The Astronomical Journal, 124:989–1000, 2002 August

A SPECTROSCOPIC SEARCH FOR λ BOOTIS AND OTHER PECULIAR A-TYPE STARS IN INTERMEDIATE-AGE OPEN CLUSTERS

R. O. Gray
Department of Physics and Astronomy, Appalachian State University, Boone, NC 28608; grayro@appstate.edu

and

C. J. Corbally
Vatican Observatory Research Group, Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721-0065; ccorbally@as.arizona.edu
Received 2001 August 30; accepted 2002 May 2

ABSTRACT

As part of our continuing search for peculiar A-type stars, especially λ Bootis stars, in open clusters of all ages, we have obtained classification spectra of 130 late B, A, and early F-type stars in 12 intermediate-age open clusters, including NGC 1039, 2281, 2548, 6633, 7039, 7063, 7092, and 7209, IC 4665, IC 4756, Stock 2, and Praesepe. The spectra were obtained with resolutions of 1.8 and 3.6 Å on the 0.8 m telescope of Appalachian State University and were classified on the MK system. Numerous classical Ap and Am stars were found among the 130, including two new Ap stars in NGC 7092. In addition, three emission-line stars and two candidate λ Bootis stars were found. Neither of these λ Bootis candidates turned out to be members of their respective clusters. Combined with 184 stars previously classified in 10 other intermediate-age open clusters, also devoid of λ Bootis stars, a statistically significant null result is obtained. We discuss the implications of this null result for our understanding of the λ Bootis mechanism.

Keywords: stars: atmospheres — stars: evolution — stars: fundamental parameters — stars: individual (λ Bootis) — stars: statistics

1. INTRODUCTION

The λ Bootis stars, first discovered by Morgan, Keenan, & Kellman (1943), are a set of Population I A-type stars that show pronounced deficiencies of the iron-peak elements by as much as 2 dex, but nearly solar abundances of C, N, O, and S. Nearly all λ Bootis stars have been discovered by the technique of spectral classification (see references in Gray & Corbally 1998); approximately 50 λ Bootis stars are now known. Approximately 2% of the field A-type stars are members of this class (see § 4).

The identification of the evolutionary state of these astrophysically challenging stars has been of vital importance since they were first discovered. A current theory that attempts to explain these stars (Venn & Lambert 1990) was motivated by the similarity of the abundance pattern in λ Bootis stars to that of the interstellar medium where refractory elements become locked up in grains whereas the less refractory elements (C, N, O, and S) remain in the gas phase. This theory invokes the accretion of metal-depleted gas onto the photospheres of these stars to explain the observed underabundances. The accretion rate required to produce the observed underabundances above the base of the superficial convection zones of these stars (which are confined to the spectral type range B9.5–F0?) is only 10^{-13} $M_\odot$ yr^{-1} (Charbonneau 1993). However, once the accretion stops, the metal deficiencies will be erased in 10^6 yr (Charbonneau 1993; Turcotte & Charbonneau 1993). This theory suggests that λ Bootis stars should be quite young A-type stars (pre–main sequence or zero-age main sequence) still associated with gas and dust.

To test this theory, Gray & Corbally (1998) obtained spectra of 60 Herbig Ae and cluster pre–main-sequence (PMS) A-type stars. Surprisingly, they discovered only one bona fide λ Bootis star (HD 37411) and one marginal λ Bootis star among this sample, yielding a frequency of approximately 2%, similar to the proportion in the field. In addition, they pointed out that the space distribution of field λ Bootis stars and the fact that most field λ Bootis stars are found far from any star formation region indicated an average age of a few × 10^8 yr for those stars. Indeed, if one uses *Hipparcos* (ESA 1997) absolute magnitudes to plot known λ Bootis stars on the theoretical H-R diagram, it is clear that essentially all λ Bootis stars lie between the zero–age main sequence (ZAMS) and the terminal-age main sequence (TAMS) (see Fig. 2 in Paunzen 1997, although the conclusion in that paper is that all λ Bootis stars are PMS objects). This rather curious situation led Gray and Corbally to suggest that a star becomes a λ Bootis star shortly before it arrives on the ZAMS and then maintains its λ Bootis character well into its main-sequence life by slow, steady accretion of metal-depleted gas from a persistent circumstellar disk. Support for this hypothesis can be found in the fact that a significant proportion of the brighter λ Bootis stars are dusty "Vega-like" stars. For instance, of the four λ Bootis stars within 40 pc (λ Boo itself, π^1 Ori, ρ Vir, and HR 8799; see § 4), all show infrared excesses indicative of circumstellar dust (Sadakane & Nishida 1986; Cheng et al. 1992), compared with approximately 18% for normal A-type main-sequence stars. Beyond 40 pc, very few λ Bootis stars have detected infrared excesses; this is probably at least partly due to detection thresholds. Some λ Bootis stars show evidence of circumstellar gas (Stürenburg 1993; Holweger & Rentzsch-Holm 1995; Andrillat, Jaschek, & Jaschek 1995; Hauck, Ballereau, & Chauville 1995; Holweger, Hempel, & Kamp 1999), although there is a high proportion (∼75%) of nondetections, a not unexpected result if the gas is in the form of a circumstellar disk. However, the question remains whether these hypothetical circumstellar disks would be able to retain sufficient quantities of gas over the entire main-sequence life of the star to maintain the required accretion rate. It clearly would be desirable to have a better estimate for the range of ages over which the λ Bootis mechanism operates.

An average age of a few $\times 10^8$ yr for the field λ Bootis stars suggests that these stars should be present in intermediate-age (Pleiades age) clusters, with a frequency of about 2%. Discovery of λ Bootis stars in intermediate-age clusters would give a valuable constraint on the ages of these stars. While Strömgren photometry can be used in the field to preselect λ Bootis candidates, which can then be verified spectroscopically, in practice there are few intermediate-age clusters that have Strömgren photometry for members later than A0. We have therefore pursued this project by obtaining classification-resolution spectra (1.8 and 3.6 Å resolutions) of A-type stars on the main sequences of selected clusters. This program has the advantage that we can use the same set of spectra to discover other peculiar A-type stars, such as Ap and Am stars in these clusters.

2. OBSERVATIONS

2.1. *Observational Sample*

For this project, twelve intermediate-age open clusters with ages between 3×10^7 and 1×10^9 yr were chosen. These clusters are listed in Table 1. A-type stars were identified in these clusters either from spectral types in the literature, or from $B-V$ photometry. Our observing strategy has been to begin with the brightest A-type stars in the cluster and then to work down the main sequence until the practical magnitude limit for signal-to-noise ratio $S/N = 100$ spectroscopy ($m_B \approx 11.0$) on our telescope is reached. This observational program is not yet complete, but access to a spectrograph on a larger telescope will be needed to make further significant progress.

This observational strategy has yielded a sample of A-type stars from intermediate-age open clusters that is reasonably bias-free, at least as far as the discovery of λ Bootis stars is concerned. It is not a complete sample; indeed definition of a complete sample would not even be possible because the full membership of many of these clusters is not known. It *is* somewhat biased toward early A-type stars, as we were not able to observe the late A-type stars in the more distant clusters. However, this bias should not affect the frequency of λ Bootis stars in this sample, as examination of the most recent compilation of λ Bootis stars[1] indicates that λ Bootis stars occur with nearly uniform frequency between spectral types A0 and F0. Rather than striving for completeness in a few open clusters, our strategy of observing stars in many open clusters was calculated to avoid peculiarities of individual open clusters that might affect the frequency of λ Bootis stars. For instance, if the frequency of λ Bootis stars is a function of the average rotational velocity of the A-type stars in a cluster, the binary frequency in a cluster, or some other factor, then concentration on a few open clusters might yield a skewed result .

TABLE 1
OPEN CLUSTERS IN STUDY

Cluster	log(age)[a]
Stock 2	8.23
NGC 1039	8.03
NGC 2281	8.36
NGC 2548	8.54
Praesepe	8.84
IC 4665	7.89
NGC 6633	8.80
IC 4756	8.92
NGC 7039	7.54
NGC 7063	8.11
NGC 7092	8.30
NGC 7209	8.62

[a] Ages are taken from the WEBDA database; see http://obswww.unige.ch/webda.

2.2. *Classification Spectroscopy*

Spectra for the 130 stars in this program were obtained using the Gray-Miller Cassegrain spectrograph on the 0.8 m telescope of the Dark Sky Observatory of Appalachian State University. The spectra were obtained with two different resolutions, 1.8 and 3.6 Å (2 pixels), using a 1200 g mm^{-1} and a 600 g mm^{-1} grating, respectively, both in the first order. The 1.8 Å resolution spectra have a spectral range of 3800–4600 Å, whereas the 3.6 Å resolution spectra have a spectral range of 3800–5600 Å. The CCD used is a thinned back-illuminated glycol-cooled Texas Instruments 1024 × 1024 CCD operating in the MPP mode. The spectra for this program have $S/N > 100$, and were reduced with IRAF,[2] using standard methods.

These spectra were classified by both authors independently against a set of MK standards observed with the same telescope and spectrograph. These classifications were then compared and iterated until complete agreement was obtained. Classifications for the 130 program stars are presented in Table 2. The numbering system used in Table 2 is that of the WEBDA database.[3]

2.3. *Strömgren uvbyβ Photometry*

One of the stars identified in this paper as a possible λ Bootis star, HD 13554 (see § 4 below) lacked Strömgren *uvby*β photometry. We obtained differential *uvby* photometry of HD 13554 on 1999 December 22–23, using 50 mm square *uvby* filters in the Dark Sky Observatory filter wheel on the 0.8 m telescope. The comparison star used was HD 13436, which has a spectral type close to that of HD 13554 and *uvby* photometry published by Perry & Johnston (1982). Aperture photometry using DAOPHOT under IRAF yielded the following indices for HD 13554: $V = 9.225$, $b-y = 0.262$, $m_1 = 0.141$, and $c_1 = 0.664$.

We do not have Hβ filters at our observatory, but our 3.6 Å resolution spectra contain the Hβ line. As an experiment, we performed synthetic photometry, using the Hβ filter passbands illustrated in Crawford & Mander (1966), on the unrectified spectra of a number of Hβ standard stars. Remarkably, we found, using the transformation equation

[1] See http://www.phys.appstate.edu/spectrum/lamboo.html.

[2] IRAF is distributed by the National Optical Astronomy Observatory, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[3] See http://obswww.unige.ch/webda.

TABLE 2
MK Classifications in Open Clusters

HD/BD	OCL	V	$B-V$	Spectral Type	Res. (Å)	Memb. Prob. (%)	N
Stock 2:							
HD 13088	2	8.17	0.20	A1 IV	3.6	M	
BD +59°428	12	10.17	0.38	kA1hA3mA3 V	3.6	M	
HD 13208	13	9.45	0.27	A1 Va	3.6	M	
BD+ 59°430	19	10.19	0.42	A2 V (wk 4481)	3.6	M	
HD 13379	28	8.83	0.38	A1 IV	3.6	M	
HD 13428	36	9.87	0.36	A1 Va	3.6	M	
BD+ 59°433	39	9.97	0.51	A2 V (wk 4481)	3.6	M	
HD 13436	40	8.40	0.35	F2 V kF2mF0	3.6	NM	
HD 13450	41	9.24	0.43	A2 Va	3.6	M	
HD 13464	49	9.42	0.60	A2 IV^{-}(n)	3.6	M	
BD +59°436	50	9.96	0.83	A3 II	3.6	NM	*
BD +59°437	51	10.38	0.47	A1 Va^{-}	3.6	M	
HD 13505	53	8.58	0.33	F1 V kF0mA7	3.6	NM	
HD 13518	56	8.55	0.39	A1 IV^{+}	3.6	M	
BD +58°405	58	10.00	0.49	A2 IVn	3.6	M	
BD +59°439	62	9.40	0.51	A2 III–IVn	3.6	M	
HD 13554	63	9.21	0.39	F1 V kA5mA5 λ Boo?	1.8	NM	*
HD 13542	65	10.15	0.44	A2 Va(n)	3.6	M	
HD 13580	72	10.16	0.36	kA1.5mA3 V	3.6	M	
HD 13591	74	8.67	0.42	A1 IV	3.6	M	
HD 13606	75	9.02	0.50	A2 IVn	3.6	M	
HD 13632	80	9.54	0.48	A2 Va kA2mA1	3.6	M	
HD 13656	83	9.23	0.45	A1 IV(n)	3.6	M	
HD 13689	93	8.39	0.33	A7 V((n)) kA9	1.8	NM	
HD 13676	99	9.12	0.54	A2.5 III–IVn	3.6	M	
NGC 1039:							
HD 16534	88	9.16	0.03	A0 III–IV	3.6	60	
HD 16655	200	8.48	0.05	A0 IIIn	3.6	0	
HD 16693	263	8.52	0.00	B9 IIInp Hg-Mn	3.6	80	*
BD +42°590	274	9.72	0.17	A1.5 Van	3.6	80	
BD +41°516	280	9.89	0.10	A1 V	3.6	0	
BD +42°596	308	8.80	0.06	A0mA1 IV	3.6	80	
BD +42°612	443	9.56	0.06	A0 IV	3.6	80	
HD 16856	520	9.22	0.15	A1.5 IV–V(n)	3.6	M:	
NGC 2281:							
BD +41°1506	38	10.15	0.15	kA2mA3 V	3.6	99	
BD +41°1507	40	10.32	0.14	A2 V mA1	3.6	99	
BD +41°1508	45	10.25	0.15	kA1.5mA3 V	3.6	99	
BD +41°1512	58	9.45	0.12	A1 IV–V	3.6	99	
HD 49010	62	9.04	0.07	kA0mA1.5 III–IV	3.6	99	
BD +41°1518	78	10.63	0.22	A5 V(n)	3.6	99	
BD +41°1519	79	10.30	0.17	kA2.5mA1.5 V	3.6	99	
BD +41°1520	82	10.08	0.14	kA1mA3 V	3.6	99	
HD 49098	86	8.62	0.22	A3 III	3.6	99	
	95	10.58	0.20	A3 V	3.6	99	
HD 49363	117	8.88	0.05	A1.5 IV^{-}	3.6	M	
NGC 2548:							
HD 68646	1005	9.26	0.04	A1.5 IV	3.6	86.3	
HD 68669	1073	8.72	0.07	A2 IV(n)	3.6	50.0	
HD 68779	1289	9.19	0.03	kA1mA1.5 IV	3.6	M	
HD 68778	1320	8.95	0.07	A2 IV^{+}	3.6	82.0	
HD 68794	1367	9.54	0.02	A1 IV	3.6	M	
HD 68878	1541	9.16	0.10	A2.5 IV(n)	3.6	M	
Praesepe:							
HD 73345	114	8.14	0.21	A7 V kA8	1.8	M	*
HD 73430	143	8.31	0.23	A7 V	3.6	M	
HD 73450	154	8.50	0.25	A9 V	3.6	96	
HD 73872	375	8.33	0.20	A8 V(n) kA6mA6	1.8	99	
IC 4665:							
HD 161165	22	8.78	0.07	B9 IVn	3.6	M	
HD 161184	23	8.05	0.07	B9 IV–V	3.6	M	
HD 161223	28	7.43	0.33	A9 V kA5mA5 (λ Boo?)	1.8	NM	*
HD 161261	32	8.26	0.06	kA0 hB8 V shell	1.8	M	*

TABLE 2—*Continued*

HD/BD	OCL	V	$B-V$	Spectral Type	Res. (Å)	Memb. Prob. (%)	N
BD +6°3516	35	10.56	0.21	A1 Van	3.6	NM	
HD 161370	39	9.39	0.31	A5 Vs	3.6	86	
HD 161426	43	9.08	0.19	A1 IV–V	3.6	83	
HD 161445	44	10.18	0.12	B9.5 Vp SiEuSrCr	3.6	NM	*
HD 161480	49	7.68	0.03	B7 V	3.6	85	*
HD 161481	50	9.10	0.26	A1 Va	3.6	84	
HD 161482	51	9.87	0.35	A2 Van	3.6	M	
HD 161572	58	7.59	0.00	B5 V	3.6	88	
HD 161552	61	9.47	0.61	F2 V	3.6	NM	
HD 161573	62	6.88	−0.01	B4 V(h)	1.8	M	*
HD 161603	64	7.34	0.02	B5 IV(e) Bd<	3.6	83	*
BD +5°3486	66	10.41	0.30	A5 V	3.6	86	
HD 161660	72	7.74	−0.01	B7 III	3.6	M	
HD 161677	73	7.12	0.02	B5 IV	3.6	47	
HD 161698	76	8.22	0.11	B8 V Hg-Mn	3.6	78	*
HD 161734	81	8.89	0.11	B8 Ve	3.6	86	
HD 161733	82	8.01	0.06	B6 V	3.6	80	*
	83	10.23	0.31	A3 V	3.6	68	
HD 161786	89	9.86	0.24	A1 Van	3.6	22	
HD 161834	94	10.20	0.27	A1 Va	3.6	NM	
HD 161940	102	9.29	0.11	A1 Vas	3.6	M	
HD 162028	105	7.49	0.02	B7 V(n)	3.6	M	
HD 162162	115	9.15	0.44	kA2 A9 Vp SrEu	3.6	NM	*
HD 162177	121	8.61	0.37	A7 IIIp SrEu	3.6	NM	*
NGC 6633:							
HD 169842	39	9.12	0.21	kA1 A5 Vp SrEuCr	3.6	M	*
HD 169959	58	7.57	0.09	A0 III	3.6	90	
HD 170079	83	9.01	0.26	A2.5 IV$^-$	3.6	51	
HD 170095	84	9.51	0.25	A2 IV–Vn	3.6	84	
HD 170158	97	9.08	0.28	A2.5 IV–V	3.6	92	
BD +6°3765	178	9.50	0.32	A3 III–IVn var	3.6	90	*
IC 4756:							
HD 171586	8	6.44	0.08	A0 Vap SrEuCr	3.6	NM	*
BD +5°3804	10	9.82	0.31	A5 IVn	3.6	M	
HD 171931	40	9.19	0.15	B8 III–IV	3.6	0	
BD +5°3834	43	9.53	0.47	F0 Vn	3.6	94	
HD 172012	58	9.19	0.15	A0 III$^+$	3.6	67	
BD +5°3844	59	9.98	0.47	kA9e A5 IIIep var	3.6	91	*
BD +5°3851	71	10.40	0.44	F0 Vn	3.6	97	
BD +5°3854	77	10.31	0.33	A4 IVn	3.6	97	
BD +5°3861	83	9.67	0.29	A4 IV–V	3.6	M	
BD +4°3822	92	9.90	0.38	kA2hA7mF1 III–IV	3.6	97	
BD +5°3867	100	9.82	0.30	A3 IV	3.6	0	
BD +5°3869	102	9.82	0.30	A8 V	3.6	96	
HD 172248	117	8.97	0.07	B8 IV	3.6	M:	
HD 172271	118	9.07	0.05	kB9 A2 IIIp SiSr ((shell))	3.6	M:	*
BD +5°3900	158	9.64	0.39	A9 V kA9mA5	3.6	93	*
NGC 7039:							
HD 201174	205	8.82		A0 Vap SrEuCr	3.6	M:	*
HD 201870	208	8.82		kF0hF2mF2 (III)	3.6	M:	
NGC 7063:							
HD 203921	1	8.88	−0.02	B8 V He-weak	3.6	95	*
BD +35°4511	2	9.61	0.00	B8 Vn	3.6	46	
BD +35°4512	5	10.24	0.05	B9.5 Va	3.6	80	
GSC 2715 2544	...	10.36	0.10	A0 Va$^+$(n)	3.6	M:	
GSC 2715 3329	...	10.02		F5 V?	3.6	NM	*
NGC 7092:							
HD 204917	19	7.35	−0.02	B9 Va kA0	1.8	97	*
BD +47°3433	25	9.07	0.11	A1 Vn	1.8	69	
BD +47°3438	34	9.15	0.16	A2 Va(n)	1.8	97	
HD 205073	60	7.85	0.04	A1 IV	1.8	94	
HD 205085	65	7.97	0.06	A1 Va(n)	1.8	96	
HD 205116	74	6.83	−0.04	A0 III–IV (Sr)	1.8	97	*
HD205117	75	7.65	0.01	kA0mA1 IV–Vs	1.8	98	
BD +47°3452	77	8.88	0.17	kA1.5hA5mA6 (III)	1.8	40	

TABLE 2—*Continued*

HD/BD	OCL	*V*	*B−V*	Spectral Type	Res. (Å)	Memb. Prob. (%)	*N*
BD +47°3453	78	9.50	0.18	A3 IVn	1.8	98	
BD +47°3454	81	8.92	0.09	A2.5 Va$^-$	1.8	98	
HD 205172	82	8.06	0.03	A1 IV k(n)A0mA0 wk 4481	1.8	0	*
HD 205171	84	8.52	0.01	kA0.5mA1 Vas (Si)	1.8	98	*
BD +47°3456	85	9.67	0.09	A1 Vn	3.6	92	
HD 205198	87	8.23	0.05	A1 IV–V	1.8	97	
HD 205210	88	6.56	0.00	A0.5 III–IV	1.8	96	
BD +47°3458	90	8.68	0.04	A1 Va$^-$(n)	1.8	97	
BD +47°3462	100	9.03	0.08	A2 Va$^-$	1.8	98	
HD 205331	118	6.83	−0.02	A0.5 III–IVs SiCr	1.8	98	*
NGC 7209:							
BD +45°3785	61	10.09	0.14	A2.5 IVn	3.6	94	
BD +45°3795	98	10.26	0.18	A2 IVn	3.6	97	

$\beta_{\rm std} = 0.205 + 1.234\beta_{\rm instr}$, that we could reproduce the Hβ indices for the standard stars to an accuracy of ± 0.003 mag. The same transformation equation applies to B-, A-, and F-type stars. Using this procedure, we determined for HD 13554 $\beta = 2.729$.

3. NOTES ON INDIVIDUAL STARS

Stars in the following notes appear in the same order as in Table 2.

BD +59°436: A probable nonmember of Stock 2. Note the high luminosity and the reddened *B−V*, indicating that the star lies behind the cluster.

HD 13554: A candidate λ Bootis star, but possible field blue straggler. See discussion in the text.

HD 13689: Classified by Pesch & McCuskey (1974) as A7 pec: weak line? Our spectrum as well is mildly peculiar. It appears to be a normal A7 V star with a slightly strong K line.

HD 16693: Classified by Ianna (1970) and Abt & Levato (1977a) as a Hg-Mn star.

HD 73345: See note in § 5.

HD 161223: Probable λ Bootis star. See discussion in the text.

HD 161261: A shell star in IC 4665. This star displays shell cores in the hydrogen lines, as well as strong shell lines such as Fe II 4233. Negative detection in the speckle binary survey of Mason, Hartkopf, & McAlister (1993).

HD 161445: Newly discovered extremely peculiar A-type star, but this star, on the basis of the comparison between its temperature type and its magnitude, is clearly not a member of IC 4665.

HD 161480: Classified as B6 Vp with slightly enhanced C II 4267 by Abt & Levato (1975).

HD 161573: A mild helium-strong star in IC 4665. Resolved binary in the speckle survey of Mason et al. (1993).

HD 161603: Be star in IC 4665. The emission is detected as an infilling of the Hβ line. "Bd <" refers to the abnormally small decrement seen in the Balmer line strength. See Gray & Corbally (1998) for an explanation of this notation. Detected in the X-ray by *ROSAT* (Giampapa, Prosser, & Fleming 1998).

HD 161698: Classified as B8.5 Vp Hg-Mn by Abt & Levato (1975).

HD 161733: Classified as B6 Vp with slightly enhanced C II 4267 by Abt & Levato (1975). Detected as a binary by speckle interferometry (McAlister & Hartkopf 1988)

HD 162162: Listed as a nonmember by Crawford & Barnes (1972).

HD 162177: Listed as a nonmember by Crawford & Barnes (1972).

HD 169842: Classified by Levato & Abt (1977) as A1 Vp (Sr II, Cr, Mn I).

BD +6°3765: Spectrum seems variable; two observations give A3 III–IV and A2 IV–V.

HD 171586=FR Ser: An extremely peculiar A-type star. The SIMBAD database calls this a "carbon star," but no references to such a classification can be found. Evidently a nonmember (on the basis of its position in the H-R diagram) of IC 4756. Classified by Abt (1985b) as A1 Vp (Sr, Cr, Si st; Ca wk).

BD +5°3844: An unusual emission-line star in IC 4756, illustrated in Figure 1. The emission in this star is characterized by a broad truncated emission core in Hβ, emission reversals in Hγ and Hδ, and a complex emission structure in the Ca II H and K lines. This spectrum was obtained on the night of 1998 July 21–22. Interestingly, a spectrum of the same star, obtained on the Steward Observatory 2.3 m Bok telescope on the night of 2001 June 4–5 shows no indication of this complex structure.

HD 172271: An interesting star, which shows a peculiar metallic line spectrum, including an enhanced Si II doublet 4128–4130, enhanced Sr II 4077, and slightly enhanced Cr II 4172, accompanied by a weak Mg II 4481 line and enhanced Fe II 4233, indicative of a weak shell. Listed in Renson (1992) as A0 Sr?

BD +5°3900: A curious star, which appears to have weak metals but a normal K line. Possible composite spectrum.

HD 201174: An extremely peculiar A-type star. Listed in Osawa (1965) as a Sr Cr star.

HD 203921: A helium-weak B-type star in NGC 7063, classified by Ahumada & Lapasset (1995) as a cluster blue straggler.

GSC 2715 3329: Noisy spectrum.

HD 204917: A red spectrum of this star, centered on Hα, obtained on the DSO 0.8 m telescope on the evening of 1993

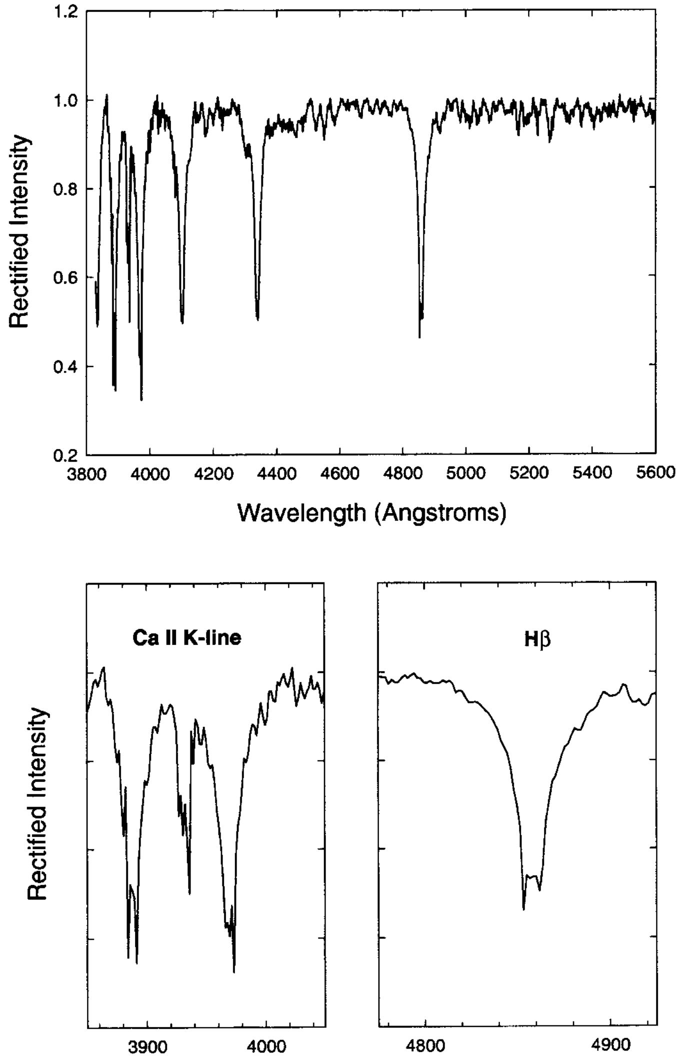

FIG. 1.—Peculiar emission-line star in IC 4756, BD +5°3844 (see text).

September 11–12 shows emission in the core of Hα. Listed in the SIMBAD database as a possible variable.

HD 205116: Newly discovered mild Ap star in NGC 7092.

HD 205172: A curious star that shows weak cores in the hydrogen lines, which cannot be due to rotation since the metal lines are not broadened. The metal lines also look slightly weak. The K line has a peculiar profile with broad wings.

HD 205171: Newly discovered peculiar A-type star in NGC 7092.

HD 205331: Maitzen et al. (1986) have published a spectrum and Δa photometry for this star, both of which concur with our classification of this star as Ap Si. They present evidence for the spectral variability of this star.

4. FREQUENCY OF λ BOOTIS STARS IN THE FIELD

One of the main goals of this study is to compare the frequency of λ Bootis stars in the field with that in open clusters in the hopes of gaining some insights into the mechanism behind the λ Bootis phenomenon. It is worthwhile, therefore, to attempt to place our estimate of the frequency of λ Bootis stars in the field, so often quoted in the literature as being "approximately 2%," on a firmer foundation.

Paunzen (2001) has recently visited this issue by using a series of progressively more distant volume-limited samples. Taking the spectral interval B8–F4, he found for his most nearly complete sample (25–50 pc) a frequency of 1.6%. This frequency is almost certainly too low for a number of reasons. First, very few λ Bootis stars are known earlier than A0, and the frequency of λ Bootis stars almost certainly begins to decline significantly in stars later than F0 because of the increasing depth of the surface convection zone in the early F-type stars. While λ Bootis stars as late as F3 probably exist, it is difficult, on the basis of spectral classification alone, to distinguish λ Bootis stars later than F0 from the intermediate Population II "field blue straggler" stars (Olsen 1979; Gray 1989). Thus we know very little about the frequency of λ Bootis stars with spectral types later than F0. In addition, Paunzen used spectral types from the Michigan HD reclassification project (Houk & Cowley 1975; Houk 1978, 1982; Houk & Smith-Moore 1988; Houk & Swift 1999) to help reduce the incompleteness in his samples. However, Houk has not classified a single star in any of the five volumes of the Michigan HD reclassification project as a λ Bootis star because they are difficult to distinguish with her spectra (see discussion in Abt 1984 and Gray 1991).

To obtain a better estimate of the λ Bootis frequency in the field we consider two samples. We confine these samples to A-type (A0–F0) main-sequence stars (luminosity classes V and IV) for the following reasons. We have discussed in the preceding paragraph the reasons why it is difficult to obtain reliable statistics for λ Bootis stars outside the spectral interval A0–F0. We also confine the sample to main-sequence stars, as it appears that all λ Bootis stars currently known lie between the zero-age main sequence and the terminal-age main sequence (see § 1 above). The only exception to this is HD 37411, which appears to be a pre–main-sequence star (Gray & Corbally 1998).

Our first sample is the sample of all A-type main-sequence stars in the *Hipparcos* catalog (ESA 1997) within a distance of 40 pc. The authors are currently engaged in a project to obtain spectra and spectral types for all the dwarf and giant stars earlier than M0 within 40 pc of the Sun. In this sample, there is a total of 152 A0–F0 field main-sequence stars, including Am and Ap stars. We currently have spectra for 145 of these stars. There are four λ Bootis stars in this sample, λ Boo itself, π^1 Ori, ρ Vir, and HR 8799, the subject of a recent paper by Gray & Kaye (1999). The remaining seven stars for which we have no spectra appear from the literature to be normal. This yields a frequency of 2.6%.

Our second sample is derived from the classifications by Abt & Morrell (1995) of nearly all the northern A-type stars in the bright star catalog. Again confining the sample to those stars classified by Abt & Morrell as A0–F0 main-sequence stars (including both Am and Ap stars in that spectral type range), we find a total of 1334 field stars. Abt & Morrell classify 41 of these stars as λ Bootis stars, giving a frequency of 3.1%. However, Abt uses criteria that are more liberal than ours (Gray 1988) to identify λ Bootis stars, and so using our criteria this is almost certainly an overestimate. We have obtained spectra for all but two of these 41 λ Boo candidates and have classified them (these classifications will be published elsewhere). We find a total of 25 λ Bootis stars in this sample of 1334 field stars, a frequency of 1.9%.

It is possible that some λ Bootis stars remain undetected in this sample of 1334 field stars, although we expect that there are very few. The stars we classify using our criteria as λ Bootis stars tend to be a subset of those classified by Abt & coworkers. In addition, there is a large overlap between the sample of Abt & Morrell and that of Gray & Garrison (1987, 1989a, 1989b). Hence we expect that 1.9% is a good lower limit to the frequency of λ Bootis stars in the field, and that the true frequency lies between 2.0% and 2.5%.

On the basis of these two samples, we will assume in what follows that the frequency of λ Bootis stars in the field among A0–F0 main-sequence stars is 2.0%.

5. OPEN CLUSTER λ BOOTIS CANDIDATES

Two candidate λ Bootis stars have been discovered during this project, HD 13554 in the open cluster Stock 2, and HD 161223 in IC 4665. HD 13554 is classified as F1 V kA5 mA5 λ Boo? (see Fig. 2). This classification notation can be interpreted as follows: the F1 type refers to the hydrogen line type, as well as the morphology of the metallic line spectrum. This type is the best indicator of the effective temperature of the star. The kA5 type refers to the strength of the Ca II K line, and the mA5 type refers to the *strength*, but not the morphology, of the metallic line spectrum. The fact that both the metallic line type and the K line type are *earlier* than the hydrogen line type implies that the star is metal-weak. HD 13554 is of particular interest, because if this star proves to be a bona fide λ Bootis star it would be the one of the latest (coolest) definitely known, with a temperature type of F1, and as such would yield interesting and important information on the relationship between the onset of convection and the λ Bootis mechanism. Unfortunately, at this spectral type, it is extremely difficult to discriminate using classification spectra between λ Bootis stars and metal-weak "thick-disk" early F-type field blue straggler stars. Proof of membership of HD 13554 in Stock 2 would be strong evidence for its λ Bootis nature.

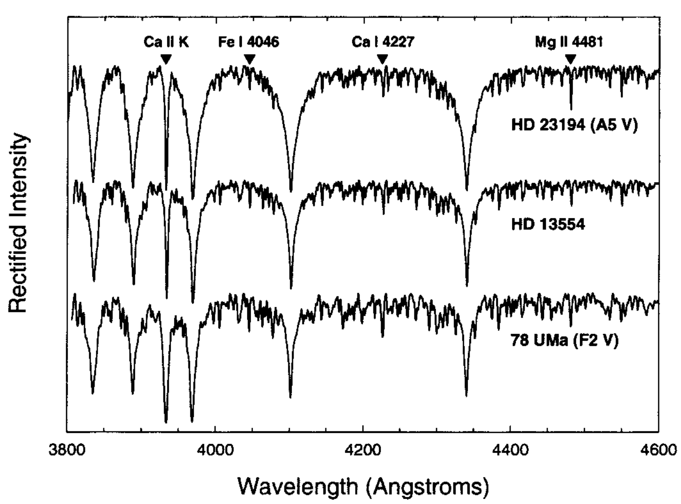

FIG. 2.—HD 13554 compared with two MK standards for A5 V and F2 V. The metal weakness of HD 13554 is evident from this comparison; the hydrogen lines of HD 13554 are similar to those of the F2 V standard (we actually classify them as F1); this implies an effective temperature near that of an F1 star. The metallic line spectrum of HD 13554, however, is closer in general strength to that of the A5 V standard. Note, however, that certain zero-volt lines, such as Ca I 4227, are slightly enhanced relative to the A5 V spectrum. This confirms the lower effective temperature.

HD 13554, which is listed as a possible member of Stock 2 by Krzemiński & Serkowski (1967), has nearly the same proper motion as Stock 2. However, the Strömgren photometry reported in § 2.3 yields, using the method of Crawford (1975), a reddening of $E(b-y) = 0.05$, which corresponds to $E(B-V) = 0.07$, considerably smaller than the reddening $E(B-V) = 0.38$ derived by Krzemiński & Serkowski (1967) for Stock 2. Becker & Fenkart (1971) give $E(B-V) = 0.43$ for Stock 2. In addition, Krzemiński & Serkowski (1967) report a polarization for HD 13554 ($p = 0.018$ mag) that is significantly smaller than the average polarization measured for Stock 2 members ($\bar{p} = 0.050$ mag).

The *Hipparcos* (ESA 1997) parallax for HD 13554 ($\pi = 8.5 \pm 10.0$ mas) does not help to resolve the question of membership in Stock 2. However, we have classified this star as F1 V metal-weak. The calibration of Keenan (1963) assigns $M_v = 2.8$ to an F1 dwarf. Considering a reddening of 0.07 and $V = 9.23$, we derive a distance modulus of 6.2 for HD 13554, giving a distance of 170 pc. The distance to Stock 2 is given by Krzemiński & Serkowski (1967) as 316 pc; Becker & Fenkart (1971) give 345 pc, and Martini (1971) 302 pc, whereas Pesch & McCuskey (1974) find a distance of 210 pc. On the basis of these considerations, it appears that HD 13554 is not a member of Stock 2 but is a more lightly reddened foreground star.

Even though it appears that HD 13554 is not a member of an open cluster, the question of whether this star is a λ Bootis star or a metal-weak field blue straggler is still open. This is an important question, as it is supposed (Charbonneau 1993; Turcotte & Charbonneau 1993) that the red boundary to the λ Bootis mechanism corresponds to the onset of convection and thus the presence of a deepening surface convection zone with declining effective temperature. There are a number of stars in the literature with spectral types later than F0 that have been classified as λ Bootis stars, but their membership in this class is uncertain. A case in point is the star HD 106223, a metal-weak F3 dwarf, which has been variously classified as a field blue straggler, a horizontal-branch star and a λ Bootis star. E. Paunzen (2001, private communication) is currently studying a set of cool λ Bootis candidates in an attempt to pin down the red edge to the distribution of λ Bootis stars.

We have classified HD 161223 as A9 V kA5 mA5 (λ Boo) and consider it to be a mild but bona fide λ Bootis star. This metal-weak A9 dwarf is in the field of IC 4665, but has a visual magnitude comparable to those of the B-type members of that cluster and thus is almost certainly a foreground star. Martin & Rodriguez (1995) have discovered that this star is a delta Scuti variable with a period of 0.144 days and that it may be multiperiodic. They noted that the Strömgren photometry for this star implies that it is metal-weak and speculated that it may be an SX Phe star instead of a δ Scuti star. This would make HD 161223 the longest-period SX Phe star known to date. It seems more reasonable to assume that this star is a λ Bootis star, as many λ Bootis stars are δ Scuti variables (Paunzen et al. 1998).

Our classification of HD 161223 as a metal-weak late A-type star may be confirmed by spectral synthesis. We use the multidimensional downhill SIMPLEX method developed by Gray, Graham, & Hoyt (2001) to determine the basic parameters of this star, using synthetic spectra calculated with the spectral synthesis code SPECTRUM (Gray & Corbally 1994) and Kurucz fluxes, both derived from

ATLAS9 stellar atmosphere models (Kurucz 1993). This method simultaneously fits the observed spectrum and fluxes from Strömgren *uvby* photometry to synthetic spectra and fluxes from an interpolated four-dimensional grid. Our model fit to HD 161223 is illustrated in Figure 3. We derive $T_{\rm eff} = 7560 \pm 80$ K, $\log g = 3.82 \pm 0.10$, $\xi_t = 3.5 \pm 0.5$ km s^{-1}, and $[{\rm M/H}] = -0.45 \pm 0.10$. A detailed discussion of the errors associated with the SIMPLEX method can be found in Gray et al. (2001). Included in Figure 3 are ultraviolet flux measurements from the *TD*-1 satellite (Thompson et al. 1978) and flux measurements derived from photometry in the Cousins *R* and *I* bands, which help to confirm the model fit. The fit is consistent with our classification and strengthens the conclusion that this star is mildly metal-weak. Comparison with the evolutionary models of Claret (1995) for $X = 0.70$ and $Z = 0.02$ suggests that this star is near the terminal-age main sequence (TAMS) and has an age of approximately 1.0 ± 0.2 Gyr. This age is a challenge to the Venn & Lambert (1990) theory of the λ Bootis mechanism as it is very difficult to understand how accretion could have continued over such a long timescale or have been initiated at such a late evolutionary stage, and thus it is of great importance to verify the λ Bootis nature of HD 161223. Observations to determine the C, N, and O abundances in this star are encouraged.

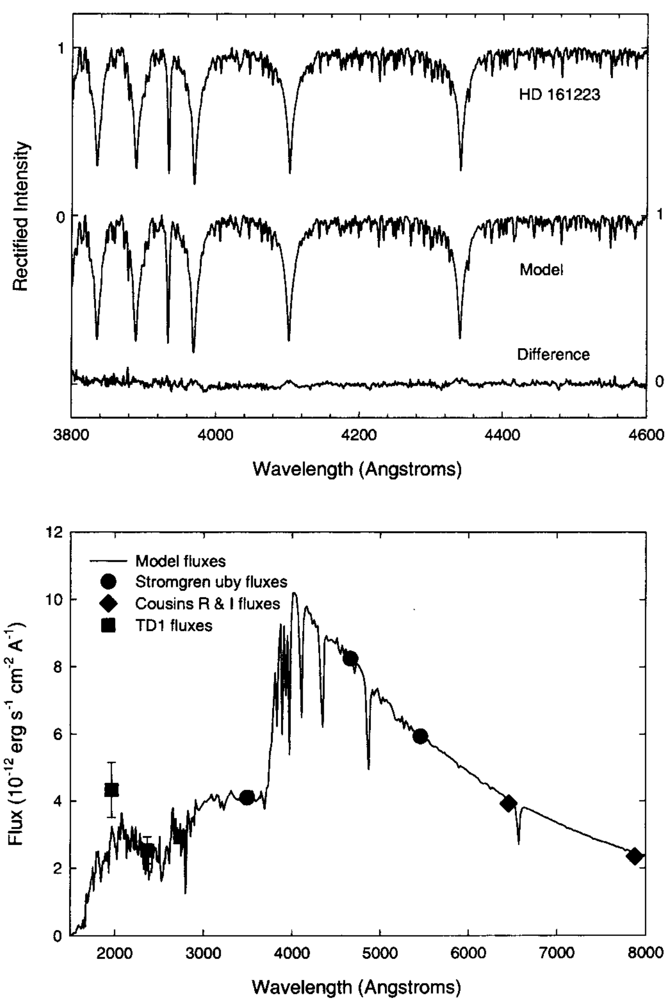

FIG. 3.—SIMPLEX method fit for HD 161223, a candidate λ Bootis star. *Top*: Observed classification spectrum compared with the model spectrum. *Bottom*: Simultaneous fit with fluxes from Strömgren *uby* photometry (*closed circles*), including ultraviolet data from the *TD*-1 satellite (*squares with error bars*), which were not used in obtaining the solution but, with the exception of the point at 1965 Å, are clearly consistent with the fit, and flux points for the Cousins *R* and *I* bands (*diamonds*) from Landolt (1983) at the effective wavelengths of 6455 and 7880 Å. No signal was detected by *TD*-1 at 1565 Å. All fluxes were dereddened using $E(b-y) = 0.10$ and the standard reddening curve from Savage & Mathis (1979).

Pavlovski, Schnell, & Maitzen (1993) used Δa photometry to isolate three λ Bootis candidates in Praesepe. They identified HD 73210, 73345, and 73872 as possible λ Bootis stars. HD 73210 was adopted by Gray & Garrison (1989b) as their low $v \sin i$ A5 III standard. This star was recently identified by Abt & Willmarth (1999) as a high-amplitude double-lined spectroscopic binary; indeed some of our classification spectra of this star show certain peculiarities that we now understand as being due to its SB2 nature. We are currently reevaluating this star as an MK standard. However, this star shows no similarities to λ Bootis stars. HD 73345 and HD 73872 are included in Table 2. Both are mildly peculiar; HD 73345 is an A7 V star with a slightly strong Ca II K line and HD 73872 shows some rotational broadening and mild line weakening, but it does not appear to be a λ Bootis star.

6. FREQUENCY OF λ BOOTIS STARS IN INTERMEDIATE-AGE CLUSTERS

From the discussion in the previous section, it is clear that out of the 130 stars in Table 2 we have not found a single λ Bootis star that is a member of an intermediate-age open cluster. It is not possible to derive a statistically meaningful statement from this result because of our small sample size. However, Gray & Garrison (1987, 1989a, 1989b) have classified nearly 150 A-type (B9–F2) stars not included in Table 2 in a number of intermediate-age clusters, some of which are not included in Table 1 (see Table 3 for a listing of these supplementary clusters). To further extend our sample size and to make our sample more nearly complete, we include classifications by Abt, Morgan, and coworkers in a long series of papers on many of the intermediate-age open clusters in Tables 1 and 3, namely, NGC 1039: Abt & Levato (1977a); α Persei: Morgan, Hiltner, & Garrison (1971), Abt (1978); Pleiades: Abt & Levato (1978); Hyades: Morgan & Hiltner (1965); NGC 2516: Abt & Morgan (1969); Praesepe: Abt (1986); IC 4665: Abt & Levato (1975); Coma Berenices: Abt & Levato (1977b); IC 2602: Abt & Morgan (1972); NGC 6475: Abt (1975); and NGC 6633: Levato & Abt (1977). We have restricted our selection of classifications

TABLE 3

SUPPLEMENTARY OPEN CLUSTERS

Cluster	log (age)[a]
Blanco 1	7.80
α Per	7.85
Pleiades	8.13
Hyades	8.90
NGC 2516	8.05
IC 2391	7.66
IC 2602	7.51
NGC 3532	8.49
Coma Berenices	8.65
NGC 6475	8.48

[a] Ages are taken from the WEBDA database; see http://obswww.unige.ch/webda.

from the literature to these authors as they (Abt, Morgan, and Levato) have had a long experience with the classification of λ Bootis stars. Other prolific classifiers, such as Houk, tend not to classify stars as λ Boo (see discussion in § 4). While Abt, as mentioned in § 4 above, tends to classify a higher proportion of stars than we do as λ Bootis stars in a given sample, those stars that we classify as λ Bootis stars tend, with few exceptions, to be a subset of those that Abt selects.

If we select only A0–F0 main-sequence (luminosity classes V and IV) stars from the above sources (see § 4 for the motivation for this selection), we derive a total sample of 263 stars, including 79 from Table 2. It is remarkable that out of this sample of 263 stars, only one star (HR 4733, in the Coma Berenices cluster) has ever been classified as a λ Bootis star.

HR 4733 (14 Com) is a well-known and interesting shell star, which was first studied in detail by Swings & Struve (1941). This star has been given a variety of classifications in the literature. Cowley et al. (1969) classified it as F0 IIInp. Abt & Levato (1977b) classified it as A9 Vn + shell and noted that it has "an extreme shell spectrum." Slettebak (1982) classified it as F0 III shell. Gray & Garrison (1989a) gave it a spectral type of A9 IVnp Sr II. Abt & Morrell (1995) classified it as a λ Bootis star (A9 Vp [λ Boo]), and Gray, Napier, & Winkler (2001) as F1 IV:np shell Sr II. Hauck et al. (1995) rejected it as a λ Boo candidate on the basis of its photometry. This star is compared in Figure 4 with the A9 IIIn MK standard γ Her and with a prototypical late-type λ Bootis star. The similarity of the spectrum of HR 4733 with the A9 IIIn standard supports its classification as a late A or early F giant or subgiant. The features that lead to its classification as a shell star are indicated in the figure (enhanced lines of Fe II and Ti II arising from metastable states, and a weak Mg II 4481 line). The enhanced Sr II lines are also indicated. A 3.6 Å resolution spectrum we have of this star shows lines of Fe II (42) (λλ4922, 5017, and 5169) strongly in absorption, also indicative of a shell. The weak Mg II 4481 line is the only feature it appears to have in common with the λ Bootis star. Dominy & Smith (1977) published a detailed analysis of the shell spectrum of this star and identified many shell lines. Although it seems likely from the variety of spectral types assigned to this star that it may be a spectrum variable, Slettebak (1982) noted no changes in the spectrum from 1950 to 1982. We conclude that HR 4733 is an unusual shell star with no relation to the λ Bootis class.

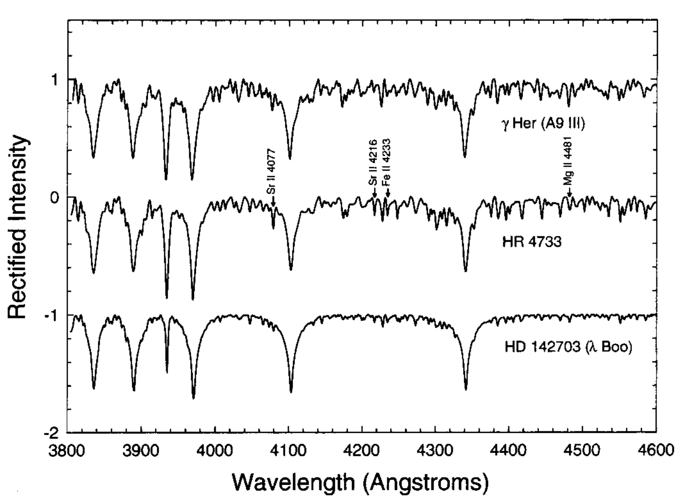

FIG. 4.—Comparison of the shell star HR 4733 (14 Com) with the A9 III MK standard (γ Her) and a late-type λ Bootis star. See text for discussion.

We thus have the result that out of a sample of 263 stars in intermediate-age open clusters not a single one is a λ Bootis star. Even if we were to extend our sample to stars earlier than A0 and later than F0, and luminosity types to giants and bright giants, no star (other than HR 4733) has been classified as λ Boo in any of the above sources or, as far as we have been able to determine, in any source by any author. To judge the statistical significance of this result, we must consider the memberships of these 263 stars in their respective clusters carefully.

We have relied heavily on the WEBDA database, which cites the most recent and complete membership studies to determine the memberships of these 263 stars. In our sample there are a few clusters that do not have quantitative membership studies based on proper motions; for other clusters only the nuclear regions have been studied. For those stars in our sample without membership probabilities we have proceeded in the following way. Every cluster in the WEBDA database has a list of nonmembers; if one of our stars is listed as a nonmember in WEBDA, we assign it a membership probability of 0%. For the remaining stars, we judge membership from the position of the star on the H-R diagram and from its spectral type. If both of these criteria are consistent with membership in the cluster, we consider it a probable member and label it " M " in Table 2 or in our list (not published here) of supplementary stars from the sources mentioned above. If one or both of these criteria are inconsistent with membership, we consider the star as a nonmember and label it " NM " in Table 2. Somewhat doubtful cases are considered possible members and are labeled " M:". For the cluster Stock 2, this job has been done for us by Krzemiński & Serkowski (1967), who also used polarization as a criterion. Guided by stars in clusters with membership probabilities we assign the following probabilities to our notation: M = 85%, M: = 50%, and NM = 0%.

We derive the following results. After correction for membership probabilities, we have a total of 65 A0–F0 main-sequence cluster members in Table 2. In our supplementary list, again corrected for membership probabilities, we have an additional 155 cluster members, making a total of 220 cluster members. While admittedly this sample is not complete—we have not observed all the A-type stars in all our clusters, nor have we observed all the available intermediate-age clusters (most others would require a larger telescope than was available for this project)—we are reasonably certain (see discussion in § 2.1) that this sample is not biased either for or against the inclusion of λ Bootis stars and that therefore we may draw valid statistical conclusions from it.

None of these cluster stars has been classified as a λ Bootis star, whereas statistically, on the basis of the 2.0% incidence in the field we derived above in § 4, we should expect 4–5 (4.4). The probability of a null result under these circumstances (the number of observed λ Bootis stars should be distributed by Poisson statistics) is only 1%. We also point out that λ Bootis stars seem to be rare in clusters of any age. Only one marginal λ Bootis star has been discovered in the young open cluster NGC 2264; other young clusters have yielded no λ Bootis stars at all (Gray & Corbally

1998). Only in the Orion Nebula region have λ Bootis stars been found in any numbers (four are known; see Paunzen & Gray 1997 and Gray & Corbally 1998), and all these are found on the periphery of that star-forming region. This suggests strongly that there is some factor external to the star and related to membership in open clusters that prevents the operation of the λ Bootis mechanism. We examine in the next section possible explanations for this result and the implications this result has for various theories proposed in the literature to explain the origin of the λ Bootis stars.

7. THE λ BOOTIS MECHANISM

The Venn & Lambert (1990) theory for the λ Bootis mechanism (see Introduction) requires the accretion of metal-depleted gas from interstellar or circumstellar material. One way to understand our null result for the presence of λ Bootis stars in open clusters is to hypothesize that this circumstellar material might be disrupted in the cluster environment. There is substantial evidence for the photoevaporaton by far-ultraviolet and Lyman continuum photons from O-type stars of circumstellar disks around protostars in the Orion Nebula (Johnstone, Hollenbach, & Bally 1998; Throop et al. 2001) and in M16 (Hillenbrand et al. 1993; Hester et al. 1996). This suggests the following hypothesis: A-type stars that formed in dense star formation regions (which survive today as open clusters) such as the Orion Nebula cluster lost their circumstellar disks by photoevaporation and thus arrived on the ZAMS without the circumstellar material required (in the Venn & Lambert theory) for the λ Bootis mechanism to operate. The present field λ Bootis stars would have formed essentially in isolation either on the peripheries of these star formation regions (as we may indeed be seeing in the Orion region) or in regions similar to the Taurus Molecular Cloud and then emerged on the main sequence with a circumstellar shell or disk. Unfortunately, almost nothing is known about the relative frequencies of gas disks around A-type stars in the field and in open clusters, and so we have no corroborating evidence to support this hypothesis. However, as we will see below, no other λ Bootis mechanism proposed in the literature seems able to account for our null result.

In three recent papers Faraggiana and colleagues have advanced the hypothesis (Faraggiana, Gerbaldi, & Burnage 1997; Faraggiana & Bonifacio 1999; Marchetti, Faraggiana, & Bonifacio 2001) that the λ Bootis phenomenon can be understood on the basis of composite spectra. The authors suggest that the composite spectrum produced by the combined light of two quite similar components can, under certain circumstances, lead to the appearance of a weak-line spectrum. They have demonstrated that a number of λ Bootis stars are indeed binaries (a mixture of spectroscopic binaries and close visual or speckle binaries), but the study has not advanced far enough that it can be said that *all* λ Bootis stars are binaries, or even that the frequency of binaries among λ Bootis stars is different from that among normal A and early F dwarfs (≈31%, all with $P > 100$ days; Abt 1965). To account for our null result in clusters, the binary frequency would need to be substantially lower in open clusters than in the field. A recent study by Abt & Willmarth (1999) found ≈26% of A- and F-type stars in two intermediate-age clusters (Praesepe & Coma) to be spectroscopic binaries. Morrell & Abt (1991) found 27% in IC 4665, and Yoshizawa (1978) found ≥25% in NGC 2281, both clusters being in our study. If we use the result of Abt (1965) for the normal A and early F field dwarfs and combine with the frequency of Am stars in the field (≈32%), almost all of which are members of short-period binaries, we find that approximately 55% of field A and early F type stars are members of short- or long-period binaries. The studies cited above suggest a binary frequency of about 26% in clusters, although these statistics are probably incomplete in terms of long-period binaries and thus may not be significantly different from the statistics in the field. However, taking the cluster statistics at face value, we estimate, on the composite spectrum hypothesis of Faraggiana et al., that we should expect 2–3 (2.6), instead of 4–5 (4.4) λ Bootis stars in our sample. This increases the probability of the null result from 1% to 7%, still quite a significant result. Thus our null result casts considerable doubt on the composite spectrum hypothesis. In addition, numerical experiments carried out by one of us (R. O. G.) to be published in a separate paper indicates that the composite spectrum hypothesis is capable only of yielding spectra that appear marginally metal-weak and cannot account for the full-fledged classical λ Bootis stars including HR 4881, the subject of a recent paper by Faraggiana et al. (2001).

However, the work of Faraggiana et al. has clearly demonstrated that a number of bona fide λ Bootis stars are in binary systems. All theories for the origin of λ Bootis stars must be considered in this light. In particular, could circumstellar disks survive in such binary systems, or could the binary system itself supply the gas required under the Venn & Lambert (1990) theory? Habing et al. (2001) find numerous examples of main-sequence stars in binary systems with circumstellar dust disks. Mathis & Lamers (1992) and Waters, Trams, & Waelkens (1992) have proposed that the gas-dust separation required in the Venn & Lambert (1990) theory could occur in binary systems. Waters et al. point out the similarity between the abundance patterns seen in λ Bootis stars and certain post–asymptotic giant branch (post-AGB) stars in wide binary systems and suggest, in the case of the post-AGB stars, that the accretion of "clean" gas from a circumsystem disk could explain these abundance patterns.

Paunzen (2001) has recently speculated that the young Orion λ Bootis stars may be formed by a different mechanism from the older λ Bootis stars that are found in the field and which we expected to find in intermediate-age open clusters. He speculates that the young λ Bootis stars found in Orion are formed by the Venn & Lambert mechanism, discussed above, whereas the older λ Bootis stars in the field are formed by the mechanism proposed by Michaud & Charland (1986), which explains the abundance anomalies on the basis of diffusion and mass loss. This mechanism requires a few $\times 10^8$ yr to produce substantial metal deficiencies and was largely rejected on the basis of the discovery by Gray & Corbally (1993) and Levato et al. (1994) of very young λ Bootis stars in Orion OB1. Paunzen's speculation is interesting, but it is not consistent with our results. The Michaud & Charland mechanism is a strictly internal mechanism and thus should be insensitive to the environment in which the star finds itself. Thus, if the Michaud & Charland mechanism is responsible for the field λ Bootis stars we should detect λ Bootis stars in intermediate-age clusters, which we do not. Hence, we consider this "dual mechanism" hypothesis unlikely.

Andrievsky (1997) has proposed that λ Bootis stars come about through the merger of contact binary systems of the W UMa type, and has attempted to show that such a scenario can account for both the frequency of λ Bootis stars in the field and for the presence of circumstellar gas around these stars. Andrievsky states that the merger mechanism implies that λ Bootis stars will be born with an equatorial rotational velocity of approximately 200 km s^{-1}, yielding an average projected rotational velocity for the class of about 150 km s^{-1}. Despite the fact that λ Bootis stars are often quoted in the literature as being "rapid rotators," 78% of the λ Bootis stars in the compilation of Gray have projected rotational velocities of less than 150 km s^{-1}, which places some doubt on this hypothesis. On the other hand, merger timescales suggest that λ Bootis stars would be formed only after 500 Myr, which could possibly help to explain the null result obtained in this paper (the young λ Bootis stars in Orion would need to be formed with a different mechanism). This suggests that λ Bootis stars might be found among the blue stragglers of clusters with ages $\geq$500 Myr. Abt (1985a) has studied blue stragglers in intermediate-age open clusters spectroscopically, but did not find any λ Bootis stars, although the sample was rather small. However, to account for the numbers of λ Bootis stars observed in the field, nearly all A-type blue stragglers would need to be λ Bootis stars.

The Venn & Lambert (1990) theory (modified and elaborated by Turcotte & Charbonneau 1993) requires λ Bootis stars to be associated with circumstellar material. In this paper, we have shown that the frequency of λ Bootis stars in open clusters is significantly lower than in the field, an observation which we suggested above may be explained by the destruction of circumstellar disks in a cluster environment. Thus, so far as it goes, our cluster null result is consistent with the Venn & Lambert theory and seems to be inconsistent with all other proposed λ Bootis mechanisms. A remaining outstanding problem with the Venn & Lambert theory is the requirement for circumstellar disks around λ Bootis stars to maintain the gas accretion rate required for the λ Bootis mechanism over the entire main-sequence lifetime of the star, a period of time which is much longer than the period gas is usually thought to persist in circumstellar disks. This suggests that if the Venn & Lambert theory is to be viable these circumstellar disks must possess a reservoir of volatiles, rich in hydrogen, that are gradually released over a period of $\sim 10^9$ yr. The observation of what appears to have been a discrete accretion event by Holweger & Rentzsch-Holm (1995) onto the λ Bootis star HR 4881 (and similar observations of rapidly appearing and disappearing absorption components in the Ca II K line of β Pic, interpreted by Ferlet, Hobbs, & Vidal-Madjar 1987 as evidence of comets) suggests that this reservoir of volatiles is in the form of a Kuiper disk of cometary nuclei. A possible mechanism for perturbing the orbits of these comets and sending a steady stream toward the star may be the presence of a planetary or proto-planetary body orbiting in or near the disk.

8. CONCLUSIONS

We have obtained spectra of and have classified on the MK system 130 A-type stars in 12 intermediate-age open clusters. This sample, combined with 184 other A-type stars in intermediate-age open clusters classified by Gray & Garrison and Abt & coauthors yields, once corrected for membership probabilities, a total of 220 A-type main-sequence cluster members. No λ Bootis stars have been found in this sample, contrary to what we would expect from the frequency in the field. This null result is significant at the 99% confidence level and suggests that some factor external to the star and related to membership in open clusters prevents the operation of the λ Bootis mechanism. We have used this null result to judge the viability of a number of mechanisms for the λ Bootis phenomenon proposed in the literature. In conclusion, we suggest as a working hypothesis that the absence of λ Bootis stars in open clusters is due to the photoevaporation by UV radiation from massive cluster stars of the circumstellar material required on the Venn & Lambert (1990) accretion theory for the λ Bootis mechanism to work.

The comments of an anonymous referee led to a substantial revision and improvement in this paper. We would also like to acknowledge useful discussions with Mike Meyer. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

Abt, H. A. 1965, ApJS, 11, 429
———. 1975, PASP, 87, 417
———. 1978, PASP, 90, 692
———. 1984, in The MK Process and Stellar Classification, ed. R. F. Garrison (Toronto: David Dunlap Obs.), 340
———. 1985a, ApJ, 294, L103
———. 1985b, ApJS, 59, 95
———. 1986, PASP, 98, 307
Abt, H. A., & Levato, H. 1975, PASP, 87, 849
———. 1977a, PASP, 89, 648
———. 1977b, PASP, 89, 29
———. 1978, PASP, 90, 201
Abt, H. A., & Morgan, W. W. 1969, AJ, 74, 813
———. 1972, ApJ, 174, L131
Abt, H. A., & Morrell, N. I. 1995, ApJS, 99, 135
Abt, H. A., & Willmarth, D. W. 1999, ApJ, 521, 682
Ahumada, J., & Lapasset, E. 1995, A&AS, 109, 375
Andrievsky, S. M. 1997, A&A, 321, 838
Andrillat, Y., Jaschek, C., & Jaschek, M. 1995, A&A, 299, 493
Becker, W., & Fenkart, R. 1971, A&AS, 4, 241
Charbonneau, P. 1993, ApJ, 405, 720
Cheng, K.-P., Bruhweiler, F. C., Kondo, Y., & Grady, C. A. 1992, ApJ, 396, L83
Claret, A. 1995, A&AS, 109, 441
Cowley, A., Cowley, C., Jaschek, M., & Jaschek, C. 1969, AJ, 74, 375
Crawford, D. L. 1975, AJ, 80, 955
Crawford, D. L., & Barnes, J. V. 1972, AJ, 77, 862
Crawford, D. L., & Mander, J. 1966, AJ, 71, 114
Dominy, J. F., & Smith, M. A. 1977, ApJ, 217, 494
ESA. 1997, The *Hipparcos* and Tycho Catalogues (ESA SP-1200) (Noordwijk: ESA)
Faraggiana, R., & Bonifacio, P. 1999, A&A, 349, 521
Faraggiana, R., Gerbaldi, M., Bonifacio, P., & Francois, P. 2001, A&A, 376, 586
Faraggiana, R., Gerbaldi, M., & Burnage, R. 1997, A&A, 318, L21
Ferlet, R., Hobbs, L., & Vidal-Madjar, A. 1987, A&A, 185, 267
Giampapa, M. S., Prosser, C. F., & Fleming, T. A. 1998, ApJ, 501, 624
Gray, R. O. 1988, AJ, 95, 220
———. 1989, AJ, 98, 1049
———. 1991, in Precision Photometry Astrophysics of the Galaxy, ed. A. G. D. Philip, A. R. Upgren, & K. A. Janes (Schenectady: L. Davis), 309
Gray, R. O., & Corbally, C. J. 1993, AJ, 106, 632
———. 1994, AJ, 107, 742
———. 1998, AJ, 116, 2530
Gray, R. O., & Garrison, R. F. 1987, ApJS, 65, 581
———. 1989a, ApJS, 69, 301
———. 1989b, ApJS, 70, 623
Gray, R. O., Graham, P. W., & Hoyt, S. R. 2001, AJ, 121, 2159
Gray, R. O., & Kaye, A. B. 1999, AJ, 118, 2993

Gray, R. O., Napier, M. G., & Winkler, L. I. 2001, AJ, 121, 2148
Habing, H. J., et al. 2001, A&A, 365, 545
Hauck, B., Ballereau, D., & Chauville, J. 1995, A&AS, 109, 505
Hester, J. J., et al. 1996, AJ, 111, 2349
Hillenbrand, L. A., Massey, P., Strom, S. E., & Merrill, K. M. 1993, AJ, 106, 1906
Holweger, H., Hempel, M., & Kamp, I. 1999, A&A, 350, 603
Holweger, H., & Rentzsch-Holm, I. 1995, A&A, 303, 819
Houk, N. 1978, Michigan Catalogue of Two-Dimensional Spectral Types for the HD Stars, Vol. 2 (Ann Arbor: Dept. Astron. Univ. Michigan)
———. 1982, Michigan Catalogue of Two-Dimensional Spectral Types for the HD Stars, Vol. 3 (Ann Arbor: Dept. Astron. Univ. Michigan)
Houk, N., & Cowley, A. P. 1975, University of Michigan Catalogue of Two-Dimensional Spectral Types for the HD Stars, Vol. 1 (Ann Arbor: Dept. Astron. Univ. Michigan)
Houk, N., & Smith-Moore, M. 1988, Michigan Catalogue of Two-Dimensional Spectral Types for the HD Stars, Vol. 4 (Ann Arbor: Dept. Astron. Univ. Michigan)
Houk, N., & Swift, C. 1999, Michigan Catalogue of Two-Dimensional Spectral Types for the HD Stars, Vol. 5 (Ann Arbor: Dept. Astron. Univ. Michigan)
Ianna, P. A. 1970, PASP, 82, 825
Johnstone, D., Hollenbach, D., & Bally, J. 1998, ApJ, 499, 758
Keenan, P. C. 1963, in Stars and Stellar Systems, Vol. 3, Basic Astronomical Data, ed. K. Aa. Strand (Chicago: Univ. Chicago Press), 78
Krzemiński, W., & Serkowski, K. 1967, ApJ, 147, 988
Kurucz, R. L. 1993, CD-ROM 13, ATLAS9 Stellar Atmosphere Programs and 2 km/s Grid (Cambridge: Smithsonian Astrophys. Obs.)
Landolt, A. 1983, AJ, 88, 853
Levato, H., & Abt, H. A. 1977, PASP, 89, 274
Levato, H., Malaroda, S., Grosso, M., & Morrel, N. 1994, in The MK Process at 50 Years, ed. C. J. Corbally, R. O. Gray, & R. F. Garrison (San Francisco: ASP), 93
Maitzen, H. M., Pavlovski, K., Catalano, F. A., Deridder, Gh., & Hensberge, H. 1986, A&AS, 65, 497
Marchetti, E., Faraggiana, R., & Bonifacio, P. 2001, A&A, 370, 524
Martin, S., & Rodriguez, E. 1995, Inf. Bull. Variable Stars, 4273, 1
Martini, A. 1971, Mem. Soc. Astron. Italiana, 42, 523
Mason, B. D., Hartkopf, W. I., & McAlister, H. A. 1993, AJ, 106, 637
Mathis, J. S., & Lamers, H. J. G. L. M. 1992, A&A, 259, L39
McAlister, H. A., & Hartkopf, W. I. 1988, Second Catalog of Interferometric Measurements of Binary Stars, CHARA Contrib. 2 (Atlanta: Georgia State Univ.)
Michaud, G., & Charland, Y. 1986, ApJ, 311, 326
Morgan, W. W., & Hiltner, W. A. 1965, ApJ, 141, 177
Morgan, W. W., Hiltner, W. A., & Garrison, R. F. 1971, AJ, 76, 242
Morgan, W. W., Keenan, P. C., & Kellman, E. 1943, An Atlas of Stellar Spectra (Chicago: Univ. Chicago Press)
Morrell, N., & Abt, H. A. 1991, ApJ, 378, 157
Olsen, E. H. 1979, A&AS, 37, 367
Osawa, K. 1965, Ann. Tokyo Astron. Obs. 2d Ser., 9, 13
Paunzen, E. 1997, A&A, 326, L29
———. 2001, A&A, 373, 633
Paunzen, E., & Gray, R. O. 1997, A&AS, 126, 407
Paunzen, E., et al. 1998, A&A, 335, 533
Pavlovski, K., Schnell, A., & Maitzen, H. M. 1993, in Peculiar versus Normal Phenomena in IAU Colloq. 138, A-Type and Related Stars, ed. M. M. Dworetsky, F. Castelli, R. Faraggiana (San Francisco: ASP), 429
Perry, C. L., & Johnston, L. 1982, ApJS, 50, 451
Pesch, P., & McCuskey, S. W. 1974, AJ, 79, 116
Renson, P. 1992, Bull. Inf. CDS, 40, 97
Sadakane, K., & Nishida, P. E. 1986, PASP, 98, 685
Savage, B. D., & Mathis, J. S. 1979, ARA&A, 17, 73
Slettebak, A. 1982, ApJS, 50, 55
Stürenburg, S. 1993, A&A, 277, 139
Swings, P., & Struve, O. 1941, ApJ, 94, 291
Thompson, G. I., Nandy, K., Jamar, C., Monfils, A., Houziaux, L., Carnochan, D. J., & Wilson, R. 1978, Catalogue of Stellar Ultraviolet Fluxes (NSSDC ADC Cat. 2059B) (London: Sci. Res. Council)
Throop, H. B., Bally, J., Esposito, L. W., & McCaughrean, M. J. 2001, Science, 292, 1686
Turcotte, S., & Charbonneau, P. 1993, ApJ, 413, 376
Venn, K. M., & Lambert, D. L. 1990, ApJ, 363, 234
Waters, L. B. F. M., Trams, N. R., & Waelkens, C. 1992, A&A, 262, L37
Yoshizawa, M. 1978, PASJ, 30, 123