Astron. Astrophys. 350, 553–565 (1999)

ASTRONOMY AND ASTROPHYSICS

The incidence of nonradial pulsation in the λ Bootis stars*

D.A. Bohlender[1,**], **J.-F. Gonzalez**[2,3,***], **and J.M. Matthews**[4,***]

[1] National Research Council of Canada, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, BC, Canada V8X 4M6 (David.Bohlender@hia.nrc.ca)
[2] European Southern Observatory, Casilla 19001, Santiago 19, Chile (jfgonzal@eso.org)
[3] Centre de Recherche Astronomique de Lyon (CNRS-UMR 5574), Ecole Normale Supérieure de Lyon, 46 allée d'Italie, 69364 Lyon Cédex 07, France (Jean-Francois.Gonzalez@ens-lyon.fr)
[4] Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, V6T 1Z4 Canada (matthews@astro.ubc.ca)

Received 30 November 1998 / Accepted 29 March 1999

Abstract. We have conducted a high-resolution, high signal-to-noise spectroscopic survey of the members of the peculiar λ Boo stars accessible from the Canada-France-Hawaii Telescope to investigate the incidence of high-degree nonradial pulsation (NRP) in these metal-deficient stars. Of 16 objects observed more than once, 9 show conclusive evidence of such NRP, which confirms that pulsational instability is a common phenomenon in the λ Boo class.

The widespread presence of NRP in the λ Boo stars indirectly supports the accretion/diffusion scenario for the formation of these objects, but unfortunately does not rule out other possible causes for the phenomena. However, extensive time-series photometry and spectroscopy of several particularly interesting pulsating members of the class noted here should provide asteroseismologists with the eigenfrequency data needed to resolve the current debate concerning the evolutionary status, and hence, the origin of these peculiar stars. From our survey, we also identify a set of four stars, including λ Boo itself, with similar fundamental parameters but remarkably different pulsation characteristic. These stars may offer vital clues as to the physical excitation of λ Boo pulsations.

Key words: stars: oscillations – stars: peculiar – stars: variables: general

1. Introduction

The last several years have seen a tremendous surge in the efforts to understand the nature and origin of the peculiar, weak-lined λ Boo stars. This was largely motivated by Venn & Lambert's (1990) interpretation of high signal-to-noise (S/N), high-resolution spectra they obtained for three of the brightest members of the class. They found that λ Boo itself, 29 Cyg, and π^1 Ori have Fe (and other metal) deficiencies of between -1.3 and -2.0 dex, while C, N, O, and S have approximately solar abundances. Most significantly, however, they point out that the abundance anomalies of these three λ Boo stars resemble that of interstellar gas in which certain elements have been selectively depleted through the formation of grains. The λ Boo phenomenon may then arise when such depleted gas is accreted by an A-type star. Charbonneau (1991) and Turcotte & Charbonneau (1993) followed with models that demonstrate that an early A star will develop photospheric abundances reminiscent of those observed in the λ Boo stars if it is accreting metal depleted interstellar gas at a rate of approximately $10^{-13} M_\odot$ yr^{-1}.

A competing idea is the original suggestion by Michaud & Charland (1986) that chemical separation acting in the presence of mass loss (rather than accretion) in A and F stars could produce underabundances of up to a factor of 3, but not by factors of 100 measured for some of the λ Boo stars by Venn & Lambert's (1990) and Stürenburg (1993). Their model also appears to run into difficulty since it predicts the appearance of underabundances only after approximately 10^9 yr, whereas several λ Boo stars appear to be very close to the zero-age main sequence (ZAMS), or may even be pre-main sequence (PMS) objects (Gray & Corbally, 1993; Gray & Corbally, 1997).

There is some observational support for circumstellar material associated with the λ Boo stars. A few members of the class have infrared flux excesses similar to that observed in Vega, which according to Venn & Lambert (1990) is a mild λ Boo star itself. This emission is likely attributable to cool, circumstellar dust (Sadakane & Nishida, 1986; Cheng et al., 1992). The presence of circumstellar gas may also be indicated by "shell" features superimposed on the photospheric profiles of several lines including Na I D, Ca II K, low-excitation Fe II and Ti II lines, O I, and Hα (Holweger & Stürenburg, 1991; Bohlender & Walker, 1994; Hauck et al., 1995; Holweger & Rentzsch-Holm, 1995; Andrillat et al., 1995; Bohlender et al., 1996; Gonzalez & Bohlender, 1998), although it is difficult to rule out an interstellar origin for some of these (Gonzalez & Bohlen-

Send offprint requests to: D.A. Bohlender

* Figs. 2–5, 7–10 are only available in the electronic version.

** *Formerly at:* Canada-France-Hawaii Telescope Corporation, PO Box 1597, Kamuela, HI 96743, USA

*** Visiting Astronomer, Canada-France-Hawaii Telescope, operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique of France, and the University of Hawaii.

der, 1998). Most exciting is the recent detection by Grady et al. (1996a) of direct evidence for accretion of circumstellar gas in the λ Boo star 131 Tau. IUE observations of mid-UV Fe I, Zn II, Si II, Al II, and C I lines show accreting gas with infall velocities up to $80\,\mathrm{km\,s^{-1}}$. We note, however, that Bohlender & Walker (1994) find that this star shows only modest λ Boo characteristics.

While the frequency with which circumstellar material is found around the λ Boo stars suggests that the Turcotte & Charbonneau (1993) model may be correct, the model runs into difficulty in another area. They predict that because of circulation currents (unlike the classical Am stars, the λ Boo stars are *not* slow rotators) the abundance peculiarities arising from the accretion event will disappear appoximately 10^6 years after the accretion stops. In other words, all λ Boo stars should be essentially ZAMS objects if the assumption is made that the accreting material is a remnant of the material from which the star formed. It is not obvious that this is the case. Bohlender et al. (1996) have plotted the members of the class in the $\mathrm{M}_V - (b-y)$ plane and show that at least one-half of the λ Boo stars lie 1 mag or more above the ZAMS. Iliev & Barzova (1995) used $uvby\beta$ colors, calibration tables of Moon & Dworetsky (1985), and Schaller et al. (1992) evolutionary tracks to demonstrate the same thing: most of the λ Boo stars appear to be in the middle of their main sequence evolution, not on the ZAMS. Paunzen (1997) on the other hand argues that several members of the class are very close to the ZAMS and postulate that the other members of the class are PMS objects. However, there appears to be no direct evidence for the latter conclusion so that the debate is likely to continue for some time.

Alternatively, an originally normal A star located anywhere on the main sequence could quite rapidly assume the abundance characteristics of a λ Boo star if a source of depleted circumstellar material is available.

Clearly no conclusion can be made yet, but the recent discovery of nonradial pulsation (NRP) in the λ Boo star HD 111604 (Bohlender et al., 1996) and the high frequency of photometric variability among members of the group (Paunzen et al., 1998a) suggests an alternative approach to measuring the evolutionary stage of at least one member of the class. Like the δ Scuti stars, this object is apparently unstable to nonradial oscillations driven by the κ mechanism. The oscillations produce velocity perturbations of the stellar rotation profile which in turn produce variations in the line profile shapes (Vogt & Penrod, 1983). Three "quantum numbers" describe the oscillations: the degree 'ℓ',the azimuthal order 'm', and the radial order or overtone 'n.' Armed with the full eigenmode spectrum of a multiperiodic pulsator, we could directly estimate the mean density of the star, and hence its evolutionary state by comparison with theoretical models.

Bohlender et al. (1996) briefly discussed the existing evidence for variability among other λ Boo stars and show that a substantial fraction of the class actually lie in the δ Scuti instability strip. Given these facts and the obvious interest in detecting more pulsating λ Boo stars we have carried out a survey of the members of the group selected from the list of Gerbaldi & Faraggiana (1993) and accessible from the Canada-France-Hawaii Telescope to search for the incidence of high-degree nonradial pulsation among the class. As we discuss below, of 18 λ Boo stars observed we have found conclusive evidence for NRP in 9 objects. The range of pulsation amplitude is large, but four more members of the class have large pulsation amplitudes that will make them attractive as additional candidates for intensive multi-site observing campaigns.

Table 1. Summary of CFHT Observing Runs

Date (UT)	Detector	Dispersion (Å mm^{-1})	Resolution	Wavelength region
1995 Mar 18	Loral3	6.76	29,000	Na I D
1995 Sep 11–12	Orbit	1.65	92,000	Na I D
1995 Sep 12	Orbit	1.19	97,000	Mg II
1996 Mar 8–10	UBC4k	1.19	97,000	Mg II
1996 Dec 18–19	UBC4k	1.65	92,000	Na I D

2. Observations

The spectra discussed here were obtained during four observing runs with the CFHT *f*/8.2 and *f*/4 coudé (*Gecko*) spectrographs in March and September 1995 and March and December 1996. The original goal of our program was an investigation of the occurrence of shell features in the Na I D lines, so most of the data were obtained with a central wavelength near 5892 Å. In fact, as mentioned by Bohlender et al. (1996) the original discovery of NRP in the λ Boo star HD 111604 was purely serendipitous.

Contamination of spectra by cosmic rays can be a problem even for relatively short exposure times while observing at the altitude of the CFHT. To limit the impact of these events on our high S/N observations of the Na I D lines we obtained several short exposures, typically with durations of 10 minutes or less, for subsequent median combining. In a few cases, including the original discovery of pulsation in HD 111604, spectrum variability could be seen in successive plots of the raw data as we were observing.

Once it was clear that several λ Boo stars were indeed variable, we obtained spectra for several stars at a central wavelength near 4500 Å, a region frequently used for observations of NRP in δ Scuti stars, and containing a Mg II line at 4481 Å, a Ti II line at 4501 Å and an Fe II line at 4508 Å.

A summary of the instrumental setup for the four observing runs is given in Table 1, and includes the dates of the runs, the detectors used, the dispersions and resolutions (derived from the FWHM of Th/Ar comparison lamp spectra), and the wavelength regions observed. In most cases, the program stars were observed for approximately one hour only, partly because we were originally unaware of variability in some of the stars and required only about an hour of observations to achieve sufficiently high S/N spectra of the Na I D features. Once some variable stars were discovered, we still limited ourselves to relatively short time series because of observing time constraints and because our intent at this point in time was simply to detect

Table 2. Fundamental Data for the Program λ Boo Stars

HD	Name/HR	V	$b-y$	m_1	c_1	β	Parallax (mas)	d (pc)	M_V	R ($R_\odot$)	$v \sin i$ (km s^{-1})
319	12	5.940	0.079	0.164	1.037	2.852	12.45	80	1.4	2.4	60
4158		9.549	0.216	0.102	0.748	2.674	13.00[a]	77	5.1	6.7[b]	100
30422	1525	6.192	0.101	0.185	0.871	2.832	17.40	57	2.4	1.6	130
31295	π^1 Ori	4.661	0.044	0.178	1.007	2.899	27.04	37	1.8	1.7[c]	120
38545	131 Tau	5.6	0.042	0.168	1.114	2.852	7.72	130	0.0	3.9	210
110411	ρ Vir	4.88	0.040	0.180	0.992	2.908	27.10	37	2.0	1.5[c]	160
111604	4875	5.890	0.112	0.147	1.024	2.798	8.43	119	0.5	3.7	185
111786	4881	6.153	0.162	0.132	0.808	2.777	16.62	60	2.3	1.8	140
125162	λ Boo	4.200	0.051	0.183	0.999	2.894	33.58	30	1.8	1.7[c]	110
142703	5930	6.123	0.182	0.116	0.724	2.736	18.89	53	2.5	1.8	110
142994		7.177	0.201	0.117	0.860	2.722	5.20[a]	192	0.8	4.1	195
183324	35 Aql	5.799	0.051	0.167	1.002	2.890	16.95	59	1.9	1.6[c]	100
192640	29 Cyg	4.920	0.099	0.158	0.928	2.832	24.37	41	1.9	2.0	90
193256	7764C	7.722	0.116	0.163	0.990	2.814	4.58	218	1.0	3.0	300
193281	7764A	6.631	0.098	0.152	1.113	2.848	4.58	218	−0.1	4.8	95
204041	8203	6.463	0.092	0.167	0.940	2.846	11.46	87	1.8	2.0	65
210111	8437	6.391	0.136	0.147	0.861	2.774	12.70	79	1.9	2.2	55
221756	15 And	5.59	0.056	0.166	1.072	2.878	13.97	72	1.3	2.0	105

[a] Parallax taken from the Tycho catalogue, with much larger uncertainties
[b] See text for discussion of M_V, d, and R derivation
[c] β outside of validity range of Crawford's (1979) calibration

evidence for NRP and not to perform detailed analyses of the program stars.

The program stars are indicated in Table 2 where for each star we give the V magnitude and $uvby\beta$ data from the on-line General Catalogue of Photometric Data (Mermilliod et al., 1997). We also include the parallax from the Hipparcos survey (ESA, 1997) in milli-arcsec (mas) and the distance and absolute magnitude deduced from it. The uncertainties of the parallaxes are typically 5 to 10 percent, which translates into 0.1 mag for M_V. Stellar radii are calculated from effective temperatures and bolometric corrections derived from calibrations by Crawford (1979) and Balona (1994) and an assumed $M_{\mathrm{bol},\odot} = 4.75$ (Cayrel de Strobel, 1996). Note, however, that four stars (indicated in the table) have β values slightly larger than the upper limit covered by Crawford's calibration.

The parallaxes of HD 4158 and HD 142994 are taken from the Tycho catalogue, also part of the Hipparcos survey but less precise, with uncertainties of 95% and 83% respectively. For HD 142994 we will therefore adopt the absolute magnitude value derived from Crawford's (1979) A-type star calibration as when compared to the Tycho paralaxes this gives a better intrinsic error in M_V of about 0.3 mag. Unfortunately the apparent bright giant HD 4158 is well outside the valid ranges of both the F and A-type star calibrations of Crawford (1975; 1979). We have therefore estimated $\log g$ and T_{eff} for HD 4158 from the grids of Moon & Dworetsky (1985) after following the procedure of Crawford and Barnes (1974) to derive reddening-free color indices. The stellar evolution tracks of Schaller et al. (1992) and an empirical estimate of the bolometric correction from Balona's (1994) calibration results in the absolute magnitude, distance and stellar radius given for HD 4158 in Table 2.

The last column gives the rotational velocity we have derived from a spectrum synthesis of the Na I D lines of each object. While $v \sin i$ measurements have been made for the majority of the program stars, we feel these new measurements are useful since the S/N and resolution of the mean spectra for each program star are generally superior to what has been obtained previously for the λ Boo stars. Line profiles have been calculated using a line synthesis program developed by one of us (DAB). These routines makes use of Kurucz's (1979) ATLAS9 model atmosphere program as a subroutine to generate an appropriate model atmosphere. For the line synthesis we have adopted the $\log g$ and T_{eff} of Stürenburg (1993) where available, or from Iliev & Barzova (1995). We adopted an overall metal abundance scale of -1.0 dex relative to the sun and adjusted the Na I abundance to give the best fit to the doublet's two profiles. Uncertainties in the $v \sin i$ are typically ± 5 km s^{-1} and are not sensitive to small variations in the adopted atmospheric parameters. In any case, the limited wavelength coverage provided by one wavelength setting with the Gecko spectrograph makes it impossible to attempt a more rigorous and self-consistent abundance analysis.

Table 3 gives for each star the number of spectra obtained in the Mg II λ4481 and Na I regions, the peak-to-peak amplitude of any detected NRP as a percentage of the continuum level or 2σ upper limits to any such features if not detected with the current observations, the average time delay between subfeatures, the estimates of the azimuthal order, and measurements of the

Table 3. Summary of Observations

HD	Name/HR	Mg II	Na I	NRP Amp (%)	Δt (min)	$\|m\|$ ± 2	P ± 0.1 (d)	$P_{\rm o}$ (min)	Phot. Var.?	$P_{\rm phot}$ (min)
319	12	0	5	< 0.8	–	–	–	–	< 4.2 mmag in b	–
4158		0	1	–	–	–	–	–	–	–
30422	1525	12	8	1.0	32	19	0.4	19	Yes	30
31295	π^1 Ori	6	5	1.0	9	30	0.2	7	< 7.4 mmag in v	–
38545	131 Tau	0	5	< 0.4	–	–	–	–	< 4.2 mmag in v	–
110411	ρ Vir	18	4	< 0.4	–	–	–	–	Yes	multimode?
111604	4875	64	6	2.5	50	20	0.7	29	Yes	144
111786	4881	0	9	1.5	39	17	0.5	23	Yes	96,43,71,46
125162	λ Boo	22	8	0.7	22	18	0.3	16	Yes	33
142703	5930	0	3	< 0.5	–	–	–	–	Yes	46?,87?
142994		0	1	~ 2	–	12?	–	–	Yes	228,140,195,174
183324	35 Aql	6	6	1.2	23	15	0.3	18	Yes	30
192640	29 Cyg	12	9	2.5	42	14	0.4	31	Yes	39,49
193256	7764C	0	2	< 0.8	–	–	–	–	< 2.6 mmag in b	–
193281	7764A	0	3	< 0.5	–	–	–	–	< 3.4 mmag in b	–
204041	8203	0	5	< 0.4	–	–	–	–	< 1.8 mmag in b	–
210111	8437	10	5	2.5	62	12	0.5	49	Yes	51,85
221756	15 And	6	7	1.2	49	17	0.6	31	Yes	63

rotation period and oscillation period in the corotating frame of reference where applicable (see Sect. 3). In the last two columns we indicate whether the star is a photometric variable or not (if not we give an upper limit, where available, to any v or b-band variations) and list any established photometric periods. An examination of Table 3 immediately reveals that only 1–3 spectra have been obtained for a number of stars. Obviously in these cases our claim of detection or non-detection of NRP should be viewed as tentative only.

The data have been reduced in a conventional manner with IRAF. Except in two cases, for the Na I D line data we have not removed telluric lines in the individual spectra since for the investigation discussed here we are interested only in differences between individual spectra and the mean spectrum for each object. During the relatively short observation interval for each star the intensities of the telluric features change very little and as a consequence they are normally entirely absent in the difference spectra. For HD 111786 and HD 210111, relatively rapid changes in the strengths of the telluric features from one spectrum to the next during our time series for these stars required that we remove telluric features in each individual exposure before producing a mean and difference spectra. We have removed telluric lines in the mean Na I D line spectra shown in the figures in the next section.

3. Results

We have followed Kennelly's (1994) approach in searching for NRP in the program λ Boo stars. For each star at each wavelength region a mean spectrum is created by averaging individual exposures. Difference spectra are then produced by subtracting the appropriate mean spectrum from the individual spectra. The mean-absolute-deviation (MAD) at each pixel is then generated from the difference and mean spectra and is given by

$$D = \sum_i \frac{|I_i - \bar{I}|}{\bar{I}} \qquad (1)$$

where I_i is the intensity at that pixel in spectrum i, $\bar{I}$ is the intensity at the same pixel averaged for the entire set of spectra, and the sum is performed over each spectrum. For each star we then plot the mean spectrum, the difference spectra, and the MAD spectrum on the same wavelength scale. Fig. 1 gives an example. NRP is usually readily seen in the difference spectra and if the MAD plot has a positive excursion at the location of each line in the spectrum then the reality of the NRP is confirmed.

We briefly discuss each program star in the subsections below. To save space, plots of spectra are included only in the cases of positive detection of NRP (with the exception of ρ Vir) and if the number of spectra warrant it we have followed the approach of Walker et al. (1987) to derive estimates for the principal mode of oscillation, assuming sectorial modes ($\ell = |m|$). In this case the principal mode $|m|$ is given by

$$|m| = 2\pi(v \sin i)/(a_o \Delta t). \qquad (2)$$

Here a_o is the average acceleration of the oscillation subfeatures at the line center and Δt is the average time between successive subfeatures crossing the line center. One wave then travels around the star in a period, P, given by

$$P = |m| \Delta t. \qquad (3)$$

If the rotational velocity is large when compared to the phase velocity of the wave then P provides an estimate of the rotation period of the star. However, Kennelly (1995) has shown that for the rapidly rotating δ Scuti stars the ratio between the rotation frequency, Ω, and the oscillation frequency, ν, is small and typically $\Omega/\nu = 0.08$. Ignoring coriolis terms, the oscillation frequency (in cycles/day) in the corotating frame of the star, $\nu_{\rm o}$, is then given by

$$\nu \sim \nu_{\rm o} - 0.02(mv \sin i/R \sin i) \quad (4)$$

where $\nu = (\Delta t)^{-1}$ is the observed frequency (in cycles/day), m is given by Eq. (2), and R is the stellar radius (in $R_\odot$). The value of $P_{\rm o} = \nu_{\rm o}^{-1}$ is tabulated in Table 3. We have assumed the waves are prograde ($\ell = -m$).

The Na I D lines were used for all stars for which we determined orders and periods. When the amplitude of the NRP was large enough in the Ti II λ 4501 line and in the Fe II λ 4508 line, i.e. for 29 Cyg, HD 210111 and 15 And (see Figs. 8, 9 and 10), they were also included in the determination. However, the Mg II λ 4481 line is actually a doublet, and the variations seen are a superposition of NRPs on the individual lines, yielding results possibly inconsistent with the other lines. For this reason, we did not take this line into account. We expect uncertainties of ± 2 on the orders and of ± 0.1 d on the periods.

3.1. HD 319 = HR 12

Abt (1984) first drew attention to the peculiarity of HD 319. It was classified as A1mA2 Vb PHL by Gray (1988). The star appears to be a moderately evolved λ Boo star (Iliev & Barzova, 1995) with relatively modest metal underabundances (Stürenburg, 1993). Its $v \sin i$ value of 60 km s^{-1} makes it a relatively sharp-lined member of the class. Five spectra of the Na I D lines region of HD 319 we obtained over two epochs show no evidence of variability. It is therefore not surprising that two hours of v and b photometry of HD 319 by Paunzen et al. (1997a) show no photometric variability larger than 4.2 mmag in b.

3.2. HD 4158

Originally noted as a λ Boo star by Graham & Slettebak (1973), Gerbaldi & Faraggiana (1993) include HD 4158 in their list of λ Boo stars based on the presence of the λ1600 feature characteristic of other members of the class. Given the star's faintness, it has been largely ignored in other studies. We have obtained a single spectrum of the Na I D line of the star and so can say nothing about line profile variability. The lack of asymmetry in the line suggests that the star is not undergoing high-amplitude NRP as are a few of the other program objects but further data would be needed to confirm this.

3.3. HD 30422 = HR 1525

Gray & Garrison (1989) discovered the λ Boo nature of HD 30422 and classified the star as A3 Vb PHL. Iliev & Barzova (1995) find that the star is only slightly evolved. Despite its relative brightness, the star has been largely ignored in the literature. An examination of Fig. 1 indicates that this lack of

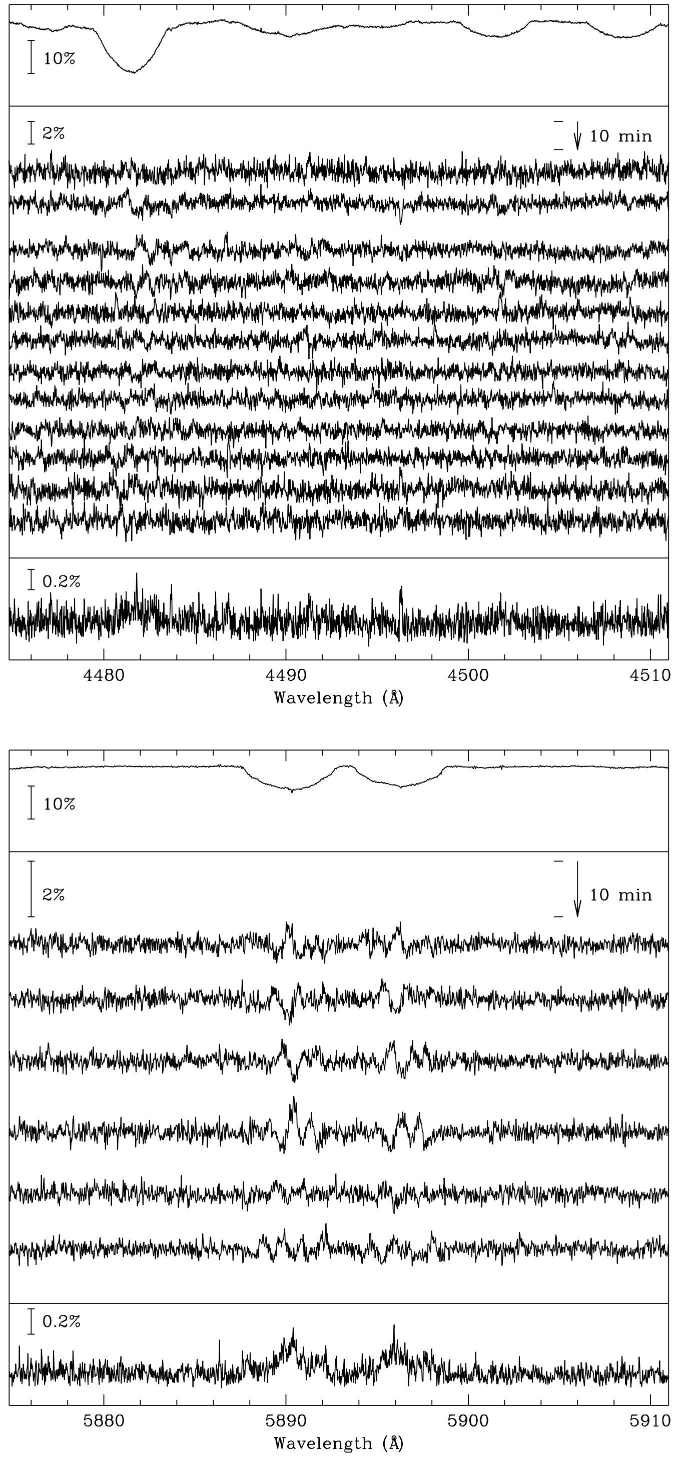

Fig. 1. Observed spectra for HD 30422 in the Mg II line region (*top*) and in the Na I D lines region (*bottom*). For each wavelength region the top panel shows the average of the spectral time series. The middle panel shows the residuals of each spectrum from the mean plotted as a function of time. Time progresses downward with the scale indicated by the arrow. The bottom panel shows the mean-absolute-deviation of the spectra from the mean as defined in the text. The relative intensity scale is indicated in each panel.

interest should change. HD 30422 is clearly a nonradial pulsator with peak-to-peak amplitude in the Na I D and Mg II lines of 1.5 to 2%. Kuschnig et al. (1996) have recently found the star to be a photometric variable. Strömgren b observations obtained over two nights give a peak amplitude of 10 mmag with a period of approximately 30 minutes.

We have performed a spectrum synthesis of the mean spectra shown in Fig. 1 and find a $v \sin i$ of 130 km s^{-1}. The analysis of the variations of the Na I D lines gave an order estimate of $|m| = 19$ and a period of $P_{\rm o} = 19$ min. The average delay between subfeatures, $\Delta t = 32$ min, is very close to the photometric period, but this is almost certainly a coincidence. NRP with $|m| = 19$ is highly unlikely to produce measureable photometric variations when the brightness variations arising from the NRP are averaged over the visible surface of the star. The photometric variations arise from lower order pulsation components not readily apparent in our limited set of spectra.

3.4. HD 31295 = π^1 Ori

π^1 Ori is the second brightest λ Boo star and has been rather thoroughly studied. Its peculiar nature was first noted by Slettebak (1954), and Gray (1988) has classified it as A0 Va NHL. Iliev & Barzova (1993; 1995) have confirmed the normal nature of the star's Balmer line profiles and estimate that the star is approximately one-third of the way through its main sequence lifetime. The star has a metal deficiency of approximately 1.0 dex and a moderate $v \sin i$ of 120 km s^{-1} (Venn & Lambert, 1990; Stürenburg, 1993). An infrared color excess (Sadakane & Nishida, 1986) suggests the presence of circumstellar material, but no evidence of circumstellar shell features has been found (Gonzalez & Bohlender, 1998), nor is there any direct evidence of a β Pic-like disk (Smith et al., 1992).

Fig. 2 conclusively shows that π^1 Ori is undergoing NRP with a peak-to-peak amplitude of approximately 1%. Using the Na I D lines, we found $\Delta t = 9$ min, $|m| = 30$ and $P_{\rm o} = 7$ min, but clearly these values are highly uncertain since they are based on a time series of only three spectra. Since there is only an upper limit to photometric variability of 7.4 mmag in v (Paunzen et al., 1997a), additional photometric (and spectroscopic) observations of this star would obviously be of interest.

3.5. HD 38545 = 131 Tau

The λ Boo star 131 Tau has recently attracted attention because of Bohlender & Walker's (1994) discovery of circumstellar features in the spectrum of the A2 Va$^+$ PHL star (Gray & Garrison, 1987), and the subsequent report of the direct detection of accretion in the star by Grady et al. (1996a). The star would thus appear to provide strong support for the Turcotte & Charbonneau (1993) accretion model. Holweger & Stürenburg (1991) and Bohlender & Walker (1994) find only slight underabundances of some elements which raises questions about the λ Boo nature of 131 Tau, but Paunzen et al. (1997b) do include it in their recent catalogue. Iliev & Barzova (1995) suggest that the star is near the end of its main sequence lifetime but the shell components of the Balmer lines almost certainly complicate the interpretation of the star's physical properties. 131 Tau would appear to be more closely related to the A-shell or Herbig Ae/Be stars, especially since other members of these groups have also been found to be undergoing accretion events (Grady et al., 1996b; Grady et al., 1996c). Rather than being in an advanced state of evolution, the star may actually be a very young object still contracting towards the ZAMS.

More than 10 hr of Strömgren v photometry of 131 Tau (Paunzen et al., 1997a) shows no evidence for variability above the 4.2 mmag level. Three Na I D line spectra we have obtained show a hint of low-order variability near the noise level of about 0.4% but because of the star's rapid rotation ($v \sin i = 210$ km s^{-1}) we suspect that this apparent variability arises from slight differences in the continuum placement for each spectrum. Until additional data are obtained, we will adopt the stance that 131 Tau is *not* a pulsating variable. This assumption is supported by the fact that the star is not located in the δ Scuti instability strip (see Sect. 4).

3.6. HD 110411 = ρ Vir

Discovered by Henry (1969) and classified as A0 Va NHL by Gray (1988), this bright λ Boo star appears to be close to the ZAMS (Iliev & Barzova, 1995) and a limited spectral analysis by Stürenburg (1993) indicates metal abundances approximately 1.0 dex below solar values and a relatively high $v \sin i$ of 160 km s^{-1}. Cheng et al. (1992) report the detection of an infrared color excess possibly indicating circumstellar dust, but there are no accompanying circumstellar gas features (Gonzalez & Bohlender, 1998).

We obtained an extensive series of 18 spectra of ρ Vir in a wavelength region containing the Mg II λ4481 line over a period of 3.25 hr. No variability in the spectra can be seen at a level of approximately 0.4% of the continuum. There is also no indication of variability in four successive observations of the Na I D lines. We show these data in Fig. 3 in order to give a clear indication of what we feel is the low-amplitude limit to our detection of NRP.

These results for ρ Vir may appear somewhat surprising given the fact that Bartolini et al. (1980) suspect that the star is an irregular photometric variable. Subsequent observations by Antonello & Mantegazza (1982) may have confirmed the variable nature of ρ Vir but they also could not determine a period from their limited number of observations. In fact, over the course of a few hours the photometric variability of the star apparently dies out completely from an initial amplitude of 10 mmag in B. This behaviour makes it tempting to suggest that ρ Vir is a multimode pulsator, but better quality photometric observations are needed before any firm conclusion can be made. It is relevant to the discussion to draw attention to the fact that this star is our only "firm" case of nondetection of NRP in this survey of the λ Boo stars. Since ρ Vir appears to lie just outside the blue edge of the δ Scuti instability strip (Sect. 4) we suspect that improved photometry may well indicate that it is *not* a variable star.

3.7. HD 111604 = HR 4875

Gerbaldi & Faraggiana (1993) included HD 111604 in their list of λ Boo stars because of the presence of the λ1600 feature in its UV spectrum. However, Paunzen et al. (1997b) do not include the star in their recent catalogue of λ Boo candidates so its exact nature remains somewhat uncertain and may have to await a detailed spectrum synthesis.

Bohlender et al. (1996) have already discussed the NRP observed in HD 111604 in some detail. The mode of oscillation, $|m|$, is on the order of 20 and individual NRP features, separated by about $\Delta t = 50$ min, circumnavigate the star approximately every 0.7 days. The peak-to-peak amplitude of the pulsation signature is quite large and exceeds 2% of the continuum level. Provins (1953) suspected that HD 111604 is a photometric variable and this has recently been confirmed by Jordan et al. (1997) from APT observations as well as Hipparcos photometry. They quote a period of approximately 0.1 days, an amplitude of 10–15 mmag, and note that the period may have changed from one observing season to the next.

We have obtained additional spectra for HD 111604 but these will be discussed in a separate paper.

3.8. HD 111786 = HR 4881

Of all of the λ Boo stars, HD 111786 has perhaps garnered the most attention after Holweger & Stürenburg (1991) discovered narrow absorption components superimposed on the broad ($v \sin i = 140\,\mathrm{km\,s^{-1}}$) photospheric components of the Na I D and Ca II K lines. They suggested that these sharp features and many other narrow features found in other wavelength regions arise from circumstellar gas. Subsequent observations of radial velocity variations in the sharp spectral feature near the photospheric Ca II K line (Holweger & Rentzsch-Holm, 1995) led to the conclusion that HD 111786 is accreting gas in a manner analogous to β Pic. First cited as a peculiar star by Andersen & Nordström (1977), Gray (1988) had already noted narrow component in the Ca II line when he classified the A1.5Va$^-$ PHL object.

However, it now appears that this particular interest may be unwarranted. Faraggiana et al. (1997) have presented convincing evidence that HD 111786 is in fact a double-lined spectroscopic binary. One member of the binary has broad lines and pronounced underabundances of metals (Stürenburg, 1993) characteristic of the λ Boo stars while the other component is cooler (an early-F star) and sharp-lined. Iliev & Barzova (1995) find that HD 111786 is more than half-way through its main sequence lifetime, but this result will likely need to be revised because of the binary nature of the star.

In our final night of CFHT observations we were able to obtain a time sequence of 9 spectra of HD 111786 in a region centered on the Na I D lines. Residuals from the mean of these spectra, shown in Fig. 4, clearly show that the star is a nonradial pulsator with a peak-to-peak amplitude of approximately 1.5% of the continuum level. Following the procedure outlined in Sect. 3 we derive an order of $|m| = 17$, $\Delta t = 39$ min and an oscillation period of $P_\mathrm{o} = 23$ min. Photometric observations of HD 111786 have been made by Kuschnig et al. (1994a) and Paunzen et al. (1998b). The latter find 4 frequencies (periods of 96, 43, 71, and 46 min) in the photometric variations, with amplitudes ranging from 5.4 to 8.0 mmag in v. Identical periods but different amplitudes are found in a reanalysis of the earlier data of Kuschnig et al. (1994a).

3.9. HD 125162 = λ Boo

The prototype of the class discovered by Morgan et al. (Morgan et al., 1943), this A0 Va (Gray, 1988) star appears to be in the middle of its main sequence lifetime (Iliev & Barzova, 1995). Venn & Lambert (1990) find a general metal deficiency of -2 dex while C, N, O, and S have roughly solar abundances. Sadakane & Nishida (1986) find evidence for circumstellar dust in the form of an IRAS infrared color excess. No direct evidence of a circumstellar disk similar to that of Vega or β Pic has been found (Smith et al., 1992), nor have any circumstellar gas features been detected (Gonzalez & Bohlender, 1998).

Fig. 5 demonstrates that we have discovered NRP in λ Boo. The amplitude of the pulsation in the Na I D lines is about 0.5% and is detectable only because of the high S/N of our spectra. In fact, this may be the lowest amplitude NRP ever reported. We note that the pulsation is not readily apparent in spectra containing the Mg II λ4481 line and obtained at a different epoch. This may be because of the extreme weakness of the Mg II and other lines in this spectral region or a reduction in the contrast of the NRP features because of the fact that the Mg II line is a blended doublet. Paunzen et al. (1997a) have found no photometric variations during 5 hrs of observations over two nights, but poor weather conditions resulted in an upper limit in b of 6.6 mmag. We expect that more precise photometry will confirm that λ Boo is a photometric variable, and in fact (Paunzen et al., 1998a) may have detected such variability at the 3 mmag level in a recent short observing run.

A $v \sin i$ of $110\,\mathrm{km\,s^{-1}}$ for λ Boo leads to an order estimate of $|m| = 18$, $\Delta t = 22$ min, and $P_\mathrm{o} = 16$ min, using the Na I D lines.

3.10. HD 142703 = HR 5930

Hauck (1986) discovered the λ Boo nature of HD 142703 and Gray (1988) classifies it as KA1hF0mA1 Va PHL. Like λ Boo itself, the star is apparently middle-aged (Iliev & Barzova, 1995). No abundance analysis of the star has been published, but the star has been quite widely observed photometrically by Paunzen and his colleagues. Paunzen & Weiss (1994) first measured a period of 46 min with an amplitude of 10 mmag in v and b. Later observations by Paunzen et al. (1995) and Paunzen & Handler (1996a) suggest a period of approximately 87 minutes with a somewhat smaller amplitude of 6 mmag. We find a $v \sin i = 110\,\mathrm{km\,s^{-1}}$.

We have obtained only three spectra of the Na I D lines for HD 142703 and find no evidence for variability at a level of 0.5% of the continuum. Additional observations should obviously be

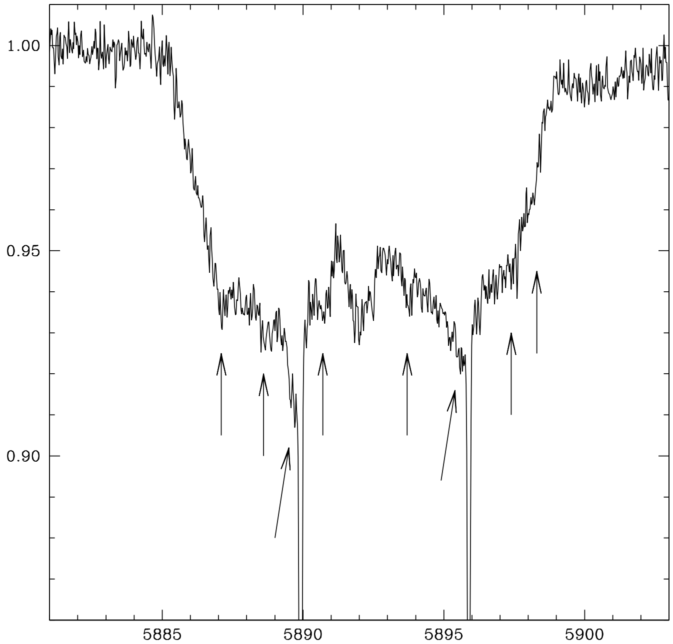

Fig. 6. The Na I D line profiles of HD 142994. The deep, narrow spectral features likely have a circumstellar origin. Possible NRP features are marked.

obtained, given that the photometric data discussed above imply that HD 142703 may also be a multimode pulsator.

3.11. HD 142994

This λ Boo star was discovered by Gray (1988) and classified as A3 Va PHL. The PHL designation arises from the fact that the Balmer line cores look like those of F0 stars. Olsen (1983) suggested possible variations in the c_1 index as did subsequent observations by Gray (1988). Weiss et al. (1994) firmly established the photometric variability, finding a period of approximately 4 hr and an amplitude of 6 mmag in b. An asymmetric light curve suggests the presence of additional frequencies, an idea confirmed by Paunzen et al. (1995). More extensive observations by Paunzen et al. (1998b) result in the detection of 4 pulsation periods (of 228, 140, 195, and 174 min with v amplitudes of 37.6, 20.4, 11.9, and 8.1 mmag respectivelty) but aliasing problems make these uncertain. We find $v \sin i = 195\,\mathrm{km\,s^{-1}}$, somewhat smaller than the value of $220\,\mathrm{km\,s^{-1}}$ quoted by Paunzen et al. (1998b).

HD 142994 appears to be one of the most evolved λ Boo stars (Iliev & Barzova, 1995; Paunzen et al., 1998b) with a $\log g$ of 3.5. This clearly poses problems for the ZAMS interpretation for the λ Boo stars, unless the star is assumed to be a PMS object (Paunzen, 1997). Unfortunately, we have obtained only a single spectrum of the Na I D lines of HD 142994. However, we believe this single spectrum, presented in Fig. 6, shows strong evidence for the presence of NRP. Ignoring what appear to be strong circumstellar features (Gonzalez & Bohlender, 1998) the Na I D line profiles are very irregular in shape. The central dip at the center of the blended feature is mostly a result of the large $v \sin i$ of the star and the blending of the two components of the doublet, but in Fig. 6 we have marked several other "dips" in each line profile. These have the same general appearance of the NRP features in the other pulsating λ Bootis stars discussed here and so leads us to state with a high degree of confidence that HD 142994 is also undergoing NRP. By simply counting the number of features visible and extrapolating over severely blended portions of the line profiles, we estimate a value of $|m|$ between 10 and 12. Obviously we can say nothing about the pulsation period(s).

Given the appearance of the spectrum and the presence of multiple frequencies in the photometric data, HD 142994 warrants additional spectroscopic observations. Identification of these periods with specific pulsation modes should enable a definitive determination of the star's evolutionary state.

3.12. HD 183324 = 35 Aql

Abt (1984) first included 35 Aql as a member of the λ Boo class and Gray (1988) classifies it as A0 Vb NHL. Iliev & Barzova (1995) find that the star is near the middle of its main sequence lifetime. The star has no obvious shell features at Ca II K or Na I D (Holweger & Stürenburg, 1991; Gonzalez & Bohlender, 1998), although Holweger & Rentzsch-Holm (1995) draw attention to a possible blue-shifted circumstellar component in the Ca II line. 35 Aql is extremely weak-lined and spectral analyses (Stürenburg, 1993; Heiter et al., 1998) confirm that it is one of the most metal-deficient λ Boo stars known with abundances typically 1.5 dex below solar values. Our $v \sin i$ of $100\,\mathrm{km\,s^{-1}}$ agrees well with the value of $90\,\mathrm{km\,s^{-1}}$ quoted in the above references.

Fig. 7 shows our Na I D line observations for 35 Aql. The six spectra demonstrate that the star clearly has high-amplitude ($> 1\%$) NRP. It is interesting to note that this NRP can also be seen in the Na I D line observations of Holweger & Stürenburg (1991) but they do not note the line asymmetries in their paper. Such NRP could also potentially produce features similar to the postulated weak circumstellar component in the Ca II line mentioned above.

Because of the very weak Fe II and Ti II lines, we have used only the Na I D lines to derive $\Delta t = 23$ min, $|m| = 15$ and $P_\mathrm{o} = 18$ min. Given the high-amplitude NRP and the possible detection of a 30 min, 2 mmag amplitude v-band photometric variation (Kuschnig et al., 1994b), 35 Aql obviously deserves additional attention.

3.13. HD 192640 = 29 Cyg

As a consequence of its relative brightness ($V = 4.92$) and moderate rotation rate ($v \sin i = 90\,\mathrm{km\,s^{-1}}$), it's not surprising that 29 Cyg is one of the most thoroughly studied λ Boo stars. Since its discovery by Slettebak (1952), several abundance analyses have been performed. The most recent detailed investigations (Venn & Lambert, 1990; Stürenburg, 1993; Heiter et al., 1998) show a general deficiency in metals (except for CNO and S) of between 1.0 and 1.8 dex relative to the solar abundance. Gray has classified the star as A0.5 Va$^-$ PHL while Iliev & Barzova (1995) estimate that the star is half-way through its main sequence lifetime. The star has a very sharp feature centered on each of its Na I D lines, but the source of these components is almost certainly interstellar (Gonzalez & Bohlender, 1998).

Photometric observations of 29 Cyg are likely the most extensive for any λ Boo star to date. Observations by Gies & Percy (1977) confirmed Walker's unpublished period of approximately 45 min. The amplitude in V given by their data is approximately 30 mmag. Additional observations have been made by Kusakin & Mkrtichian (1996) and Paunzen & Handler (1996a). The former present 8 nights of multisite photometry and find that multiple frequencies are present in the star's light curve. Their reanalysis of Gies & Percy's (1977) data also suggests multiple periods. In both cases the two highest amplitudes have periods of 38.5 and 48.9 minutes. The Hipparcos catalogue (ESA, 1997) also mentions a possible photometric period of 46.6 min.

Given the relatively large photometric variations of 29 Cyg, the results of our spectroscopic search for evidence of NRP in the star shown in Fig. 8 are not surprising: 29 Cyg has very high-amplitude nonradial pulsation features in its spectrum. The amplitude of the NRP features approach 2% of the continuum level. In this survey only two stars (HD 111604 and HD 210111) have higher amplitude pulsational features. The variations of the Ti II and Na I D lines enable us to derive approximate values of $\Delta t = 42$ min, $|m| = 14$ and $P_\mathrm{o} = 31$ min. The time delay between subfeatures is again remarkably close to the photometric period.

The combination of brightness and high-amplitude photometric and spectroscopic variability of 29 Cyg makes it a prime candidate for an intensive multisite photometric and spectroscopic campaign.

3.14. HD 193256 = HR 7764C and HD 193281 = HR 7764A

This is an interesting visual double star. The A component, HD 193281, has been classified as A3mA2 Vb PHL (Gray & Corbally, 1993), while the C component, HD 193256, is A2 Va PHL (Gray & Garrison, 1987). Both stars have a circumstellar, or probably more likely an interstellar component to the Na I D lines and possibly the Ca II K line (Holweger & Stürenburg, 1991). The surface gravities of the two stars are rather low for the class (Iliev & Barzova, 1995) which suggests that the two stars are somewhat evolved. The metal deficiency of the two stars is moderate (Stürenburg, 1993). We find a $v\sin i$ of $300\,\mathrm{km\,s^{-1}}$ for HD 193256, by far the largest for any member of the class.

Gronbech & Olsen (1976) reported large residuals in the c_1 index for HD 193281. On the other hand, Paunzen et al. (1997a) found upper limits to photometric variability in the b band of 3.4 and 2.6 mmag for the A and C components respectively. Our limited number of spectra show no conclusive evidence for the existence of NRP but the quality of the spectra for these two stars is somewhat compromised by their southerly declination and relative faintness. We will, however, point out that the possible variability in both stars noted by Holweger & Rentzsch-Holm (1995) and which they attribute to possible variations in circumstellar features do look somewhat like the signature of NRP. These two objects should be observed more extensively before any firm conclusions with regard to circumstellar material or variability are made.

3.15. HD 204041 = HR 8203

Gray and Garrison (1987) first noted the metal-weak nature of the spectrum of HD 204041 and classified the star as A1 Vb PHL. It appears to be in the middle of the main sequence (Iliev & Barzova, 1995). The star's metal abundances are approximately 1.0 dex below solar abundances and it has a relatively low $v\sin i$ of $65\,\mathrm{km\,s^{-1}}$.

Paunzen et al. (1997a) find no evidence for variability larger than 1.8 mmag in b from 4.2 hrs of observations. Our 3 spectra of the Na I D line region also show no evidence for variability at a level of 0.04%. We note, however, that the detection of the signature of NRP becomes increasingly difficult as $v\sin i$ decreases because of the smaller number of resolution elements over which a stellar line profile extends. Additional observations of HD 204041 would be worthwhile.

3.16. HD 210111 = HR 8437

Originally discovered by Hauck (1986), HD 210111 was classified as kA2hA5mA2 Vas PHL by Gray and Corbally (1993). The metal-weak nature of its spectrum was confirmed by Stürenburg (1993) who finds a typical metal deficiency of 1.0 dex relative to the sun. HD 210111 is also the slowest rotator in our sample, with $v\sin i = 55\,\mathrm{km\,s^{-1}}$, and appears to be somewhat evolved (Iliev & Barzova, 1995).

Photometric observations by Paunzen et al. (1994) show that HD 210111 is a multiperiodic variable. The two largest amplitudes (approximately 5 and 4 mmag in b) correspond to periods of 51.4 and 84.7 minutes. Our Mg II and Na I spectral data are shown in Fig. 9. The fact that HD 210111 is variable is obvious. In fact the star has not only the distinction of having the largest amplitude NRP signature in our λ Boo star sample, with the peak-to-peak amplitude of approximately 3% of the continuum level, but, to the best of our knowledge, also has the largest amplitude NRP observed in *any* class of main-sequence stars. In retrospect, the NRP in HD 210111 can be recognized as the pronounced asymmetry of the Na I D line profiles published by Holweger & Stürenburg (1991), as well as in various metal lines contained in their spectrum of the Ca II K line.

The profile variations of the Ti II, Fe II and Na I D lines were used to derive $\Delta t = 62$ min, $|m| = 12$ and $P_\mathrm{o} = 49$ min. Clearly the multiperiodic, high-amplitude NRP apparently present in HD 210111 makes it a very promising candidate for future observations.

3.17. HD 221756 = 15 And

Abt (1984) included 15 And in his list of λ Boo candidates and Gray (1988) classfies it as A1 Va$^+$ P/NHL. It may be a transitional object between PHL and NHL types. In any case, this object again seems to be rather evolved (Iliev & Barzova, 1995). Stürenburg's (1993) analysis indicates that it has relatively modest λ Boo characteristics with metal deficiencies on the order of 0.5 dex below solar values. We find a $v \sin i$ of 105 km s^{-1} which agrees well with previously published results. The star has what appears to be a circumstellar feature at Na I D superimposed on broad photospheric line profiles (Gonzalez & Bohlender, 1998).

Paunzen & Handler (1996b) obtained photometry of 15 And on two nights and confirm the variability first suspected by Rufener & Bartholdi (1982). In Strömgren b they find an amplitude of 6.6 mmag and a period of approximately 63 min. Our spectral time series for 15 And are shown in Fig. 10. This star is another example of a λ Boo star undergoing NRP. Using the Ti II, Fe II and Na I D lines, we found $\Delta t = 49$ min, $|m| = 17$ and $P_{\rm o} = 31$ min. The NRP features have an amplitude of approximately 1% of the continuum level.

4. Discussion

The main results of the discussion in Sect. 3 are summarized in Table 3. More than half of the 16 λ Boo stars for which we have obtained multiple high-resolution, high S/N spectra show conclusive evidence of the distinctive spectral signature of NRP. One object, HD 142994, for which we have obtained only a single spectrum is almost certainly also undergoing NRP as indicated by distortions in its rotationally broadened Na I D line profiles. Of the apparent nondetections, only one, ρ Vir, has what could be called an extensive high S/N time series. None of the remaining 7 program stars have more than 3 contiguous observations at a single wavelength and none have upper limits to the possible NRP amplitudes below the lowest amplitudes revealed by our more extensive, higher S/N observations. Therefore, we expect that subsequent high-quality observations of these poorly-sampled objects are likely to result in a substantially higher fraction of λ Boo stars known to be undergoing NRP. This is reinforced by the fact that 2 of our null detections are known or suspected photometric variables.

The very existence of NRP in the λ Boo stars already argues that the origin of the λ Boo phenomena is quite different than that of the classical Am stars, as current theoretical models suggest (Charbonneau, 1991; Turcotte & Charbonneau, 1993). For A-type stars in which both the mass-loss rate and rotational velocity are low, there are no strong meridional circulation currents to mix the outer envelope. Radiative pressure alone is insufficient to support helium against gravitational settling and within a few 10^6 years of a slowly rotating A-star's formation the He II convection zone disappears. With it the driving mechanism for pulsation in such a star vanishes. Other heavier elements then begin to diffuse upwards into or downwards out of the atmosphere depending on the precise atmospheric temperature structure and the radiative forces exerted on particular elements in the appropriate stages of ionization. This scenario describes the well-established picture for the origin of the slowly-rotating Am stars, whose peculiar abundances arise from just such diffusion processes occurring in their stable outer envelopes. It is also a well-known observational fact that most Am stars do not pulsate because helium has disappeared from their envelopes. (There are rare exceptions: Kurtz et al. (1995) have reported δ Scuti-type pulsation in HD 40765, which may be an evolved Am star, and certainly shows spectral peculiarities without magnetism.)

However, Charbonneau (private communication) points out that if the accretion scenario is indeed correct for the λ Boo stars, the accretion rate of $10^{-13} M_\odot$ yr^{-1} required by his model is more than sufficient to prevent the disappearance of the He II convection zone in these stars. As a result they should all have conditions in their outer envelopes conducive to the onset of pulsation. The observed frequency of NRP we find in the λ Boo stars is in fact as high, or higher than that observed in stars with normal spectra (Breger, 1979), but this may be a result of the high S/N of our spectra compared to earlier surveys. We have plotted in Fig. 11 the positions of the program λ Boo stars in the $b-y$ vs. M_V colour-magnitude diagram along with the location of the photometrically-defined δ Scuti instability strip (Breger, 1979). Despite their chemical peculiarities, Gray (1988) finds that the temperature types based on the hydrogen line cores are in good agreement with the $b-y$ colours, for both NHL and PHL λ Boo stars. Because of this, and the precision of the Hipparcos M_V, our program stars should thus be fairly accurately located in the colour-magnitude diagram relative to the instability strip, which was determined for chemically normal stars. Of the 18 stars observed, 12 fall within the δ Scuti instability strip (Breger, 1979). Five other objects lie just outside of the blue edge of the instability strip, while only 131 Tau appears to be truly outside of the zone of pulsational instability.

Fig. 11 seems to support Charbonneau's idea. All but one of the λ Boo stars which we have observed thoroughly and which lie in the δ Scuti star instability strip are nonradial pulsators. Seven other members of the class that appear to lie within this region have been observed 3 or fewer times, and at S/N levels insufficient to rule out low-amplitude pulsation such as that seen in λ Boo itself. Two of these, however, are definite photometric variables. As discussed above, ρ Vir is the only star for which we have obtained an extensive set of spectra which does not show evidence of NRP. We again point out, however, that this is the bluest star in our sample and is likely not within the instability strip and so is not then expected to be a pulsating variable. It should also be noted that some stars in the instability strip may pulsate with amplitudes too low to be observable even with high quality data such as those presented here and may thus appear constant.

Unfortunately, while this discussion does lend support to the accretion picture for the origin of the λ Boo stars it does not rule out other possible causes for the phenomena. For example, if the λ Boo stars arise from some mechanism not requiring a role to be played by diffusion processes then there would be no reason for the stars not to pulsate if the He II convection zone is intact and the objects in question occupy a space in the instability strip. All that can be said at this point is that the λ Boo stars definitely are not the result of "parameter-free" diffusion, but this has already been reasonably well established.

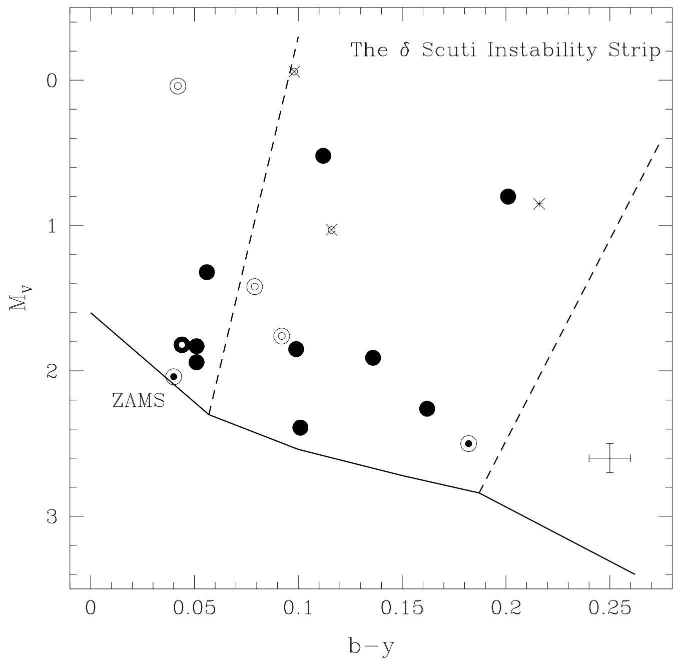

Fig. 11. $b-y$ vs. M_V color-magnitude diagram of the program λ Boo stars. Filled circles indicate variable stars and empty circles denote non-variable stars. Photometric variability is represented by the smaller of the two concentric circles for each object, and the detection, or nondetection, of NRP by the larger circles. Large and small crosses represent cases where the existence of NRP or photometric variability is uncertain. The dashed lines indicate the photometrically determined boundaries of the δ Scuti instability strip, and the error bars in the lower right show error estimates for the location of each star in the diagram.

With regard to nonradially pulsating stars in general, it might be hoped that the group of λ Boo pulsators might shed some light on the effect variations in basic fundamental quantities might have on the pulsational characteristics of a star. Unfortunately, we find no correlation between either spectroscopic or photometric variability and $b-y$ or $v \sin i$ (see Table 2). The variable stars do appear to have somewhat lower values of M_V and hence to be closer to the ZAMS, but 4 of the 5 stars located within the instability strip and furthest from the ZAMS have a limited number of lower quality spectroscopic observations so this may well be a selection effect. However, this tendancy also appears to be the case in Fig. 4 of Paunzen et al. (1998a), who studied the photometric variability of a larger sample of λ Boo stars.

The range of oscillation periods, $P_{\rm o}$, given in Table 3 are consistent with those observed in δ Scuti stars, although there may be a tendency for somewhat shorter periods. This could arise for several reasons. These periods, if correct, could represent higher radial overtones than the closer-to-fundamental δ Scuti modes seen photometrically (see also (Paunzen et al., 1998a)). Alternatively, the spectroscopically visible modes could be harmonics or resonances of the photometrically determined modes. Alternatively, the modes may actually be retrograde, in which case the periods would tend to be substantially longer. Finally, given the short duration of most of our spectrum time series and

Table 4. An interesting λ Boo star subgroup.

Name	$\log g$	$T_{\rm eff}$ (K)	[Fe]	$v \sin i$ $\rm km\,s^{-1}$	NRP Amp. (%)
π^1 Ori	4.25	8970	−0.9	120	1.0
35 Aql	4.22	9260	−2.7	100	1.2
ρ Vir	4.36	8970	−1.0	160	< 0.4
λ Boo	4.0	8650	−2.05	110	0.7

the low-amplitude variations seen in some stars, it is possible that in some cases the $|m|$ values have been overestimated by substantial amounts. In fact the two stars with the highest amplitude spectrum variability, 29 Cyg and HD 210111, which we would therefore expect to have the most accurately determined $|m|$, have $P_{\rm o}$ values very close to observed photometric periods. Regardless of this discussion, the short periods are very difficult to reconcile with g-mode pulsation so it is almost certainly accoustic pulsations in the λ Boo stars which are responsible for the observed spectrum variations.

We draw attention to a small subgroup of λ Boo stars in Fig. 11 which strikes us as intriguing from both observational and theoretical viewpoints. These four stars are located very close together in the HR diagram, just above the ZAMS and just to the left of the blue edge of the instability strip. Their basic properties are given in Table 4 where, except for λ Boo, the values of $\log g$, $T_{\rm eff}$, and [Fe] are taken from Stürenburg (1993). We have used the results of Venn & Lambert (1990) for λ Boo. We note, however, that their adopted values of $\log g = 4.0$ and $T_{\rm eff} = 8700$ for π^1 Ori differ substantially from the values of Stürenburg for this star. If a similar scale difference is assumed for λ Boo then clearly these four stars will have very similar $\log g$ and $T_{\rm eff}$ but remarkably different pulsation characteristics. We recommend that a careful, and internally consistent abundance analysis (i.e. a simultaneous determination of $\log g$, $T_{\rm eff}$, and metallicity with an appropriate choice of line-blanketed model atmosphere) be carried out for all four stars. The challenge will then be for the theoreticians to explain why these remarkably similar stars behave so differently.

The popular accretion model of Turcotte & Charbonneau (1993) requires the λ Boo stars to be young objects, and thus close to the ZAMS (see Sect. 1). From Fig. 11, it appears that about two thirds of our program stars lie less than one magnitude above the ZAMS, in contrast to what was found by Bohlender et al. (1996). The reason of this discrepancy is our use of absolute magnitudes derived from Hipparcos parallaxes, which are, for most stars, larger than those obtained from photometric calibrations (see Table 2).

Paunzen (1997) also recently used Hipparcos data to derive ages for λ Boo stars from new Main Sequence (MS) and PMS evolutionary models. Contrary to Iliev & Barzova (1995) who found the stars to be in the middle of their life on the MS, he states that they are very young objects. From the positions of his program stars in the HR diagrams, he infers that 6 stars, including our program stars HD 30422, π^1 Ori, ρ Vir, λ Boo, and 35 Aql, are very close to the ZAMS. Their ages derived from

MS and PMS models agree and are about 10^7 years. These stars are also close to the ZAMS in our colour-magnitude diagram (Fig. 11). Paunzen (1997) goes on to suggest that for three additional stars, 131 Tau, HD 111786, and 15 And, there is a high degree of confidence in reaching the same conclusions, despite the fact that the ages given by the MS and PMS models differ substantially. However, we note that the value of M_V he gives for 131 Tau is wrong, although the distance he inferred from the Hipparcos parallax is correct. This star is actually very far from the ZAMS (see Table 2 and Fig. 11). Paunzen finally speculates that all λ Boo stars are PMS objects but provides no direct support for this conjecture other than the fact that all of his program stars can indeed be modelled by either a MS or a PMS model. Unfortunately the same can be said of virtually any star, whether it be a MS, PMS, or evolved object. From our experience, 131 Tau is the only λ Boo star which does possibly show spectral characteristics somewhat analogous to the PMS Herbig-Haro Ae/Be stars as we have already noted in Sect. 3. So, while Hipparcos data are indispensable for improving our estimates of the absolute magnitudes and distances of the λ Boo stars, we believe they do not provide any conclusive evidence about the evolutionary state of the stars.

The existence of NRP in many of the λ Boo stars should provide us with the tool to resolve this debate on the evolutionary state, and hence the validity of the accretion/diffusion origin of the stars, once and for all. This is because of the fact that the pulsational properties of a star change during its evolution as a result of progressive changes in its internal structure. An analysis of the complete mode spectrum of these stars, preferably obtained via a two-dimensional Fourier analysis of a long time series of high-resolution, high S/N spectra (Kennelly, 1994), should give a reasonable, *direct* estimate of their evolutionary states when the observed frequency spectrum of the pulsation is compared to theoretical predictions. However, in order to use the eigenspectra to diagnose clearly the stellar properties, we need to be able to restrict ℓ and m for each frequency. Because these stars are likely oscillating in modes of low degree *and* low overtone, asymptotic theory does not apply. Only a few out of a wide range of potential modes are actually excited, and a number of models may match the observed frequencies equally well. High-resolution spectroscopy of the line profile variations resulting from these modes gives us a way to identify the mode parameters, which when combined with longer term photometry (and the resulting better frequency resolution), is the only way to get a unique fit to a model. Success in such a project can therefore only be obtained from very high-quality data obtained in extensive multisite photometric and spectroscopic campaigns for these objects.

5. Summary

High-resolution, high S/N spectra of 18 λ Boo stars obtained at the CFHT have resulted in conclusive evidence for the existence of NRP in 9 members of the class. Two other members of the program stars are photometric variables which suggests that the incidence of NRP among the λ Boo class is large. This supports the similar conclusion reached by Paunzen et al. (1998a) based on their study of photometric variability in a large sample of the class.

The very occurrence of NRP in the λ Boo stars provides some indirect support for the accretion/diffusion scenario for the formation of these stars. However, the possibility of using the tools of asteroseismology to determine their true evolutionary state from their pulsation spectrum should conclusively settle the active debate concerned with the origin of the class.

Several λ Boo stars immediately suggest themselves as excellent candidates for multisite photometric and spectroscopic campaigns. We urge such efforts for the bright, high-amplitude variables, namely HD 30422, HD 111604, 35 Aql, 29 Cyg, and HD 210111. Of these, 29 Cyg provides the most attractive combination of brightness ($V = 4.92$) and large-amplitude spectroscopic ($\approx 2.5\%$) and photometric (30 mmag) variability.

We also recommend that additional photometry be obtained for π^1 Ori since this object is a confirmed nonradial pulsator. If the low-amplitude photometric variability of λ Boo is confirmed, then π^1 Ori is the only star of our sample showing NRP without accompanying photometric variations. Previous photometry has suffered from rather high upper limits of $v = 7.4$ mmag. Improved photometry would also be of interest for ρ Vir.

Acknowledgements. This research has made use of the Simbad database, operated at CDS, Strasbourg, France, and the Canadian Astronomy Data Centre, which is operated by the Herzberg Institute of Astrophysics, National Research Council of Canada.

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