Astron. Astrophys. 330, 605–611 (1998)

ASTRONOMY AND ASTROPHYSICS

Pulsation of the λ Bootis stars HD 111786 and HD 142994*

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Received 20 May 1997 / Accepted 19 September 1997

Abstract. The detection of possible nonradial pulsation modes among some λ Bootis stars offers the prospect of using asteroseismology to determine their masses and ages, thereby testing competing theories for the origin of their chemical peculiarities. As a step toward this goal, we conducted multi-site photometric campaigns spanning two weeks each for two λ Bootis stars already known to show oscillations with periods from 0.75 to 4 hr: HD 111786 and HD 142994. Comparison of the observed eigenfrequency spectrum with model eigenmode spectra can constrain the age of the star. Since two of the main proposed mechanisms for the λ Bootis phenomenon (mass loss coupled with diffusion, and accretion) predict widely different stellar ages, such an analysis could distinguish between these options.

Frequency analysis of campaign data yielded four frequencies for each program star. The best matches of our observed eigenfrequencies to Main Sequence stellar models (which include the effects of rotation on the stellar structure and the pulsation modes) suggest that both stars are too far from the Zero-Age Main Sequence, to be consistent with the widely favoured accretion scenario. However, we caution that the results are preliminary and suggest future observing strategies to confirm/deny this finding.

Key words: stars: early type; oscillations; variables; δ Sct; individual: HD 111786; HD 142994

1. Introduction

In recent years, asteroseismic tools have been applied successfully to nonradially pulsating stars to obtain information about their global and atmospheric properties. Advances in observation and theory are producing improved astrophysical descriptions for classes of multiperiodic pulsators such as δ Scuti variables, the magnetic CP2 stars and white dwarfs. The same techniques show promise for solar-type stars, Be stars, and newly discovered variable stars in the mid-range of the Main Sequence, including the pulsating λ Bootis stars.

The λ Bootis stars are nonmagnetic chemically peculiar stars (Population I, A- to F-type dwarfs) whose spectra show significant underabundances of metals (with the notable exceptions of C, N, O and S). The origin of the λ Bootis phenomenon remains controversial. There are currently two main competing theories: mass loss coupled with diffusion (Michaud & Charland 1986) and accretion (Venn & Lambert 1990). The latter model requires that λ Bootis stars are very close to the Zero-Age Main Sequence (ZAMS; Turcotte & Charbonneau 1993), so an independent determination of the age and evolutionary state of these stars could resolve the debate about the two scenarios. Both theories are discussed in more detail by Paunzen et al. (1997).

Despite the fact that λ Bootis stars are found within the classical Instability Strip in the H-R diagram, they were not considered prime candidates for pulsation, since there is a general empirical exclusion between chemical peculiarity and δ Scuti-type variability. However, Weiss et al. (1994) defied those expectations when they discovered light variations in the λ Bootis star HD 142994 with a period near 4 hr and indications of other periodicities. Soon after, Kuschnig et al. (1994) were able to add HD 111786 to the list of variable λ Bootis stars (dominant period near 0.75 hr). Then Bohlender et al. (1996) discovered spectral line profile variations in another λ Bootis star, HD 111604, consistent with nonradial pulsation (NRP) of degree $\ell \simeq 20$ and period $P \simeq 17$ hr. Together, these results suggest that some λ Bootis stars are unstable to a range of NRP modes, which means it may be possible to apply asteroseismology to determine their evolutionary states and test the proposed mechanisms for λ Bootis formation.

However, in order to do this, one must have photometric or/and spectroscopic data in which the eigenfrequencies of adjacent modes and the fine-splitting induced by rotation and other effects can be resolved and clearly identified. For ground-based

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* Based on observations obtained at CTIO, SAAO and with the Hipparcos satellite

Table 1. Journal of observations for the two multisite campaigns. Obs.: observers were CK (C. Koen), PM (P. Martinez), JM (J. Matthews), RM (R. Medupe), EP (E. Paunzen)

Site	Obs.	HJD_{start} 2449800+	HJD_{end} 2449800+	length [h]	N_{obs}
HD 111786					
SAAO	PM	29.2315	29.3489	2.82	22
CTIO	EP	29.5713	29.8018	5.53	87
CTIO	EP	30.5022	30.8548	8.46	135
SAAO	PM	31.2598	31.5586	7.17	44
CTIO	EP	31.5038	31.8229	7.66	151
SAAO	PM	32.2539	32.5548	7.22	62
CTIO	EP	32.5418	32.8096	6.43	125
CTIO	EP	33.5593	33.8009	5.80	98
SAAO	RM	35.2613	35.5446	6.80	58
SAAO	RM	36.2531	36.4854	5.58	57
CTIO	EP	39.5012	39.7415	5.77	101
HD 142994					
SAAO	CK	62.2851	62.5944	7.42	38
CTIO	JM	63.4408	63.5951	3.70	19
SAAO	CK	66.3159	66.5168	4.82	27
CTIO	JM	68.5441	68.8491	7.32	26
SAAO	PM	69.2889	69.5808	7.01	35
CTIO	JM	69.4854	69.8513	8.78	39
SAAO	PM	70.2767	70.5808	7.30	35
CTIO	JM	70.4814	70.6976	5.19	23
CTIO	JM	72.5609	72.8524	7.00	32

CTIO: 60-cm Lowell telescope, EMI 9781 A tube
SAAO: 50-cm telescope, Hamamatsu R943-02 tube

observations, this requires that the data be collected in multi-site campaigns, to reduce the daily gaps inherent in single-site data whose Fourier transform will have a complex window function and hence strong spectral aliasing/leakage. Good examples of successful multi-site campaigns on δ Scuti stars (whose timescales and amplitudes are characteristic of the λ Bootis variations) are the GLOBUS photometric effort by Breger et al. (1996) on FG Virginis and the MUSICOS spectroscopic work on θ^2 Tauri (Kennelly & Walker 1996). These campaigns led to the identification of individual pulsation modes and constraints on the masses, luminosities and ages of these stars.

With the same ultimate goals in mind, we organized photometric campaigns for the variable λ Bootis stars HD 111786 and HD 142994 at the Cerro Tololo Interamerican Observatory (CTIO) and the South African Astronomical Observatory (SAAO). A third site (Mt. John Observatory in New Zealand) was also included in the original observing scheme, but unfortunately no data were obtained from there due to technical problems. Nevertheless, experience has shown that data from two sites widely spaced in longitude can increase the observational duty cycle enough to reduce aliasing significantly.

2. The target stars

2.1. HD 111786

This star was classified by Gray (1988) as A1.5 Va$^-$ (λ Boo) with peculiar hydrogen lines. The metallic-line spectrum

Table 2. Program and comparison stars

HD	HR	V	b − y	m_1	c_1	Sp
111786	4881	6.1	0.161	0.131	0.805	λ Boo
111226	4857	6.4	-0.004	0.091	0.600	B8 V
111295	4860	5.7				G5 III
142994		7.2	0.199	0.117	0.870	λ Boo
142945		8.0	0.389	0.121	0.251	F8 V
143181		7.3				B9 V

shows an unusual morphology: Fe I 4046Å , Sr II 4077Å and Ca I 4426Å are slightly too strong for hydrogen lines typical of an A1.5 star. Observations in the UV-region (Faraggiana et al. 1990) confirmed the star's membership in the λ Bootis class. An abundance analysis by Stürenburg (1993) revealed in an underabundance of heavy elements (Na, Mg, Ca, Fe, etc.) of about 1.5 dex relative to the Sun, but the amount of C appears solar. Bohlender & Landstreet (1990) reported an upper limit for a possible magnetic field of about 500 G. Newer high resolution spectroscopy (Holweger & Rentzsch-Holm 1995) indicated a variable circumstellar component which was explained by the authors as evidence of gas dynamics in an accretion disc. This interpretation was contradicted by Faraggiana et al. (1997), who presented evidence for a double-line spectroscopic binary system. Variability of HD 111786 was reported by Kuschnig et al. (1994). These data were, for the first time, fully analyzed as described in Sect. 3.

2.2. HD 142994

The detection of pulsation in HD 142994 (Weiss et al. 1994) initiated our photometric survey for pulsation in λ Bootis stars. Since the discovery observations were not obtained differentially with comparison stars, it was decided to reobserve the star (Paunzen et al. 1995). Measurements during two nights resulted in a frequency of 7.9 d^{-1} and an amplitude of 60 mmag in Strömgren b. Multiperiodic behavior was evident but could not be resolved in only two nights of data. This made HD 142994 an intriguing target for our multisite campaign.

Unfortunately, not much is known about HD 142994. Gray (1988) classified this star as A3Va (λ Boo) with peculiar hydrogen lines similar to F0. High-resolution spectroscopy obtained at McDonald Observatory (Handler, private communication) yielded a $v \sin i \approx 220\,\mathrm{km\,s^{-1}}$. There are no published observations of this star in the IR and UV, nor have detailed abundances been derived.

3. Observations, reduction and analysis

Time series in both Strömgren v and b were obtained at CTIO and SAAO in the classical three-star (variable–comparison–check) technique using standard photomultiplier tubes (Table 1). An integration time of 30 seconds was used throughout the campaign for both bandpasses. Typically, our program and comparison (Table 2) stars were observed at least every six minutes in order to cover the shortest expected pulsation cycles with at least 5 to 7 phase points. We also monitored several

Table 3. Frequencies and amplitudes, determined with a simultaneous sine fit; σ(f) = 0.03 d^{-1} = 0.4 μHz, σ(A) = 0.3 mmag

Designation	Frequency [d^{-1}]	Frequency [μHz]	v Amplitude [mmag]
HD 111786			
f_1	31.01	358.9	8.0
f_2	20.31	235.1	6.0
f_3	33.36	386.1	5.8
f_4	15.02	173.8	5.4
HD 142994			
f_1	6.31	73.0	37.6
f_2	10.25	118.6	20.4
f_3	7.36	85.2	11.9
f_4	8.29	95.9	8.1

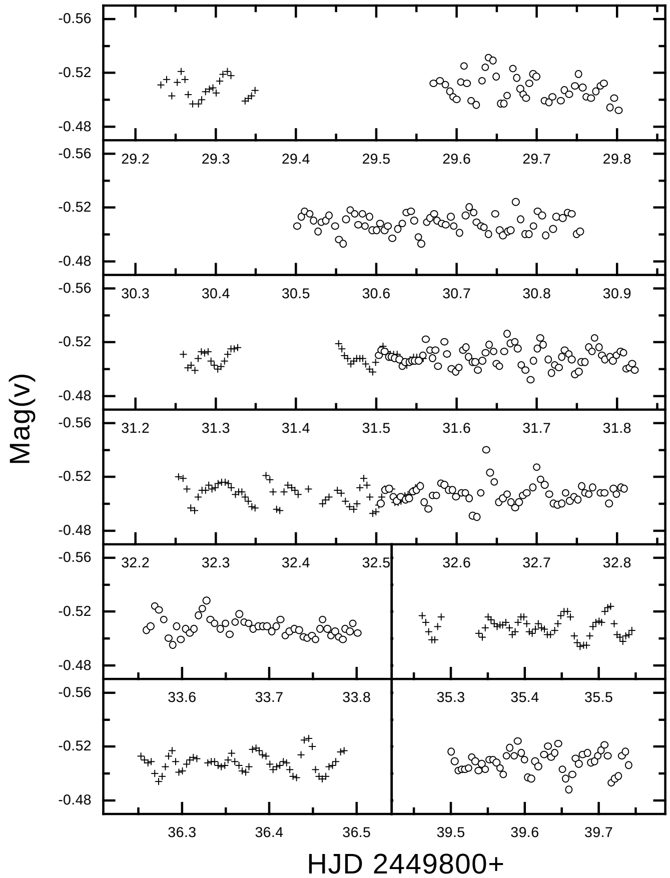

Fig. 1. Differential photometry of HD 111786 and HD 111295 for Strömgren v. Crosses are data from SAAO, open circles are data from CTIO

E-region standards at the beginning, middle and end of each night to calibrate the photometric systems. With only two sites effective in the campaigns and nights lost due to the weather, we achieved an overall duty cycle of 27% for HD 111786 and 21% for HD 142994 in roughly two weeks dedicated to each star. The longest contiguous time series for each star was about 14 hours, significantly longer than could have been achieved from a single site.

All data were corrected for atmospheric extinction, sky background and dead time (τ_{SAAO} = 30 ns for SAAO, and 80 ns < τ_{CTIO} < 120 ns for CTIO). Although several independent measurements for the dead time constant were obtained at CTIO, no single value for τ_{CTIO} could be determined for the entire observing run. A value between 80 ns and 120 ns yields the same statistical significance, depending on the elimination of data points with low count rates. We speculate that scattered light may have affected our measurements. However, with typical count rates for our measurements of $8 \cdot 10^4$ cps, the difference between 80 ns and 120 ns results in a photometric error - mainly as an offset - of only 0.1 %. The error introduced by selecting τ_{CTIO} = 100 ns is therefore significantly less than the scintillation noise and we do not expect any influence on our analysis of pulsation with periods between 0.5 and 4 hr.

The differential lightcurves for both multisite campaigns are shown in Fig. 1 and 2. The observations from the two sites match well where they overlap in time and illustrate the good quality of both the observing conditions and the subsequent data reduction.

Fourier analysis of the data revealed a set of frequencies which were subsequently used for a simultaneous multi-sine fit whose amplitudes, frequencies and phases were free parameters. These standard techniques do not improve the detection threshold but were found to be appropriate for the analysis of our data set (for a general description of the used method see Sect. 3 in Handler et al. 1997). Figs. 3 and 4 show the amplitude spectra and Table 3 summarizes the dominant frequencies (σ(f) = 0.03 d^{-1} = 0.4 μHz) and amplitudes (σ(A) = 0.3 mmag) we found. Those frequencies were found in *all* four time series for each individual λ Bootis star (i.e., [variable minus comparison] and [variable minus check] in v, and the corresponding two sets of differential data in b). Note that the amplitudes given in Table 3 refer to the least squares multi-site fits, whereas the peaks in the Fourier spectra of Figs. 3 and 4 are essential *single* sine fits.

Following the "significance criterion" for a detected amplitude peak (amplitude signal–to–noise ratio of four) given by Breger et al. (1993), we find a noise level (dominated by the photon noise) in the amplitude spectra of about 1.5 mmag (HD 111786) and 4 mmag (HD 142994). This indicates a formal $\sim 4-5\sigma$ detection for all the frequencies in HD 111786 and $\sim 5-9\sigma$ detections of the two most prominent frequencies in HD 142994.

For HD 111786 we find the frustrating result that $(f_1 - 1\,\mathrm{d}^{-1}) = 2 \times f_4$, and that in general there seem to be simple harmonic relations among the principal frequencies (e.g., $f_1/f_2 \sim 3/2$; $f_2/f_4 \sim 4/3$). A similar situation exists for HD 142994. For this star, the problem is even more severe: $f_1 = f_2 - 4\,\mathrm{d}^{-1} = f_3 - 1\,\mathrm{d}^{-1} = f_4 - 2\,\mathrm{d}^{-1}$, within the quoted errors for the frequency determination. In this case, we are likely more prone to aliasing since fewer cycles of this star's longer periods are being sampled in our data.

The apparent harmonic behavior of HD 111786 may have a physical explanation in terms of genuine harmonic overtones or

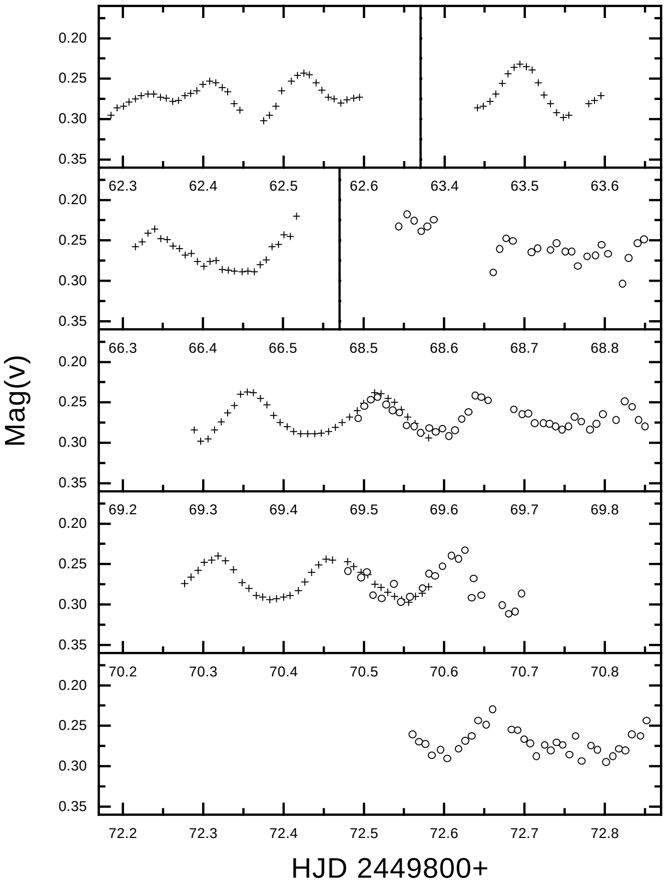

Fig. 2. Differential photometry of HD 142994 and HD 143181 for Strömgren v. Crosses are data from SAAO, open circles are data from CTIO

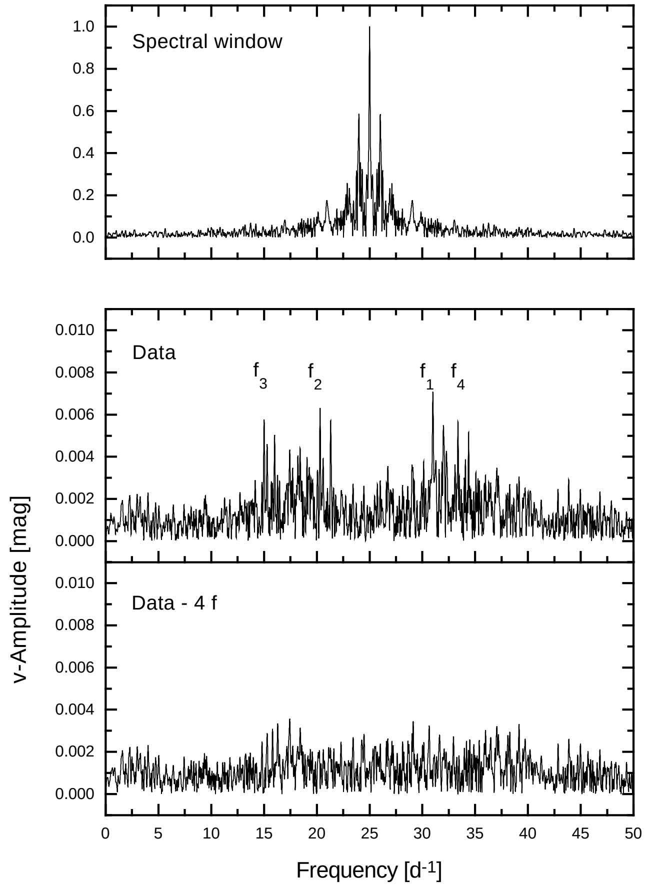

Fig. 3. Amplitude spectra and spectral window for the HD 111786 data

pulsational resonances, but such an interpretation will require data with a better duty cycle.

Therefore, to reinforce the frequency identifications for HD 111786, we have fully analyzed the photometry of that star by Kuschnig et al. (1994), whose data have a similar duty cycle of 30% but span only one week. The presented only a preliminary analysis of their data with the aim to establish variability and not to resolve as many frequencies as possible. Their data (HD 111786 – HD 111295, Strömgren v) were averaged to a time resolution of 30 seconds (Fig. 5) and the same time series analysis technique was applied as to the new data. The results listed in Table 4 indicate a small difference in the amplitudes, but the frequencies are in excellent agreement with those determined from our campaign data. This lends confidence to our frequency identification. A merging of both data sets for HD 111786 did not improve the results due to the large time gap.

Table 4. Frequencies for HD 111786 from SAAO data obtained by Kuschnig et al. (1994); $\sigma(\mathrm{f}) = 0.03\ \mathrm{d}^{-1} = 0.4\ \mu\mathrm{Hz}$, $\sigma(\mathrm{A}) = 0.3$ mmag

Designation	Frequency [d^{-1}]	Frequency [μHz]	v Amplitude [mmag]
f_1	31.02	358.9	11.4
f_2	33.36	386.1	6.8
f_3	15.01	173.7	6.2
f_4	20.30	235.0	4.8

4. Discussion

As a first step to identify possible pulsation modes, we have estimated some of the fundamental parameters (mass, radius, temperature, etc.) for HD 111786 and HD 142994 from published photometric indices in order to compute appropriate stellar models. Both Geneva colour indices (Künzli et al. 1997) and those in the Strömgren system (Crawford 1979; Napiwotzki et al. 1993) yield within the error bars (estimated following the given references) consistent results for our λ Bootis stars, as shown in Table 5. The validity of the used calibrations (based on "normal" (solar abundant) stars) for (chemically peculiar and fast rotating) λ Bootis stars has been proved by a comparison with Hipparcos as well as spectroscopic data (Paunzen 1997).

In order to independently check the validity of the calibrations, we have used the Hipparcos data for HD 111786 (no measurements are available for HD 142994) to derive $\log L/L_{\odot}$ from the observed parallax. With $M_{\mathrm{V}} = 2.24(10)$, a bolometric correction $B.C. = -0.11$ and $M_{\mathrm{Bol}}(\odot) = 4.64$ (Schmidt-Kaler 1982), we derive $\log L/L_{\odot} = 1.00(8)$, which is in excellent agreement with the determined photometric value (note that

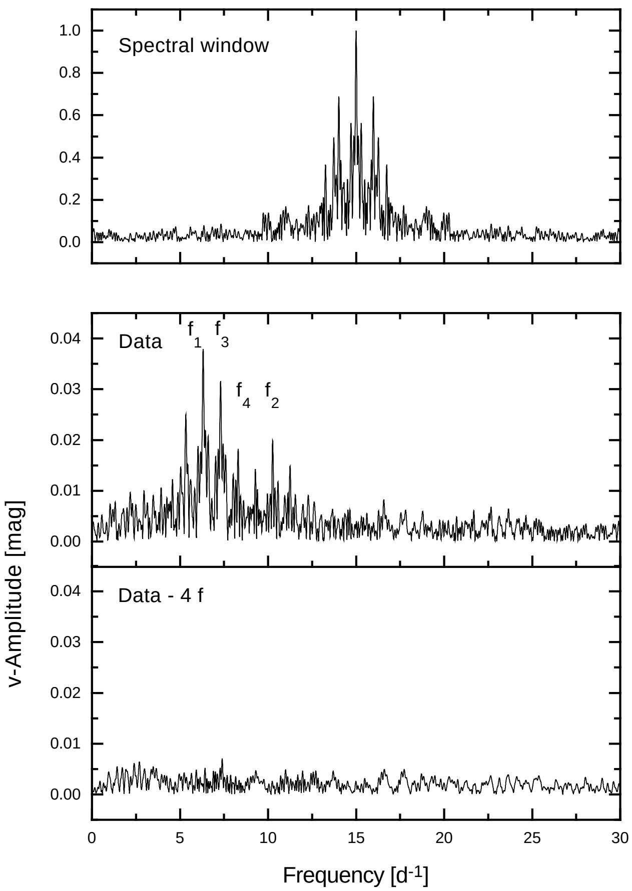

Fig. 4. Amplitude spectra and spectral window for the HD 142994 data

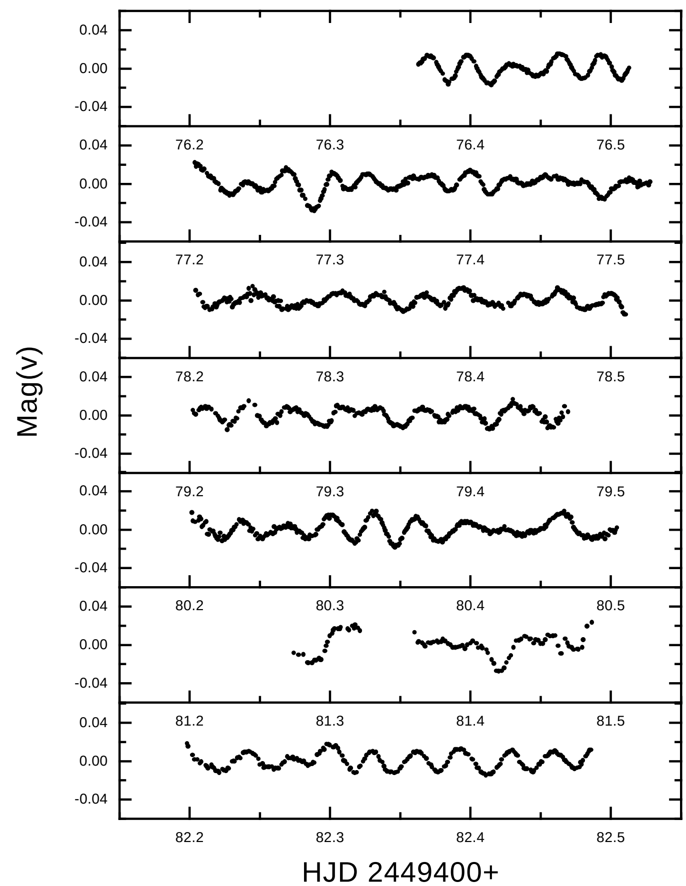

Fig. 5. Differential photometry of HD 111786 and HD 111295 in Strömgren v from Kuschnig et al. (1994)

Cayrel de Strobel (1996) gives $M_{\rm Bol}(\odot) = 4.75$ resulting in $\log L/L_{\odot} = 1.04$).

We therefore adopted the values (and corresponding error estimates) of surface gravity and effective temperature in Table 5 for model calculations. Because both program stars have large $v \sin i$ values, we also tried to include the effects of rotation in our models.

The models were computed using a standard stellar evolution code which was developed in its main parts by B. Paczynski, M. Kozlowski and R. Sienkiewicz (private communication). The latest version of this code uses the OPAL opacities and equation of state. The effects of uniform stellar rotation were taken into account, assuming that the star conserves its global angular momentum during evolution off the ZAMS. We calculated the models assuming an initial hydrogen abundance X = 0.70 and a heavy element abundance Z = 0.02, consistent with solar abundant Population I. The standard mixing-length theory of convection with $\alpha = 1.0$ was used.

The choice of the mixing-length parameter has only a small effect on our models because they are too hot to produce an effective convection in the envelope. As a test, we have computed the appropriate models with $\alpha = 1.7$. The changes in the eigenfrequencies are about 0.01 d^{-1}, which is below the estimated error of the observed frequencies (Table 3).

We note that the computation of evolutionary stellar models with solar abundance for *all* elements seems to be appropriate for the study of (chemically peculiar) λ Bootis stars because the main contribution to the *overall* metallicity is due to C, N and O (solar abundant in λ Bootis stars). Furthermore, there are strong indications that the λ Bootis phenomenon is restricted to the stellar surface (Holweger & Rentzsch-Holm 1995; Iliev & Barzova 1995; Paunzen et al. 1997).

The resulting evolutionary tracks and the locations of HD 111786 and HD 142994 based on the parameters in Table 5 are shown in Fig. 6. It is clear that rotation plays an important role in the evolution of stars with masses typical for λ Bootis stars (models taking rotation into account result in younger ages than "nonrotating" models). Unfortunately, it is impossible to specify the ages of these two stars to a precision of better than about $1 - 2 \times 10^8$ years (roughly 10 – 20% of the age estimates in Table 5).

For these same models, we have performed a linear nonadiabatic analysis of low-degree oscillations ($\ell \leq 3$) using the code developed by W. Dziembowski (for a general description see Dziembowski 1977). Note that the photometric variations must correspond to low-degree modes if they are seen in integrated light. In this code, the effects of rotation on the oscillation fre-

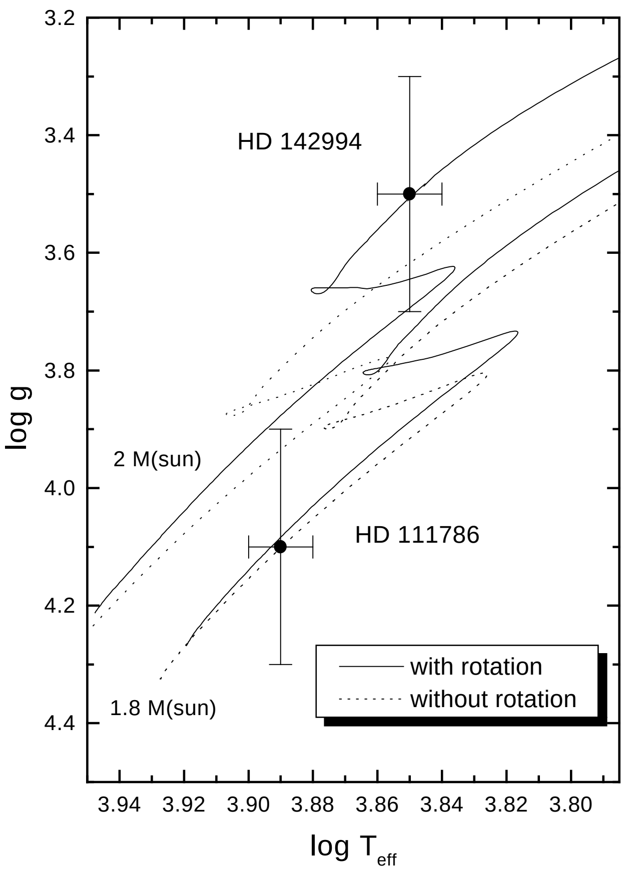

Fig. 6. Evolutionary tracks for HD 111786 and HD 142994. For the initial models we have chosen rotational velocities of 150 and 220 km s^{-1}, respectively. The dashed lines correspond to evolutionary tracks for non-rotating stars. The error bars are estimated within the photometric calibration

Table 5. Fundamental parameters derived for HD 111786 and HD 142994. Values in column 'EP97' are from Paunzen et al. (1997) and in column 'IL95' from Iliev & Barzova (1995)

	HD 111786		HD 142994	
	EP97	IL95	EP97	IL95
$\log T_{\rm eff}$ ($\pm$0.01)	3.89	3.88	3.85	3.86
$\log g$ ($\pm$0.2)	4.1	4.0	3.5	3.5
$\log L/L_{\odot}$ ($\pm$0.2)	1.1	1.1	1.5	1.7
$M/M_{\odot}$ ($\pm$0.1)	1.8	1.8	2.0	2.2
$\log t$ ($\pm$0.05)	8.76	8.99	8.97	8.96
$v \sin i$ ($\pm$20)	150		220	

quencies are treated up to second order in the rotational velocity using the method developed by Dziembowski & Goode (1992). The observed frequency spectra for both stars are compared to the model eigenfrequencies in Fig. 7, where the models were selected such that the bulk of the unstable eigenmodes are in the same range as the observed frequencies. This figure also illustrates the crowding of possible unstable modes with increasing ℓ. Due to the second order effects, the rotational mode splitting is nonequidistant. For the model of HD 111786 we have derived the following frequencies of an $\ell = 1$ triplet: 18.42 d^{-1} ($m = +1$), 20.83 d^{-1} ($m = 0$) and 21.32 d^{-1} ($m = -1$).

The number of observed frequencies is much less than the number of unstable modes. In the observational frequency range for HD 111786 (15 – 33 d^{-1}) we have approximately 45 unstable modes for $\ell \leq 2$ and approximately the same number of modes for $\ell = 3$ (but about 970 unstable modes for 1 – 100 d^{-1}). Therefore, we only observe less than 10% of unstable modes for $\ell \leq 2$ (or less than 5% for $\ell \leq 3$). For HD 142994 only axisymmetric modes ($m = 0$) are shown because the full frequency spectrum is much more dense for such an evolved (post-MS) model. In the observed frequency range the total number of unstable modes for $\ell \leq 3$ is about 320. All nonradial modes in this range of frequencies are of mixed character: they exhibit gravity-type behavior in the stellar interior and acoustic-type behavior in the envelope.

This makes it impossible to match any given eigenmode with an observed frequency unless we have independent mode identification (possibly through fitting of corresponding variations in the spectral line profile; see Kennelly & Walker 1996; Bohlender et al. 1996). Within the error boxes shown in Fig. 6, the main qualitative characteristics of the theoretical eigenspectra (richness of the modes in the observed frequency region, nonregularities in the mode distribution) will not change significantly for the chosen evolutionary stages. There would be, of course, a notable shift for the different m and ℓ modes (important for a possible mode identification).

Despite the ambiguities, the evolutionary and eigenfrequency models are both consistent with stellar ages of the order 6×10^8 yr and 10^9 yr, respectively for HD 111786 and HD 142994. Such relatively advanced ages for $\sim$2M$_{\odot}$ stars are inconsistent with the accretion hypothesis for the origin of λ Bootis stars (Paunzen et al. 1997). We note that possible overshooting from the convective core will extent the Main Sequence part of the evolutionary track to smaller values of $\log g$. In order to test this effect, we have computed the models of both stars (1.8 and 2.0M$_{\odot}$) taking the overshooting from the convective core into account. The overshooting distance was chosen to be $0.2H$(p) where H(p) is the local pressure scale height at the edge of the convective core (Dziembowski & Pamyatnykh 1991). The age of the model for HD 111786 with $\log T_{\rm eff} = 3.89$ changes due to overshooting from $5.8 \cdot 10^8$ to $6.3 \cdot 10^8$ years. For HD 142994 with $\log T_{\rm eff} = 3.85$ it changes from $9.3 \cdot 10^8$ to $1.02 \cdot 10^9$ years for the chosen advanced evolutionary stage or to $8.6 \cdot 10^8$ years for the MS-model with the overshooting. Also, at the chosen evolutionary stage the frequency spectra of the models with and without overshooting are similar. Therefore the inclusion of the overshooting does not change our conclusions. In the case of overshooting, HD 142994 would be still in the Main Sequence evolutionary stage (but not on the ZAMS). We also stress again that our photometric oscillation data do not have sufficient duty cycle, and the models offer so many possible matches to individual eigenmodes, that a final conclusion on this issue is premature.

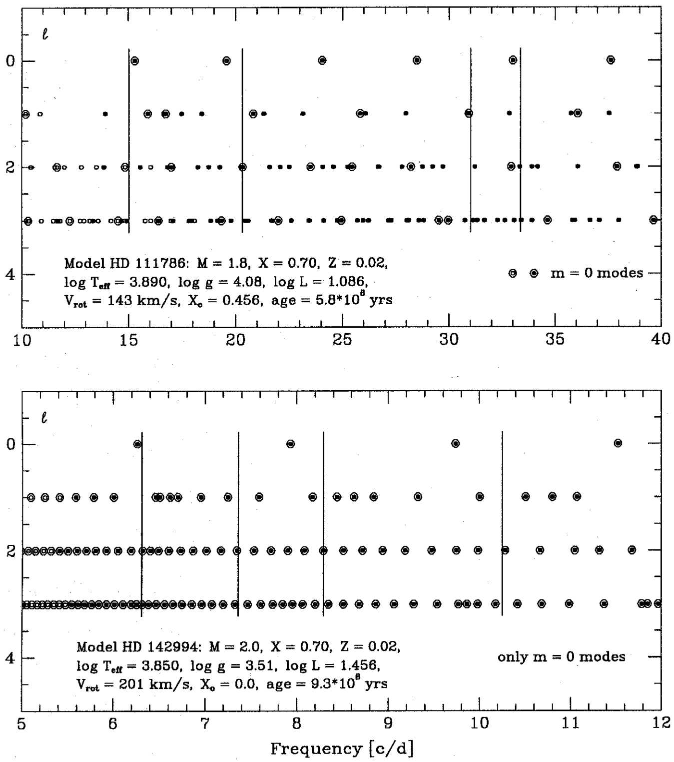

Fig. 7. Computed frequency spectra of low-degree oscillations including frequency shifts due to rotation, based on models described in Sect. 4. Horizontal sets of points correspond to fixed values of spherical harmonic degree. Filled circles mark the unstable modes. Vertical lines are the observed frequencies from Table 3

5. Conclusion

The results of our multisite campaigns on the λ Bootis stars HD 111786 and HD 142994 clearly show how important it is to achieve a duty cycle of at least 70% to overcome the 1-cycle/day aliasing problem. Since the computed eigenmode spectra are quite rich, a time base exceeding the two weeks of our present campaigns would be desirable to improve the observed frequency resolution. Also, given the stars' rapid rotation rates, higher frequency resolution might make it possible to see rotational splitting of the eigenfrequencies and independently assign a value of the degree ℓ and/or azimuthal order m to each. Spectroscopy of possible line-profile variations associated with the photometric oscillations could also lead to mode identifications. Then the pulsation models could be refined to match modes of specific ℓ and m to the observations.

Nevertheless, even this preliminary study demonstrates the diagnostic potential of asteroseismology to discriminate between the two leading theories to explain λ Bootis stars. Our early results show that the observed frequency spectra can be fitted by Main Sequence and post-Main Sequence models. Such an evolutionary scenario seems to contradict the predictions of the much favoured accretion theory. Further observations should allow to derive better frequency spectra in order to perform a precise mode identification.

Acknowledgements. This research was carried out within the working group *Asteroseismology-AMS* with funding from the Fond zur Förderung der wissenschaftlichen Forschung (project *S7303-AST*). JMM would like to acknowledge funding from a Research Grant through the Natural Sciences & Engineering Research Council (NSERC) Canada. AAP acknowledges partial financial support from the Russian Fund for Basic Research (grant 95-02-06359) and from the Polish Committee for Scientific Research (grant 2-P304-013-07). We would like to thank C. Koen and R. Medupe for obtaining some photometric data as well as G. Handler for providing a high resolution spectrum of HD 142994. We are also grateful to the Director and staff of CTIO for support during the observing runs. Special thanks go to the anonymous referee who helped to improve this work. Use was made of the Simbad database, operated at CDS, Strasbourg, France.

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