\section{Introduction}

The group of \(\lambda\) Bootis stars stand out among the chemically peculiar (CP) stars of the upper main-sequence. The CP stars normally exhibit strong overabundances of elements, probably caused by magnetic fields, slow rotation or atmospheric diffusion (e.g. Netopil et al. 2008). However, the \(\lambda\) Bootis stars are a small group (only 2 per cent) of late-B to early-F stars that show moderate to extreme (surface) underabundances (up to a factor 100) of most Fe-peak elements, but solar abundances of lighter elements (C, N, O and S). Several members of the group exhibit a strong infrared excess and a disc (Paunzen et al. 2003; Booth et al. 2013).

To explain the peculiar chemical abundances, Venn & Lambert (1990) suggested they are caused by selective accretion of circumstellar material. One of the principal features of that hypothesis is that the observed abundance anomalies are restricted to the stellar surface. On the basis of this hypothesis, Kamp & Paunzen (2002) and Martinez-Galarza et al. (2009) developed models which describe the interaction of the star with its local interstellar and/or circumstellar environment, whereby different degrees of underabundance are produced by different amounts of accreted material relative to the photospheric mass. The fact that the fraction of \(\lambda\) Bootis stars on the main sequence is so small would then be a consequence of the low probability of a star–cloud interaction within a limited parameter space. For example, the effects of meridional circulation dissolves any accretion pattern a few million years after the accretion has stopped.

Since the early 1990s, the pulsational behaviour of the group members was extensively studied because almost all \(\lambda\) Bootis stars are located within the classical \(\delta\) Scuti/\(\gamma\) Doradus instability strip (Paunzen et al. 2002b; Breger et al. 2006; Paunzen & Reegen 2008; Murphy 2014). It was deduced that at least 70 per cent of the group members inside the classical instability strip pulsate. They do so with first and second overtones modes (\(Q < 0.020\)) typical for \(\delta\) Scuti-type pulsators. Only a few stars, if any, pulsate in the fundamental mode. In general, the amplitudes do not exceed a few mmags. The period–luminosity–colour relation for this group is, within the errors, identical to that of the normal \(\delta\) Scuti stars (Paunzen et al. 2002b).

In this paper, we have selected 15 targets from the 66 \(\lambda\) Bootis stars in the lists of Gray & Corbally (1998) and Paunzen (2001) which have at least 1000 data points in the Wide Angle Search for Planets (WASP) archive and are fainter than \(V = 8\) mag to avoid the effects of saturation. We analysed the time series of these 15 group members to search for variability and compared our result with those in the literature.

Observations, target selection and data analysis are described in Section 2; results are presented and discussed in Section 3. We conclude in Section 4.
2 TARGET SELECTION, OBSERVATIONS AND REDUCTIONS

The photometric data used for this study were from SuperWASP; the WASP instruments are described in Pollacco et al. (2006), with the reduction techniques described in Smalley et al. (2011) and Holdsworth et al. (2014). The aperture-extracted photometry from each camera on each night is corrected for primary and secondary extinction, instrumental colour response and system zero-point relative to a network of local secondary standards. The resultant pseudo-V magnitudes are comparable to Tycho magnitudes.

We have selected all 66 bona fide δ Bootis stars from the lists by Gray & Corbally (1998) and Paunzen (2001) which are fainter than 8th magnitude to affect the saturation of the photometric data. Furthermore, only objects with more than 1000 data points for which no two approximately equal brightness stars within the 3.5-pixel (∼50 arcsec) WASP photometry aperture were processed.

In total, we analysed the light curves of 15 group members. For two stars, HD 101108 and HD 290492, the analysed WASP photometry includes a companion. BD+26 2097, the companion of HD 83041 (single frequency), HD 125889 (multiperiodic) and HD 294253 (no significant frequency detected) are presented. Four stars (HD 23392, HD 261904 and HD 294253) are well outside the instability strips whereas HD 90821 is just on the edge. Variability was not detected for any of these stars, with upper limits between 2.0 and 3.0 mmag.

Employing the methods and starting values listed by Paunzen et al. (2002a,b) we re-evaluated the log $T_{\text{eff}}$ and log $L/L_\odot$ for our targets. Photometric data were taken from the General Catalogue of Photometric Data (GCPD; Memm.lliod, Memm.llioid & Hauck 1997). Where possible, averaged and weighted mean values were used throughout. Hipparcos parallax measurements (van Leeuwen 2007) for stars with a precision better than 30 per cent were used. Table 1 lists the basic information, the log $T_{\text{eff}}$ and log $L/L_\odot$ together with results from former pulsation studies.

The light curves were examined in more detail using the PE program package PERANSO (Husar 2006). The differences for the different methods are within the derived errors depending on the time-series characteristics, i.e. the distribution of the measurements over time and the photon noise. We applied these methods to the data sets of four pulsating metallic-lined Am stars (Renson 1984, 29800, 37494 and 55094) taken from Smalley et al. (2011). The errors are in the same range as for our target stars lending confidence in the reduction and analysis techniques.

The detailed observational dates and results of the time-series analysis for all targets are listed in Table 2.

3 ANALYSIS

For eight targets, we detected variability (Table 2). Three of them (HD 101108, HD 125889 and HD 184779) are newly discovered pulsators. For seven stars, no statistically significant frequencies were detected. However, we were able to lower the upper limits compared to those previously published. In Fig. 1, the Fourier spectra of HD 83041 (single frequency), HD 125889 (multiperiodic) and HD 294092 (no significant frequency detected) are presented. It is well known that WASP data are affected by daily aliases and systematics at low frequencies (Smalley et al. 2011). The noise at these frequencies (lower than 5 d$^{-1}$) is certainly not white but, except for HD 83277, we did not detect any suspicious peak below this limit.

Fig. 2 shows the log $T_{\text{eff}}$ versus log $L/L_\odot$ diagram of our programme stars (Table 1) together with the borders of the δ Scuti and η Doradus instability strips taken from Breger & Pamyatnykh (1998) and Dupret et al. (2004), respectively. Four stars (HD 23392, HD 36726, HD 261904 and HD 294253) are well outside the instability strips whereas HD 90821 is just on the edge. Variability was not detected for any of these stars, with upper limits between 0.8 and 3.0 mmag. Two apparently constant stars (HD 83277 and HD 290492) are within the instability strips. The case of HD 83277 is discussed below.

1 http://gcpd.physics.muni.cz/
2 http://www.peranso.com/
Table 2. Data characteristics, frequencies, amplitudes and upper limits for our targets. The results of the individual stars are described in more detail in Section 3.

| HD     | HJD(start) (2450000+) | Δt (d) | Ndata | Frequency (d⁻¹) | Amplitude (mmag) | Upper limit (mmag) |
|--------|-----------------------|--------|-------|----------------|-----------------|-------------------|
| 23392  | 4721.635 74           | 859.864 26 | 14 887 | 1.0            |                 |                   |
| 36726  | 5496.452 15           | 478.951 17 | 5232  | 1.5            |                 |                   |
| 83041  | 3860.200 96           | 2204.164 76 | 11 178 | 14.5293        | 1.6             |                   |
| 83277  | 3860.233 15           | 749.117 44 | 5377  | 3.0⁵          |                 |                   |
| 90821  | 3131.373 78           | 1094.156 01 | 4096  | 0.8            |                 |                   |
| 101108 | 3128.403 56           | 1108.132 57 | 4579  | 2.2            |                 |                   |
| 105058 | 5651.403 81           | 56.058 100 | 9137  | 14.5293        | 1.6             |                   |
| 120896 | 4516.723 63           | 1100.875 98 | 4443  | 7.6138         | 5.6             |                   |
|        |                       |         |       | 19.6300        | 3.5             |                   |
|        |                       |         |       | 12.2889        | 3.0             |                   |
|        |                       |         |       | 8.4705         | 2.6             |                   |
|        |                       |         |       | 9.9511         | 2.4             |                   |
|        |                       |         |       | 21.0899        | 2.3             |                   |
|        |                       |         |       | 3.0111         | 2.2             |                   |
|        |                       |         |       | 20.1347        | 2.0             |                   |
| 125889 | 3860.389 89           | 2246.075 93 | 28 492 | 15.6547        | 3.5             |                   |
|        |                       |         |       | 5.1457         | 2.7             |                   |
|        |                       |         |       | 6.1680         | 2.1             |                   |
| 184779 | 3860.440 19           | 2246.953 36 | 26 432 | 12.5687        | 13.9            |                   |
|        |                       |         |       | 13.8351        | 6.8             |                   |
|        |                       |         |       | 10.4756        | 3.0             |                   |
|        |                       |         |       | 21.0441        | 8.8             |                   |
|        |                       |         |       | 23.3159        | 8.7             |                   |
|        |                       |         |       | 9.7829         | 6.6             |                   |
|        |                       |         |       | 24.8817        | 6.1             |                   |
|        |                       |         |       | 12.9278        | 4.2             |                   |
|        |                       |         |       | 9.6737         | 3.1             |                   |
|        |                       |         |       | 18.8933        | 3.0             |                   |
|        |                       |         |       | 36.8489        | 2.6             |                   |
|        |                       |         |       | 14.6698        | 2.0             |                   |
| 191850 | 3860.486 08           | 2246.914 80 | 25 537 | 13.5330        | 35.1            |                   |
|        |                       |         |       | 21.0441        | 8.8             |                   |
|        |                       |         |       | 23.3159        | 8.7             |                   |
|        |                       |         |       | 9.7829         | 6.6             |                   |
|        |                       |         |       | 24.8817        | 6.1             |                   |
|        |                       |         |       | 12.9278        | 4.2             |                   |
|        |                       |         |       | 9.6737         | 3.1             |                   |
|        |                       |         |       | 18.8933        | 3.0             |                   |
|        |                       |         |       | 36.8489        | 2.6             |                   |
|        |                       |         |       | 14.6698        | 2.0             |                   |
| 261904 | 5137.626 95           | 485.731 94 | 1178  | 1.8            |                 |                   |
| 290492 | 4743.495 61           | 1231.907 71 | 24 418 | 0.8            |                 |                   |
| 290799 | 5496.479 00           | 478.924 32 | 3499  | 22.5300        | 7.2             |                   |
| 294253 | 5496.479 00           | 478.924 32 | 3336  | 1.5            |                 |                   |

Note. ⁵There might be frequencies in the range 1–5 d⁻¹ present, see text.

Three stars (HD 83041, HD 120896 and HD 125889) could be, with the errors of log $T_{\text{eff}}$ and log $L/L_\odot$, located in the $\gamma$ Doradus instability strip. Recently, Paunzen et al. (2014) discovered that the $\lambda$ Bootis star HD 54272 is also a $\gamma$ Doradus-type pulsator. For HD 83041 and HD 125889, we were not able to detect any significant frequency in the $\gamma$ Doradus domain (0.8–5 d⁻¹). However, the lowest frequency (3.0111 d⁻¹) found for HD 120896 could be due to $\gamma$ Doradus-type pulsation or due to alias effects.

In the following, we discuss the results of some targets in more detail.

HD 83041: Paunzen & Handler (1996) published a frequency of 15.16 d⁻¹. The difference to our result (14.5293 d⁻¹) can be well explained by the very broad peak in their fourier spectrum due to the short time basis of the earlier observations and the resultant spectral window function.

HD 83277: for the range of frequencies higher that 5 d⁻¹, we find no significant amplitudes above 3 mmag. This result is in line with those by Paunzen et al. (2002b). However, the frequency range between 1 and 5 d⁻¹ shows a rather rich spectrum which is just at a $4\sigma$ level. Follow-up observations are needed to confirm the reality of these frequencies.

HD 101108: this is a multiperiodic pulsator with amplitudes below 2 mmag. We find a rich spectrum of frequencies in the range between 6 and 30 d⁻¹. Due to the low amplitudes, we are not able to identify individual frequencies common in all data sets. This star is a very interesting target for follow-up observations.
Figure 1. Fourier spectra of HD 83041 (single frequency), HD 125889 (multiperiodic) and HD 290492 (no significant frequency detected).

**HD 105058:** our result (19.8097 d$^{-1}$) is not in line with that (24.8 d$^{-1}$, about 58 min) published by Paunzen et al. (1998). The latter observed this star for 1.8 h covering less than two pulsation cycles. This fact, together with a possible multiperiodic behaviour, could explain the difference.

**HD 290799:** the detected frequency is exactly 1 d$^{-1}$ lower than published by Paunzen et al. (2002b). They have observed this object for 7.8 h in Strömgren $b$. There are two WASP data sets from which the second one shows significantly larger amplitudes than the first one. HD 290799 is located in the Orion OB1 association. There are several fainter stars in its vicinity which results in a higher noise level than for the other targets.

### 3.1 Models for the multiperiodic target stars

The important question we try to answer with our data set is whether or not λ Bootis stars are intrinsically metal-weak (i.e. metal-weak Pop I stars). This does not appear to have been raised very often in the literature. The basic assumption for such an investigation is that all λ Bootis stars are still before the terminal-age main sequence. Casas et al. (2009), for example, made a detailed asteroseismological analysis of the pulsational behaviour of 29 Cygni (HR 7736, A0.5 Va− λ Boo; Gray 1988). This star is one of the prototypes of the λ Bootis group and exhibits very strong underabundances of the Fe-peak elements compared to the Sun (Paunzen et al. 2002a). From their best-fitting models, they concluded that HR 7736 is an intrinsically metal-weak main-sequence object. We investigated the five multiperiodic target stars HD 105058, HD 120896, HD 125889, HD 184779 and HD 191850 in that respect.

For such an analysis, the accurate knowledge of the basic stellar parameters (effective temperature, surface gravity and metallicity) together with the rotational velocity are needed.

First of all, we explored the $\upsilon$ sin $i$ values and metallicities ([M/H]) of these stars in more detail. In the ESO archive\(^3\) FEROS spectra of these stars, except for HD 105058, with a resolution of about 48 000, covering a spectral range from 3800 to 7900 Å, are available. Initial reductions of the spectra and their conversion into 1D images were carried out within IRAF.\(^4\)

The $\upsilon$ sin $i$ values were determined measuring the full width at half-maximum (FWHM) of the Mg II 4481 Å line and comparing them with the standard relation listed by Slettebak et al. (1975). We compared the derived FWHM with those of other comparable strong lines and find an excellent agreement. For HD 120896, HD 125889, HD 184779 and HD 191850, we find $\upsilon$ sin $i$ values of 125, 95, 80 and 60 km s$^{-1}$, respectively. The errors are about ±5 km s$^{-1}$.

Synthesized spectra were computed using the program SPECTRUM\(^5\) (Gray & Corbally 1994) and modified versions of the ATLAS9 code

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\(^3\) http://archive.eso.org

\(^4\) http://iraf.noao.edu/

\(^5\) http://www.appstate.edu/~grayro/spectrum/spectrum.html
taken from the Vienna New Model Grid of Stellar Atmospheres, NEMO\(^6\) (Heiter et al. 2002). The astrophysical parameters were taken from Table 1. The spectra were convolved with the instrumental profile and the rotational profiles using the \(\upsilon \sin i\) values listed above. A visual comparison of the observed and synthetic line profiles yields an excellent agreement. To estimate the \([M/H]\) value, we used different scaled metallicity models from \([-0.2\) to \(-2.0\) dex. For HD 120896, HD 125889 and HD 184779, we find a very similar metallicity of about \(-0.5\) dex (\([Z] = 0.004\)) whereas HD 191850 is more underabundant with \([M/H] = 0.002\). The latter is in perfect accordance with the result of the RAdial Velocity Experiment (RAVE) survey (Siebert et al. 2011).

For HD 105058 the same techniques were applied to the spectrum published by Tomasella, Munari & Zwitter (2010) which has a resolution of only 20 000. The result is \(\upsilon \sin i = 135 \pm 5\) km s\(^{-1}\) and \([M/H] = −1.0\) dex.

As a next step, theoretical tracks were calculated for several different values of metallicity, \(0.004 < [Z] < 0.025\). We used the Opacity Project data (Seaton 2005), the scaled chemical composition by Asplund et al. (2009), the Warsaw–New Jersey evolutionary code (Pamyatnykh et al. 1998) and the linear non-adiabatic pulsational code by Dziembowski (1977).

### 3.2 Results from the models

Fig. 3 shows the Hertzsprung–Russell diagram (HRD) with the location of all variable stars. The observational values of the effective temperature and luminosity were taken from Table 1. From this figure we conclude that the stars are on the main sequence only in the case of metallicity \([Z] > 0.007\) for no convective core overshooting, i.e. \(\alpha_{ov} = 0.0\). To investigate the influence of the latter, we also calculated evolutionary tracks for two values of the overshooting parameter, namely \(\alpha_{ov} = 0.0\) and \(0.2\). Fig. 4 shows that the effect is quite strong. A higher efficiency of the core overshooting results in a much more extended main-sequence phase. If we assume \(\alpha_{ov} = 0.2\) then \([Z] > 0.004\) is needed for locating the stars on the main sequence. This value is still much higher than deduced from the spectra. From this analysis we would conclude that these objects are intrinsically not metal-weak.

As the next step, we performed a detailed asteroseismic analysis of the detected frequencies in the light of different metallicity values. For this, we used the results of HD 120896, HD 184779 and HD 191850 because they have very similar astrophysical parameters.

**Main-sequence hypothesis:** to place the stars on the main sequence, we need to assume a metallicity \([Z] > 0.007\) or include effective convective core overshooting. For \(\alpha_{ov} = 0.2\) we need about \([Z] > 0.004\). So, if the stars are on the main sequence, we can derived some constrains on the lowest plausible value of the metallicity (Figs 3 and 4).

Fig. 5 shows the instability parameter \(\eta\), as a function of the frequency for pulsational models. Modes are excited when \(\eta > 0\). The models have \(\log T_{\text{eff}} = 3.862\) and \(\log L/L_{\odot} = 1.206\). Different colours indicate various metallicities, circles indicate radial modes (\(\ell = 0\)) and squares indicate dipole modes (\(\ell = 1\)). Short vertical lines above the \(\eta = 0\) line indicate the observational frequency spectrum for HD 120896 (green), HD 184779 (blue) and HD 191850 (red). We notice that the unstable modes cover almost the entire

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\(^6\) http://www.univie.ac.at/nemo
The instability parameter, $\eta$, as a function of the pulsational frequency for three star models on the main sequence. All models have $\log T_{\text{eff}} = 3.862$ and $\log L/L_\odot = 1.206$. We assumed initial hydrogen abundance $X = 0.7$ and mixing-length parameter $\alpha_{cv} = 1.8$. Different colours indicate various metallicities, circles indicate radial modes ($\ell = 0$) and squares indicate dipole modes ($\ell = 1$). Short vertical lines above the $\eta = 0$ line indicate the observational frequency spectrum for HD 120896 (green), HD 184779 (blue) and HD 191850 (red).

Observational spectrum. Increasing the initial hydrogen abundance does not change the results significantly. The same is true if we change the mixing-length parameter to $\alpha_{cv} = 1$. A more significant impact on the models is the overshooting efficiency. For $\alpha_{ov} = 0.2$, we were able to derive models for metallicity $[Z] = 0.005$, while for $\alpha_{ov} = 0.0$, we need $[Z] = 0.008$.

We conclude that if the stars are on the main sequence, a much higher intrinsic metallicity than the values derived from observations are needed to explain the observed frequencies. However, only a detailed mode identification, which is not possible from the presented data, would allow us to define even more strict constrains for the models.

Post-main-sequence hypothesis: in Fig. 6 we present the same analysis as in Fig. 5 but for four different metallicities, $[Z] = 0.004$ (black), 0.007 (green), 0.015 (blue) and 0.025 (red). The left instability border appears at a frequency that is sufficiently low to explain...
almost all observed modes. The only exception is a very low frequency of HD 120896. This mode cannot be the retrograde mode shifted to low frequency due to the fast rotation; it would require a rotational velocity of the order of 1000 km s\(^{-1}\). The low-frequency instability border at about \(\nu \sim 7\) d\(^{-1}\) is almost insensitive to the metallicity, but the high-frequency border depends strongly on \([Z]\). Because the interaction of convection and pulsation are not well described in the present theory, the true position of the high-frequency instability border is quite uncertain.

A higher value of the initial hydrogen content slightly increases the instability of high-frequency modes. It is due to the fact that high-frequency modes are partially driven through the HI-ionization zone. High-frequency modes have an increase of the work integral near the HI opacity bump. Since convection transports almost the entire energy in this zone, this pulsation driving effect can be artificial. For the chosen effective temperature and luminosity, we were not able to find models beyond the main sequence for \([Z] > 0.025\). For a more effective core overshooting, we could not find models with \([Z] > 0.015\). The tracks are shifted to the right on the HRD, and the loop after the main sequence appears for lower values of the effective temperature. The mixing-length parameter, \(\alpha_{\text{cv, ass eto}}\), was set to 1.8. The change of this parameter to 1.0 did not cause a significant effect.

In this regime, there are quite strong effects of the chosen \(T_{\text{eff}}\) and \(\log L/L_{\odot}\) values. The instability of modes depends quite strongly on the exact position of a star on the HRD. For a given \([Z]\), a higher effective temperature gives instability for higher frequencies. The low-frequency instability border is shifted to about 9 d\(^{-1}\). For cooler models, we derived instability for lower frequencies, but high-frequency modes were slightly more stable. More luminous models could not explain the instability of high-frequency modes, while less luminous ones have problems with low-frequency modes. This is interesting because the lowest frequencies were found for HD 120896, which is the least luminous star. But its effective temperature is also lower than for the remaining stars, and this effect should cancel the luminosity effect.

The theoretical evolutionary changes of frequencies are of the order of \(10^{-7}\) d\(^{-1}\) yr\(^{-1}\), which are too small to detect with the current data.

We conclude that with the frequencies found in this work we are not able to reject the possibility that the stars are beyond the main sequence. Both low and high metallicities are possible because the instability of modes depends mainly on the helium ionization zone.

4 CONCLUSION

We analysed the time series of WASP data sets of 15 well-established \(\lambda\) Bootis stars. This small group of CP objects of the upper main-sequence is an excellent target to investigate the effects of diffusion, rotation and accretion in the presence of classical \(\delta\) Scuti/\(\gamma\) Doradus-type pulsation.

For eight targets, we were able to detect (multiperiodic) variations with amplitudes between 1.6 and 35.1 mmag. Four of the probable constant stars are not located in the instability strip. A comparison of our results with those from the literature yields an excellent agreement.

We made an asteroseismic analysis of the multiperiodic stars to tackle the question as to whether the chemical peculiarity is intrinsic or restricted to the stellar surface. For this, we estimated the metallicities and projected rotational velocities from high-resolution archival spectra. We then used state-of-the-art pulsation models to characterize the (in)stability properties. From this analysis we conclude that if the stars are still on the main sequence, which is the most accepted hypothesis (Stütz & Paunzen 2006), they are not intrinsically metal-weak. If they are beyond the terminal-age main sequence, the results are ambiguous. We suggest detailed spectroscopic follow-up observations of the presented multiperiodic \(\lambda\) Bootis stars to identify individual modes. Such spectroscopic observations have been already successfully performed for one member of the group, 29 Cygni, by Mkrtichian et al. (2007). Similar studies for \(\delta\) Scuti stars of comparable magnitudes have been published (Poretti et al. 2009) proving the feasibility. The expected high-precision parallaxes and thus distances as well as luminosities from the Gaia satellite mission (Michalik, Lindegren & Hobbs 2015) will hopefully significantly improve the accuracy of the position of the investigated stars in the HRD; at least for those which are not too bright.
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