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# First orbital elements for the $\lambda$ Bootis spectroscopic binary systems HD 84948 and HD 171948*

## Implications for the origin of the $\lambda$ Bootis stars

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**Abstract.** We present high-resolution spectroscopic observations of the two $\lambda$ Bootis type spectroscopic binary systems HD 84948 and HD 171948. Both systems consist of two true $\lambda$ Bootis stars, as has already been proven by a detailed abundance analysis taking into account the binary nature. Nevertheless, we have obtained non-LTE abundances for carbon and oxygen in order to investigate those important elements. The abundances fit excellently into the typical pattern for this group, leaving no doubt that all four components are true $\lambda$ Bootis stars. With the help of the derived orbital elements it is possible to establish the ages of the two systems. For the first time we can estimate the evolutionary status of Galactic field $\lambda$ Bootis stars. The origin of those nonmagnetic, metal-weak, Population I, late B- to early F-type stars is still controversial. The two widely discussed theories explaining the $\lambda$ Bootis phenomenon (diffusion together with either accretion of circumstellar matter or mass-loss) predict significantly different evolutionary stages for this group of objects (close to either the Zero-Age Main Sequence or Terminal-Age Main Sequence). It is already known that very young members of the group exist in the Orion OBI association and probably in NGC 2264. Hipparcos data established six further Galactic field $\lambda$ Bootis stars which are close to the Zero-Age Main Sequence, whereas the evolutionary status for the other objects remained undetermined. The Hipparcos data reveal that the Galactic space motions of both the systems that we discuss here are typical of those of Population I objects. The photometric data from the Hipparcos mission confirm the pulsation previously discovered for HD 84948 with a period of about 110 min and a $V$-amplitude of about 14 mmag. For HD 84948, we estimate from the mass ratio an age of about 1 Gyr, ruling out a possible Pre-Main-Sequence status. HD 171948 has an age of about 0.01 to 0.1 Gyr which is close to the Zero-Age Main Sequence. We therefore conclude that the $\lambda$ Bootis phenomenon can be found continuously from very early stages to the Terminal-Age Main Sequence, suggesting that different mechanisms might work at different stages of stellar evolution producing the same abundance pattern.

**Key words.** stars: chemically peculiar – stars: early-type – binaries: spectroscopic

## 1. Introduction

For about ten years much effort has been spent to explain the so-called $\lambda$ Bootis stars. That small group comprises late B- to early F-type, Population I stars with apparently solar abundances of the light elements (C, N, O and S) and moderate to strong underabundances of Fe-peak elements. The two competing theories involve diffusion together with either accretion (rather unevolved ages; $6.0 < \log t$ (years) $\leq 7.5$) or mass-loss (rather evolved ages; $\log t > 8.5$). For a review of those theories see Paunzen (1999). Two other models conclude that $\lambda$ Bootis stars are either one single metal-weak object that has resulted from a merging process of a W UMa type binary system (Andrievsky 1997) or two apparent

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* Based on observations at BNAO Rozhen; SAAO and with the Hipparcos satellite.

**Table 1.** Some fundamental parameters of HD 84948 and HD 171948. Bolometric magnitudes, luminosities together with derived masses and ages for Pre-Main as well as Main Sequence models from Paper I. Compared are the mass ratios of those models and the observed ones. In parenthesis are the errors in the final digits of the corresponding quantity.

| | HD 84948 HIP 48243 | | HD 171948 HIP 91234 | |
|---|---|---|---|---|
| | A | B | A | B |
| $T_{\rm eff}$ (±200 K) | 6600 | 6800 | 9000 | 9000 |
| $\log g$ (±0.15 dex) | 3.3 | 3.7 | 4.0 | 4.0 |
| $v \sin i$ (±5 km s$^{-1}$) | 45 | 55 | 15 | 10 |
| $v_{\rm micro}$ (±0.5 km s$^{-1}$) | 3.5 | 3.5 | 2 | 2 |
| $M_{\rm Bol}$ [mag] | 0.38 (30) | 1.75 (30) | 1.76 (18) | |
| $\log L/L_\odot$ | 1.75 (8) | 1.20 (8) | 1.19 (8) | |
| $\mathcal{M}_{\rm PMS}$ [$M_\odot$] | 3.0 (1) | 2.0 (1) | 2.0 (1) | |
| $\log t_{\rm PMS}$ | 6.3 (3) | 6.8 (3) | 7.0 (1) | |
| $q_{\rm PMS}$ | 1.50 (12) | | 1.00 (12) | |
| $\mathcal{M}_{\rm MS}$ [$M_\odot$] | 2.3 (1) | 1.8 (1) | 2.0 (1) | |
| $\log t_{\rm MS}$ | 9.0 (1) | 8.9 (1) | 7.0–8.0 | |
| $q_{\rm MS}$ | 1.28 (12) | | 1.00 (12) | |
| $q_{\rm orbit}$ | 1.17 (3) | | 1.04 (3) | |

"solar-abundance" stars mimicking a metal-weak composite spectrum (Faraggiana & Bonifacio 1999).

We know of very young members of the $\lambda$ Bootis group: there are five of them (Paunzen 2000) in the Orion OBI association and one candidate in NGC 2264 (both of which have an age of $\log t \approx 7.0$). Gray & Corbally (1998) reported the discovery of a metal-weak Herbig Ae star, which could be a further link between $\lambda$ Bootis and true Pre-Main-Sequence (PMS hereafter) objects.

Up till now, however, it has been almost impossible to derive a definitive conclusion for the Galactic field stars. Other than for members of open clusters with a known age, the calibration within evolutionary diagrams is not unequivocal.

Iliev & Barzova (1995) made an analysis of a sample of $\lambda$ Bootis stars using photometrically calibrated parameters as well as appropriate stellar-evolution grids. They concluded that most of their program stars are in the middle of their Main-Sequence evolution, casting doubt upon the diffusion/accretion model.

Paunzen (1997) analyzed the Hipparcos data of the group members and partly contradicted the findings of Iliev & Barzova (1995). They found that six stars are very close to the Main Sequence. Furthermore it was proposed that all other program stars are in a Pre-Main-Sequence phase evolving to the Zero-Age Main Sequence (ZAMS hereafter).

Later on, Bohlender et al. (1999) and Faraggiana & Bonifacio (1999) challenged that hypothesis with plausible arguments such as the resulting unusually vigorous star-forming activity in the solar neighbourhood (note that 80% of all $\lambda$ Bootis members are within 250 pc) and a statistical analysis of normal type stars.

Gray & Corbally (1998) have already stated that the $\lambda$ Bootis phenomenon can be found from very early stages to well into the Main Sequence life of A-type stars. That conclusion was based on the incidence of $\lambda$ Bootis stars among very young A-type stars which is not very different from the incidence among Galactic field stars.

We were therefore left with the following picture: $\lambda$ Bootis stars were found in a rather short age interval on or shortly before the ZAMS ($7.0 < \log t < 8.0$). But what about the large sample of Galactic field members that could be either in a PMS stage or evolving from the ZAMS?

The only reliable way out of this dilemma for the Galactic field members is the examination of spectroscopic-binary systems. Since the derived mass-ratios of the components are significantly different for the PMS and MS models (especially far away from the ZAMS; Palla & Stahler 1993) it is possible to distinguish between the two evolutionary stages if orbital elements are known.

Besides HD 111786 (Faraggiana et al. 1997), HD 84948 and HD 171948 (Paunzen et al. 1998; Paper I hereafter) seemed the most promising candidates. In Paper I it was shown that the mass-ratio of HD 84948, in particular, would be a significant discriminant of its evolutionary status.

Before we can draw conclusions about the evolutionary stages of the $\lambda$ Bootis stars in HD 84948 and 171948, the true natures of all four components of those binaries has to be established unambiguously. A non-LTE abundance analysis of carbon and oxygen was therefore performed. The derived values fit the abundance pattern typical of the group very well.

In this paper we present spectroscopic observations to determine the orbital parameters of HD 84948 and HD 171948. Besides giving the orbits, we conclude that HD 84948 is indeed evolving from the ZAMS, in clear contradiction to the diffusion/accretion theory. Furthermore, the hypothesis proposed by Paunzen (1997) should be rejected or modified.

## 2. Observations and data reduction

Observations of both stars were made with the coudé spectrograph at the 2-m RCC telescope of the Bulgarian National Astronomical Observatory Rozhen during 1997–2001. The Photometrics AT200 camera with a SITe SI003AB 1024 × 1024 CCD chip attached to the Third camera was used. Typical seeing conditions were $2''-3''$, and the slit width was set to 300 $\mu$m which corresponds to $0\farcs8$ on the sky. The spectra were taken with a 632 mm$^{-1}$ Bausch & Lomb grating in four different spectral regions centred on 5900 Å (Na D), 7120 Å (C-region), 7770 Å (O-triplet) and on 8580 Å (Ca-triplet) with a resolution of about 30 000 for the first two and about 22 000 for the other two regions.

A hollow-cathode FeAr lamp (ThAr since January 2000) was used to produce a reference spectrum with a $FWHM$ of about 2 pixels for the comparison lines. Flat fields were made by using a tungsten projection lamp mounted in front of the entrance slit. The spectra were

**Table 2.** Observed spectra and measured radial velocities at the Na D region for HD 84948 (upper panel) and HD 171948 (lower panel). The last two columns list the differences between the observed and calculated radial velocities.

| Date | JD | Primary Velocity $[\mathrm{km\,s^{-1}}]$ | Secondary Velocity $[\mathrm{km\,s^{-1}}]$ | Phase | $(O–C)_{Prim.}$ $[\mathrm{km\,s^{-1}}]$ | $(O–C)_{Second.}$ $[\mathrm{km\,s^{-1}}]$ |
|---|---|---|---|---|---|---|
| 1998 Oct. 08.09 | 2451094.59 | −15 | | 0.567 | – | – |
| 09.11 | 095.61 | −72 | +57 | .705 | −4.9 | +6.4 |
| Dec. 28.97 | 176.47 | −14 | | 11.611 | – | – |
| 30.01 | 177.51 | −70 | +56 | .751 | +3.9 | −2.5 |
| 1999 Feb. 24.72 | 2451234.22 | −13 | | 19.400 | – | – |
| 26.89 | 236.39 | −62 | +52 | .693 | +3.3 | +3.5 |
| 27.88 | 237.38 | −77 | +68 | .826 | +3.7 | +1.5 |
| 28.84 | 238.34 | −12 | | .957 | – | – |
| Apr. 05.89 | 274.39 | −78 | +65 | 24.820 | +2.5 | −1.2 |
| May 08.75 | 307.25 | +23 | −74 | 29.251 | −7.8 | −10.3 |
| 2000 Mar. 26.00 | 2451629.50 | −74 | +50 | 72.717 | −5.0 | −2.8 |
| 26.97 | 630.46 | −79 | +70 | .847 | +1.6 | +3.7 |
| May 20.76 | 685.26 | +39 | −67 | 80.238 | +4.1 | +1.5 |
| Nov. 06.99 | 855.50 | +46 | −85 | 103.199 | −1.6 | −1.7 |
| 08.07 | 856.57 | −16 | | .345 | – | – |
| Dec. 10.04 | 888.54 | −63 | +36 | 107.656 | −4.0 | −5.2 |
| 12.98 | 891.48 | +88 | −121 | 108.053 | +7.6 | +0.6 |
| 2001 Jan. 03.89 | 2451913.39 | +42 | −79 | 111.009 | −2.3 | +0.4 |
| 04.92 | 914.42 | +62 | −103 | .147 | −3.9 | +1.6 |
| 10.98 | 920.48 | −14 | | .964 | – | – |
| 11.90 | 921.40 | +84 | −118 | 112.089 | +1.8 | +5.8 |
| 1997 Sep. 19.72 | 2450711.22 | −56 | −8 | 0.130 | −6.2 | −8.3 |
| 1998 June 10.90 | 2450975.40 | −45 | – | 12.170 | −6.8 | – |
| July 13.87 | 2451008.37 | −5 | −53 | 13.673 | −3.2 | −3.2 |
| 14.03 | 008.54 | −6 | −53 | .680 | −3.9 | −3.4 |
| 14.80 | 009.30 | −5 | −50 | .715 | −1.2 | −2.2 |
| 14.99 | 009.49 | −7 | −50 | .724 | −2.7 | −2.8 |
| 15.81 | 010.31 | – | −46 | .761 | – | −2.0 |
| Aug. 06.79 | 032.29 | – | −44 | 14.763 | – | −0.2 |
| Oct. 05.72 | 092.22 | −4 | −51 | 17.495 | −1.8 | −1.6 |
| 06.64 | 093.14 | −1 | −50 | .536 | +0.1 | +0.5 |
| 1999 Feb. 25.10 | 2451234.60 | −80 | +31 | 23.984 | −1.1 | +0.4 |
| 27.07 | 236.57 | −69 | +22 | 24.073 | +1.6 | +0.0 |
| 28.10 | 237.60 | −52 | +4 | .120 | +1.1 | +0.3 |
| Mar. 01.09 | 238.59 | −41 | – | .166 | −1.6 | – |
| Oct. 26.67 | 478.18 | −66 | +17 | 35.085 | +0.2 | −0.3 |
| 31.72 | 483.22 | – | −41 | .315 | – | −3.9 |
| Nov. 01.74 | 484.24 | – | −44 | .361 | – | −2.4 |
| 02.72 | 485.22 | – | −47 | .406 | – | −2.0 |
| 07.65 | 500.15 | −63 | +18 | 36.086 | +2.6 | +1.3 |
| 2000 Mar. 24.02 | 2451627.52 | −37 | – | 41.891 | −2.3 | – |
| 24.05 | 627.55 | −34 | – | .893 | +1.3 | – |
| 26.03 | 629.53 | −77 | +32 | .983 | +1.6 | +1.8 |
| 26.06 | 629.56 | −75 | +32 | .984 | +4.0 | +1.3 |
| Apr. 15.11 | 649.61 | −36 | – | 42.898 | +1.5 | – |
| 18.12 | 652.62 | −84 | +34 | 43.035 | −1.0 | −0.8 |
| 19.03 | 653.54 | −69 | +21 | .077 | +0.3 | +0.5 |
| May 20.00 | 684.50 | +2 | −45 | 44.488 | +4.5 | +4.1 |
| 20.90 | 685.40 | +3 | −46 | .529 | +4.3 | +4.4 |
| June 12.84 | 708.34 | +1 | −50 | 45.575 | +1.6 | +1.0 |
| 13.83 | 709.33 | +0 | −50 | .620 | +0.7 | +1.0 |
| 14.85 | 710.35 | −1 | −49 | .666 | +0.6 | +1.1 |
| July 22.77 | 748.28 | – | −40 | 47.395 | – | +4.2 |
| 23.83 | 749.33 | +1 | −42 | .443 | +5.4 | +5.1 |

**Table 2.** continued.

| Date | JD | Primary Velocity [km s$^{-1}$] | Secondary Velocity [km s$^{-1}$] | Phase | (O–C)$_{\rm Prim.}$ [km s$^{-1}$] | (O–C)$_{\rm Second.}$ [km s$^{-1}$] |
|---|---|---|---|---|---|---|
| 2000 Aug. 08.87 | 2451765.37 | −35 | – | 48.174 | +2.2 | – |
| 13.76 | 770.26 | – | −41 | .397 | – | +3.4 |
| 16.81 | 773.30 | +3 | −49 | .536 | +4.2 | +1.5 |
| 19.80 | 776.30 | −1 | −50 | .672 | +0.8 | −0.1 |
| 24.94 | 781.44 | −39 | – | .906 | +1.8 | – |
| Nov. 07.72 | 856.22 | – | −41 | 52.314 | – | −3.9 |
| 08.70 | 857.20 | – | −45 | .359 | – | −3.5 |

bias-subtracted and flat-fielded with standard IRAF procedures. Special attention was paid to the removal of the telluric lines with the help of spectra of fast-rotating hot stars. The typical signal-to-noise ratio for most of the spectra is between 150 and 250. Wavelength calibration resulted in a r.m.s. wavelength error of typically 0.005 Å. Additional observations in the same spectral regions were made for two IAU radial-velocity standard stars, *o* Aql (HR 7560, $V = 5.10$, F8 V) and 5 Ser (HR 5694, $V = 5.10$, F8 III). No systematics were found above the error limit of 2 km s$^{-1}$.

The log of observations and the radial-velocity measurements are listed in the first three columns of Table 2. Sodium D1 and D2 lines are the lines that are most satisfactory for R.V. purposes in the observed spectra, and our measurements were restricted to those lines alone.

A triple structure is clearly visible in most spectra of HD 171948 obtained in the Na D region. The weakest lines have a nearly constant radial velocity of −16 (2) km s$^{-1}$, while the other two components follow short-period orbital changes. To check the possibility that the weakest lines could belong to a real third component of the system with a much longer orbital period, we carried out additional observations in the near-IR Ca-triplet region. Not being resonance lines, the Ca lines are not expected to be sensitive to the presence of interstellar matter. To avoid phase differences, the exposures in the Na D region and in the Ca-triplet region were made immediately one after the other, or quasi-simultaneously.

Only two lines have been observed in the Ca-triplet region instead of three in the Na D-region. According to the wavelength separation they do belong to the components of the binary system, thus, the conclusion can be drawn that the weakest sodium line has an interstellar origin.

Additional observations in the two selected regions were made for two nearby stars HD 171799 ($V = 7.64$, HIP 91166, A0) and HD 171569 ($V = 7.21$, HIP 91088, A0). Both stars have been used as standards during the photometric observations of HD 171948 (Paper I). The fast rotating star HD 171569 with sharp absorption details which are clearly visible represents the case when interstellar lines are superimposed on the stellar spectrum. In opposite, there are only the lines of stellar origin in the spectrum of the slow rotating star HD 171799. One remark concerning its spectral type: according to SIMBAD it is A0. But our spectrum unveils a type which is more like F0.

**Table 3.** The orbital elements: $P$ (period), $\gamma$ (radial velocity of the system), $K_{1,2}$ (semi-amplitudes of the radial velocity curves), $e$ (eccentricity), $\omega$ (periastron longitude), $T_1$ (time of periastron passage), $a$ (semimajor axis), $i$ (inclination), $f(m)$ (mass function) and $q$ (mass ratio) for both program stars. The orbits are portrayed in Fig. 3. In parenthesis are the errors in the final digits of the corresponding quantity.

| | HD 84948 | HD 171948 |
|---|---|---|
| $P$ [d] | 7.4139 (7) | 21.9414 (32) |
| $\gamma$ [km s$^{-1}$] | −12.79 (88) | −25.31 (40) |
| $K_1$ [km s$^{-1}$] | 82.1 (1.8) | 42.3 (9) |
| $K_2$ [km s$^{-1}$] | 95.9 (1.9) | 44.1 (8) |
| $e$ | 0.452 (19) | 0.430 (14) |
| $\omega$ [°] | 292.3 (2.6) | 164.6 (2.2) |
| $T_1$ [JD] | 2 451 579.703 (41) | 2 451 454.374 (89) |
| $a_1 \sin i$ [Gm] | 7.47 (18) | 11.52 (25) |
| $a_2 \sin i$ [Gm] | 8.72 (20) | 12.01 (24) |
| $a \sin i$ [Gm] | 16.19 (27) | 23.53 (34) |
| $m_1 \sin^3 i$ [$M_\odot$] | 1.659 (99) | 0.552 (28) |
| $m_2 \sin^3 i$ [$M_\odot$] | 1.422 (88) | 0.529 (28) |
| $f(m_1)$ [$M_\odot$] | 0.303 (22) | 0.127 (8) |
| $f(m_2)$ [$M_\odot$] | 0.481 (33) | 0.144 (9) |
| $q$ | 1.17 (3) | 1.04 (3) |
| rms [km s$^{-1}$] | 4.2 | 3.1 |

The accuracy of an individual radial velocity was near 3 km s$^{-1}$ for HD 171948 and 4–5 km s$^{-1}$ for the more rapidly rotating components of HD 84948.

The spectra of HD 171948 taken on JDs 2451773 and 2451776 were obtained at SAAO. The Giraffe spectrograph, fibre-fed by the 1.9-m telescope, was used. The instrument is modelled on the MUSICOS spectrograph (Baudrand & Böhm 1992); a full description can be found on the SAAO website (`http://da.saao.ac.za`).

## 3. Program stars

Both systems have already been analyzed and described in detail in Paper I. Here we give a short overview of those results as well as some new data published by Heiter (2000). Furthermore, a detailed non-LTE abundance analysis of carbon and oxygen (key elements of the λ Bootis abundance pattern) was made in order to prove the membership of both systems in the λ Bootis group. The physical parameters of all program stars are listed in Table 1; they were derived by detailed abundance analyses that took into account the binary natures of both systems.

Paunzen (2000) has shown that the distribution of projected rotational velocities for the λ Bootis group is not different from that of apparently "normal"-type stars. The rather low $v \sin i$ values found for the components are therefore in line with the results for other members of this group (e.g. HD 84123; Heiter 2000). It is not clear if these systems are pseudo-synchronized (see Sect. 4.1) but tides are certainly acting on the components of HD 171948 (though is very hard to give a quantitative number for such an interaction) and may contribute to reduce – or increase – the rotational velocities.

### *3.1. Non-LTE abundances for carbon and oxygen*

We have used the same regions (7120 Å and 7770 Å) of high-resolution spectra for both systems in order to derive non-LTE abundances for carbon and oxygen. The same techniques, atmospheric models and atomic line data were used as listed in Paunzen et al. (1999). The synthetic spectra were calculated taking into account the ratio of the individual continuum fluxes as described in Paper I. For the individual stars, the astrophysical parameters listed in Table 1 were used.

The region from 7100 Å to 7130 Å contains nine C I as well as seven C II lines whereas the 7770 Å region includes the strong O I triplet.

Each system was observed at four different phases in an effort to ensure that heavy blending did not compromise the abundance estimates. We find carbon to be moderate underabundant (−0.8 (4) dex as well as −1.2 (4) dex for HD 84948 (A and B) and HD 171948 (A and B), respectively) and oxygen nearly solar abundant (−0.6 (3) dex and +0.2 (3) dex for HD 84948 (A and B) as well as −0.4 (3) dex for HD 171948 (A and B), respectively). The variation of the abundances for HD 84948 is in line with the intrinsic scatter of the absolute values found also for other members of this group (Kamp et al. 2001). There is also no correlation of the light element abundances with the effective temperature or surface gravity.

One of the most outstanding characteristics of the λ Bootis pattern is the strong anticorrelation of carbon and oxygen with respect to silicon. Figure 1 shows the location of our program stars in a [C/Si] as well as an [O/Si] versus [Si] plot.

The oxygen abundance for HD 171948 given by Heiter (2000) is, within the errors, in agreement with ours. The values for carbon should be taken only as approximations, because the resolution of our spectra is lower by a factor of two and the signal-to-noise ratio is also lower than in Paunzen et al. (1999). Furthermore, the equivalent widths of the relevant spectral lines are very small. Notice that, even with that limitation, the values fit very well within

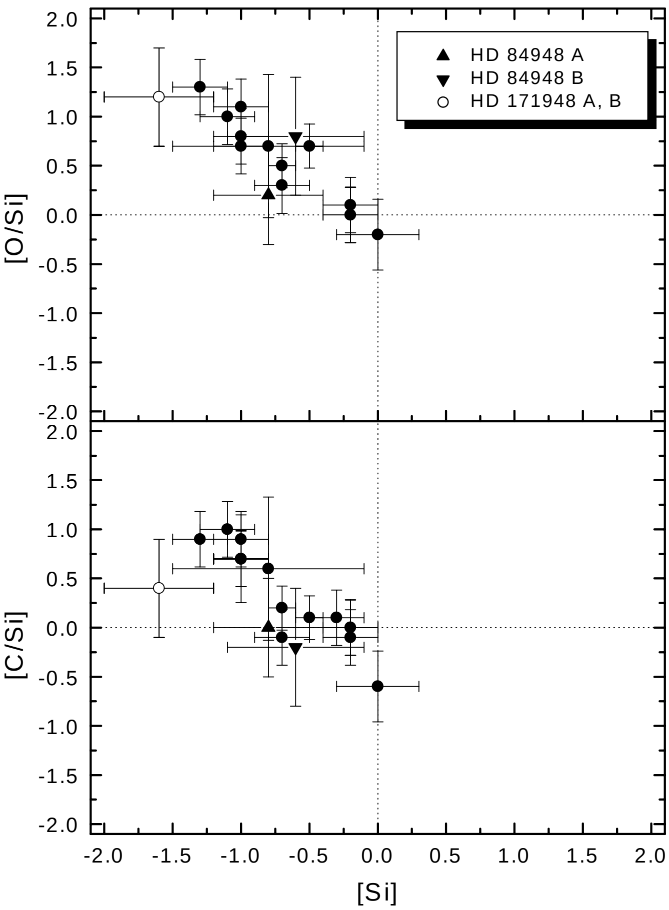


**Fig. 1.** The anticorrelation between the silicon abundance and the oxygen and carbon abundances. The well established λ Bootis stars taken from Paunzen (2000), are indicated by the filled circles.

those for well established λ Bootis stars. However, the non-LTE abundances for oxygen constitute a convincing diagnostic of the membership in that group.

### *3.2. HD 84948*

This system was already found to show a metal-weak character at spectral-classification resolution by Abt (1984). Paunzen (2000) confirmed that finding, also taking into account the apparent binary nature.

The two components show rather different astrophysical parameters (Table 1) and abundances. The components of this system are among the few λ Bootis stars whose abundances of Zn (−0.9 and −0.4 dex, respectively) are measurable. Since a solar Zn abundance is predicted by the diffusion/accretion theory, our result might be taken as a further hint that that mechanism does not play a significant rôle for this system.

It was shown (Venn & Lambert 1990; Stürenburg 1993; Heiter 2000) that a typical abundance pattern exists for the group of λ Bootis stars. One has to keep in mind that there is a confusion at the cooler end of the "λ Bootis region" that is discussed in great detail by Gray (1988, 1989). The components of HD 84948 do in fact show the same typical abundance pattern as other members of the λ Bootis group.

The newly analyzed spectra lead also to a better estimate of the effective temperature and surface gravity. With the more accurate values we were also able to recalibrate the program stars in the $\log T_{\rm eff}$ versus $\log L/L_\odot$ diagram (Table 1, Fig. 2). The details of that procedure are described in Paper I. To check this new value independently, we have reanalyzed the derived equivalent width ratios for about 50 individual lines from all published spectra (U. Heiter, private communication). For those elements which exhibit almost the same absolute abundances for both components, we get a luminosity ratio of slightly more than three (note that Table 1 lists a value of 3.5).

Another interesting fact is that pulsation was detected for HD 84948 (Paper I). The Hipparcos photometric data confirmed that finding (Sect. 4.3). Unfortunately, no new photometric observations have been obtained since then. With the derived mass and inclination as given in Sect. 4.1 and a detailed asteroseismological investigation further stellar characteristics should be determinable.

### *3.3. HD 171948*

This system consists of two very similar components (Table 1). The classification-resolution spectrum is therefore not influenced by the superposition of the two fluxes. Abt (1984) and Paunzen & Gray (1997) clearly established the system as being of true λ Bootis type.

The components of HD 171948 exhibit the most extreme underabundances of the heavy elements found for λ Bootis stars to date, the only comparable values being those of the type star (Heiter 2000). No variability has been found so far.

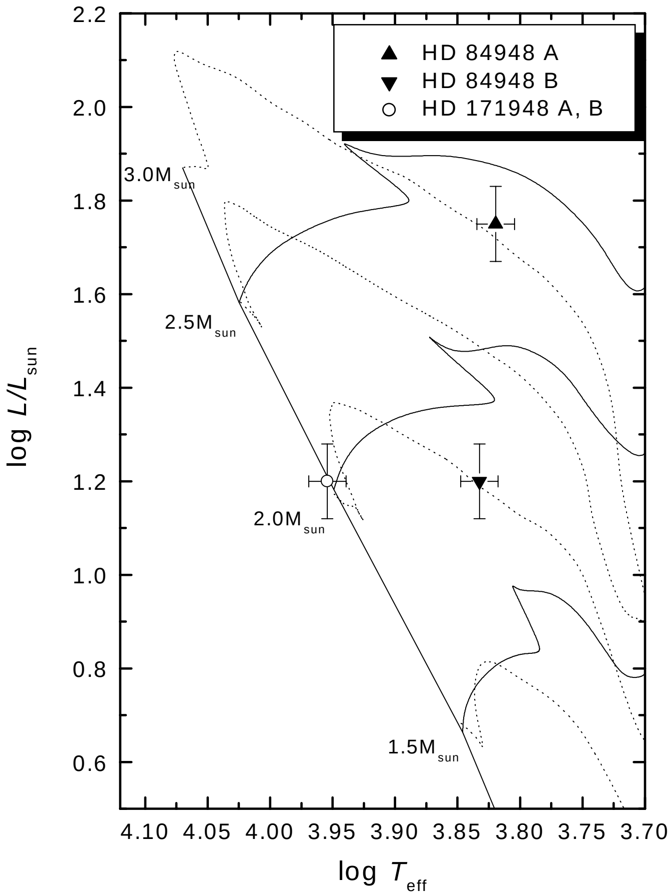


**Fig. 2.** The location of the program stars in the Hertzsprung–Russell diagram. The dotted lines are the PMS models from Palla & Stahler (1993) whereas the solid lines are MS models from Claret (1995). The luminosities for HD 171948 A and B are within the error bars identical.

## 4. Results

In the following sections we present the results of our spectroscopic survey in order to estimate the orbital elements. Furthermore, the Hipparcos data were used to derive Galactic space motions and to test the systems for variability.

### *4.1. Orbital elements*

Table 2 presents the 61 observations (21 for HD 84948 and 40 for HD 171948). In total, 15 measurements for HD 84948, 31 for HD 171948 A and 33 for HD 171948 B were used to determine the orbital elements (the other observations were not used owing to heavy blending). All observations were weighted uniformly. The orbital elements are listed in Table 3 whereas the orbits are portrayed in Fig. 3. The orbital elements were derived with a program developed by R. F. Griffin (see Griffin 2001; Hummel et al. 2001) which was used to determine similar elements for more than 150 individual spectroscopic binary systems.

The phase coverage of HD 84948 and HD 171948 is good enough to warrant confidence in the derived elements. Since both systems are non-contact it is appropriate to use evolutionary models calculated for apparent "single" stars.

For HD 84948 we get a mass-ratio of 1.17. Comparing that with the values for PMS and MS evolutionary status, we can immediately rule out a PMS nature for the system (at a $10\sigma$ level). This is, therefore, the first evidence that at least some Galactic field λ Bootis stars are indeed on a track away from the ZAMS. The age of this system is close to 1 Gyr (using the appropriate stellar evolutionary models from Claret 1995), ruling out the diffusion/accretion theory as explanation for the origin of the observed abundance pattern. However, the fact that rather "old" λ Bootis stars exist does, obviously, not prove the correctness of the diffusion/mass-loss theory itself. But a more general physical process causes a typical abundance pattern and it establishes as soon as the conditions for its onset are fulfilled. A similar abundance pattern is also seen for "metal poor" post-AGB stars (Mathis & Lamers 1992). These objects are highly evolved, in general, supergiants with effective temperatures ($T_{\rm eff}$) ranging from 6000 to 7500 K and surface gravities ($\log g$) of 1 to 2 dex. The accretion of circumstellar matter resulting from a strong

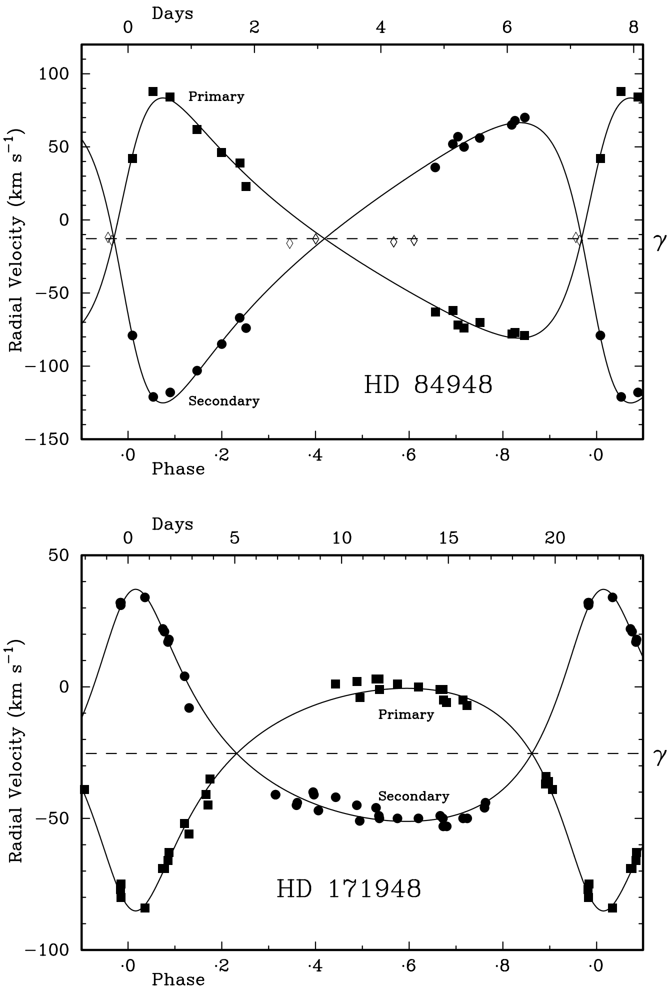


**Fig. 3.** The orbits of the program stars with the elements listed in Table 3. Fast rotation makes the lines in the spectra of HD 84948 blend together when their velocities are not very different; the open diamonds in the upper panel identify the unresolved observations, which were not taken into account in the orbital solution.

stellar wind was proposed to explain the observed abundance pattern in these objects. Since for neither of our systems mass transfer is expected (for A/F type stars only semi-detached binary systems show such behaviour) a similar scenario can be ruled out to function here.

With very similar components, HD 171948 seems to lie well on the ZAMS with an age of $\log t = 7.0$ to 8.0 (taking the models from Palla & Stahler 1995). The system seems, therefore, to be older than the $\lambda$ Bootis stars of the Orion OBI association and NGC 2264 but significantly less evolved than HD 84948; it provides a further indication that the $\lambda$ Bootis phenomenon can be found continuously from the ZAMS until the TAMS.

The orbital elements do not provide the actual masses of the stars concerned, but only the masses multiplied the unknown factor $\sin^3 i$. Looking at the problem from a different angle, we could say that the elements do not provide the actual inclinations, because they are compounded with the masses of the components. By *assuming* values for the masses we can derive estimates of the inclinations, and owing to the cube-root dependence of $\sin i$ on the masses the uncertainties in $i$ are not large. If we adopt $2\,M_\odot$ as the mass of a $\lambda$ Bootis star, then the inclination of HD 84948 is about 66° ($\sin i \sim 0.91$) and that of HD 171948 is about 40° ($\sin i \sim 0.64$).

The two orbits have very similar eccentricities, a little above 0.4. At such an eccentricity, the pseudo-synchronous rotational period (Hut 1981) is shorter than the orbital period by a factor of about 2.4, making it about 3 days for HD 84948 and 9 days for HD 171948.

Tidal effects in binary stars may not only result in synchronized rotations but also in circularized orbits; the time-scales for the two processes are different from one another, synchronization occurring often more quickly, and both depend very strongly on the separations of the components, the important quantity being the *minimum* (periastron) separation.

We have therefore investigated if the observed orbital elements are compatible with the predictions of the tidal evolution theory combined with results of stellar evolution models. We adopt two mechanisms for the tidal braking:

a) the tide equilibrium is restored by the turbulent viscosity on a time scale of the order of $R^2/\nu$ making this process efficient for stars with convective envelopes. The time scales for circularization and synchronization, respectively, are (Zahn 1984; Claret & Cunha 1997):

$$\frac{1}{\tau_{\rm sync}} = \frac{6\,k_2}{t_f} \cdot q^2 \cdot \frac{MR^2}{I} \cdot \left(\frac{R}{a}\right)^6 \quad (1)$$

$$\frac{1}{\tau_{\rm circ}} = \frac{21\,k_2}{t_f} \cdot q(q+1) \cdot \left(\frac{R}{a}\right)^8 \quad (2)$$

where $k_2$ is the apsidal motion constant, $q$ the mass ratio, $R$ the stellar radius, $a$ is the semimajor axis of the orbit and $I$ is the moment of the inertia. The convective friction time is given by

$$t_f = \left[\frac{MR^2}{L}\right]^{1/3} \quad (3)$$

where $M$ is the stellar mass and $L$ the luminosity. Zahn (1989) revised the theory and instead of $k_2$ he introduced a new parameter $\lambda_2$ which depends on the structure of the convective envelope. For more details see Zahn (1989) and Claret & Cunha (1997);

b) the other mechanism we take into account is the dissipation of the gravity modes produced in the convective core and damped at the stellar surface. The respective time scale can be written as

$$\tau_{{\rm sync}R} = 2.03\,\beta^2\,M^{7/3} \cdot \frac{(1+q)^2}{q^2} \cdot {E_2}^{-1} \cdot \frac{P^{17/3}}{R^7} \quad (4)$$

$$\tau_{{\rm circ}R} = 17.1\,M^3 \cdot \frac{(1+q)^{5/3}}{q} \cdot {E_2}^{-1} \cdot \frac{P^7}{R^9} \quad (5)$$

$$\beta^2 = \frac{I}{MR^2} \quad (6)$$

where $\beta$ is the radius of gyration; $M$, $R$, $L$ are given in solar units, $P$ is given in days and $E_2$ is a parameter similar to the apsidal motion constant but much more sensitive to structural changes (see Claret & Cunha 1997 for details and the computation of $E_2$). The corresponding time scales are in years. The differential equations for the turbulent dissipation can be also translated to this system of units:

$$\tau_{\mathrm{sync}T} = 3.95 \times 10^2\ \beta^2 M^{7/3} \cdot \frac{(1+q)^2}{q^2} \cdot \frac{L^{-1/3}}{\lambda_2} \cdot \frac{P^4}{R^{16/3}} \quad (7)$$

$$\tau_{\mathrm{circ}T} = 1.99 \times 10^3\ M^3 \cdot \frac{(1+q)^{5/3}}{q} \cdot \frac{L^{-1/3}}{\lambda_2} \cdot \frac{P^{16/3}}{R^{22/3}}. \quad (8)$$

Adopting modern stellar interior models (Claret 1995) and integrating the corresponding differential equations the critical times for circularization and synchronization can be computed for both binaries.

The results for HD 171948 are not significant since the components are very similar and the effects of differential evolution cannot be checked or even detected. The critical time for circularization ($\log t_{\mathrm{circ}R} \approx 9.1$) is compatible with the derived age which is around 0.01 Gyr.

The case of HD 84948 is more interesting and seems puzzling. The critical time for circularization is of the same order as the inferred age ($\log t = 9.0$). As a consequence, this system should present a circular orbit instead of a high eccentric one. It is true that the role of the absolute dimensions (mainly the radius) are very important to calculate the critical times. Especially those parameters are not known within a sufficient accuracy. This strongly limits our conclusions but does not fully invalidate them. In order to try to clarify the question (of course, within the quoted limitations) let us follow the radii evolution of the components of HD 84948. The tidal evolution theory predicts that the circularization of the orbit would be achieved when $\log g(\mathrm{primary}) = 3.15$ and $\log g(\mathrm{secondary}) = 4.07$ dex. This means that the primary would be in a fast stage of evolution while the secondary would still be in a MS phase. However, if we consider the observational uncertainties, the internal error and the fast evolution of the primary, the scenario is not so strange since the primary could increase its radius during a very short time interval achieving the circularization. Rapid processes in tidal evolution were detected and analyzed before – thus showing different features – e.g. for TZ For and Capella (Claret & Giménez 1995).

### 4.2. Galactic space motion

To test further the Population I nature of both systems, the Hipparcos data (Perryman et al. 1997) were used to derive Galactic space motions. A right-handed coordinate system for $U$, $V$ and $W$ was used, so they are positive in the directions of the Galactic center, rotation and the North Galactic Pole. The standard solar motion in that system would be (+10.4, +14.8, +7.3). Our calculations and error propagation followed the approach by Johnson & Soderblom (1987). The estimated values for HD 84948 (+4.7, −9.7, −12.2) and HD 171948 (−10.3, −24.1, −3.0) are typical for Population I stars (Robin & Crézé 1986). Membership of HD 84948 in intermediate Population II can therefore again be rejected.

### 4.3. Hipparcos photometric data

We have extracted the photometric data from the Hipparcos mission for both systems. For HD 84948 B, the reported variability is confirmed at a $3.2\sigma$ level. The estimated period is 106 min (113 min reported in Paper I) whereas the amplitude is 14 mmag (15 mmag). That nicely confirms the $\delta$ Scuti-type pulsation of this system, making it an interesting target for a multisite campaign. With a known mass and age, appropriate pulsation models would allow to identify particular modes in order to investigate the stellar interior.

As expected, the data for HD 171948 reveal a constant brightness; the upper limit for any pulsation is about 4 mmag whereas 2.6 mmag was reported in Paper I.

No eclipses or other long-term variations were detected. That is not surprising, since the derived orbital inclinations of both systems (Sect. 4.1) are not large enough to encourage any expectation of eclipses.

## 5. Conclusion

We have presented radial velocities measured from high-resolution spectra in order to derive orbital elements for the two $\lambda$ Bootis spectroscopic binary systems HD 84948 and HD 171948.

A non-LTE abundance analysis for carbon and oxygen establishes that both systems consist of true $\lambda$ Bootis stars.

The Hipparcos data reveal for both systems Galactic space motions typical for stars of Population I type, as well as confirming the pulsation of HD 84948. The photometric data set of HD 171948 shows no variability, with an upper limit of 4 mmag.

We estimate an age of 0.01 to 0.1 Gyr for HD 171948 whereas HD 84948 is significantly more evolved (1 Gyr). For the latter, the diffusion/accretion theory can be (in its present form) immediately ruled out. The age is compatible with the constraints of the diffusion/mass-loss theory. It seems that that model, although often neglected, can explain at least some of the $\lambda$ Bootis stars found in the Galactic field. Furthermore, one might tend to believe that the simple picture of one theory responsible for the $\lambda$ Bootis phenomenon has to be reviewed. It has been shown that the diffusion/accretion as well as diffusion/mass-loss theory is capable of producing the observed abundance pattern at widely different evolutionary stages.

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