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Published in:
Astronomy & Astrophysics

DOI:
10.1051/0004-6361:20020361

Citation for published version (APA):

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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*

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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 $H$, $\Omega$, 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 donor: 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 ≈180 WDs have been checked for RV variations yielding a sample of 18 DDs with $P < 6.3 \text{d}$ (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,

* Based on data obtained at the Paranal Observatory of the European Southern Observatory for programs Nos. 165.H-0588, 266.D-5658, and 167.D-0407.

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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,
as theoretical simulations suggest that only a few percent of all close DDs are potential SN Ia 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 SN Ia 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 SN Ia 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 RVs (ESO SN Ia 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 (α2000 = 14h16m52.1s, δ2000 = −9°02′04″, Bpg = 16.2) 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 Hα core separated by 4.6 Å, corresponding to 210 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 Å) 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 determination of accurate orbital parameters with a relatively small number of spectra.

Six Hα 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 (±20 Å) 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 ±50 Å and then held fixed), and a linear polynomial to reproduce the overall spectral trend. Fitting of the Hα 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...
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 RVs 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: \( P = 12^h 25^m 39^s \). 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

\[
\text{Hel.JD}(T_0) = 2451976.911 + 0.51781 \times E
\]

\[\pm 0.001 \pm 0.00001. \]  

(1)

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

\[
\frac{M_B}{M_A} = \frac{K_A}{K_B} = 1.28 \pm 0.02 .
\]

(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

\[
z = \frac{GM}{Rc^2}
\]

(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.

<table>
<thead>
<tr>
<th>Hel. JD</th>
<th>Heliocentric RV</th>
</tr>
</thead>
<tbody>
<tr>
<td>51684.68064</td>
<td>A = −110 ± 4, B = 98 ± 4</td>
</tr>
<tr>
<td>51687.61061</td>
<td>A = 129 ± 4, B = −80 ± 4</td>
</tr>
<tr>
<td>51977.66606</td>
<td>A = 47 ± 9, B = −3 ± 11</td>
</tr>
<tr>
<td>51977.67313</td>
<td>A = 24 ± 4, B = −4 ± 6</td>
</tr>
<tr>
<td>51977.73444</td>
<td>A = −50 ± 5, B = 70 ± 5</td>
</tr>
<tr>
<td>51977.77310</td>
<td>A = −106 ± 4, B = 92 ± 5</td>
</tr>
<tr>
<td>51977.81012</td>
<td>A = −119 ± 9, B = 104 ± 11</td>
</tr>
<tr>
<td>51977.87692</td>
<td>A = −98 ± 5, B = 91 ± 6</td>
</tr>
<tr>
<td>51978.67757</td>
<td>A = 67 ± 4, B = −34 ± 6</td>
</tr>
<tr>
<td>51978.75510</td>
<td>A = −50 ± 4, B = 56 ± 4</td>
</tr>
<tr>
<td>51978.85895</td>
<td>A = −124 ± 5, B = 112 ± 5</td>
</tr>
<tr>
<td>51979.68326</td>
<td>A = 92 ± 8, B = −64 ± 9</td>
</tr>
<tr>
<td>51979.88119</td>
<td>A = −123 ± 7, B = 113 ± 8</td>
</tr>
<tr>
<td>51987.70636</td>
<td>A = −95 ± 3, B = 92 ± 5</td>
</tr>
<tr>
<td>52003.59657</td>
<td>A = −29 ± 3, B = 39 ± 4</td>
</tr>
<tr>
<td>52003.82394</td>
<td>A = −25 ± 3, B = 44 ± 3</td>
</tr>
<tr>
<td>52004.58719</td>
<td>A = 41 ± 4, B = −20 ± 5</td>
</tr>
<tr>
<td>52137.53531</td>
<td>A = 127 ± 3, B = −87 ± 4</td>
</tr>
</tbody>
</table>

**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 \( N \).

<table>
<thead>
<tr>
<th>Comp.</th>
<th>( \gamma_0 [\text{km s}^{-1}] )</th>
<th>( K_{A/B} [\text{km s}^{-1}] )</th>
<th>( N )</th>
<th>( \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.1 ± 1.1</td>
<td>128.2 ± 1.6</td>
<td>18</td>
<td>23.7</td>
</tr>
<tr>
<td>B</td>
<td>16.4 ± 1.3</td>
<td>99.9 ± 1.7</td>
<td>18</td>
<td>25.2</td>
</tr>
</tbody>
</table>

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 fulfill 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 single star evolution and cooling curves computed by Wood (1995) for white dwarfs with a “thick” hydrogen layer (\( M_H = 10^{-4} M_{WD} \)) and a “thin” layer (\( M_H = 0 \)). 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 \( M_H = 0 \). The resulting masses are 0.01 \( M_\odot \) larger/lower if we adopt the (\( M_H = 10^{-4} M_{WD} \)) 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 km s\(^{-1}\) for component A and 123 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 \( \AA \). 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\(\beta\) 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 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 \( (M_H = 0) \) 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

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

<table>
<thead>
<tr>
<th>spectrum</th>
<th>( \phi )</th>
<th>( T_{\text{eff}} ) [K]</th>
<th>( \log g ) [cm/s(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0.459</td>
<td>9739 \pm 29</td>
<td>8.12 \pm 0.04</td>
</tr>
<tr>
<td>P1,2</td>
<td>0.472</td>
<td>9722 \pm 27</td>
<td>8.21 \pm 0.04</td>
</tr>
<tr>
<td>P13</td>
<td>0.975</td>
<td>9924 \pm 26</td>
<td>8.29 \pm 0.04</td>
</tr>
<tr>
<td>P14</td>
<td>0.449</td>
<td>9822 \pm 19</td>
<td>8.08 \pm 0.02</td>
</tr>
</tbody>
</table>

Fig. 4. Fit of four spectra of HE 1414–0848 taken close to conjunction (cf. Table 3).
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 $\AA$) to determine the atmospheric parameters. In Method 2 we performed a simultaneous fit of all Balmer lines from H$\alpha$ to H$\beta$.

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 ± 550 K for component A and 10790 ± 550 K for B from Method 2 (9330 ± 640 K and 10310 ± 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 ≈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 ($T_{\text{eff}}(A) = 8900$ K and $T_{\text{eff}}(B) = 10800$ 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 $V = 15$ mag. 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 1σ 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 Hα and Hβ were used in the fit. Columns 7–10 correspond to Method 2, which used Hα to Hγ.

<table>
<thead>
<tr>
<th>spectrum</th>
<th>φ</th>
<th>T_{eff}(B)</th>
<th>σ(B)</th>
<th>T_{eff}(A)</th>
<th>σ(A)</th>
<th>T_{eff}(B)</th>
<th>σ(B)</th>
<th>T_{eff}(A)</th>
<th>σ(A)</th>
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<tr>
<td>P1</td>
<td>0.458</td>
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<td>10143</td>
<td>20</td>
<td>10065</td>
<td>78</td>
<td>9427</td>
<td>60</td>
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<td>P1_1</td>
<td>0.471</td>
<td>9668</td>
<td>210</td>
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<td>9819</td>
<td>204</td>
<td>9735</td>
<td>131</td>
</tr>
<tr>
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<td>9950</td>
<td>102</td>
<td>9345</td>
<td>88</td>
<td>7837</td>
<td>105</td>
<td>9974</td>
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</tr>
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<td>P7</td>
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<td>P8</td>
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<td>9900</td>
<td>137</td>
<td>9441</td>
<td>111</td>
<td>10210</td>
<td>48</td>
</tr>
</tbody>
</table>

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 reliable 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 ≈150 R_☉ has components with initial masses of ≈4 and 3 M_☉. 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 ≈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 12h25m39s and semi-amplitudes of 128 km s^{-1} and 100 km s^{-1}, respectively. We combined the mass ratio computed from these amplitudes and the measured difference of gravitational redshifts and determined masses of 0.55 ± 0.03 M_☉ and 0.71 ± 0.03 M_☉ 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 HE1414−0848 system is 1.26 ± 0.06 M_☉, 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_{eff} = 10 800 ± 550 K for the more massive component B and T_{eff} = 8900 ± 550 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 HE1414−0848 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 the masses of the two white dwarfs and its orbital period.

Acknowledgements. We express our gratitude to the ESO staff, for providing invaluable help and conducting the service observations and pipeline reductions, which have made this work possible. This project is supported by the DFG (grant Na365/2-1). L.Y. acknowledges support by RFBR and "Program Astronomy" grants and warm hospitality and support of the Astronomical Institute "Anton Pannekoek".

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