = 7.59$), NGC 2264 ($\log t = 6.99$), NGC 2301 ($\log t = 8.19$), NGC 3532 ($\log t = 8.40$), NGC 6025 ($\log t = 7.75$) and NGC 6475 ($\log t = 8.11$). Furthermore, candidates in the Orion OB1 association ($\log t = 7.00$) were investigated. Only one new member of the λ Bootis group in NGC 2264 and three new in the Orion OB1 association were detected. Gray & Corbally (1998, 1999) performed a much more extensive search for new λ Bootis stars in open clusters. Table 3 lists the observed clusters and the number of found λ Bootis stars. Interesting enough, only five λ Bootis stars in one open cluster and association (NGC 2264 and Orion OB1) were detected. In total, 24 clusters with ages from 10^7 to 7×10^8 yr were investigated. The only reliable conclusion from Table 3 is: "*Young λ Bootis stars do exist*". All other conclusions are pure speculation due to the unknown completeness of the observed sample. Not having found any λ Bootis stars in these clusters does not mean that they do not exist. Another reason for the lack of λ Bootis stars in open clusters might be the different conditions at early evolutionary stages in clusters compared to the Galactic field.

Table 4. Distances reached for a given absolute magnitude M_V and constant visual magnitudes $V_\#$ (V_5 means $V = 5$ mag) as well as the corresponding magnitude-spectral distribution of disc stars in the solar neighbourhood from Robin & Crézé (1986).

M_V	V_5	V_6	V_7	Stars pc^{-3}
0.0	100	158	251	8.000 E-06
0.5	79	126	200	1.660 E-05
1.0	63	100	158	8.200 E-05
1.5	50	79	126	1.408 E-04
2.0	40	63	100	1.760 E-04
2.5	32	50	79	3.580 E-04
3.0	25	40	63	3.700 E-04

Table 5. Number of stars within a given distance and corresponding space volume using the magnitude-spectral distribution from Table 4. The last four columns list the apparent visual magnitudes for the corresponding absolute magnitudes in order to reach the given distance ($V_{0.0}$ means the estimated visual magnitude V for an absolute magnitude $M_V = 0.0$ mag).

r	$\#_{\rm stars}$	$V_{0.0}$	$V_{1.0}$	$V_{2.0}$	$V_{3.0}$
12.5	9	0.48	1.48	2.48	3.48
25.0	75	1.99	2.99	3.99	4.99
37.5	254	2.87	3.87	4.87	5.87
50.0	602	3.49	4.49	5.49	6.49
62.5	1176	3.98	4.98	5.98	6.98
75.0	2032	4.38	5.38	6.38	7.38
87.5	3227	4.71	5.71	6.71	7.71
100.0	4817	5.00	6.00	7.00	8.00
112.5	6859	5.26	6.26	7.26	8.26
125.0	9408	5.48	6.48	7.48	8.48
137.5	12523	5.69	6.69	7.69	8.69
150.0	16258	5.88	6.88	7.88	8.88

Table 6. Distances for all well established λ Bootis stars from Gray & Corbally (1993), Paunzen (2000) and Table 2. The values were derived from the Hipparcos database or photometrically (stars with an asterisk). In parentheses are the errors in the final digits of the corresponding quantity.

HD	V [mag]	r [pc]	HD	V [mag]	r [pc]
319	5.93	80(5)	109738*	6.35	86(5)
6870	7.48	97(6)	110377	6.22	68(4)
7908	7.30	88(8)	110411	4.88	37(1)
11413	5.94	75(4)	111005	7.95	174(31)
13755*	7.84	186(12)	111604	5.87	119(10)
15165	6.70	118(12)	111786	6.14	60(3)
23392*	8.26	229(16)	120500	6.60	143(19)
24472*	7.09	105(6)	120896	8.50	205(48)
30422	6.18	57(2)	125162	4.18	30(1)
31295	4.64	37(1)	125889*	9.82	316(23)
35242	6.34	75(6)	130767	6.91	128(13)
290492*	9.27	279(20)	142703	6.11	53(2)
36726*	8.81	259(18)	142994*	7.18	191(13)
290799*	10.63	400(31)	148638*	7.90	327(24)
294253*	9.69	472(37)	149130*	8.49	268(19)
261904*	10.20	594(49)	153747	7.41	188(35)
54272*	8.80	201(14)	154153	6.18	66(5)
64491	6.23	60(3)	156954*	7.67	108(6)
74873	5.89	61(4)	168740	6.13	71(4)
75654	6.38	78(4)	168947*	8.10	231(16)
81290*	8.86	252(18)	170680	5.12	65(3)
83041*	8.80	268(19)	175445*	7.79	205(14)
83277*	8.30	222(15)	183324	5.79	59(3)
84123	6.84	110(11)	184779*	8.90	372(28)
87271	7.13	147(19)	191850*	9.62	421(33)
90821*	9.20	492(39)	192640	4.93	41(1)
91130	5.90	75(4)	193256*	7.72	200(13)
101108*	8.83	305(22)	193281	6.56	218(76)
102541*	7.94	123(7)	198160	5.67	73(6)
105058	8.89	188(37)	204041	6.45	87(8)
105759*	6.55	102(6)	210111	6.37	79(6)
106223	7.42	110(10)	216847	7.06	148(15)
107233*	7.36	92(5)	221756	5.55	72(3)

Recent results from the Hipparcos mission have shown (Gómez et al. 1998; Paunzen 2000; this work can be requested from the author) that the well established λ Bootis stars of the Galactic field comprise the whole area from the Zero Age Main Sequence to the Terminal Age Main Sequence ($\approx 10^9$ yr for an A-type star). There seems to be no "gap" between very young and rather evolved evolutionary stages (as already suggested by Gray & Corbally 1998).

Note that the diffusion/accretion theory (Michaud & Charland 1986) predicts very young whereas the diffusion/mass-loss theory (Turcotte & Charbonneau 1993) predicts rather evolved λ Bootis stars. The other two formulated theories (Andrievsky 1997; Faraggiana & Bonifacio 1999) do not depend upon any particular ages. Do we see two different astrophysical mechanisms working at different evolutionary stages of a star but manifesting in the same way? A very fascinating idea but not provable up to now. The role of evolved λ Bootis stars was already discussed extensively by Gray (1988). Evolved in this context means a giant or subgiant object which corresponds to a luminosity class of I to IV. He proposed four candidates from the literature: HD 89353, HD 97411, HD 106223 and HD 130158. HD 106223 is classified as λ Bootis star in this work (the luminosity class is V). HD 89353 is a well investigated post-AGB star (van Winckel et al. 1995). HD 97411 seems to be a normal late B-type star (Edwards 1976) whereas HD 130158 is classified as A0 III (wk 4481) in Paper II.

The estimation of the percentage of λ Bootis stars among all Galactic field stars is important in order to put constraints for theories explaining this phenomenon. The incidence of λ Bootis stars is strongly depending on the completeness of accurate classification spectroscopy available for a given visual magnitude range.

Gray & Garrison (1987) included in their work a complete sample of stars from the Bright Star Catalogue and its Supplement (Hoffleit & Jaschek 1982) brighter than $V = 5.0$ mag with spectral types from B8 to F2. In addition, some stars fainter than that were also included in their sample. Abt & Morrell (1995) classified all A-type stars from the Bright Star Catalogue with $-30^{\circ} < \delta < +70^{\circ}$. Taking into account the results from the Michigan spectral catalogue (Houk 1978, 1982; Houk & Cowley 1975; Houk & Smith-Moore 1988), the limiting magnitude for a complete sample of appropriate spectral classifications is between 6.5 and 7.0 mag.

First of all, the number of stars within a given volume depending on the spectral type in the solar neighborhood has to be determined. We have used the magnitude-spectral distribution of disc stars in the solar neighborhood from Robin & Crézé (1986) for $0.0 < M_V < 3.0$ mag (roughly B8 to F4) and the simple relation:

$$M_V - m_V = 5 \log r - 5.$$

The apparent interstellar reddening was not considered since we are only interested in distances up to 150 pc from the Sun. Table 4 lists the distances reached for a given absolute magnitude and constant visual magnitudes. If we take $V = 7.0$ mag as limit then the sample is complete up to roughly 60 pc for objects as late as F4. Table 5 lists the number of stars within a given distance and corresponding volume using the magnitude-spectral distribution from Robin & Crézé (1986).

The distances for the well established λ Bootis stars have been taken from Paunzen (2000). A detailed description of the estimation can be found therein. Table 6 lists these distances with the corresponding errors.

The percentage of λ Bootis stars among all Galactic field stars in the corresponding distance is derived as:

- 25 to 50 pc: 1.6%
- 50 to 75 pc: 1.4%
- 75 to 100 pc: 0.8%
- 100 to 125 pc: 0.5%
- 125 to 150 pc: 0.3%.

This means that the λ Bootis stars comprise only a maximum of about 2% of all Galactic field stars of the spectral domain between B8 and F4. Gray & Corbally (1998) derived a percentage of 2% for λ Bootis stars among Pre-Main-Sequence objects. This is in very good agreement with the value given above.

From a theoretical point of view two main explanations might be mentioned for these very low numbers:

- The λ Bootis phenomenon has a very short lifetime ($\approx 10^6$ yr) independent of the evolutionary status;
- The constraints for the development of the λ Bootis phenomenon are very tight.

However, it seems that the mechanism producing the peculiarities is much more complex than just diffusion together with accretion or mass-loss.

5. Conclusion

As a final result of our spectroscopic survey for new λ Bootis stars, 26 newly discovered λ Bootis stars and the confirmation of 18 candidates are reported. Furthermore, 44 metal-weak objects have been discovered which might be connected to this group. In total, more than 700 stars were classified.

The detection rate of the chosen photometric box is on average 6% but strongly increases at $(b-y) > 0.100$ mag. We were able to show that this result is not affected by interstellar reddening.

The biased sample (chosen by photometric boxes) is not distinguished from all A-type stars by the rotational velocity distribution. Only for the luminosity classes IV and III (especially for the cooler sample) the determined mean $v \sin i$ values are very high compared to the mean derived for all A-type stars from Abt & Morrell (1995).

The overall percentage of λ Bootis among normal type stars is about 2% in the Galactic field and open clusters.

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