14th European Workshop on White Dwarfs
ASP Conference Series, Vol. 334, 2005
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Subdwarf B Binaries from the SPY Project

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Abstract. In the course of our search for double degenerate binaries as potential progenitors of type Ia supernovae with the ESO VLT (ESO - SN Ia progenitor survey - SPY), several sdB binaries were discovered. We report on the analysis of six radial velocity variable sdB stars from the SPY project. Radial velocity curves have been measured. Effective temperatures, surface gravities and helium abundances are determined, as well as metal abundances. We highlight some strong abundance anomalies.

1. Introduction

There is general consensus that the precursors of type Ia supernovae are white dwarfs in close binary systems. These white dwarfs accrete matter from their companions until a critical mass limit is reached. The two scenarios for SN Ia formation differ in the nature of the companion. While it is a main sequence or red giant star in the so-called *single degenerate* scenario, it is another white dwarf in the *double degenerate* scenario.

The purpose of the *Supernova Ia progenitor survey* (SPY) was to check the double degenerate scenario by observational means. Thus, we observed more than 1000 WD over the course of four years at the ESO VLT equipped with UVES in order to check the objects for radial velocity (RV) variations (cf. Napiwotzki et al. 2003). Follow-up observations of promising objects were performed in order to derive system parameters like periods P and RV semi-amplitudes K. In combination with quantitative spectral analyses we computed the systems' total masses and merging times. Recently, a very promising SN Ia precursor candidate was discovered by Napiwotzki et al. (these proceedings) in the course of our project.

Due to misclassification in the input catalog the SPY sample contains a number of subdwarf B stars (Lisker et al. 2004). Since these objects are immediate precursors of white dwarfs, they are promising objects with respect to the search for SN Ia precursors, too. Maxted et al. (2000), for example, found the sdB binary KPD 1930+2752 to be a SN Ia precursor candidate. Thus promising RV variable sdB stars were included in our follow-up observations as well.

In this paper we present the results of an analysis of six sdB binaries discovered by SPY.

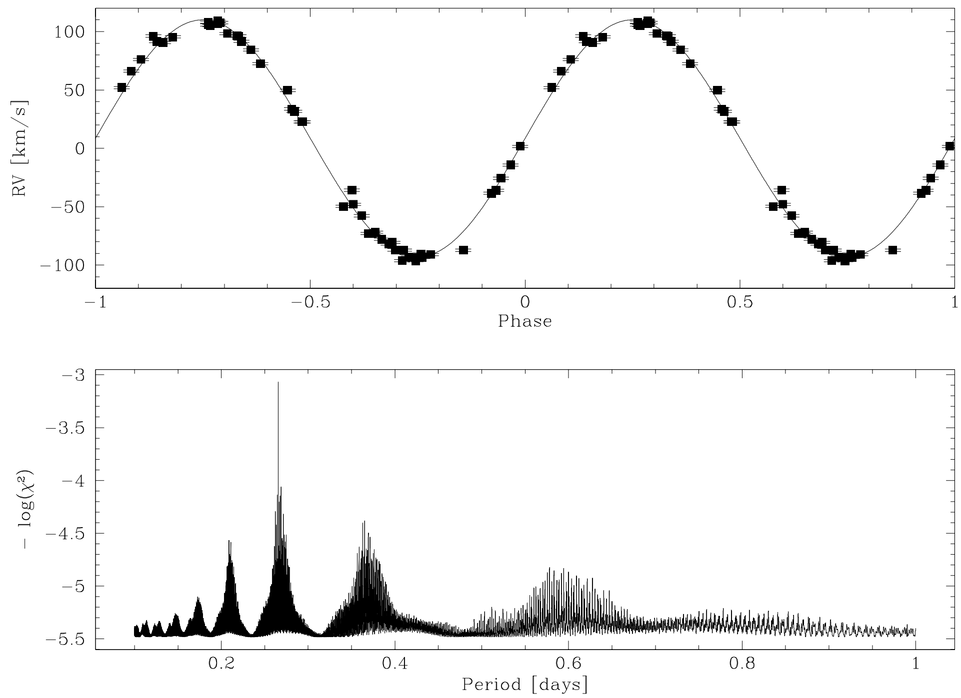

Figure 1. Sample best fit RV curve and power spectrum for an sdB star (HE 0532-4503). Upper panel: Measured radial velocities as a function of orbital phase and fitted sine curve. Lower panel: Power spectrum.

2. Observations and Radial Velocity Curves

All program stars were observed at least twice in the course of the SPY project at the ESO VLT. Additional observations were made during follow-up campaigns at the the ESO NTT (equipped with EMMI), the ESO VLT (UVES), the Calar Alto Observatory 3.5m telescope (TWIN) and the WHT (ISIS).

The RV of each spectrum was measured by fitting Gaussians to the observed Hα line profiles and all available He I lines. In addition, a linear function was used to reproduce the continuum and a Lorentzian to model the broad Hα line wings. The RVs were determined with respect to the central wavelengths of the fitted Gaussians. Sinusoidal functions were fitted for a range of periods, yielding *"power spectra"* which indicate the quality of the sine-fits as a function of period. Having fixed the periods, we subsequently fitted the semi-amplitudes K, the system velocities γ and the ephemerides $HJD(\mathrm{T}_0)$ using sine curves again. As an example, Fig. 1 displays the resulting power spectrum and best-fit sine curve for HE 0532−4503. The ephemerides for all program stars are given in Tab. 1, as well as the semi-amplitudes K and the derived system velocities γ.

Table 1. Ephemeris, RV semi-amplitudes K and system velocities γ

System	Ephemeris [hel.JD$_0$−2 450 000]	K [km s^{-1}]	γ [km s^{-1}]
WD 0048−202	3 097.5596 ± 7.4436 $\times E$	47.9	−26.5
HE 0532−4503	3 099.9975 ± 0.2656 $\times E$	101.5	8.5
HE 0929−0424	3 100.0585 ± 0.4400 $\times E$	114.3	41.4
HE 1448−0510	3 097.0703 ± 7.1588 $\times E$	53.7	−45.5
HE 2135−3749	3 099.6520 ± 0.9240 $\times E$	90.5	45.0
HE 2150−0238	3 100.6081 ± 1.3209 $\times E$	96.3	−32.5

Table 2. Effective temperatures, surface gravities and helium abundances of the program stars

System	$T_{\rm eff}$ [K]	$\log g$ [cgs]	$\log[n_{\rm He}/n_{\rm H}]$
WD 0048−202	29 960	5.50	≤ -4.00
HE 0532−4503	25 390	5.32	−3.21
HE 0929−0424	29 470	5.71	−1.99
HE 1448−0510	34 690	5.59	−3.06
HE 2135−3749	30 000	5.84	−2.54
HE 2150−0238	30 200	5.83	−2.44

3. Quantitative Spectral Analysis

Prior to quantitative spectral analysis the spectra were corrected for the measured RV and coadded in order to increase the S/N ratio. Effective temperatures ($T_{\rm eff}$), surface gravities ($\log g$) and helium abundances ($log\,[n_{\rm He}/n_{\rm H}]$) were determined by fitting simultaneously each observed hydrogen and helium line with a grid of metal-line blanked LTE model spectra. The procedure used is described in detail in Napiwotzki et al. (1999). Because of its sensitifity to non-LTE effects, the Hα line was excluded from this analysis. Results are displayed in Tab. 2, a sample fit is shown in Fig. 2.

In addition, LTE metal abundances were derived for the program stars from measured equivalent widths using the classical curve-of-growth method. Some stars (e.g. HE 2135−3749) show very rich abundance patterns with many species, while others like HE 1448−0510 are extremely metal poor. In order to derive upper limits to elemental abundances in these cases, we assumed the detection limit for metal lines to be equal to the S/N level (in terms of equivalent width). Results are given in Tab. 3.

4. Nature of the Unseen Companion

Since the spectra of the program stars are single-lined, they reveal no information about the orbital motion of the sdBs' companions, and thus we can only compute

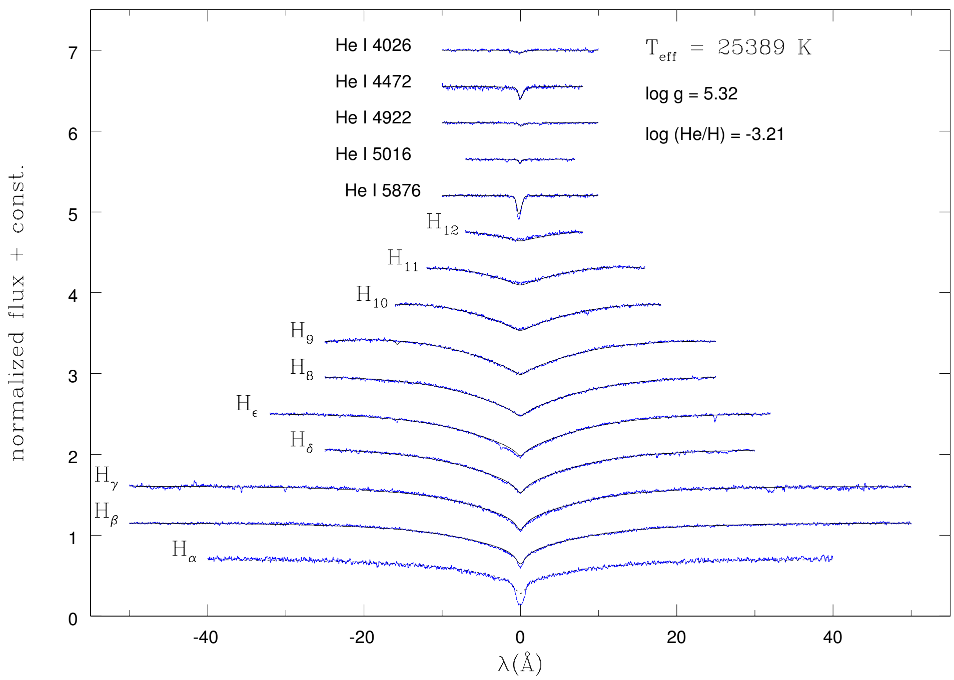

Figure 2. Sample model fit for a sdB star (HE 0532-4503) based on 47 UVES spectra.

the mass function

$$f_{\rm m} = \frac{M_{\rm comp}\sin^3 i}{(M_{\rm comp}+M_{\rm sdB})^2} = \frac{PK^3}{2\pi G}. \tag{1}$$

Although the RV semi-amplitude K and the period P are determined by the RV curve, $M_{\rm sdB}$, $M_{\rm comp}$ and $\sin^3 i$ remain free parameters. Binary population synthesis models (Han et al. 2003) indicate a most likely mass of $M_{\rm sdB} = 0.47\,{\rm M}_\odot$ for sdB stars, which we adopt for the following analysis. Assuming $i = 90°$ we are able to compute the companions' minimum masses from equation 1. The statistically most probable inclination angle is $\sin^3 i = 52°$ which yields the most likely systems' compositions. Our results are summarized in Tab. 4.

4.1. Tidally Locked Rotation?

For close binary systems, the components' stellar rotational velocities may be tidally locked to their orbital motions (see e.g. Napiwotzki et al. 2001), which means

$$v_{\rm rot} = \frac{2\pi R_\star}{P}. \tag{2}$$

Measurement of the projected rotational velocities $v_{\rm rot}$ sin i would therefore allow to determine the systems' inclination angles i. In order to derive $v_{\rm rot}$ sin i,

Table 3. Metal abundance patterns of the program stars (relative to solar values)

System	Abundances ϵ					
	C II	N II	O II	Mg II	Al III	Si III
	Si IV	S II	S III	Ar II	Ar III	Ca III
	Ti III	Fe III	Zn III			
WD 0048−202	—	−0.67	−1.38	−1.00	−0.71	−1.50
	−1.98	—	−1.41	—	—	—
	+1.84	−0.27	—			
HE 0532−4503	−2.29	−0.79	−1.17	−0.72	—	−1.22
	—	−0.28	−0.82	—	—	—
	—	0.16	—			
HE 0929−0424	−1.81	−0.14	−1.07	−0.80	−0.53	−0.93
	—	—	−0.80	+0.79	—	—
	—	0.00	—			
HE 1448−0510	≤−2.17	≤−1.24	≤−2.17	−0.59	≤−0.93	—
	—	—	≤+0.80	≤+0.67	—	—
	—	≤−0.46	—			
HE 2135−3749	—	−0.36	—	—	—	—
	—	−0.12	−0.58	+0.74	+0.50	+1.89
	+1.61	−0.87	+1.94			
HE 2150−0238	—	−0.25	≤−2.17	≤−1.53	≤−1.18	≤−2.00
	—	—	−0.26	+0.92	—	—
	—	≤−0.71	—			

Table 4. Mass functions, and masses (minimum mass $M_{\rm comp}^{90^\circ}$ and most probable mass $M_{\rm comp}^{52^\circ}$) of the unseen companions.

System	$f_{\rm m}$ $[M_\odot]$	$M_{\rm comp}^{90^\circ}$ $[M_\odot]$	$M_{\rm comp}^{52^\circ}$ $[M_\odot]$
WD 0048−202	0.085	0.47	0.57
HE 0532−4503	0.029	0.25	0.37
HE 0929−0424	0.068	0.36	0.51
HE 1448−0510	0.115	0.56	0.68
HE 2135−3749	0.071	0.36	0.51
HE 2150−0238	0.122	0.48	0.70

we compared the observed spectra with rotationally broadened, synthetic line profiles (see also Karl et al., these proceedings). The latter ones were computed for the stellar parameters given in Tab. 2 and Tab. 3. Since sharp metal lines are much more sensitive to rotational broadening than Balmer or helium lines, we concentrated on strong N II lines between 5000 and 5008 Å.

Tab. 5 displays the resulting projected rotational velocities $v_{\rm rot}\sin i$, as well as the deduced inclination angles i and corresponding masses $M_{\rm comp}$. While no

Table 5. Periods and projected rotational velocities, as well as inclination angles and masses of the unseen companion computed for tidally locked rotation.

System	P [d]	$v_{\rm rot}$ sin i [km s^{-1}]	i [deg]	$M_{\rm comp}$ [$M_\odot$]
HE 0532−4503	0.2656	9	11	5.0
HE 0929−0424	0.4400	6	19	2.7
HE 2135−3749	0.9240	4	32	1.0
HE 2150−0238	1.3209	8	$\sin i > 1$	–
HE 1448−0510	7.1588	—	—	—
WD 0048−202	7.4436	≤ 5	$\sin i > 1$	–

rotation velocity could be determined for HE 1448−0510 due to the lack of suitable metal lines, the remaining five stars are slow rotators with projected rotational velocities below 10 km s^{-1}. For the short period systems HE 0532−4503, HE 0929−0424 and HE 2135−3749 we deduce inclination angles between 11° and 32°. The analyses of WD 0048−202 and HE 2150−0238, however, yield unreasonable sin $i > 1$. A possible explanation is, that the latter systems are NOT tidally locked, which is plausible because they have rather long periods. The masses deduced for the companions of the short-period systems are quite large, as can be seen from Tab. 5. For the HE 2135−3749 system, the sdB companion's mass is 1 $M_\odot$ which indicates a massive white dwarf. The companions in HE 0532−4503 and HE 0929−0424 are even more massive, possibly indicating black holes. Because black holes are rare objects it is very unlikely that our small sample of six RV variable sdBs contain two of them. For these objects, stellar rotation and orbital motion may be locked in a period-ratio that differs from unity (like Mercury, for which the ratio is 3/2).

Since the projected rotational velocities are small, the crucial parameter for the measurement of $v_{\rm rot}$ sin i and subsequently for $M_{\rm comp}$ is the spectral resolution of the instrument. Our spectra, however, have been measured through rather wide slits. Their spectral resolution is therefore seeing dependent, and thus we have used information from the seeing monitor to determine the instrumental profile. Additional observations using a small slit, i.e. a well defined instrumental profile will be necessary.

Acknowledgments. C.K. gratefully acknowledges financial support by the conference organizers.

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