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# High resolution spectroscopy of bright subdwarf B stars[⋆,⋆⋆,⋆⋆⋆]

## I. Radial velocity variables

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**ABSTRACT**

Radial velocity curves for 15 bright subdwarf B binary systems have been measured using high precision radial velocity measurements from high S/N optical high-resolution spectra. In addition, two bright sdB stars are discovered to be radial velocity variable but the period could not yet be determined. The companions for all systems are unseen. The periods range from about 0.18 days up to more than ten days. The radial velocity semi amplitudes are found to lie between 15 and 130 km s$^{-1}$. Using the mass functions, the masses of the unseen companions have been constrained to lower limits of 0.03 up to 0.55 $M_{\odot}$, and most probable values of 0.03 up to 0.81 $M_{\odot}$. The invisible companions for three of our program stars are undoubtedly white dwarfs. In the other cases they could be either white dwarfs or main sequence stars. For two stars the secondaries could possibly be brown dwarfs. As expected, the orbits are circular for most of the systems. However, for one third of the program stars we find slightly eccentric orbits with small eccentricities of $\epsilon \approx 0.02$–$0.06$. This is the first time that non-circular orbits have been found in sdB binaries. No correlation with the orbital period can be found.

**Key words.** stars: subdwarfs – stars: horizontal-branch – stars: fundamental parameters – binaries: close

## 1. Introduction

While the evolutionary status of subdwarf B (sdB) stars as extreme horizontal branch stars is well established (e.g. Heber et al. 1984; Heber 1986; Saffer et al. 1994; Maxted et al. 2001; Edelmann et al. 2003a, and others), their origin has been under discussion for years. Indications that many sdB stars are members of binary systems suggest that binary interaction is important for their evolution. In addition to composite spectrum binaries discovered e.g. by Ferguson et al. (1984), Allard et al. (1994), Theissen et al. (1993, 1995), Jeffery & Pollacco (1998), Ulla & Thejll (1998), and others, several single-lined binary sdB stars have been identified from variable Doppler line shifts resulting from orbital motion (e.g. Green et al. 2001; Maxted et al. 2001). On the other hand, there are also many subdwarf B stars showing no indication of any companion. However, this can also be explained by close binary interaction. From a theoretical point of view, Han et al. (2002, 2003) elucidated in detail three channels that can produce sdB stars from close binary systems: (i) the common envelope ejection channel with one or two common envelope phases. The first phase results in a sdB and a main sequence star with periods between 0.05 and 40 days, the second phase results in a binary with a white dwarf companion and a wider range of orbital periods. (ii) The stable Roche lobe overflow channel: results in a binary with a main sequence secondary and a wide range of orbital periods of 0.5 days up to 2000 days. (iii) The merger channel: two helium white dwarfs merge into one single sdB star.

A recent comparison of a large observational sdB sample with these models demonstrated that in principle, all sdB stars could be produced by close binary evolution when adopting the three above channels (Lisker et al. 2005). However, there is disagreement between the observational and theoretical samples concerning the fractional/differential population of the Extended Horizontal Branch (EHB) by sdB stars, which still leaves room for the possibility of a single-star evolutionary channel. Therefore, more detailed radial velocity studies of sdB stars are crucial for a reliable evolution of current sdB formation theories.

⋆ Based on observations collected at the German-Spanish Astronomical Center (DSAZ), Calar Alto, operated by the Max-Planck-Institut für Astronomie Heidelberg jointly with the Spanish National Commission for Astronomy.
⋆⋆ Based on observations collected at the European Southern Observatory at La Silla, Chile, ESO proposal No. 65.H-0341(A), 69.D-0016(A), and 073.D-0495(A).
⋆⋆⋆ Table 3 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.125.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?/A+A/442/1023

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In a series of papers we will present detailed analyses of a sample of more than five dozen of bright ($B \lesssim 13$ mag) hot subluminous stars selected from the *Catalogue of Spectroscopically Identified Hot Subdwarf Stars* (Kilkenny et al. 1988; Østensen 2004). These bright stars are ideally suited for detailed studies, but apparently have been largely overlooked previously. We want to derive the binary frequency, atmospheric parameters and population characteristics (Paper II), as well as the metal abundances, isotopic anomalies and rotation velocities (Paper III; some preliminary results are given by Edelmann, Heber & Napiwotzki 2001).

In this paper (Paper I) we present the results of 17 bright, short period radial velocity (RV) variable sdB systems amongst all analyzed bright subdwarf B star. For 15 of them we could determine their orbital parameters with high accuracy. Preliminary results for some of them have already been reported by Edelmann et al. (2001, 2003b, 2004). Section 2 describes the observations and data reduction procedures. Section 3 is dedicated to the determination of the radial velocity curves, orbital parameters and the resulting most probable nature of the unseen companions. Finally, in Sect. 4 we discuss the results of our analysis and highlight the likely eccentric orbits for five program stars. We summarize and conclude the paper in Sect. 5.

## 2. Observations

### 2.1. Program stars

All radial velocity variable sdB stars presented in this paper (see Table 1 for the list of all stars including coordinates and $B$ magnitudes) have been selected from a sample of more than five dozen bright blue stars, in which we searched for RV variations (see forthcoming Paper II).

Our search has already led to the discovery of a spectacular binary (HD 188112, Heber et al. 2003) consisting of a sdB star of too low mass ($M = 0.24\ M_\odot$) to sustain helium burning, and a massive compact companion ($M > 0.7\ M_\odot$). We obtained five new spectra for HD 188112 to improve the orbital parameters.

### 2.2. Observations and data reduction

Optical echelle spectra with high S/N were obtained at two observatories:

80 spectra were obtained at the German-Spanish Astronomical Center (DSAZ) on Calar Alto, Spain, with the 2.2 m telescope equipped with the Fiber-Optics Cassegrain Echelle Spectrograph (FOCES). We used the Tektronic CCD Chip (1024×1024 pixel) with a pixel size of 24 $\mu$m, the 200 $\mu$m entrance aperture, and a slit width of 2 arcsec, resulting in a nominal resolution of $\lambda/\Delta\lambda = 30\,000$. The DSAZ spectra cover the wavelengths from 3900 Å to 6900 Å. The spectra were reduced as described in Pfeiffer et al. (1998) using the IDL macros developed by the Munich Group.

191 spectra were obtained at the European Southern Observatory (ESO) on La Silla, Chile, with the Fiber-fed Extended Range Optical Spectrograph (FEROS) mounted until October 2002 on the 1.52 m ESO telescope, and afterwards on the 2.2 m telescope. We used the standard setup (EEV CCD Chip with 2048 × 4096 pixel, pixel size of 15 $\mu$m, entrance aperture of 2.7 arcsec) with a nominal resolution of $\lambda/\Delta\lambda = 48\,000$. The ESO spectra cover the wavelengths from 3600 Å to 8900 Å. The spectra were reduced using the on-line data reduction provided at ESO (Pritchard 2004) applying the ESO-MIDAS program package.

For the summary of the observing runs performed for our program stars see Table 2.

**Table 1.** Coordinates and $B$ magnitudes for our program stars. Detailed information concerning the observing runs is given in Table 2.

| star | $\alpha$ (2000) | $\delta$ (2000) | $B$ (mag) | run # |
|---|---|---|---|---|
| Ton S 135 | $00^h03^m22.^s1$ | $-23°38'58''$ | 13.0 | 7 |
| PG 0001+275 | $00^h03^m55.^s7$ | $+27°48'37''$ | 12.6 | 1, 4 |
| Ton S 183 | $01^h01^m17.^s6$ | $-33°42'45''$ | 12.5 | 7 |
| PG 0133+114 | $01^h36^m26.^s1$ | $+11°39'33''$ | 12.1 | 2, 4 |
| CD−24° 731 | $01^h43^m48.^s4$ | $-24°05'10''$ | 11.6 | 3, 7 |
| HE 0230−4323 | $02^h32^m54.^s6$ | $-43°10'28''$ | 13.5 | 7 |
| BPS CS 22169−0001 | $03^h56^m23.^s3$ | $-15°09'20''$ | 12.6 | 7, 8 |
| CPD−64° 481 | $05^h47^m59.^s3$ | $-64°23'03''$ | 11.1 | 7, 8 |
| PG 1232−136 | $12^h35^m18.^s9$ | $-13°55'09''$ | 13.1 | 8 |
| [CW83] 1419−09 | $14^h22^m40.^s3$ | $-09°17'20''$ | 11.7 | 8 |
| [CW83] 1735+22 | $17^h37^m26.^s5$ | $+22°08'58''$ | 11.6 | 1, 4 |
| HD 171858 | $18^h37^m56.^s7$ | $-23°11'35''$ | 10.4 | 3, 5, 6 |
| HD 188112 | $19^h54^m31.^s4$ | $-28°20'21''$ | 10.0 | 3, 5−7 |
| JL 82 | $21^h36^m01.^s2$ | $-72°48'27''$ | 12.2 | 7 |
| PB 7352 | $22^h55^m43.^s2$ | $-06°59'39''$ | 12.1 | 3, 5−7 |
| LB 1516 | $23^h01^m56.^s0$ | $-48°03'46''$ | 12.7 | 3, 5, 7 |
| PHL 457 | $23^h19^m24.^s5$ | $-08°52'37''$ | 12.7 | 7 |

**Table 2.** Summary of the observations.

| run # | date (start of nights) | observatory | observers |
|---|---|---|---|
| 1 | 1999 Jul. 19–23 | DSAZ | E/P |
| 2 | 2000 Jan. 28–Feb. 01 | DSAZ | E/K |
| 3 | 2000 Sep. 06–09 | ESO | E |
| 4 | 2001 Aug. 27–31 | DSAZ | E/K |
| 5 | 2002 Aug. 07–10 | ESO | L |
| 6 | 2002 Aug. 14–21, Nov. 26 | DSAZ | sm |
| 7 | 2004 Oct. 31–Sep. 04 | ESO | A |
| 8 | 2005 Feb. 23–Mar. 01 | ESO | A |

Observers: A = Altmann M.; E = Edelmann H.; K = Karl C.; L = Lisker T.; P = Pfeiffer M.; sm = service-mode.

## 3. Analysis

### 3.1. Radial velocity measurements

The radial velocities are determined by calculating the shifts of the measured wavelengths of He I 5876 Å, and all clearly identified metal lines (mostly Si III triplet at 4553 Å, 4568 Å, and 4575 Å, N II at 4666 Å, 5667 Å, and 5680 Å, and Si II at 6347 Å, and 6371 Å) to laboratory wavelengths. We used the ESO-MIDAS software package to fit Gaussian curves to

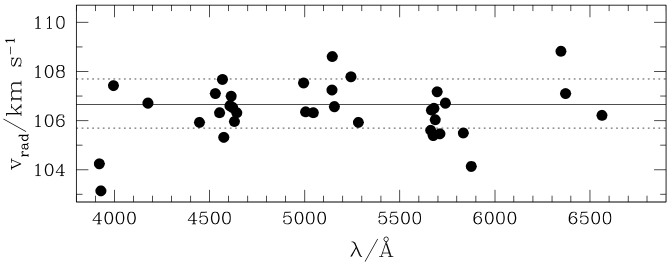


**Fig. 1.** Radial velocity determination for one spectrum of CPD−64° 481. The dots denote the radial velocities determined for all measured lines. Note the very good consistency irrespective of the wavelength. The straight line indicates the mean value, and the dashed lines the 1$\sigma$ error limit.

the absorption lines in order to determine their central wavelengths. After the measurement, the DSAZ values were corrected to heliocentric values. Due to the automatic correction for the earth's movement of the ESO spectra during the on-line reduction process, the measured wavelengths correspond to heliocentric values.

The errors for the given RV values which are derived from the measurements of single lines are unrealistically small (typically: ~0.1 km s$^{-1}$). The systematic errors that arise from the observations (placement of the stars disc on the slit, S/N), and from the data reduction (e.g. wavelength calibration) are dominant. To estimate the real errors we plotted for all single spectra the derived RVs for all measured absorption lines versus the corresponding wavelength positions. This is exemplarily shown for one spectrum in Fig. 1. No wavelength dependent trend for the obtained RV values could be found for any of our observations. From each plot the mean RV value together with a "realistic" 1$\sigma$ error limit (which is in most cases about 1−2 km s$^{-1}$) can be determined.

The resulting RV's for all program stars together with the individual errors are listed in Table 3.

### 3.2. Orbital parameters

The period search was carried out by means of a periodogram analysis based on the Singular Value Decomposition (SVD) method. A sine-shaped RV curve is fitted to the observations for a multitude of phases which are calculated as a function of period (see Napiwotzki et al. 2001). The difference between the observed radial velocities and the best fitting theoretical RV curve for each phase set is evaluated in terms of the logarithm of the sum of squared residuals ($\chi^2$) as a function of period, yielding the power spectrum of the data set which allows to determine the most probable period of variability (see e.g. Lorenz, Mayer & Drechsel 1998).

For twelve (70%) of our program stars, the determined periods are unequivocal. But there are some cases, for which aliases exist which are less likely but cannot completely be ruled out (cf. Fig. 2).

- BPS CS 22169−0001: beside the most prominent period of 0.1780(3) days (number in parentheses give the uncertainty of the last given digit) one alias exist at 0.2170(5) days.
- CPD−64° 481: two periods of 0.276992(5) days and 0.277433(5) days, which corresponds to a time difference of 38 s ($\widehat{=}$ 0.0016 × $P$), result from our analysis.
- PG 0133+114: an alias of $\Delta P$ = +53 s exist (corresponding to an error for the period of 0.05%).
- [CW83] 1735+22: many alias periods of $\Delta P$ ≈ 3 m ($\widehat{=}$0.0016 × $P$) exist.
- CD−24° 731: there are many alias periods of $\Delta P$ ≈ 34 m ($\widehat{=}$0.004 × $P$).

However, for our purposes, a "perfect" determination of the period is desirable but not necessary (see below). Figure 2 shows the resulting power spectra and Fig. 3 shows the best fit RV curves for 15 stars.

Unfortunately, we could not determine unambiguous periods for two stars (see Fig. 4).

- PHL 457: prominent periods are 2.54, 0.93, 0.47, 0.70, 2.00, and 1.57 days (ordered by power). The number of measurements (only four) is too low to allow a reliable fit to be made. At least, periods larger than three days cannot match the observations.
- LB 1516: a large number of aliases are present. The most likely period is 10.36 days. Periods shorter than 9 days or larger than 27 days can be excluded.

Table 4 summarizes the orbital parameters (period, ephemery, systemic velocity, and semi amplitude) for all analyzed stars.

### 3.3. Eccentric orbits?

Our high-precision measurements allow us to search for possible deviations from the adopted sine curve.

The residuals to the sine fits plotted in Fig. 3 indicate that the RV values for most of our program stars are well reproduced by sinusoidal curves (eccentricity $\epsilon < 0.02$, i.e. our detection limit). This means that the orbits for the majority of our analyzed stars are most likely circular. However, for three stars (PG 1232−136, [CW83] 1419−09, and PG 0133+114), and less significantly also for PB 7352 and PG 0001+275, periodic deviations of the residuals are noticed. Triple systems can be ruled out on a very high confidence level, because for all five systems the period of the remaining residuals are exactly one half of the binary orbital period, respectively. Observational or analytical effects are also not very likely. Especially for the most significant cases PG 1232−136 and [CW83] 1419−09, all RV measurements are from one observing run. For both stars, during all nights the setup has not been changed, nor has the data reduction, or analysis method. PG 0133+114 also clearly shows periodic deviations of the residuals. Its observations were carried out during different observing runs but at the same observatory (cf. Tables 1–3). For comparison, [CW83] 1735+22 does not show any sign of a periodic deviation of the residuals at all, although it has almost the same period as PG 0133+114 and was observed mainly during the same observing runs as PG 0133+114 and PG 0001+275. The alternative, a somewhat eccentric orbit, is more plausible. To test this we took the best fitting sinusoidal for each star, calculated a set of theoretical RV curves with varying eccentricities

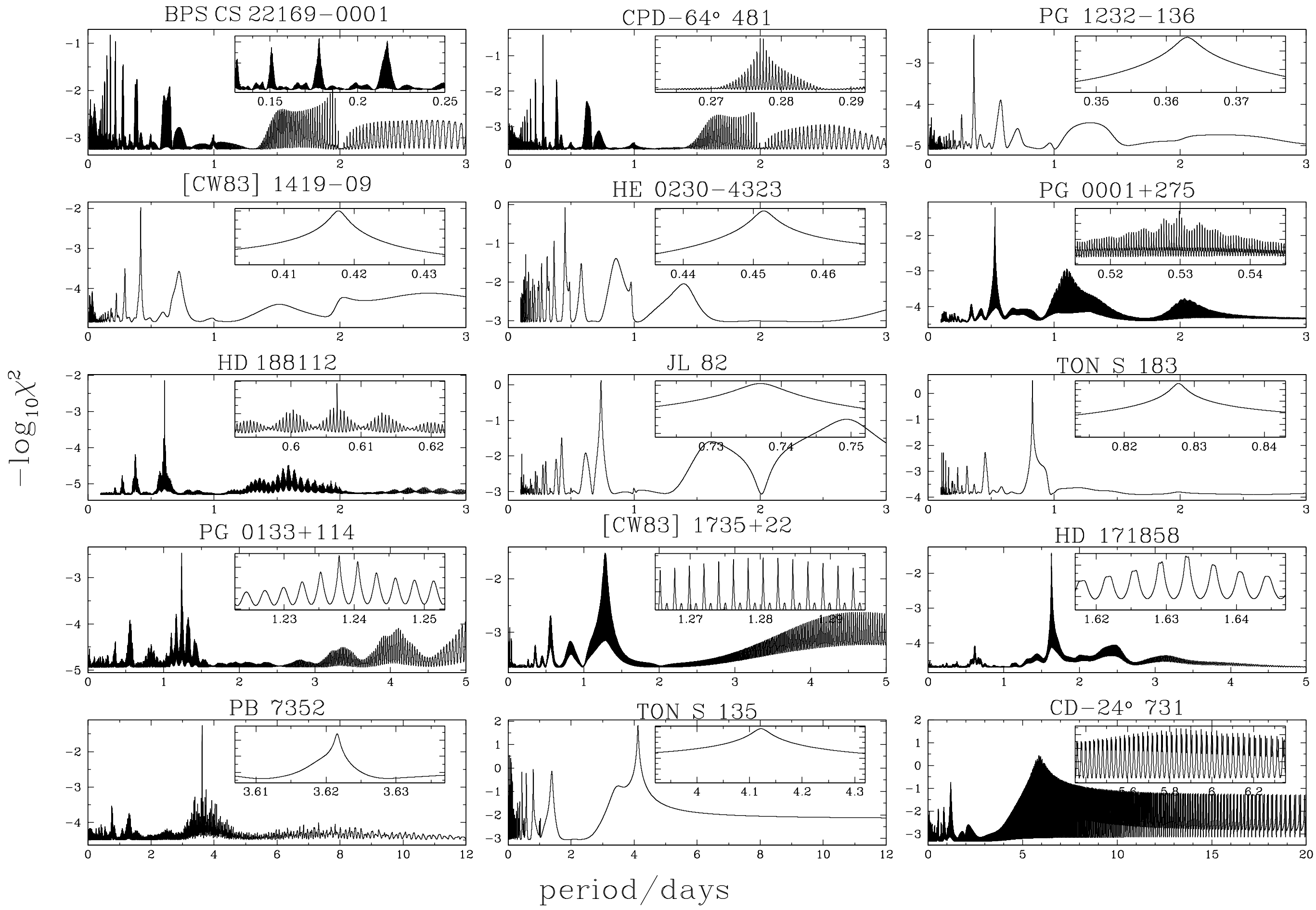


**Fig. 2.** Power spectra of the measurements, together with details of the region around the main peak (ordered by increasing periods: *from top left to bottom right*).

and periastron angles Ω, and fit these curves to the observed RV values. We double checked the results by using an additional program (Mayer, priv. comm.) which fits all parameters, including eccentricity and periastron angles, simultaneously to the observed data points.

Both methods give exactly the same results: The observed RV points for three stars can be reproduced best assuming a non-circular orbit (see Fig. 5). For PG 1232−136 we determined an eccentricity of $\epsilon = 0.060 \pm 0.005$ and a periastron angle of $\Omega = 162.5° \pm 0.5°$, for [CW83] 1419−09 the points match best by applying an eccentricity of $\epsilon = 0.039 \pm 0.005$ together with a periastron angle of $\Omega = 355.6° \pm 0.5°$, and for PG 0133+114 the observed RV points are fitted almost perfectly by using an eccentricity of $\epsilon = 0.025 \pm 0.005$ and a periastron angle of $\Omega = 101.5° \pm 0.5°$.

The data points for PB 7352 and PG 0001+275 can also be matched significantly better for non-zero eccentricities than assuming circular orbits (see Fig. 5). For PB 7352 an eccentricity of $\epsilon = 0.024 \pm 0.01$ and a periastron angle of $\Omega = 85.8° \pm 1.0°$ results, while fore PG 0001+275 we determine an eccentricity of $\epsilon = 0.022 \pm 0.015$ together with a periastron angle of $\Omega = 222.8° \pm 2.0°$

As the circularization time-scale strongly depends on the period ($t_{\rm cir} \sim P^{49/12}$, Tassoul & Tassoul 1992) one would expect that the eccentricity would be correlated with the period. However, for our five stars this is not the case; i.e. the star with the longest period (PB 7352) does not have the largest eccentricity, nor does the star with the shortest period (PG 1232−136) have the smallest eccentricity. However, lacking a better explanation, we suggest that their orbits are probably not circular, making these close binaries the first for which eccentric orbits are detected.

### 3.4. Mass determination of the unseen companions

Since the stars are single-lined binaries, we can only derive the mass function

$$f_m = \frac{M_{\rm comp.}^3 \sin^3(i)}{(M_{\rm sdB} + M_{\rm comp.})^2} = \frac{PK^3}{2\pi G}.$$

Using the mass function and adopting the canonical mass of the sdB star of $M = 0.5\ M_\odot$ (Heber 1986), lower limits (inclination $i = 90°$) to the masses of the unseen companions can be derived. From a statistical point of view, most probable masses can also be calculated by adopting an average inclination of $i = 52°$ for the invisible secondaries.

For the five systems for which we detected a somewhat non-circular orbit, the mass determination stays the same assuming

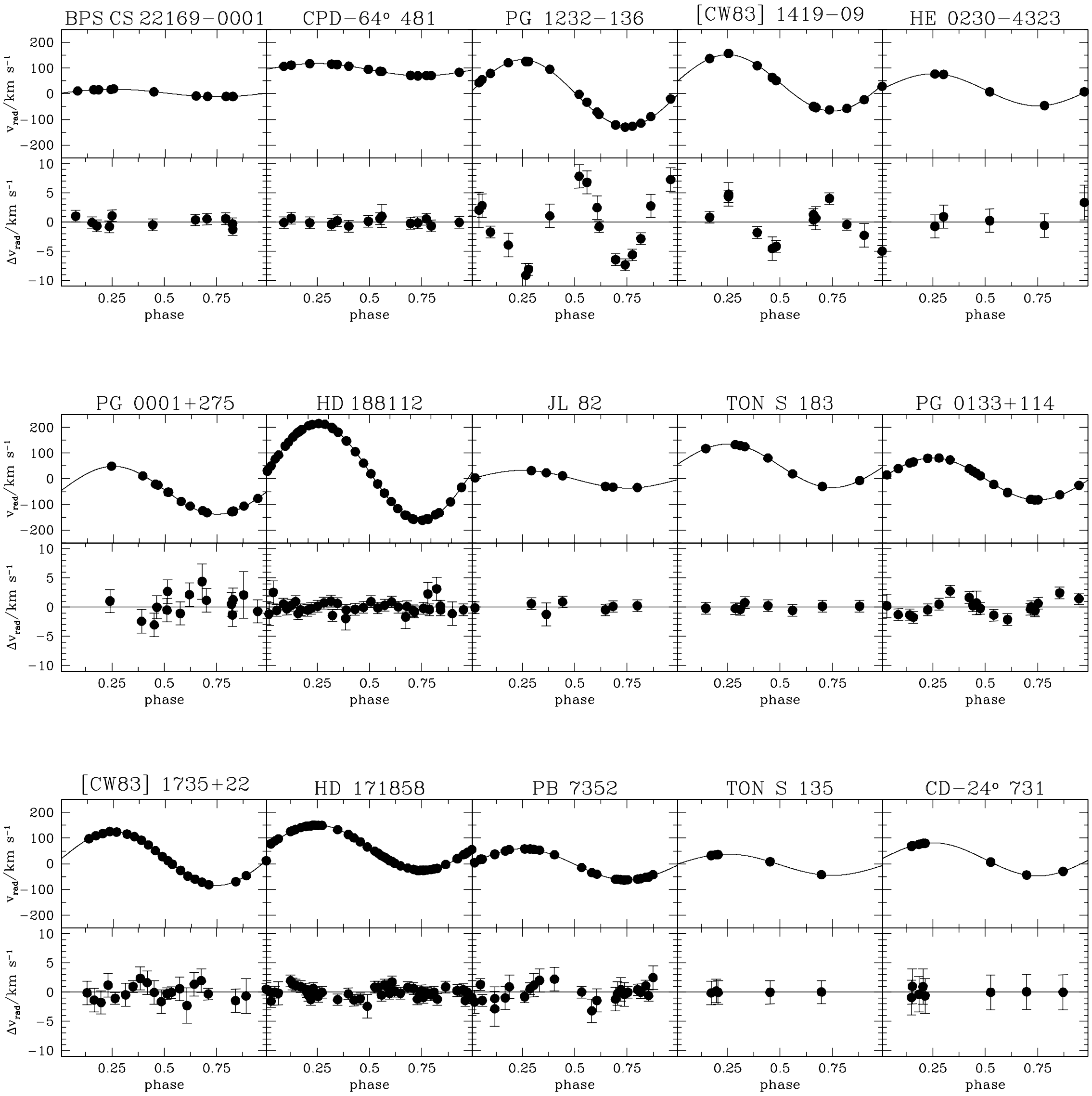


**Fig. 3.** Measured radial velocities as a function of orbital phase and fitted sine curves, together with the residuals ($\Delta v_{\rm rad} = v_{\rm obs} - v_{\rm sine}$) to the sine fits including error bars for all program stars (ordered by increasing periods: *from top left to bottom right*).

a circular orbit, because the discovered very small eccentricities do not alter the results. Also for the four stars for that alias periods exist which cannot be ruled out (cf. Sect. 3.2), the results do not change if the second (or third) best period is applied. As described in Sect. 3.2 for two stars (PHL 457 and LB 1516) no meaningful periods could be determined due to the low numbers of data points. Therefore we shall not discuss these two stars further.

The mass functions and the lower limits to the companion masses, as well as their most probable values, are denoted in Table 4.

### 3.5. Comparison with previous results

Two of our program stars, HD 171858 and PG 0133+114, have been discovered independently to be RV variable by Morales-Rueda et al. (2003).

For HD 171858, they determined orbital parameters which differ noticeably from our values ($\Delta P \approx 0.1$ days, $\Delta K \approx 6$ km s$^{-1}$, and $\Delta\gamma_0 \approx 11$ km s$^{-1}$). However, due to the poor phase coverage of Morales-Rueda et al. (only 12 RV measurements all close to the maximum and minimum of the RV curve in contrast to our 48 RV data points with an almost perfect sampling), the differences are understandable. Their estimate of the minimum mass for the invisible companion of 0.51 $M_\odot$ is in reasonable agreement with our result of 0.46 $M_\odot$.[1]

For PG 0133+114 Morales-Rueda et al. used 18 RV measurements to determine a period of $P = 1.2382(2)$ days (number in parentheses give the uncertainty of the last given digit) which is only slightly different to our result of $P = 1.23787(3)$ days (20 RV measurements). Their RV semi amplitude agrees very well with our value ($\Delta K \approx 1$ km s$^{-1}$). Only their system velocity of $\gamma_0 = +6 \pm 1$ km s$^{-1}$ does not match with our

[1] Morales-Rueda et al. (2003) used for the mass of the sdB primary, as we do, the canonical mass of $M = 0.5$ $M_\odot$.

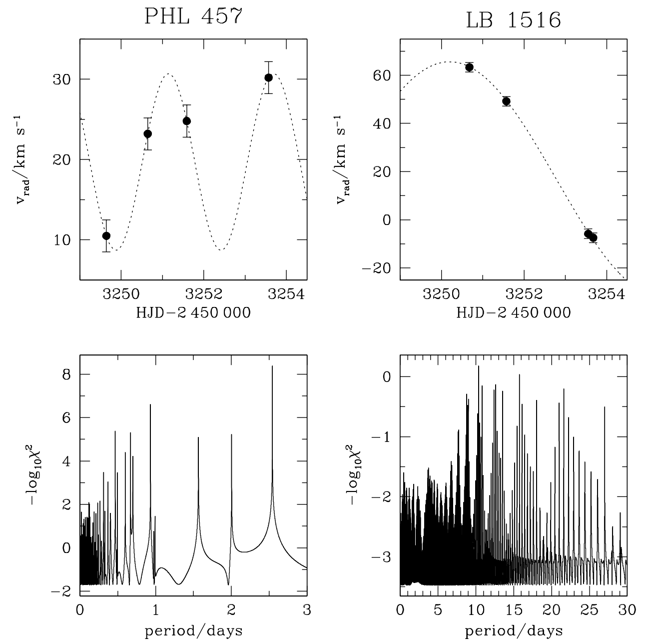


**Fig. 4.** Radial velocity measurements and power spectra (*lower panel*) for two radial velocity variable program stars for which no reliable or unique solution could be obtained yet. Additionally are plotted the radial velocity curves (dotted lines) for the most prominent period. Note that for LB 1516 only the RV values from the latest observing run (ESO Sep. 2004) are plotted to visualize the variability. For the power spectrum of LB 1516 four additional points are included (cf. Table 3).

result of $\gamma_0 = -0.3 \pm 0.2$ km s$^{-1}$. The resulting lower limit of $M = 0.388\ M_\odot$, determined by Morales-Rueda et al. for the companion, however, is again close to our result of 0.36 $M_\odot$.

New measurements for HD 188112 allowed us to increase the accuracy of the orbital parameters. Our results of $P = 0.6065812(5)$ days, $K = 188.4 \pm 0.2$ km s$^{-1}$, and $\gamma_0 = +26.7 \pm 0.2$ km s$^{-1}$, are consistent with our former determinations ($P = 0.606585(2)$ days, $K = 188.3 \pm 0.5$ km s$^{-1}$, and $\gamma_0 = +26.6 \pm 0.3$ km s$^{-1}$, Heber et al. 2003).

### *3.6. Nature of the unseen companions*

The companions are most likely either late type main sequence stars or white dwarfs. Spectral signatures of degenerate companions would not be detectable at optical wavelength due to the faintness of the white dwarfs. However, spectral features arising from a late type main sequence star could be detectable if the star is sufficiently bright. Therefore we have searched for absorption lines which are prominent in cool stars, e.g. the Ca II H and K line, the G-band, the Mg I triplet at 5167 Å, 5173 Å, and 5184 Å, or the Ca II triplet (CaT) at 8498 Å, 8542 Å, and 8662 Å (cf. Jeffery & Pollacco 1998). None are found. A more detailed analysis will be presented in the forthcoming Paper II.

We estimate that any cool main sequence star that contributes more than 10% of light in the $I$ band should be detectable via the CaT search. Even at a spectral type as late as M 1 the CaT lines are strong with equivalent width larger than 1 Å (Jones et al. 1984). Adopting $M(I) = 4.6$ mag for the sdB star this corresponds to a companion spectral type of ≈M 1 or a mass of ≈0.45 $M_\odot$ (Drilling & Landolt, 2000). Accordingly we classify the companion as a white dwarf if its minimum mass exceeds 0.45 $M_\odot$. This is the case for CD−24° 731, [CW83] 1735+22, HD 171858, and HD 188112. If we adopt the statistically most likely inclination angle, the corresponding minimum companion mass of PB 7352, PG 0133+114, PG 1232−136, Ton S 183, and [CW83] 1419−09 exceeds 0.45 $M_\odot$. Therefore it is likely that several of those systems host a white dwarf. In all other cases the companion type can not be constrained further from our observations, they could be either main sequence stars or white dwarfs[2]. The minimum companion masses for BPS CS 22169−0001 and CPD−64° 481 are so small (0.03 $M_\odot$ and 0.05 $M_\odot$, respectively) that they may be brown dwarfs if the inclination is larger than 20° and 38°, respectively.

Table 4 summarizes the probable nature for all companions to our program stars.

## 4. Discussion

The unseen companions of three stars are white dwarfs whereas in the other cases they are either low mass main sequence stars or white dwarfs. The periods are in almost all cases shorter than ten days (dictated by our search strategy). This indicates that all observed RV variable sdB stars have evolved through at least one common envelope phase, consistent with the theoretical prediction of Han et al. (2003).

After such a common envelope phase the orbit of the resulting close binary system should be circular, irrespective of a possible former eccentric orbit, like found for all former observed close hot subdwarf or white dwarf binary systems. Also from our analysis, most of our radial velocity curves can be reproduced best by assuming a circular orbit. However, for five systems (which comprise one third of our sample) we detected periodic deviations from fitted sinusoidal curves.

These deviations can be removed almost perfectly for PG 1232−136, [CW83] 1419−09, and PG 0133+114 by introducing small eccentricities of $\epsilon = 0.025$–$0.06$. Also for PB 7352 and PG 0001+275 the observed data points can be matched significantly better assuming a very small eccentricity of $\epsilon \approx 0.02$.

Unfortunately, for all five stars it is unclear whether their companions are main sequence stars or white dwarfs, i.e. we do not know whether the stars have evolved during one or two common envelope phases. If their companions are white dwarfs, it is really hard to believe that the orbits of the stars remain eccentric although the systems have undergone two common envelope phases. On the other hand, if the companions are main sequence stars, the observed very small eccentricities could maybe be remnants of a former highly eccentric orbit.

Could a small remaining eccentricity be a tracer of main sequence companions (only one mass exchange phase)? Further

[2] The mass distribution of white dwarfs peaks near 0.6 $M_\odot$ (see e.g. Liebert et al. 2005; Madej et al. 2004, and references therein). However, white dwarfs with masses as low as 0.2 $M_\odot$ do exist (see e.g. Heber et al. 2003; Liebert et al. 2004).

**Table 4.** Orbital parameters for our program stars, ordered by increasing periods from the top to the bottom. Given are the periods $P$, the ephemeris for the time $T_0$ defined as the conjunction time at which the stars moves from the blue side to the red side of the RV curve, the system velocities $\gamma_0$, the RV semi-amplitudes $K$, the mass functions $f_m$, the masses of the system components ($M^{i=90°}_{\rm comp.}$ and $M^{i=52°}_{\rm comp.}$) assuming the canonical mass of $M = 0.5\ M_\odot$ for the sdB primary, and the nature of the unseen companions due to their determined masses (bd = brown dwarf, ms = main sequence star, wd = white dwarf). All numbers in parentheses give the uncertainty of the last given digit.

| Star | $P$ days | HJD($T_0$) $-2\,450\,000$ | $\gamma_0$ [km s$^{-1}$] | $K$ [km s$^{-1}$] | $f_m$ [$M_\odot$] | $M^{i=90°}_{\rm comp.}$ [$M_\odot$] | $M^{i=52°}_{\rm comp.}$ [$M_\odot$] | nature comp. |
|---|---|---|---|---|---|---|---|---|
| BPS CS 22169-0001 | 0.1780(3) | 3423.614(5) | $2.8 \pm 0.3$ | $14.9 \pm 0.4$ | 0.00006(2) | 0.03 | 0.03 | bd/ms/wd |
| CPD−64° 481 | 0.2772(5) | 3249.969(5) | $94.1 \pm 0.3$ | $23.8 \pm 0.4$ | 0.00038(3) | 0.05 | 0.06 | bd/ms/wd |
| PG 1232−136 | 0.3630(3) | 3423.478(5) | $4.1 \pm 0.3$ | $129.6 \pm 0.4$ | 0.0818(8) | 0.41 | 0.58 | ms/wd |
| [CW83] 1419−09 | 0.4178(2) | 3424.842(5) | $42.3 \pm 0.3$ | $109.6 \pm 0.4$ | 0.0567(6) | 0.34 | 0.49 | ms/wd |
| HE 0230−4323 | 0.4515(2) | 2151.573(5) | $16.6 \pm 1.0$ | $62.4 \pm 1.6$ | 0.011(2) | 0.17 | 0.22 | ms/wd |
| PG 0001+275 | 0.529842(5) | 2152.20358(5) | $-44.7 \pm 0.5$ | $92.8 \pm 0.7$ | 0.043(1) | 0.29 | 0.41 | ms/wd |
| HD 188112 | 0.6065812(5) | 2151.937898(5) | $26.7 \pm 0.2$ | $188.4 \pm 0.2$ | 0.420(1)* | 0.73 | 1.22 | wd** |
| JL 82 | 0.7371(5) | 2151.332(5) | $-1.6 \pm 0.8$ | $34.6 \pm 1.0$ | 0.0031(3) | 0.10 | 0.13 | ms/wd |
| Ton S 183 | 0.8277(2) | 2151.586(5) | $50.5 \pm 0.8$ | $84.8 \pm 1.0$ | 0.052(2) | 0.32 | 0.45 | ms/wd |
| PG 0133+114 | 1.23787(3) | 2151.2667(5) | $-0.3 \pm 0.2$ | $82.0 \pm 0.3$ | 0.0712(2) | 0.36 | 0.52 | ms/wd |
| [CW83] 1735+22 | 1.280(6) | 2152.16(5) | $20.6 \pm 0.4$ | $104.6 \pm 0.5$ | 0.152(3) | 0.53 | 0.78 | wd |
| HD 171858 | 1.63280(5) | 2153.3684(5) | $62.5 \pm 0.1$ | $87.8 \pm 0.2$ | 0.114(1) | 0.46 | 0.67 | wd |
| PB 7352 | 3.62166(5) | 2151.1821(5) | $-2.1 \pm 0.3$ | $60.8 \pm 0.3$ | 0.084(1) | 0.40 | 0.58 | ms/wd |
| Ton S 135 | 4.122(8) | 2152.49(5) | $-3.7 \pm 1.1$ | $41.4 \pm 1.5$ | 0.030(3) | 0.26 | 0.36 | ms/wd |
| CD−24° 731 | 5.85(30) | 2153.5(2) | $20 \pm 5$ | $63 \pm 3$ | 0.15(3) | 0.55 | 0.81 | wd |
| PHL 457 | <3 | | | | | | | |
| LB 1516 | 7…27 | | | | | | | |

* HD 188112 is not an EHB star but a progenitor of a helium core white dwarf with a mass of only $M = 0.24\ M_\odot$ (Heber et al. 2003).
** Heber et al. (2003) suggest that the compact secondary could also be a neutron star or a black hole.

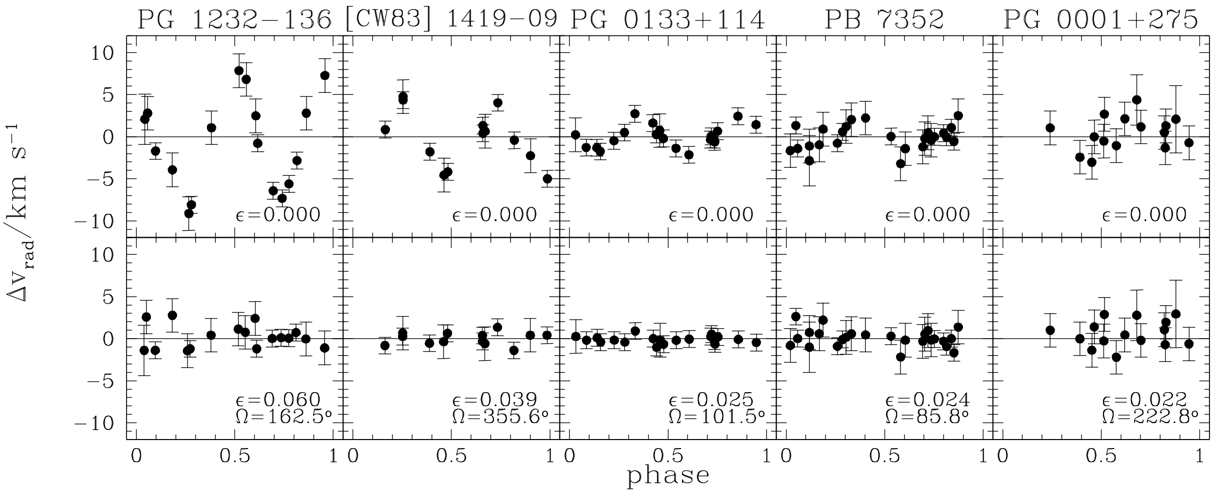


**Fig. 5.** Residuals to the fits including error bars for PG 1232−136, [CW83] 1419−09, PG 0133+114, PB 7352, and PG 0001+275 for two different eccentricities. *Upper part*: fits using vanishing eccentricities, *Lower part*: best matching fits.

investigations are necessary to verify this assumption. In particular, it would be most rewarding to measure light curves and search for a reflection effect indicative of a main sequence companion.

## 5. Summary and conclusion

We have determined the radial velocity curves for 17 bright binary subdwarf B systems using high precision radial velocity measurements from high S/N optical high-resolution spectra, and derived orbital parameters for the 15 unambiguous cases. The companions are unseen in the spectra.

For most systems the orbits are circular (eccentricity $\epsilon < 0.02$, i.e. our detection limit). However, for five sdB stars we discovered that their orbits are probably non-circular with small eccentricities of $\epsilon = 0.022{-}0.060$. These close binaries are the first for which eccentric orbits have been detected.

Using the canonical mass for the sdB primary of $M = 0.5\ M_\odot$ and the mass function, the nature of the invisible secondaries for all program stars could be constrained. Three systems consist of a sdB star and a white dwarf because the companion mass exceeds ~0.45 $M_{\odot}$. The companions of two systems are possibly brown dwarfs. For all other systems the nature of the unseen companions remain unclear; they could either be main sequence stars or white dwarfs.

Important questions remain to be answered. Are the periodic deviations really due to eccentric orbits? If so, are the radial velocity curves of all other close binary sdB systems, which have been determined by other groups really consistent with circular orbits or were the observations performed so far simply too inaccurate to detect such small eccentricities? To verify or clarify the nature of the invisible companions more high-precision measurements of radial velocity variable sdB systems and further investigations such as searching for eclipses or reflection effects are necessary.

The next step will be to determine the binary frequency of our sample. Additional observations, however, are required to achieve this goal. Forthcoming papers will also present the results of quantitative spectral analyses to measure atmospheric parameters and abundances, and the kinematics of the sample population will be studied to assign their membership.

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