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## Binaries discovered by the SPY project

### II. HE 1414–0848: A double degenerate with a mass close to the Chandrasekhar limit\*

R. Napiwotzki<sup>1</sup>, D. Koester<sup>2</sup>, G. Nelemans<sup>3</sup>, L. Yungelson<sup>4</sup>, N. Christlieb<sup>5</sup>, A. Renzini<sup>6</sup>, D. Reimers<sup>5</sup>,  
H. Drechsel<sup>1</sup>, and B. Leibundgut<sup>6</sup>

<sup>1</sup> Dr. Remeis-Sternwarte, Astronomisches Institut der Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany

<sup>2</sup> Institut für Theoretische Physik und Astrophysik, Universität Kiel, 24098 Kiel, Germany

<sup>3</sup> Institute of Astronomy, Madingley Road, CB3 0HA Cambridge, UK

<sup>4</sup> Institute of Astronomy of the Russian Academy of Sciences, 48 Pyatnitskaya Str., 109017 Moscow, Russia

<sup>5</sup> Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, 21029 Hamburg, Germany

<sup>6</sup> European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany

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**Abstract.** In the course of our search for double degenerate (DD) binaries as potential progenitors of type Ia supernovae with the UVES spectrograph at the ESO VLT (ESO SN Ia Progenitor survey – SPY) we discovered that the white dwarf HE 1414–0848 is a double-lined DA+DA binary with an orbital period of  $P = 12^{\text{h}}25^{\text{m}}39^{\text{s}}$ . Semi-amplitudes of  $128 \text{ km s}^{-1}$  and  $100 \text{ km s}^{-1}$  are derived for the individual components. The amplitude ratio and the measured difference in gravitational redshift is used to estimate the masses of the individual components:  $0.55 M_{\odot}$  and  $0.71 M_{\odot}$ . Hence the total mass of the HE 1414–0848 system is  $1.26 M_{\odot}$ , only 10% below the Chandrasekhar limit. The results of a model atmosphere analysis are consistent with our mass estimated from the orbit. Temperatures of the individual components are also determined. Possible scenarios for the formation of this system are discussed. The system will merge due to loss of angular momentum via gravitational wave radiation after two Hubble times. HE 1414–0848 does not qualify as an SN Ia progenitor, but it is the most massive close DD known today.

**Key words.** stars: early-type – binaries: spectroscopic – stars: fundamental parameters – white dwarfs

## 1. Introduction

Supernovae of type Ia (SN Ia) play an outstanding role in the study of cosmic evolution. In particular they are regarded as one of the best standard candles to determine the cosmological parameters  $H_0$ ,  $\Omega$  and  $\Lambda$  (e.g. Riess et al. 1998; Leibundgut 2001). However, the nature of their progenitors remains a mystery (e.g. Livio 2000).

There is general consensus that the SN event is due to the thermonuclear explosion of a white dwarf (WD) when a critical mass (likely the Chandrasekhar limit) is reached, but the nature of the progenitor system remains unclear. While it must be a binary, with matter being transferred to the WD from a companion until the critical

mass is reached, two main options exist for the nature of the mass donator: either another WD in the so-called double degenerate (DD) scenario (Iben & Tutukov 1984), or a red giant/subgiant in the so-called single degenerate (SD) scenario (Whelan & Iben 1973).

As progenitor candidate, the DD model considers a binary with the total mass of the white dwarf components larger than the Chandrasekhar mass, which merges in less than a Hubble time due to the loss of angular momentum via gravitational wave radiation. Several systematic radial velocity ( $RV$ ) searches for DDs have already been undertaken starting in the mid 1980's (see Marsh 2000 for a review). By now, combining all the surveys  $\approx 180$  WDs have been checked for  $RV$  variations yielding a sample of 18 DDs with  $P < 6^{\text{d}}3$  (Marsh 2000; Maxted et al. 2000a). Six of the 18 known DDs are double-lined systems (in three of these systems the companion is barely detectable). None of the 18 known DD systems seems massive enough to qualify as a SN Ia precursor. This is not surprising,

Send offprint requests to: R. Napiwotzki,

e-mail: [napiwotzki@sternwarte.uni-erlangen.de](mailto:napiwotzki@sternwarte.uni-erlangen.de)

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as theoretical simulations suggest that only a few per cent of all close DDs are potential SNIa progenitors (Iben et al. 1997; Nelemans et al. 2001). Recently, the binary KPD 1930+2752, consisting of a subluminous B (sdB) star and an invisible white dwarf component, was proposed as potential SNIa progenitor by Maxted et al. (2000b). The system mass exceeds the Chandrasekhar limit, and the system will merge within a Hubble time. However, it is not clear, if the merger event will produce a SNIa explosion (Ergma et al. 2001).

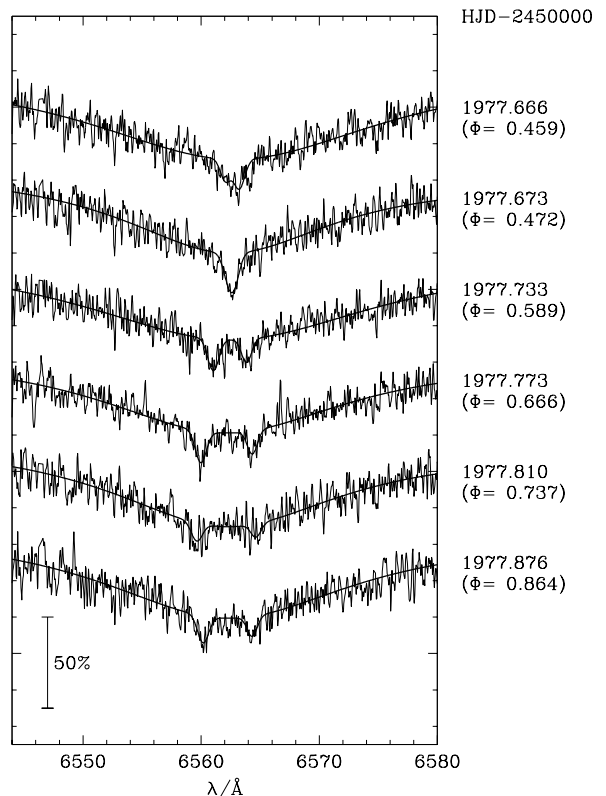
In order to perform a definite test of the DD scenario we have embarked on a large spectroscopic survey of 1500 white dwarfs using the UVES spectrograph at the ESO VLT UT2 (Kueyen) to search for white dwarfs and pre-white dwarfs with variable  $RV$ s (ESO SNIa Progenitor survey – SPY). The SPY project yields a wealth of new  $RV$  variable DDs (Napiwotzki et al. 2001b). An analysis of the subdwarf B + white dwarf system HE 1047–0436 was presented in the first paper of this series (Napiwotzki et al. 2001a).

Among the newly detected DDs are six new double-lined binaries. In all systems both WD components can be easily recognised. Here we report on follow-up spectroscopy of HE 1414–0848 (cf. Sect. 2). The determination of the radial velocity curves, orbital parameters, and masses for both components is described in Sect. 3. A model atmosphere analysis is carried out and the results are compared with the analysis of the  $RV$  curves in Sect. 4. We finish with a discussion of the HE 1414–0848 system and possible formation scenarios.

## 2. Observations and data analysis

HE 1414–0848 ( $\alpha_{2000} = 14^{\text{h}}16^{\text{m}}52.1^{\text{s}}$ ,  $\delta_{2000} = -9^{\circ}02'04''$ ,  $B_{\text{pg}} = 16^{\text{m}}2$ ) was discovered by the Hamburg ESO survey (HES; Wisotzki et al. 2000; Christlieb et al. 2001) as a potential cool white dwarf and, therefore, was included in our survey. The survey spectra showed that it is a double-lined system consisting of two DA white dwarfs. Both components were visible in the  $H_{\alpha}$  core separated by  $4.6 \text{ \AA}$ , corresponding to  $210 \text{ km s}^{-1}$ , in both discovery spectra. This indicated high orbital velocity and a short period, making HE 1414–0848 a high-priority target for follow-up studies.

Fifteen high resolution ( $0.3 \text{ \AA}$ ) echelle spectra of HE 1414–0848 have been secured with VLT-UVES between March 9 and April 5, 2001 in service mode. Details on the observational set up of the UVES instrument and the data reduction can be found in Koester et al. (2001) and Napiwotzki et al. (2001b). The chosen observing strategy was to start with several closely spaced exposures during the first night. This should provide us with a rough first estimate of the period and radial velocity curve, which could be used to extrapolate the orbit to the next nights. Consequently, a decreasing number of spectra was taken during the following nights, finishing with single exposures separated by more than one day. This strategy in conjunction with the high quality of the UVES data allowed the



**Fig. 1.**  $H_{\alpha}$  region of the spectra covering a timespan of  $5^{\text{h}}$  in the night of March 8/9, 2001 together with the fits described in Sect. 3. The numbers indicate the Julian date of the exposures and the orbital phase  $\phi$  (cf. Fig. 3). Star “A” in the text corresponds to the blueward shifted line core in, e.g., the JD 2451977.773 exposure, “B” to the red component. Observed spectra were smoothed with a three pixel boxcar ( $0.09 \text{ \AA}$ ).

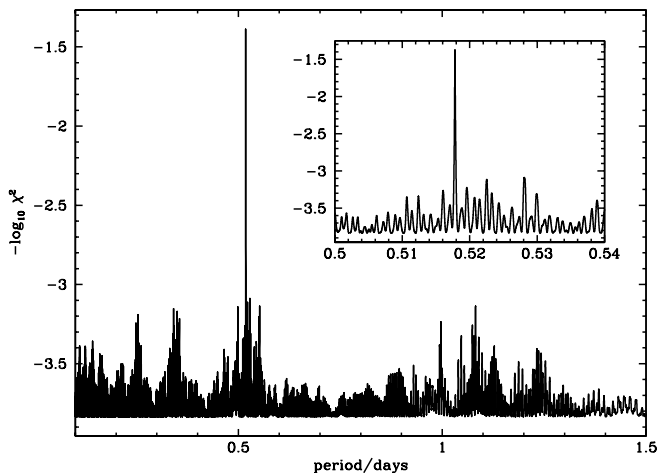
determination of accurate orbital parameters with a relatively small number of spectra.

Six  $H_{\alpha}$  spectra taken during the first night of the follow-up observations are displayed in Fig. 1 together with a fit of both components as described in Sect. 3. The rapid change of the spectral appearance due to the orbital motion is obvious.

## 3. Radial velocity curve and orbital parameters

Although the line cores of both components are similar, the left one in Fig. 1 is slightly deeper and broader (called component A further on). We used this in a first step to identify both stars in each spectrum. In a second step we fitted the central region ( $\pm 20 \text{ \AA}$ ) by using two Gaussians (one for every component), a Lorentzian to model the line wings (parameters of the Lorentzian were determined from a fit covering  $\pm 50 \text{ \AA}$  and then held fixed), and a linear polynomial to reproduce the overall spectral trend. Fitting of the  $H_{\alpha}$  profiles was performed with a downhill simplex algorithm, which will be described in a forthcoming paper.

In a third step we fitted  $RV$  curves for a range of periods and produced a “power spectrum” indicating the fit quality as a function of period (like the one presented



**Fig. 2.** Power spectrum of the  $RV$  measurements of component A. The inset shows details of the region around the main peak.

in Fig. 2). In a fourth step we inspected the phased  $RV$  curves using periods corresponding to peaks in the power spectrum and compared them with the measured values. Most could be ruled out, because of discrepant  $RV$  measurements. Finally, one unambiguous solution remained.

In the fifth and last step we extrapolated the derived  $RV$  curves back to the time of the discovery observations and to an additional spectrum taken in August 2001. We used the phase information to identify the components in these exposures, and added the  $RV$ s to our analysis. Individual measurements are listed in Table 1. Since the spectra span more than one year, a very accurate period could be determined:  $P = 12^{\text{h}}25^{\text{m}}39^{\text{s}}$ . Results for both components agree within 1 s. Semi-amplitudes  $K_{A/B}$  and the “system velocities”  $\gamma_0$  are given in Table 2. Accordingly the ephemeris for the time  $T_0$  defined as the conjunction time at which star A moves from the blue side to the red side of the  $RV$  curve (i.e. star A is closest to the observer) is

$$\text{Hel.JD}(T_0) = 2451976.911 + 0.51781 \times E \quad (1)$$

$$\pm 0.001 \pm 0.00001.$$

Error limits are given in the second line. The mass ratio of both white dwarfs can be computed from the ratio of  $RV$  amplitude:

$$\frac{M_B}{M_A} = \frac{K_A}{K_B} = 1.28 \pm 0.02. \quad (2)$$

From Fig. 3 and Table 2 it is evident that the “system velocities”  $\gamma_0$  derived for component A and B differ much more than naively expected considering the error bars:  $\gamma_0(B) - \gamma_0(A) = 14.3 \pm 1.7 \text{ km s}^{-1}$ . However, this is easily explained by the mass dependent gravitational redshift of white dwarfs

$$z = \frac{GM}{Rc^2}. \quad (3)$$

This offers the opportunity to determine masses of the individual white dwarfs in the HE 1414–0848 binary.

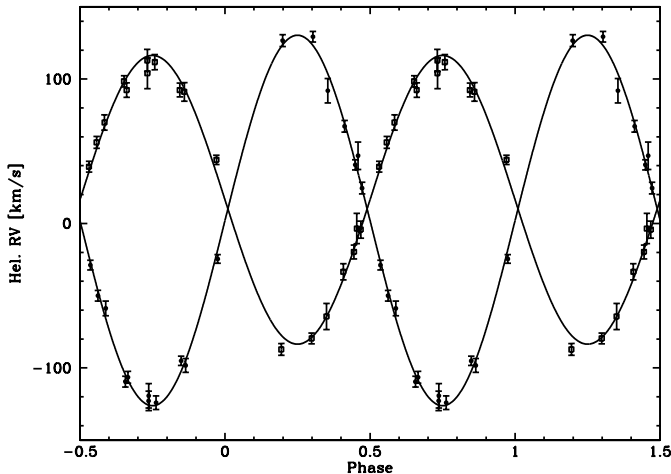
**Table 1.** Fitted heliocentric radial velocities. Hel. JD was calculated for the middle of the exposures.

Hel. JD –2 400 000	Heliocentric $RV$	
	A	B
51684.68664	$-110 \pm 4$	$98 \pm 4$
51687.61061	$129 \pm 4$	$-80 \pm 4$
51977.66606	$47 \pm 9$	$-3 \pm 11$
51977.67313	$24 \pm 4$	$-4 \pm 6$
51977.73344	$-59 \pm 5$	$70 \pm 5$
51977.77310	$-106 \pm 4$	$92 \pm 5$
51977.81012	$-119 \pm 9$	$104 \pm 11$
51977.87602	$-98 \pm 5$	$91 \pm 6$
51978.67757	$67 \pm 4$	$-34 \pm 6$
51978.75510	$-50 \pm 4$	$56 \pm 4$
51978.85895	$-124 \pm 5$	$112 \pm 5$
51979.68326	$92 \pm 8$	$-64 \pm 9$
51979.88119	$-123 \pm 7$	$113 \pm 8$
51987.70636	$-95 \pm 3$	$92 \pm 5$
52003.59657	$-29 \pm 3$	$39 \pm 4$
52003.82394	$-25 \pm 3$	$44 \pm 3$
52004.58719	$41 \pm 4$	$-20 \pm 5$
52137.53531	$127 \pm 3$	$-87 \pm 4$

**Table 2.** Orbital parameters of the HE 1414–0848 system. Given are the “system” velocities  $\gamma_0$ ,  $RV$  amplitudes  $K_{A/B}$ , the  $\chi^2$  values of the fits and the number of data points  $N$ .

Comp.	$\gamma_0$ [ $\text{km s}^{-1}$ ]	$K_{A/B}$ [ $\text{km s}^{-1}$ ]	$N$	$\chi^2$
A	$2.1 \pm 1.1$	$128.2 \pm 1.6$	18	23.7
B	$16.4 \pm 1.3$	$99.9 \pm 1.7$	18	25.2

For a given mass-radius relation gravitational redshift can be computed as a function of white dwarf mass. Since the mass ratio is given by Eq. (2), only one combination of masses can fulfil both constraints. Since HE 1414–0848 is the outcome of common envelope evolution, it is not clear which mass-radius relation to use. We performed the analysis with mass-radius relations constructed for  $T_{\text{eff}} = 9800 \text{ K}$  (cf. Sect. 4) from three different white dwarf cooling tracks, which should give us an estimate of systematic errors introduced by a particular choice. We used the tracks computed by Blöcker et al. (1997), which result from the self-consistent calculation of single star evolution and cooling curves computed by Wood (1995) for white dwarfs with a “thick” hydrogen layer ( $M_{\text{H}} = 10^{-4} M_{\text{WD}}$ ) and a “thin” layer ( $M_{\text{H}} = 0$ ). The resulting white dwarf masses are  $M_A = 0.55 \pm 0.03 M_{\odot}$  and  $M_B = 0.71 \pm 0.03 M_{\odot}$  for Wood’s models with ( $M_{\text{H}} = 0$ ). The resulting masses are  $0.01 M_{\odot}$  larger/lower if we adopt the ( $M_{\text{H}} = 10^{-4} M_{\text{WD}}$ ) models or the tracks of Blöcker et al. (1997), respectively. Thus the choice of a particular mass-radius relation is of little importance. The mass sum of both white dwarfs is  $M = 1.26 \pm 0.06 M_{\odot}$  (errors propagated from the orbital parameters + possible systematic errors). Thus HE 1414–0848 is the most massive DD ever found with a total mass only 10% below the Chandrasekhar limit!



**Fig. 3.** Measured radial velocities as a function of orbital phase and fitted sine curves for HE 1414-0848. Filled circles correspond to component “A” and open rectangles to “B”. Note the difference of the “systemic velocities”  $\gamma_0$  between both components caused by the gravitational redshift.

The separation between both white dwarfs is quite small, only  $2.9 R_{\odot}$ . Thus HE 1414-0848 obviously underwent phases of strong binary interaction in its history. From the size of the orbits and the period orbital velocities can be computed:  $164 \text{ km s}^{-1}$  for component A and  $123 \text{ km s}^{-1}$  for B. The comparison with the observed  $RV$  amplitudes allows us to determine the inclination of this system as  $i = 52^{\circ}$ .

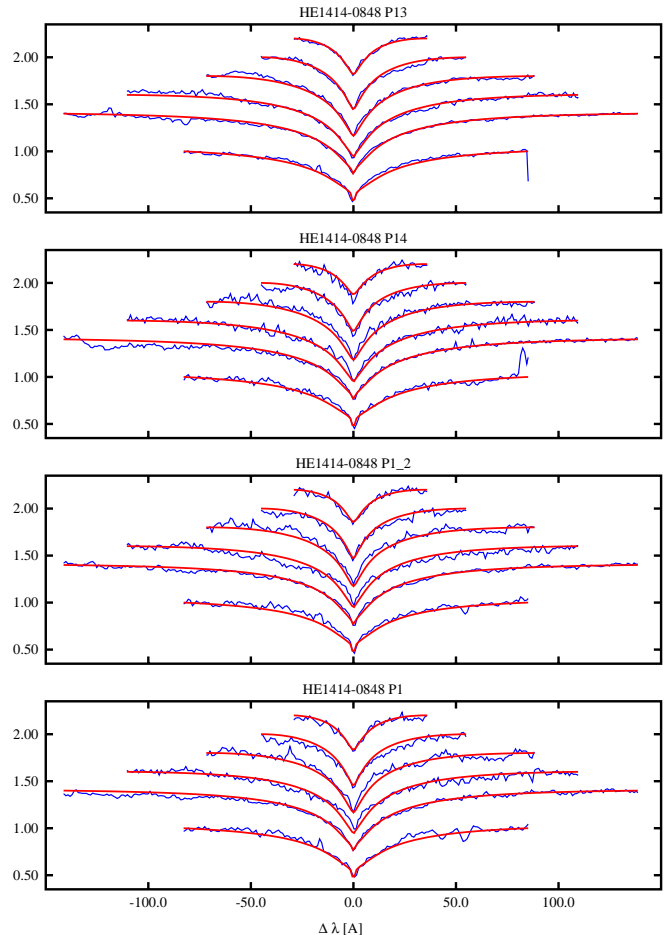
## 4. Spectroscopic analysis

### 4.1. Spectral fitting with one model

Further insight into the HE 1414-0848 system can be gained from a model atmosphere analysis. Since this system is double-lined the spectra are a superposition of both individual white dwarf spectra. A deconvolution is beyond the scope of this paper, but an analysis of the combined spectrum will already allow us to derive constraints on this system. We used four spectra obtained close to conjunction for this purpose (Table 3). Radial velocity differences are small and do not cause significant artificial broadening of the line profiles.

The spectra were rebinned to a resolution of approximately  $1 \text{ \AA}$ . A large grid of LTE DA models computed with a model atmosphere code described in Finley et al. (1997) was used for the analysis. A simultaneous fit of the Balmer lines  $H\alpha$  to  $H_8$  using a  $\chi^2$  minimisation technique was performed. For details refer to Koester et al. (2001 and references therein). The fits are shown in Fig. 4 and individual results are given in Table 3. The average parameters are  $T_{\text{eff}} = 9800 \pm 90 \text{ K}$  and  $\log g = 8.17 \pm 0.09$  (errors correspond to the scatter of individual measurements).

Since the observed spectra are a combination of spectra of both components, the interpretation of this result is not straightforward. However, we expect that the analysis results represent some sort of average of the



**Fig. 4.** Fit of four spectra of HE 1414-0848 taken close to conjunction (cf. Table 3).

**Table 3.** Orbital phases  $\phi$  and fit results for the spectra displayed in Fig. 4.

spectrum	$\phi$	$T_{\text{eff}}$ [K]	$\log g$ [ $\text{cm/s}^2$ ]
P1	0.459	$9739 \pm 29$	$8.12 \pm 0.04$
P1.2	0.472	$9722 \pm 27$	$8.21 \pm 0.04$
P13	0.975	$9924 \pm 26$	$8.29 \pm 0.04$
P14	0.449	$9822 \pm 19$	$8.08 \pm 0.02$

individual values of both components (especially, if both components are similar as in the case of HE 1414-0848; cf. next section). We used Wood’s (1995) mass radius-relation for ( $M_{\text{H}} = 0$ ) to estimate a mass of  $0.68 \pm 0.06 M_{\odot}$  for these parameters. This is consistent with the results of our analysis of the  $RV$  curve.

### 4.2. Spectral fitting with two models

Fitting the combined spectra of the two white dwarfs can only give an approximate average of the atmospheric parameters. We have therefore tried to use 14 individual spectra covering different phases of the orbit and fit them with a combination of two DA spectra (another spectrum – 12 – has a very perturbed  $H\alpha$  profile and could not be

used). The quality of these spectra varies and the total number of fit parameters is high – it is not possible to determine them unambiguously. We have therefore used the radial velocities of the individual components and their masses from the radial velocity curve and held them fixed during the fitting. Surface gravities are 8.18 and 7.87; this also determines the relative weight of the two model spectra from the radius, obtained from the mass-radius relation of Wood (1995); the weight ratio is 40:60. The only remaining parameters are then the two effective temperatures of the models, which are obtained through a  $\chi^2$  fitting routine similar to the methods described in Koester et al. (2001).

Table 4 gives the results for two different attempts. With Method 1 we have used only the inner parts of H $\alpha$  and H $\beta$  (80–100 Å) to determine the atmospheric parameters. In Method 2 we performed a simultaneous fit of all Balmer lines from H $\alpha$  to H $\delta$ .

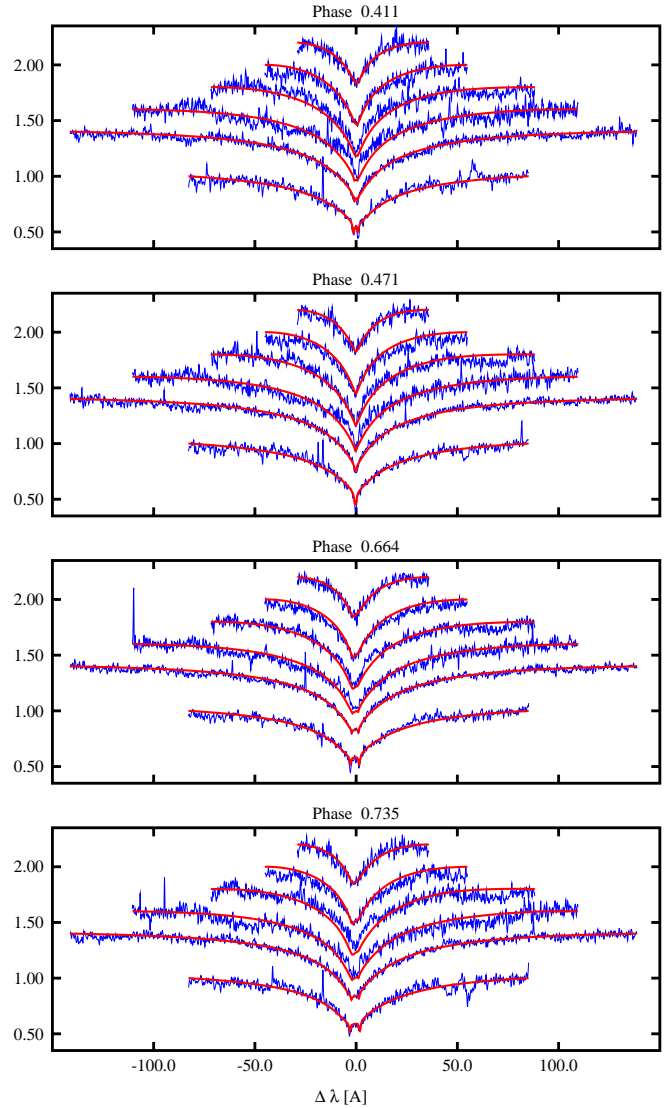
This exercise demonstrates that the individual temperatures are similar for both components and are in fact fairly close to the values obtained from fitting the combined spectra with one average model. However, the scatter from the different spectra is quite large – even the assignment, which of the two stars is the hotter one is not the same in all phases. Obviously the demand on the signal-to-noise ratio and on the calibration is higher for this method than for fitting single stars, especially if the two spectra are very similar as in this case.

The most meaningful results can be expected during the quadrature phases ( $\phi = 0.25$  and 0.75), when the  $RV$  separation between both components is largest. Thus not unexpectedly the scatter of the temperature determinations for the corresponding spectra P3, P4, P5, P6, and P10 (marked boldface in Table 4) is relatively small. Our best temperature estimates are  $8900 \pm 550$  K for component A and  $10\,790 \pm 550$  K for B from Method 2 ( $9330 \pm 640$  K and  $10\,310 \pm 480$  K if Method 1 is adopted). The error margins correspond to the scatter of individual measurements. Sample spectra fitted with these parameters for several orbital phases are displayed in Fig. 5.

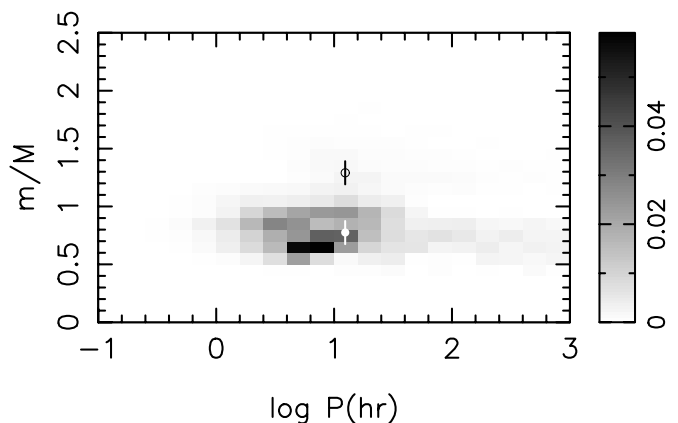
## 5. Discussion

From the above derived temperatures we can estimate the ages of both components using cooling tracks for white dwarfs. Ages were interpolated from the tracks of Wood (1995) for the masses of the white dwarfs (temperatures from Method 2 adopted). Resulting ages are  $(1.2 \pm 0.2) \times 10^9$  yrs for A and  $(1.0 \pm 0.3) \times 10^9$  yrs for B. Thus the cooling ages of both white dwarfs are very similar and although B is  $\approx 2000$  K hotter than A it could, within our error margins, have been formed first.

We can compare the properties of HE 1414–0848 with the outcome of computations for the synthesis of the population of double white dwarfs of (Nelemans et al. 2001). In Fig. 6 we compare the predicted distribution over period and mass ratios for systems with masses similar to the masses of HE 1414–0848. The mass ratio in this plot



**Fig. 5.** Combination of the best fitting model spectra for components A and B ( $T_{\text{eff}}(\text{A}) = 8900$  K and  $T_{\text{eff}}(\text{B}) = 10\,800$  K and four different phases of the binary orbit.



**Fig. 6.** Period-mass distribution for the current population of DDs in the Galaxy for systems in which at least one white dwarf has a mass above  $0.7 M_{\odot}$  from the best model (A3) of Nelemans et al. (2001). Grey shades indicate the expected number of systems brighter than  $V = 15^m$ . The symbols show the possible mass ratios for HE 1414–0848 depending on which of the two components was formed first.

**Table 4.** Results for the effective temperatures and their  $1\sigma$  formal errors of the two DA components from spectra of different phases. Index (B) indicates the more massive star. Columns 3–6 correspond to Method 1, where only the inner parts of H $\alpha$  and H $\beta$  were used in the fit. Columns 7–10 correspond to Method 2, which used H $\alpha$  to H $\delta$ .

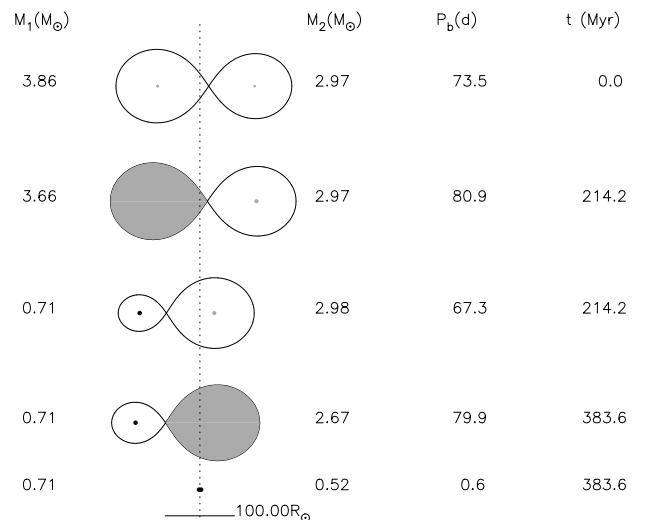
spectrum	$\phi$	$T_{\text{eff}}(\text{B})$	$\sigma(\text{B})$	$T_{\text{eff}}(\text{A})$	$\sigma(\text{A})$	$T_{\text{eff}}(\text{B})$	$\sigma(\text{B})$	$T_{\text{eff}}(\text{A})$	$\sigma(\text{A})$
P1	0.458	8614	76	10 143	20	10 065	78	9427	60
P1_2	0.471	9668	210	9812	133	9819	204	9735	131
P2	0.581	9950	102	9345	88	7837	105	9974	12
<b>P3</b>	0.664	9811	148	9756	99	11 076	18	8612	28
<b>P4</b>	0.736	10 867	22	8482	41	10 916	22	8329	38
<b>P5</b>	0.863	10 769	32	8793	38	9814	113	9798	72
<b>P6</b>	0.847	10 006	141	9900	87	11 056	31	9154	24
P7	0.534	9748	171	9858	109	9807	171	9803	110
P8	0.411	9303	111	10 161	48	10 198	69	9411	59
P9	0.561	8087	72	10 219	9	10 862	20	8574	32
<b>P10</b>	0.761	10 100	139	9696	99	11 075	20	8611	31
P11	0.353	9765	267	9728	172	11 087	37	7648	81
P13	0.973	9722	131	9823	83	10 151	62	9683	45
P14	0.447	10 005	219	9900	137	9441	111	10 210	48

$m/M$  is defined as the mass of the last formed white dwarf over the mass of the first formed white dwarf. Since in the case of HE 1414–0848 it is not reliably known which white dwarf formed first, we plotted both possible mass ratios, 1.28 and 0.78, in Fig. 6. The population synthesis indicates a larger probability for the systems with  $m/M = 0.78$ . In Fig. 7 we give an example of a scenario leading to such a DD system.

A binary with an initial semi-major axis of  $\approx 150 R_{\odot}$  has components with initial masses of  $\approx 4$  and  $3 M_{\odot}$ . The primary fills its Roche lobe in the AGB stage and unstable mass transfer ensues. We estimate the outcome of the mass transfer using an angular momentum balance (Nelemans et al. 2000). The orbit of the system shrinks slightly and the primary becomes a hot carbon-oxygen (CO) white dwarf. After  $\approx 170$  Myr the secondary fills its Roche lobe as an AGB star. The mass transfer is again unstable, the common envelope is lost, and a close binary consisting of two CO white dwarfs, just like HE1414-0848, is the result (see Fig. 7). The period of the system decreases during the subsequent evolution due to angular momentum loss via radiation of gravitational waves.

## 6. Conclusions

We report the discovery of the double-lined radial velocity variable binary HE 1414–0848. We measured accurate radial velocities for both components from high resolution spectra and derived an orbital period of  $12^{\text{h}}25^{\text{m}}39^{\text{s}}$  and semi-amplitudes of  $128 \text{ km s}^{-1}$  and  $100 \text{ km s}^{-1}$ , respectively. We combined the mass ratio computed from this amplitudes and the measured difference of gravitational redshifts and determined masses of  $0.55 \pm 0.03 M_{\odot}$  and  $0.71 \pm 0.03 M_{\odot}$  for the components using a mass-radius relation. This is the first application of this method to a DD system. The total mass of the HE 1414–0848



**Fig. 7.** A possible scenario for the formation of a system similar to HE1414-0848, starting with a  $3.86 + 2.97 M_{\odot}$  star in a 73.5 day orbit. The black line shows the Roche lobe for both stars, filled grey if the star fills its Roche lobe. The ruler at the bottom shows the scale.

system is  $1.26 \pm 0.06 M_{\odot}$ , only 10% below the Chandrasekhar limit, making it the most massive DD ever found in a  $RV$  survey. It will merge within two Hubble times (24 Gyrs).

We performed spectral fitting of both individual components and derived  $T_{\text{eff}} = 10\,800 \pm 550 \text{ K}$  for the more massive component B and  $T_{\text{eff}} = 8\,900 \pm 550 \text{ K}$  for component A. Ages can be estimated from the WD cooling tracks of Wood (1995). The resulting cooling ages for both white dwarfs are close to 1 Gyr.

We compared the resulting orbital parameters of HE 1414–0848 with the outcome of theoretical calculations for the formation of DDs and find that

HE 1414–0848 seems to be a fairly typical double white dwarf in terms of the masses of the two white dwarfs and its orbital period.

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