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DISCOVERY OF 4 RADIAL VELOCITY VARIABLE SDB STARS WITH ECCENTRIC ORBITS

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Abstract. Radial velocity curves for 14 bright subdwarf B close binary systems have been measured using high precision radial velocity measurements from high S/N optical high-resolution spectra. The companions for all systems are unseen. The periods range from about 0.18 days up to about 6 days. The radial velocity semi-amplitudes are found to lie between 15 and 130 $\mathrm{km\,s^{-1}}$. 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. The orbits for most observed systems are circular. However, small periodic deviations of the measured radial velocity points from the adopted theoretical sine curve are discovered for four program stars. These deviations can be perfectly matched assuming slightly eccentric orbits with small eccentricities of e = 0.02–0.06. Possibly, this is the first time that non-circular orbits have been detected in sdB binaries.

Key words: stars: hot subdwarfs – stars: horizontal branch – stars: mass function – binaries: close

1. INTRODUCTION

The origin of subdwarf B (sdB) stars has been under discussion for years. Since many apparently single sdB stars show variable Doppler line shifts resulting from orbital motion (e.g., Green, Liebert & Saffer 2001; Maxted et al. 2001), close binary interaction appears to be important for the evolution of sdB stars. 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, (ii) the stable Roche lobe overflow channel and (iii) the merger channel. Adopting these three channels in principle all sdB stars, i.e., also single sdB stars (as mergers), could be produced by close binary evolution.

Surveys keep going on to find radial velocity variable sdB stars and the number of sdB binaries for which the orbits have been measured is steadily increasing (see, e.g., Morales-Rueda et al. 2006) and has now risen to more than five dozen.

The unseen companions can only be white dwarfs or low mass main-sequence stars. Some of such systems may qualify as type Ia Supernova progenitors as exemplified by the subdwarf B star KPD 1930+2752, for which Maxted, Marsh & North (2000) found a massive WD companion ($M \geq 0.95\ M_{\odot}$) and the system mass to exceed the Chandrasekhar mass limit (see also Geier et al. 2006). The typical mass for WDs is about 0.6 $M_{\odot}$, thus it is not very likely to find a system like KPD 1930+2752, i.e., exceeding the mass limit. Nevertheless, in the context of evolutionary theory for close binaries, systems with lower masses are also very interesting, because they went through a common envelope phase (or two such phases if the companion is a white dwarf). The physics of common envelope evolution is still unclear, but very important for the future evolution of binary stars in general.

The observational results agree reasonably well with the theoretical predictions of Han et al (2003). However, the observations suffer from one main bias: almost all studies were based on sdB stars drawn from surveys for UV excess objects (e.g., Palomar Green, PG, Green et al. 1986, or Hamburg ESO, HE, Wisotzki, Reimers & Wamsteker 1991). These stars are mostly rather faint ($B > 13$ mag), and therefore most likely at larger distances. Some bright sdB stars ($B = 10-12$ mag) certainly have been overlooked, because they are not listed in the PG or HE catalogs or misidentified due to saturation effects of photographic survey plates.

The *Catalogue of Spectroscopically Identified Hot Subdwarf Stars* (Kilkenny, Heber & Drilling 1988; Østensen 1996) contains more than 2300 such objects. Several (~ 200) of them are brighter than 13th mag and some as bright as 10th magnitude. These bright stars are ideally suited for detailed spectroscopic studies[1]. Hence we select a sdB sample mostly brighter than $B = 13$ mag, which should contain stars much closer from us than in the samples of Maxted et al. (2001) and Napiwotzki et al. (2004).

Here, we present the results of 14 bright ($B \leq 13$ mag), short period radial velocity (RV) variable sdB systems.

2. OBSERVATIONS AND ANALYSIS

We obtained optical echelle spectra with high S/N 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), and at the European Southern Observatory (ESO) on La Silla, Chile, with the Fiber-fed Extended Range Optical Spectrograph (FEROS) mounted until 2002 October on the 1.52 m ESO telescope, and afterwards on the 2.2 m telescope. The spectra have a nominal resolution of $\lambda/\Delta\lambda = 30\,000$ (DSAZ) and $48\,000$ (ESO), and cover the wavelengths from 3900 Å to 6900 Å (DSAZ) and 3600 Å to 8900 Å (ESO).

The radial velocities are determined by calculating the shifts of the measured wavelengths of Balmer Hα, He I 5876 Å, and all clearly identified metal lines (typically more than 30 lines due to N II, O II and Si III) to laboratory wavelengths. Gaussian curves are fitted to the absorption lines in order to determine their central wavelengths. After the measurement, all values were corrected to heliocentric values.

[1] Our aim is not only to discover new radial velocity variable sdB stars, but also to determine their atmospheric parameters, metal abundances, isotopic anomalies and rotation velocities (Edelmann, Heber & Napiwotzki 2001; Edelmann et al. 2006).

Table 1. Orbital parameters for our program stars, ordered by increasing periods from the top to the bottom. Given are the periods P, the system velocities γ_0, the RV semi-amplitudes K, the minimum masses of the system components $M_{\rm comp}$, 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	γ_0 [km s^{-1}]	K [km s^{-1}]	$M_{\rm comp}$ [$M_\odot$]	Nature comp.
22169−0001	0.1780(3)	2.8 ± 0.3	14.9 ± 0.4	0.03	bd/ms/wd
CPD −64° 481	0.2772(5)	94.1 ± 0.3	23.8 ± 0.4	0.05	bd/ms/wd
PG 1232−136	0.3630(3)	4.1 ± 0.3	129.6 ± 0.4	0.41	ms/wd
[CW83] 1419−09	0.4178(2)	42.3 ± 0.3	109.6 ± 0.4	0.34	ms/wd
HE 0230−4323	0.4515(2)	16.6 ± 1.0	62.4 ± 1.6	0.17	ms/wd
PG 0001+275	0.529842(5)	-44.7 ± 0.5	92.8 ± 0.7	0.29	ms/wd
JL 82	0.7371(5)	-1.6 ± 0.8	34.6 ± 1.0	0.10	ms/wd
Ton S 183	0.8277(2)	50.5 ± 0.8	84.8 ± 1.0	0.32	ms/wd
PG 0133+114	1.23787(3)	-0.3 ± 0.2	82.0 ± 0.3	0.36	ms/wd
[CW83] 1735+22	1.280(6)	20.6 ± 0.4	104.6 ± 0.5	0.53	wd
HD 171858	1.63280(5)	62.5 ± 0.1	87.8 ± 0.2	0.46	wd
PB 7352	3.62166(5)	-2.1 ± 0.3	60.8 ± 0.3	0.40	ms/wd
Ton S 135	4.122(8)	-3.7 ± 1.1	41.4 ± 1.5	0.26	ms/wd
CD −24° 731	5.85(30)	20 ± 5	63 ± 3	0.55	wd

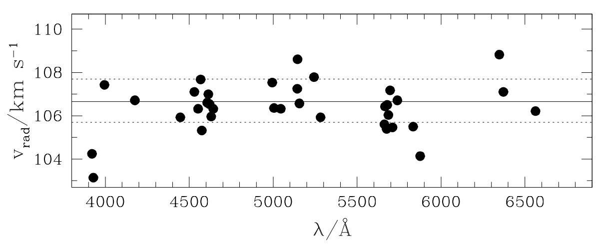

Fig. 1. Radial velocity determination for one spectrum of CPD −64 481. The dots denote the radial velocities determined for all measured lines. Note the very good consistency irrespective of the wavelength. The straight line indicates the mean value, and the dashed lines the 1σ error limit.

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}). To estimate the dominating 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), we plotted the RVs for all measured absorption lines versus the corresponding wavelength positions for all single spectra (shown for one spectrum in Figure 1). From each plot the mean RV value together with its corresponding error limit (mostly 1–2 km s^{-1}) can be determined. No wavelength dependent trend for the obtained RV values could be found for any of our observations.

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 (χ^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). Table 1 summarizes the orbital parameters (period, systemic velocity and semi-amplitude) for all analyzed stars.

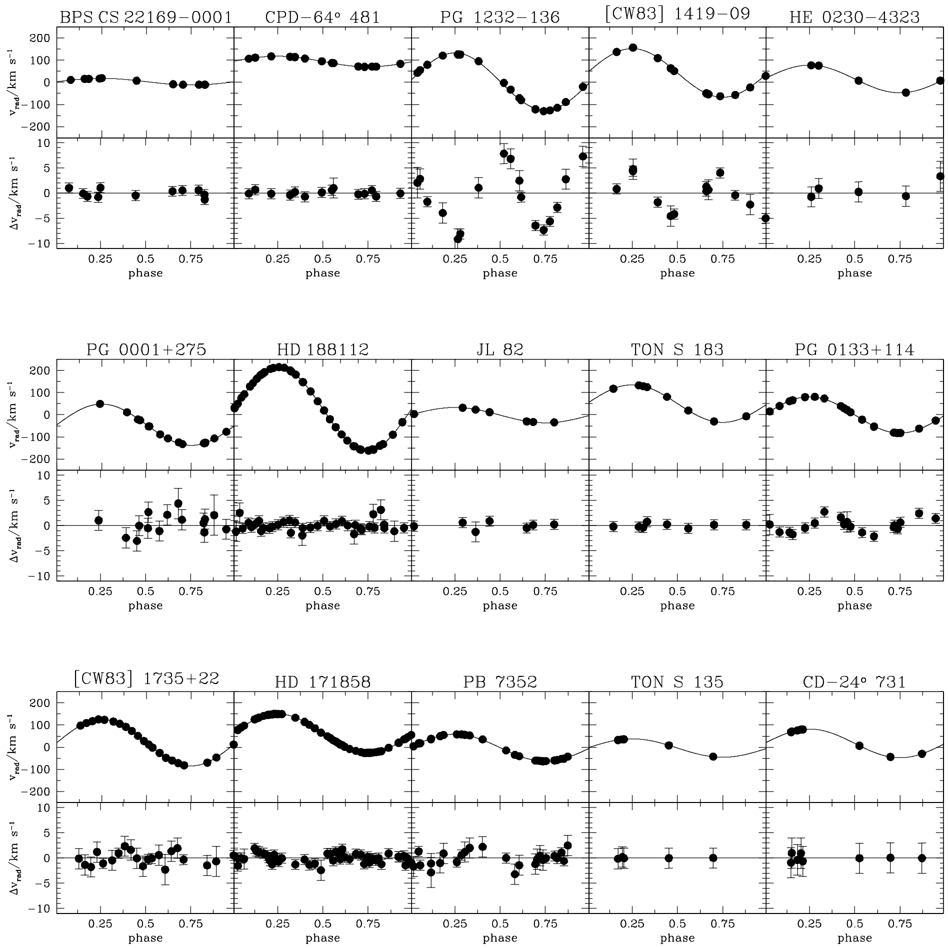

Fig. 2. Measured radial velocities as a function of orbital phase and fitted sine curves, together with the residuals ($\Delta v_{\rm rad} = v_{\rm obs} - v_{\rm sine}$) to the sine fits including error bars for all program stars (ordered by increasing periods: from top left to bottom right).

3. ECCENTRIC ORBITS?

In Figure 2 the residuals to the sine fits are plotted. One can see that the RV values for most of our program stars are well reproduced by sinusoidal curves (semi-amplitudes of possible periodic deviations of the residuals ≤ 2 km s^{-1}, i.e., our detection limit[2]). This means 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 potentially also for PB 7352, periodic deviations of the residuals can be seen. There are some possibilities to explain such periodic deviations:

[2] A semi-amplitude of 2 km s^{-1} for the periodic deviations of the residuals for a system with a semi-amplitude of 100 km s^{-1} is equivalent to an eccentricity of $e = 0.02$.

(i) Triple systems. This can be ruled out on a very high confidence level. Because the time-span of the observations for all four systems were within a few weeks and the period of the remaining residuals are exactly one half of the binary orbital period, respectively. However, the influence of a third light might play a role.

(ii) Observational or analytical effects. These 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. 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.

(iii) A somewhat eccentric orbit. To test this we took the best fitting sinusoidal for each star, calculated a set of theoretical RV curves with varying eccentricities and periastron angles Ω, and fit these curves to the observed RV values. Another attempt was made by applying a 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 Figure 3). For PG 1232−136 we determined an eccentricity of $e = 0.060 \pm 0.005$ and a periastron angle of $\Omega = 162.5^\circ \pm 0.5^\circ$, for [CW83] 1419−09 the points match best by applying an eccentricity of $e = 0.039 \pm 0.005$ together with a periastron angle of $\Omega = 355.6^\circ \pm 0.5^\circ$, and for PG 0133+114 the observed RV points are fitted almost perfectly by using an eccentricity of $e = 0.025 \pm 0.005$ and a periastron angle of $\Omega = 101.5^\circ \pm 0.5^\circ$. The data points for PB 7352 can also be matched better for a non-zero eccentricity than assuming a circular orbit (see Figure 3), however, by a very much lower significance level. An eccentricity of $e = 0.024 \pm 0.01$ and a periastron angle of $\Omega = 85.8^\circ \pm 1.0^\circ$ result.

We have also checked whether the small eccentricities are actually significant using the standard test of Lucy & Sweeney (1971). All four systems passed the test and lie well below the $p = 0.05$ level (PG 1232−136: $p = 6 \times 10^{-9}$, [CW83] 1419−09: $p = 3 \times 10^{-5}$, PG 0133+114: $p = 6 \times 10^{-7}$ and PB 7352: $p = 2 \times 10^{-4}$). The random distribution of periastron angles of those four stars supports our conclusion that eccentric orbits are the cause for the periodic deviations.

(iv) Gravitational deformation of the sdB primary due to tidal forces in a bound rotating system (like seen for KPD 1930+2752). This can also be ruled out. From the lack of the broadening of the spectral lines we have been able to exclude tidally locked rotation, e.g., for PG 1232−136 which shows the largest periodic deviations.

As the circularization time-scale strongly depends on the period ($t_{\mathrm{cir}} \sim P^{49/12}$, Tassoul & Tassoul 1992) one would expect that the eccentricity would be correlated with the period. However, for our four 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. Surprisingly, the opposite is the case!

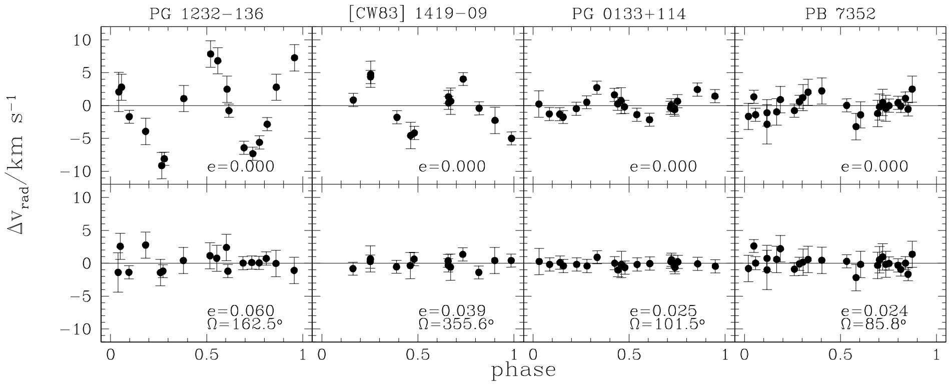

Fig. 3. Residuals to the fits including error bars for PG 1232−136, [CW83] 1419−09, PG 0133+114, PB 7352 and PG 0001+275 for two different eccentricities. Upper panel: fits using vanishing eccentricities, lower part: best matching fits.

However, lacking a better explanation, we suggest that the orbits of four of our program stars are probably not circular, making these close binaries the first for which eccentric orbits are detected

4. NATURE OF THE UNSEEN COMPANIONS

The lower limits to the companion masses of the unseen companions, resulting from the mass function by adopting the canonical mass of the sdB star of $M = 0.5\ M_\odot$ (Heber 1986), are given in Table 1.

The companions are most likely either white dwarfs or late type main-sequence stars. Spectral signatures of degenerate companions would not be detectable at optical wavelength due to the faintness of the white dwarfs. On the other hand, assuming the star is sufficiently bright, spectral features arising from a late-type main-sequence star could be seen. Therefore we searched for lines which are prominent in cool stars, e.g., the Ca II H and K lines, 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 Åand 8662 Å (cf. Jeffery & Pollacco 1998). None are found.

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 M1 the CaT lines are strong with equivalent width larger than 1 Å (Jones, Alloin & Jones 1984). Adopting $M(I) = 4.6$ mag for the sdB star this corresponds to a companion spectral type of $\approx$M1 or a mass of $\approx 0.45\ M_\odot$ (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 and HD 171858. 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. 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 1 summarizes the probable nature for all companions to our program stars.

5. 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, as found for all former observed close hot subdwarf or white dwarf binary systems. Also, most of our radial velocity curves can be reproduced best by assuming a circular orbit. However, for four systems (which comprise one fourth 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 the observed data points can be matched better assuming a very small eccentricity of $\epsilon \approx 0.02$.

Unfortunately, for all four 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.

Another point arises concerning the common envelope itself. Terman, Taam & Hernquist (1994) show that during the common envelope phase the initial spiral-in of the companion is very eccentric, but their modeling shows also that the orbit circularizes very quickly. Did the common envelope phase for sdB stars in eccentric orbits last shorter and are they younger than "normal" sdB binaries?

6. SUMMARY AND CONCLUSION

We have determined the orbital parameters for 14 bright binary subdwarf B systems using high precision radial velocity measurements from high S/N optical high-resolution spectra. The companions are unseen in the spectra.

For most systems the orbits are circular. However, for four sdB stars we discovered that their orbits are probably non-circular with small eccentricities of $e =$ 0.022–0.060. These close binaries are probably 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 $\sim 0.45\ M_{\odot}$. 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 from fitted sine shaped RV curves 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 photometric observations are necessary to search for eclipses or reflection effects.

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