Post-common envelope binaries from SDSS-X: The origin of low-mass white dwarfs

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ABSTRACT

We present the first white dwarf mass distributions of a large and homogeneous sample of post-common envelope binaries (PCEBs) and wide white dwarf-main sequence binaries (WDMS) directly obtained from observations. Both distributions are statistically independent, with PCEBs showing a clear concentration of systems towards the low-mass end of the distribution, and the white dwarf mass distribution of wide WDMS binaries being similar to those of single white dwarfs. Our results provide evidence that the majority of low-mass (\(M_{\text{wd}} \lesssim 0.5\,\text{M}_\odot\)) white dwarfs are formed in close binaries.

Key words: Binaries: spectroscopic – stars: white dwarfs – binaries: close – stars: evolution

1 INTRODUCTION

The mass distribution of hydrogen atmosphere white dwarfs is strongly clustered around an average value of \(\sim 0.6\,\text{M}_\odot\) (Koester et al. 1979; Marsh et al. 1997; Kepler et al. 2007; Holberg et al. 2008), as predicted by models of single star evolution. In addition to the pronounced peak at \(\sim 0.6\,\text{M}_\odot\), a second peak at lower masses, \(\sim 0.4\,\text{M}_\odot\), has been frequently found (e.g. Bergeron et al. 1992; Bragaglia et al. 1997; Liebert et al. 2003; Kepler et al. 2007). Given the evolutionary time scale of low-mass single main sequence stars that are supposed to form such low-mass (\(M_{\text{wd}} \lesssim 0.5\,\text{M}_\odot\)) white dwarfs significantly exceeds the Hubble time, the existence of low-mass white dwarfs has been interpreted as the result of strong mass transfer interactions in binaries. In this scenario the more massive (primary) star in a main sequence binary fills its Roche-lobe on the giant branch, and dynamical unstable mass transfer onto the less massive (secondary) star leads to the formation of a common envelope engulfing both the core of the primary star and the lower mass secondary star. Orbital energy released due to the shrinkage of the binary orbit is supposed to rapidly expel the envelope, and may terminate the growth of the He core of the primary star before it reaches a sufficient mass for He-ignition. The outcome of this close binary evolution is a post-common envelope binary (PCEB) consistent of a (possibly low-mass He-core) white dwarf and the (basically unaltered) low-mass secondary (Paczynski 1976; Webbink 1984; Iben & Tutukov 1986).

The hypothetical binary origin of low-mass white dwarfs is observationally supported by the large fraction of low-mass white dwarfs in short orbital period double white dwarfs (e.g. Marsh et al. 1995), in neutron star-white dwarf binaries (e.g. Sigurdsson et al. 2003) and in subdwarf B star-white dwarf pairs (e.g. Maxted et al. 2002), as well as the existence of some PCEBs with low-mass white dwarf primaries (e.g. Schreiber & Gänscicke 2002; Nebot Gómez-Morán et al. 2009; Pyrzas et al. 2002; Zorotovic et al. 2010).

However, also a fair number of apparently single low-mass white dwarfs are known that exhibit neither radial velocity variations, nor infrared flux excess, the typical hallmarks of white dwarfs with close companions (Maxted et al. 2000; Napliwotzki et al. 2007; Kilic et al. 2010). Possible explanations for the existence of these systems include supernova type Ia explosions in semi-detached close binaries that blow away the envelope of the companion thus exposing its low-mass core (Justham et al. 2009), severe mass-loss on the first giant branch (Kilic et al. 2007), that may even lead to the formation of low-mass white dwarfs with CO-cores (Prada Moroni & Straniero 2009), stellar envelope ejection due to the spiral-in of close giant planets (Nolemans & Tauris 1998), or the merging of two very low-mass white dwarfs (Han et al. 2002).
Table 1. White dwarf masses for the 211 SDSS WDMS binaries (76 PCEBs and 135 wide WDMS binary candidates) used in this work. In the last column we indicate whether the object is a PCEB (1) or a wide WDMS binary (0). The complete table can be found in the electronic edition of the paper.

| Object                  | M_{wd}[M_{\odot}] | error[M_{\odot}] | pceb? |
|-------------------------|--------------------|------------------|-------|
| SDSS J00453.9−265420.4  | 0.606              | 0.095            | 0     |
| SDSS J00559.87−054416.0 | 0.615              | 0.055            | 0     |
| SDSS J00651.91+284647.1 | 0.590              | 0.048            | 0     |
| SDSS J01749.24−000955.3 | 0.496              | 0.034            | 1     |
| SDSS J0321.86+073934.4  | 0.369              | 0.015            | 1     |
| SDSS J0360.59+070047.2  | 0.584              | 0.019            | 0     |

So far, conclusive studies testing the close binary origin of low-mass white dwarfs have been prevented by the lack of a sufficiently large and homogeneous sample of PCEBs. This is now rapidly changing thanks to the Sloan Digital Sky Survey (SDSS, York et al. 2000; Abazajian et al. 2009; Yanny et al. 2009) from which ∼2000 white dwarf/main sequence (WDMS) binaries have been spectroscopically identified (Silvestri et al. 2007; Schreiber et al. 2007; Heller et al. 2007; Rebassa-Mansergas et al. 2007, 2008; Schreiber et al. 2008, 2010). This population of WDMS binaries consists of wide systems whose stellar components did not interact and thus evolved like single stars, and close binaries that suffered from dynamically unstable mass transfer, i.e. PCEBs. Based on extensive radial velocity follow-up of the SDSS WDMS binary sample (Rebassa-Mansergas et al. 2007, 2008; Schreiber et al. 2008, 2010), we demonstrate here that the mass distribution of the white dwarfs in PCEBs does indeed differ significantly from that of white dwarfs that do not undergo binary interactions, containing a large fraction of low-mass white dwarfs.

2 THE SAMPLE

SDSS spectroscopy has been very efficient in identifying WDMS binaries: 1602 systems were found in Data Release (DR) 6 by Rebassa-Mansergas et al. (2010). Several hundred more were discovered from a dedicated WDMS SEGUE (the SDSS Extension for Galactic Understanding and Exploration, see Yanny et al. 2009) survey (Nebot Gómez-Morán et al. 2011a, A&A in prep.), and we are currently compiling the final addition of systems from DR 7 (Rebassa-Mansergas et al. 2011 in prep.), taking the total number of WDMS binaries in SDSS to over 2000. The system parameters of all the SDSS/SEGUE WDMS binaries were determined by decomposing the SDSS spectra into their white dwarf and companion star contributions, and subsequently fitting the white dwarf spectra with models. This procedure is described in detail in Rebassa-Mansergas et al. (2007). However, intensive tests of our white dwarf fitting routine using SDSS spectra of single white dwarfs (see Sect. 3) revealed that we over-estimated the errors on the white dwarf parameters by a factor ∼2. We have hence re-fitted all WDMS binary spectra to obtain more realistic uncertainties of the white dwarf parameters. Updated uncertainties for the WDMS binaries not studied here will be provided in Rebassa-Mansergas et al. (2011) in prep.

The vast majority of the SDSS WDMS binaries in our sample are spatially unresolved. Given the typical distances of > 100 pc, and assuming a typical resolution of ∼1” for the SDSS images, these systems may hence have binary separations of up to many tens of astronomical units and orbital periods of up to hundreds of years. This implies that the SDSS WDMS binary sample contains both wide binaries, in which the white dwarf progenitor evolved as a single star, and PCEBs, in which the two stars interacted when the white dwarf progenitor evolved off the main sequence. We have obtained radial velocity information spanning at least two nights from our follow-up observations of several hundred SDSS WDMS binaries (e.g. Rebassa-Mansergas et al. 2008; Schreiber et al. 2008, 2010) supplemented by the SDSS sub-spectra (all SDSS spectra are the result of combining at least three individual sub-exposures, see Rebassa-Mansergas et al. 2007, 2010). As in Schreiber et al. (2010) we classify systems exhibiting significant radial velocity variations, i.e. the null hypothesis that radial velocity is constant can be rejected on a confidence level ≥ 0.9973 (3σ), and that therefore must have short orbital periods (∼ a few days), as PCEBs. WDMS binaries that do not exhibit radial velocity variations are designated as strong wide binary candidates, and may be either genuine wide binaries, or PCEBs that were not recognized as such due to (a combination of) a low orbital inclination, long orbital period, and unlucky phase coverage. We discuss the number of PCEBs potentially missed using these criteria in Sect. 3.

To the 670 systems analyzed by Schreiber et al. (2010) we added seven systems with uncertain secondary mass and excluded 46 systems with rather uncertain white dwarf parameters. From the resulting sample of 629 systems we considered then only objects containing hydrogen-rich (DA) white dwarfs with effective temperatures exceeding 12000 K. Below this limit an increase in surface gravity (as obtained from spectral model fitting) is observed, probably related to the description of convection in the framework of the mixing-length approximation (Koester et al. 2003; Tremblay et al. 2014). Finally, we considered only WDMS binaries with errors in the white dwarf mass smaller than 0.1 M_{\odot}. The latter condition is rather arbitrary but the conclusions of the paper are independent on the exact value of uncertainty we adopt. The final numbers of PCEB and wide WDMS binary candidates in our sample are 76 and 135 respectively (211 in total). The WDMS binaries and their white dwarf masses plus corresponding errors are given in Table 1. The radial velocity measurements for the seven objects that have not been presented in Schreiber et al. (2010) but have been used in this work are given in Table 1 and a description of the observations and instrument setup can be found in Nebot Gómez-Morán et al. (2011b), in prep.

3 WHITE DWARF MASS DISTRIBUTIONS

The white dwarf mass distributions of the complete WDMS sample, the PCEBs, and the wide binary candidates are shown in the top panels of Fig. 1. The mass distribution of the complete sample is bi-modal with the strongest peak near ∼ 0.55 M_{\odot}, and a lower peak near ∼ 0.4 M_{\odot}. The mass distribution of the PCEBs (right top panel) reveals a clear
Figure 1. Top panels: white dwarf mass distributions obtained from the complete sample of WDMS binaries (gray), from the PCEBs (right panel, black), and from the wide WDMS binary candidates (left panel, black) used in this work. Bottom panel: the cumulative mass distributions of our PCEBs (dashed blue line) and wide WDMS binary candidates (black line). A two-sample KS-test (Table 3) shows that the two distributions represent different parent populations, i.e. are statistically independent.

Table 2. Radial velocities and heliocentric Julian dates (HJD) for the seven additional WDMS binaries used in this work in addition to the systems from Schröder et al. (2010). The last column indicates the telescope where the data were taken: Gemini South (GS), Very Large Telescope (VLT), William Herschel Telescope (WHT). If the radial velocities were measured from SDSS spectra we use the quotation SDSS.

| Object (SDSSJ)   | HJD       | RV         | error     | obs. |
|------------------|-----------|------------|-----------|------|
| 103837.22+015058.4 | 2454854.8083 | 21.6 | 11.5 | GS |
|                  | 2454855.8003 | -5.5 | 12.6 | GS |
|                  | 2452317.7990 | 4.8  | 11.4 | SDSS|
| 122752.72-015053.0 | 2454935.6564 | 113.6 | 5.8  | VLT |
|                  | 2454944.6149 | 97.7  | 6.3  | VLT |
|                  | 2451993.8006 | 120.1 | 14.0 | SDSS|
| 135228.14+091039.0 | 2454514.8310 | 5.0  | 4.6  | GS  |
|                  | 2454536.8304 | 58.5  | 9.8  | GS  |
|                  | 2453559.1615 | 17.8  | 16.4 | SDSS|
| 143551.64+043209.9 | 2454884.8206 | -2.6 | 4.5  | VLT |
|                  | 2454892.8258 | 4.4  | 5.1  | VLT |
|                  | 2452923.8680 | 19.1  | 16.6 | SDSS|
| 184117.99+410628.3 | 2454599.9360 | 20.1 | 15.2 | SDSS|
|                  | 2454617.8310 | -2.3 | 14.9 | SDSS|
|                  | 2454617.8520 | -31.5 | 15.3 | SDSS|
| 210426.91+101813.7 | 2454741.5720 | -90.5 | 5.9  | VLT |
|                  | 2454756.5199 | -103.3 | 9.2  | VLT |
| 223530.61+142855.0 | 2453919.6404 | -165.5 | 6.5  | WHT |
|                  | 2453920.5956 | 211.3 | 6.6  | WHT |

4 COMPARING SDSS SINGLE WHITE DWARF AND WDMS BINARY MASS DISTRIBUTIONS

The mass distribution of field white dwarfs has been subject to more than three decades of investigations. Early investi-
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Fig. 2. Top panels: white dwarf mass distributions obtained from the complete sample of field white dwarfs (gray non-shaded, see Table 3 and Sect. 4), from the PCEBs (right panel, white shaded), and from the wide WDMS binary candidates (left panel, white shaded) used in this work. To facilitate the comparison the distributions have been normalized. Bottom panel: the cumulative mass distributions of our PCEBs (blue long-dashed), wide WDMS binary candidates (magenta short-dashed), and field white dwarfs (black). KS-tests applied among the three distributions are given in Table 3.

In the previous section, we have shown that the mass distributions of white dwarfs in PCEBs and wide binary candidates differ significantly, with a larger fraction of low-mass white dwarfs among the PCEBs. Here, we compare the white dwarf mass distribution of the PCEBs and the wide WDMS binary candidates with that of field white dwarfs.

When comparing white dwarf mass distributions, many factors can introduce systematic differences, such as the wavelength range (Kepler et al. 2006) and signal-to-noise ratio (Liebert et al. 2005) of the observational data, the details of the fitting procedures, and the model grids adopted for the analysis (e.g. Tremblay et al. 2010). To keep such systematic differences to a minimum, we decided to fit a large sample of field DA white dwarfs from SDSS with the same routine and model grid (Rebassa-Mansergas et al. 2007; Koester et al. 2005) as used for the WDMS binaries. We adopted the DA sample of Kepler et al. (2007), which consists of white dwarfs classified as single and non-magnetic (for details see Eisenstein et al. 2006), but retrieved the corresponding DR7 spectra which were processed by the same pipeline as the WDMS binary spectra. For the vast majority of the 7167 spectra, our results were consistent with those of Kepler et al. (2007). Significant differences were found for 265 spectra, where it is most likely that either our fits, or those of Kepler et al. chose the wrong of the “hot” and “cold” solutions (see Rebassa-Mansergas et al. 2007 for a discussion of this problem). These 265 systems were removed from the field DA sample.

Fig. 2 (top left panel) illustrates that the mass distributions of field white dwarfs and those in wide binaries are very similar, suggesting that white dwarfs in both subsamples evolve in a very similar way. A two-sample KS test of the field white dwarfs vs. wide WDMS binary candidates, limited to 2069 systems with a 0.1 $M_\odot$ uncertainty and effective temperatures > 12000 K in the white dwarf parameters, gives a KS probability of ∼5 per cent (see Table 3 and the bottom panel of Fig. 2). There are, hence, no strong indications for white dwarfs in wide WDMS binaries evolving in a different way from isolated field white dwarfs. We note that the relatively low KS probability obtained in this exercise may be a consequence of selection effects in SDSS affecting the mass distributions, and of some PCEBs not identified by our radial velocity survey hiding among the wide WDMS binary candidates. Finally, it is worth noting that extremely low-mass ($\lesssim 0.35 M_\odot$) white dwarfs seem to be present in the apparently single white dwarf sample but absent among the wide WDMS binaries. Further discussions of these issues are provided in the following Sections.

A KS test between the PCEB and field white dwarf
5 PCEB FRACTIONS

We have shown that the mass distributions of PCEBs and wide WDMS binaries differ significantly. While the former contains a much larger fraction of low-mass white dwarfs, the latter is similar to single white dwarf mass distributions. In other words, the fraction of PCEBs among WDMS binaries containing low-mass white dwarfs seems to be significantly larger than for WDMS binaries containing high-mass white dwarfs. However, caution is needed to interpret these results as most of our PCEBs have been classified according to few radial velocity measurements spread over at least two nights. This PCEB identification method is obviously less sensitive to PCEBs with low inclinations and/or long orbital periods and hence a certain fraction of PCEBs will be hiding among the wide WDMS binary candidates. In the following we correct for this bias using Monte-Carlo methods.

To determine the most likely fraction of PCEBs for each white dwarf mass-bin (we adopt a mass-bin of 0.05 M⊙) we need to know the probability for each system being a PCEB. For those systems showing strong radial velocity variations over the orbital period (2 hr − 2 days) we randomly selected 10 000 times the phases and inclinations for each system and calculated the corresponding radial velocities. Averaging the fraction (fA) of WDMS binaries containing a low-mass white dwarf among those WDMS binaries gives a KS probability of only 0.77 per cent (see Table 3 and the bottom panel of Fig. 2), clearly confirming that white dwarfs in PCEBs have indeed evolved in a different way than field white dwarfs.

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To determine the most likely fraction of PCEBs for each white dwarf mass-bin (we adopt a mass-bin of 0.05 M⊙) we need to know the probability for each system being a PCEB. For those systems showing strong radial velocity variations this probability equals one. For those systems classified as wide binaries we need to calculate the PCEB detection probability. Taking into account the times of observations and the stellar masses we performed Monte-Carlo simulations similar to those presented in Schreiber et al. (2010) and Nebo Gómez-Morán et al. (2011b, in prep.), i.e. for typical PCEB orbital periods (2 hr − 2 days) we randomly selected 10 000 times the phases and inclinations for each system and calculated the corresponding radial velocities. Averaging the fraction of > 3 σ radial velocity variations over the orbital period gives the averaged PCEB detection probability for each system (εi). The most likely fraction of PCEBs can then be calculated analogous to Maxted et al. (2000b). We assume two models, i.e. all WDMS binaries are PCEBs (model M1) or a certain fraction (fA) of WDMS binaries are PCEBs (model M2). Using Bayes’ theorem we obtain for the probability ratio of the two models given our data D:

$$P(D|M2) = \frac{f_A^{N_A} \prod q_i}{\prod p_i},$$

where

$$p_i = 1 - \epsilon_i,$$

and

$$q_i = f_A[1 - \epsilon_i].$$

The measured values entering these equations are the number of PCEBs N_A and the detection probabilities of the wide WDMS binary candidates (εi). We have calculated the probability ratio for values of fA ranging from 0 to 1 with a step-size of 0.01 for each white dwarf mass-bin. The maximum value indicates the most probable fraction of PCEBs which is shown by the dashed line in Fig. 3 together with the measured PCEB fraction (solid line). It appears that the bias-corrected PCEB fraction is close to 100 per cent for the lowest mass systems and decreases relatively sharply at Mwd > 0.5 M⊙ from ~ 80 per cent to ~ 40 per cent.

6 WIDE WDMS BINARIES CONTAINING LOW-MASS WHITE DWARFS

Because of their uncertain origin, the fraction of wide WDMS binaries containing low-mass white dwarfs is of crucial importance. The measured fraction of systems containing a low-mass white dwarf among those WDMS binaries that do not show significant radial velocity variations is 27 per cent. However, as shown above, a certain fraction of these systems are certainly PCEBs that we did not identify due to low inclinations, long orbital periods, or unfortunate sampling of the orbital phase (see Sect. 5). In this section we investigate in more detail the true fraction of low-mass white dwarfs among wide WDMS binaries implied by our

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1 The phases are assumed to be uniformly distributed over 0 − 2π while the inclinations have been chosen uniformly from the distribution sin(i).

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**Table 3.** Results of two-sample Kolmogorov-Smirnov tests comparing the cumulative white dwarf mass distributions of four different samples used in this work: “PCEB”, “wide WDMS”, “all WDMS” and “field WD”, standing for PCEBs, wide WDMS binary candidates, the complete WDMS binary sample, and field DA white dwarfs from Kenler et al. (2007) respectively (see Sect. 2 and Sect. 4 for details). The number of systems for each sample are also indicated in the second and fourth columns.

| Sample 1 | N | Sample 2 | N | KS Prob. [per cent] |
|----------|---|----------|---|--------------------|
| PCEB     | 76| wide WDMS| 135| 0.414              |
| field WD | 2069| wide WDMS| 135| 4.731              |
| field WD | 2069| PCEB     | 76 | 0.770              |
observations. For this purpose we first divide our sample in high-mass ($M_{\text{wd}} > 0.5 M_\odot$) and low-mass ($M_{\text{wd}} \leq 0.5 M_\odot$) systems and determine the bias corrected fraction of PCEBs in both sub-samples. As the uncertainty of our white dwarf mass estimates is typically $\sigma \sim 0.05 - 0.1 M_\odot$ and therefore the theoretically predicted clear separation of low-mass and high-mass white dwarfs at $M_{\text{wd}} = 0.5 M_\odot$ is smeared out, we additionally require $M_{\text{wd}} + s f \times \sigma < 0.5 M_\odot$ and $M_{\text{wd}} - s f \times \sigma > 0.5 M_\odot$ with $s f = 0, 0.5, 1.0, 1.5, 2.0$. $s f = 0$ corresponds to our complete WDMS binary sample. As $s f$ increases, the number of WDMS binaries that we consider drops, because we are excluding systems close to the boundary separating low and high white dwarf masses. As in Sect. 8 we show in Fig. 4 the most likely PCEB fraction is given by the highest probability ratio, i.e. $f_A = f_{\text{PCEB}, h} = 0.45$ (see the solid curve in Fig. 4) while the most likely PCEB fraction for WDMS binaries containing high-mass white dwarfs is significantly smaller, i.e. $f_A = f_{\text{PCEB}, h} = 0.45$ (see the dashed curve in Fig. 4). The error of the most likely value is calculated by requiring the probability on each side of the maximum to reach 68.27 per cent, as indicated by the shaded regions in Fig. 4. This results in asymmetric errors reflecting the asymmetry of the probability functions. Finally, the fraction of low-mass white dwarfs among wide WDMS binaries ($f_{\text{WIDE}, c}$) can be calculated using the estimated PCEB fractions $f_{\text{PCEB}, h}$ and $f_{\text{PCEB}, l}$ according to

$$f_{\text{WIDE}, c} = \frac{N_{\text{WDMS}, l}(1 - f_{\text{PCEB}, l})}{N_{\text{WDMS}, h}(1 - f_{\text{PCEB}, h}) + N_{\text{WDMS}, l}(1 - f_{\text{PCEB}, l}),}$$

where $N_{\text{WDMS}, h}$ and $N_{\text{WDMS}, l}$ represent the number of WDMS binaries containing high-mass and low-mass white dwarfs, respectively, in the considered sample. The resulting PCEB fractions and the estimated fraction of low-mass white dwarfs among wide systems are listed in Table 4 for the different choices of $s f$. We would like to highlight two numbers given in this table. On the one hand we see that the fraction of wide WDMS binaries containing low-mass white dwarfs ($f_{\text{WIDE}, c}$) is $\sim 1 - 15$ per cent. The origin of these systems is unclear and is further discussed in Sect. 8. On the other hand, the most likely PCEB fraction for WDMS binaries containing low-mass white dwarfs ($f_{\text{PCEB}, l}$) is $\sim 80 - 99$ per cent. This shows that the large majority of WDMS binaries containing low-mass white dwarfs have formed as a consequence of common envelope evolution. For comparison, the most likely PCEB fraction for WDMS binaries containing high-mass white dwarfs is significantly smaller, i.e. $f_{\text{PCEB}, h} \sim 41 - 45$ per cent. In the next section we estimate the fraction of PCEBs among all low-mass white dwarfs (WDMS binaries with low mass white dwarf plus apparently single low-mass white dwarfs).

7 ARE MOST LOW-MASS WHITE DWARFS FORMED IN CLOSE BINARIES?

We have shown that $\sim 80 - 99$ per cent of the WDMS binaries containing low-mass white dwarfs are PCEBs. Roughly 10 per cent of apparently single white dwarfs also have low masses. If we assume a binary fraction of 60 per cent for solar type and more massive stars (e.g. Duquennoy & Mayor

| $s f$ | $f_{M_{\text{wd}} > 0.5}$ | $N_{\text{PCEB}, h}$ | $N_{\text{WIDE}, h}$ | $f_{\text{PCEB}, h}$ | $f_{\text{PCEB}, l}$ | $f_{M_{\text{wd}} < 0.5}$ | $N_{\text{PCEB}, l}$ | $N_{\text{WIDE}, l}$ | $f_{\text{PCEB}, h}$ | $f_{\text{PCEB}, l}$ | $f_{\text{WIDE}, c}$ |
|-------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.06 ± 0.03 | 39 | 99 | 0.28 ± 0.04 | 0.41 ± 0.05 | 0.35 ± 0.03 | 37 | 36 | 0.51 ± 0.06 | 0.80 +0.05 | 0.05 | 0.27 ± 0.04 | 0.15 ± 0.03 |
| 0.67 ± 0.04 | 30 | 85 | 0.26 ± 0.04 | 0.38 ± 0.05 | 0.33 ± 0.04 | 29 | 28 | 0.51 ± 0.07 | 0.80 ±0.04 | 0.05 | 0.25 ± 0.04 | 0.13 ± 0.03 |
| 1.00 ± 0.04 | 46 | 72 | 0.25 ± 0.04 | 0.36 ± 0.07 | 0.32 ± 0.04 | 44 | 24 | 0.53 ± 0.07 | 0.80 +0.08 | 0.05 | 0.25 ± 0.04 | 0.10 ± 0.03 |
| 1.50 ± 0.04 | 20 | 54 | 0.27 ± 0.05 | 0.39 ± 0.08 | 0.30 ± 0.04 | 17 | 15 | 0.53 ± 0.09 | 0.80 ± 0.13 | 0.05 | 0.22 ± 0.05 | 0.10 ± 0.03 |
| 1.50 ± 0.05 | 17 | 37 | 0.31 ± 0.06 | 0.45 ± 0.08 | 0.32 ± 0.05 | 16 | 9 | 0.64 ± 0.10 | 0.90 ± 0.14 | 0.05 | 0.20 ± 0.06 | 0.01 ± 0.03 |

Figure 4. Probability ratio as a function of PCEB fraction $f_A$ for WDMS binaries containing low-mass (solid line) and high-mass (dashed line) white dwarfs. The most likely fraction of PCEBs is given by the highest probability ratio, i.e. $f_A = 0.99$ for low-mass white dwarfs, and $f_A = 0.45$ for high-mass white dwarfs. The error of the most likely value is calculated by requiring the probability on each side of the maximum to reach 68.27 per cent indicated by the shaded regions.
and take the fraction of low-mass white dwarfs in our sample of WDMS binaries \( f_{M_{\text{wd}}<0.5} \) at face value, the 80-99 per cent of PCEBs among WDMS binaries containing low-mass white dwarfs make up a fraction of

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0.6 \times f_{M_{\text{wd}}<0.5} \times f_{\text{PCEB,1}} = 0.67 - 0.82
\]

of all low-mass white dwarfs (those in WDMS binaries in addition to those low-mass white dwarfs that are apparently single). In contrast, an analogous estimate for high-mass white dwarfs gives that only \( \sim 21 - 24 \) per cent of all high-mass white dwarfs (those among WDMS binaries plus those apparently single high-mass white dwarfs) are formed in close binaries.

8 POTENTIAL SELECTION EFFECTS IN THE WHITE DWARF MASS DISTRIBUTIONS

Taking into account observational biases due to our radial velocity method of identifying PCEBs in the white dwarf mass distributions of close and wide WDMS binaries, we calculated in the previous sections the most likely fraction of wide WDMS binaries containing low-mass white dwarfs (Sect. 7), as well as estimated the fraction of all low-mass white dwarfs that has formed in close binaries (Sect. 7). However, selection effects intrinsic to the SDSS survey may also have affected our white dwarf mass distributions. In what follows we consider the implications of the SDSS magnitude limits and the identification of WDMS binaries from their SDSS spectra.

8.1 The impact of a magnitude limited sample

A recurrent problem in using large-area surveys for population studies is that they are magnitude limited, rather than volume limited, and hence the survey volume will be a function of the intrinsic brightness, or absolute magnitude of the stars in the sample under study. In the case of SDSS, the magnitude limits are \( \sim 15.5 \) across all bands at the bright end, where the imaging saturates, and \( i \sim 19.1 \) at the faint end, which corresponds to the limit of the main quasar survey, which provided a large fraction of the SDSS WDMS binaries, but is also representative as a generic limit for the bulk of the spectroscopic follow-up within SDSS.

The absolute magnitude of white dwarfs depends on their effective temperature and radius, with the temperature decreasing with age as the white dwarfs cool, and the radius is decreasing with increasing mass, as they follow a mass-radius relation for degenerate objects. We have adopted the cooling sequences of Benvenuto & Althaus (1999) and Bergeron et al. (1992) to compute the effective temperature and absolute \( i \)-band magnitude for a 0.4 M\(_{\odot}\) He-core white dwarf and a 0.6 M\(_{\odot}\) CO-core white dwarf (Fig. 4, left, top two panels). Adopting the SDSS magnitude limits mentioned above, the absolute magnitude translates into a minimum and maximum distance at which SDSS may obtain follow-up spectroscopy for the star (Fig. 4, left, third panel from the top). The effective survey volume of SDSS is calculated by integrating, for all cooling ages \( \tau \), over a spherical cap in galactic coordinates for \( b > 30 \) and an adopted scale height of \( H_z = 200 \) pc for distances \( d_{\text{min}} \leq d \leq d_{\text{max}} \) (Fig. 4, left, bottom panel). For any given \( \tau \), the ratio of the two effective survey volumes \( V_{\text{He}}/V_{\text{CO}} \) gives the probability ratio of finding a He-core white dwarf compared to a CO-core white dwarf. To obtain the total probability ratio, we need to take into account that white dwarfs of different mass and core composition cool at different rates. Assuming a constant formation rate of white dwarfs, we integrate the survey volume over the cooling age,

\[
\int_{T_{\text{eff}(\text{min})}}^{T_{\text{eff}(\text{max})}} V \, d\tau
\]

We restrict this integral to cooling ages corresponding to \( T_{\text{eff}(\text{min})} = 12000 \) K, the temperature cut-off imposed on our sample by the “Balmer line problem” outlined in Sect. 2 and \( T_{\text{eff}(\text{max})} \) to the highest values available in the cooling models (corresponding to such low cooling ages that the integral is a good approximation of the total age-volume space). We find that, for field white dwarfs, it is \( \sim 2.75 \) more likely to find a 0.4 M\(_{\odot}\) He-core white dwarf within the SDSS spectroscopic follow-up than a 0.6 M\(_{\odot}\) CO-core white dwarf.

8.2 Identifying the spectroscopic composite nature of a WDMS binary

In order to identify a WDMS binary from SDSS spectroscopy, both stars need to be detectable within the composite spectrum. For late-type secondary stars, this implies an upper limit on the white dwarf temperature, \( T_{\text{eff}(\text{max})} \), at which we will be able to discern the companion in the SDSS spectrum. Conversely, the detection of white dwarfs next to early-type companions results in a lower limit on the white dwarf temperature, \( T_{\text{eff}(\text{min})} \). These temperature limits will depend somewhat on the white dwarf radius, and hence its mass. We have simulated composite spectra for a wide range of white dwarf temperatures and companion spectral types, adopting either a 0.4 M\(_{\odot}\) He-core or a 0.6 M\(_{\odot}\) CO-core white dwarf, and subjected those spectra to the same identification criteria as the observed SDSS spectra (Rebassa-Mansergas et al. 2010). Full details of this analysis will be given in a forthcoming paper where we investigate the overall completeness of the SDSS WDMS binary population. Here, we restrict the approach to estimate the relative bias within that WDMS binary population with respect to the white dwarf mass. For the latest spectral type companions, M8 and M9, we find \( T_{\text{eff}(\text{max})} = 16000 \) K and 13000 K for the 0.4 M\(_{\odot}\) He-core white dwarf, and \( T_{\text{eff}(\text{max})} = 24000 \) K and 19000 K for the 0.6 M\(_{\odot}\) CO-core white dwarf. For all other companion spectral types, we fix \( T_{\text{eff}(\text{max})} = 26000 \) K, limited by the He-core cooling models of Benvenuto & Althaus (1999). The corresponding cooling age is sufficiently small that the integrals defined above are

\[^2\] We used Bergeron’s updated grids available at [http://www.astro.umontreal.ca/~bergeron/CoolingModels/](http://www.astro.umontreal.ca/~bergeron/CoolingModels/)

\[^3\] A more detailed approach would require to take into account the exact tiling of the SDSS spectroscopy, however this would not significantly change the results.
Figure 5. The effective survey volume as a function of white dwarf cooling age for single white dwarfs (left), a WDMS binary with an M4 companion (middle) and a WDMS binary with an M9 companion (right). From top to bottom, the panels show: (1) the effective temperature for a 0.6 $M_\odot$ CO-core (solid line) and a 0.4 $M_\odot$ He-core white dwarf (dashed line). The effective temperature $> 12000$ K cut-off of our WDMS binary sample is indicated by the dotted horizontal line. (2) the absolute $i$-band magnitude of the system. (3) the saturation limit of SDSS ($\approx 15.5$) implies a minimum distance for the systems (lower two curves), the limiting magnitude of the main quasar survey ($\approx 19.1$) translates into a maximum distance (upper two curves). (4) the effective survey volume for an assumed scale height $H_z = 200$ pc and a Sloan-type sky coverage. The relative bias for He-core white dwarfs relative to CO-core white dwarfs (Fig. 6) has been calculated by integrating the effective survey volume over the cooling age range in which the systems can be identified as WDMS binaries from the SDSS spectroscopy (solid and dashed bold lines in the bottom middle and bottom right panels). For single white dwarfs the integral is restricted to cooling ages corresponding to $T_{\text{eff}}(\text{min}) = 12000$ K, and $T_{\text{eff}}(\text{max})$ to the highest values available in the cooling models (solid and dashed bold lines in the bottom left panel).

Figure 6. Relative probability ratio of finding a WDMS binary containing a He-core white dwarf rather than a CO-core white dwarf among objects with SDSS spectroscopy obtained as part of the main quasar survey, with the spectral type of the companion star running from M0 (left) to M9 (right). The right-most dot gives the probability ratio for single white dwarfs. The black dots take into account both the effective survey volume (Fig. 5) as well as the spectral-type dependent limits on the white dwarf temperature (and hence cooling age) imposed by the need for detecting signatures of both stars in the composite SDSS spectra. Shown as gray dots are the the probability ratios taking into account only the effective survey volumes.

We then repeat the calculation carried out in the previous Section, adding the absolute $i$-band magnitude of the companion (using the values of West et al. 2005) to that of the white dwarf, and integrating the survey volume between the cooling ages corresponding to the lower and upper limits on the white dwarf temperature. The evolution of the $i$-band magnitude $M_i$, the distance limits within SDSS, and the survey volume as a function of white dwarf cooling age are given in Fig. 5 for M4 (middle panels) and M9 (right panels) companions. For the M4 companion, $M_i$ converges to the absolute magnitude of the secondary star as the white dwarf cools, resulting in only mild variations in the survey volume as a function of cooling age. In contrast, the M9 companion contributes only little to the $i$-band even late in the evolution of the binary, and hence the change in the survey volume is very similar to that of a single white dwarf. Finally, we calculate the ratio of the integral in Eq. (6) for the 0.4 $M_\odot$ He-core white dwarf with respect to the 0.6 $M_\odot$ CO-core white dwarf for each companion spectral type (Fig. 6). This ratio can be interpreted as the probability ratio of finding a WDMS binary containing a He-core white dwarf compared to finding a WDMS binary containing a CO-core white dwarf within the SDSS follow-up spectroscopy. As expected, this bias is only mild for early-type companions, where the secondary star dominates the $i$-band light of the system – with the exception of M0 companions, where the CO-core white dwarfs have a larger $T_{\text{eff}}(\text{min})$ than the He-core, and hence the integral over the cooling age is smaller. For later type companions, the ratio gradually evolves towards that of single white dwarfs, except for M8 and M9 companions, where the larger size of the He-core white dwarfs results in lower $T_{\text{eff}}(\text{max})$ compared to the CO-core white dwarfs, and correspondingly lower integrals of $V d\tau$.

Given that the bulk of the WDMS binaries analysed here have companions with spectral types in the range M3–
Table 5. Taking into account selection effects intrinsic to SDSS we provide here both the revised fraction of low-mass white dwarfs among WDMS binaries \( f_{M_{\text{wd}}<0.5} \), as well as the revised fraction of low-mass white dwarfs among wide WDMS binaries \( f_{\text{WIDE,c}} \). The ranges provided are obtained by assuming different values of \( sf \), as defined in Table 4 and Sect. 6. The most likely PCEB fractions for WDMS binaries containing low- and high-mass white dwarfs \( (f_{\text{PCEB,1}} \) and \( f_{\text{PCEB,2}} \)), as well as the fraction of WDMS binaries containing high-mass white dwarfs \( (f_{M_{\text{wd}}>0.5}) \) remain the same as in Table 4. The revised fractions of all low-mass and high-mass white dwarfs (those in WDMS binaries in addition to those white dwarfs that are apparently single) formed in close binaries (denoted here as \( f_{\text{CLOSE,1}} \) and \( f_{\text{CLOSE,2}} \), respectively, see Sect. 7) are also provided. For completeness we also give the corrected fraction of low-mass white dwarfs among single white dwarfs \( f_{\text{inwd,s}} \).

| \( f_{M_{\text{wd}}<0.5} \) | \( f_{\text{WIDE,c}} \) | \( f_{\text{CLOSE,1}} \) | \( f_{\text{CLOSE,2}} \) | \( f_{\text{inwd,s}} \) |
|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 0.20-0.23                | 0.005-0.10               | 0.72-0.88                | 0.27-0.30                | 0.37                     |

M4 (Schreiber et al. 2010), the bias that they contain He-core white dwarfs is \( \sim 1.5 \), which is lower than the bias for single white dwarfs, \( \sim 2.75 \). This implies slightly revised low-mass white dwarf fractions among our WDMS binaries. Considering equation 4 and 5 but taking into account the additional bias, we provide in Table 5 the best estimates for the low-mass white dwarf fractions among our WDMS binaries. Note that the most likely PCEB fractions for WDMS binaries containing low- and high-mass white dwarfs \( (f_{\text{PCEB,1}} \) and \( f_{\text{PCEB,2}} \)), as well as the fraction of WDMS binaries containing high-mass white dwarfs \( (f_{M_{\text{wd}}>0.5}) \) remain the same as given in Table 4.

A direct consequence of the selection effects outlined above is that the low-mass peak in the white dwarf mass distribution of PCEBs (Fig. 1) is expected to be less pronounced. However, the detected excess of low-mass white dwarf in PCEBs remains as both close and wide WDMS binaries are affected by the same bias. On the other hand, comparing white dwarf mass distributions of wide WDMS binaries and single white dwarfs is somewhat affected as the bias towards the detection of low-mass white dwarfs in both subsamples is slightly different. This may partly explain the relatively low KS probability of 4 per cent between the two distributions obtained in Sect. 4.

8.3 A note on resolved binaries on SDSS images

As discussed in more detail in Schreiber et al. (2010), very wide and not too distant WDMS binaries can be resolved on their SDSS images, and are herefore excluded from our WDMS binary sample. This implies that we slightly overestimated the PCEB fractions. However, this effect should not dramatically change our results, i.e. by not more than 5 – 10 per cent (Schreiber et al. 2010).

9 DISCUSSION

The main results found in the previous sections can be summarized as follows. White dwarf mass distributions of PCEBs and wide WDMS binaries differ significantly. While the former contains a much larger fraction of low-mass white dwarfs, the latter is similar to single white dwarf mass distributions. This is the so far strongest observational confirmation that large numbers of low-mass white dwarfs are formed due to binary interactions. However, even if we take into account observational biases and selection effects, \( \sim 0.5-10 \) per cent of the whole WDMS binary sample also contains low-mass white dwarfs of uncertain origin. In the following we discuss the implications of these results on white dwarf mass distributions in general and the origin of apparently single low-mass white dwarfs in particular.

9.1 Wide WDMS binaries as proxies for single white dwarfs

We have shown that the mass distribution of wide WDMS binaries is similar to that of single white dwarfs. On the one hand, this might seem trivial to interpret as the primary in a wide binary should evolve into a white dwarf the same way a single star does. On the other hand, the initial mass function (IMF) of the primary stars in wide binaries and the IMF of single stars are not necessarily identical. For example, the binary fraction of low-mass (i.e. \( M<1\,M_{\odot} \)) main sequence stars seems to depend on the mass of the primary star (Lada 2006). However, here we need to consider only binary stars with primaries \( \geq 1\,M_{\odot} \), as lower mass stars are still on the main sequence and have not yet evolved into white dwarfs. The measured binary fractions for solar type stars is \( \sim 60-70 \) per cent (e.g. Duquennoy & Mayor 1991), and similar fractions are obtained for higher mass stars (Dawson & Schröder 2010). Hence, it is not surprising that the white dwarf mass distribution of wide WDMS binaries resembles the single white dwarf mass distribution and we may use it as a proxy for the single white dwarf mass distribution. In particular, the \( \sim 0.5-10 \) per cent of low-mass white dwarfs among wide WDMS binaries (Table 5) can be compared with the fraction of single low-mass white dwarfs.

9.2 The origin of low-mass white dwarfs in wide binaries

As mentioned in the introduction, a second peak at \( \sim 0.4\,M_{\odot} \) containing about 10 per cent (\( \sim 4 \) per cent if we take into account selection effects in SDSS, see Table 5 of the systems has been frequently found in single white dwarf mass distributions (e.g. Bergeron et al. 1992, Braggia et al. 1993, Liebert et al. 2003, Kepler et al. 2007). Note that this peak is not obvious to the eye in Fig. 2 (gray distribution, due to the size of the binning used). Extensive radial velocity surveys have shown that about the half of these apparently single white dwarfs are in fact double degenerates (see e.g. Kilic et al. 2007b, and references therein). The remaining \( \sim 2 \) per cent however, represent a population of low-mass white dwarfs that do not show any signs for a companion, i.e. no infrared excess and no radial velocity variations (see Maxted et al. 2000, Napiwotzki et al. 2007). Possible explanations for the existence of these stars include severe mass-loss on the first giant branch (Kilic et al. 2007b), stellar envelope ejection due to nearby giant planets (Nellemans & Tauris 1998), the merging of two very low-mass white dwarfs (Han et al. 2002, Iben & Tutukov 1986).
Iben (1990), or supernova type Ia explosions in semi-detached close binaries that blow away the envelope of the companion thus exposing its low-mass core (Justham et al. 2000). Interestingly, the fraction of low-mass white dwarfs among wide WDMS binaries estimated in Sect. 5 i.e. ~ 0.5 – 10 per cent, resembles the typical ~ 4 per cent of low-mass white dwarfs among apparently single white dwarfs. Given that hierarchical triple systems are a common configuration (e.g. Tokovinin 1997), it appears plausible to assume that a significant fraction of the wide binaries containing a low-mass white dwarf are in fact triple systems, or descendants from triple systems, either containing close double degenerate primaries, or low-mass white dwarfs that formed from the merging of two very low-mass white dwarfs. Indeed, a handful of triple systems containing a short-period double degenerate are known: WD 1704+481 has been identified by Maxted et al. (2000b) and Finley & Craig (2001) as a triple-degenerate, containing a He-core plus CO-core close binary double degenerate with an orbital period of 0.1448 d and a wide, average-mass CO-core white dwarf companion. WD 1824+040 (G21–15) is a similar triple, containing a close double-degenerate (see Saffer et al. 1998) with a 6.266 d orbital period (Maxted & Marsh 1999) and a wide, cool white dwarf companion (Farhi et al. 2005). Even more relevant to the discussion here are PG 1204+450, a close double-degenerate (Saffer et al. 1998) with a period of 1.6 d (Maxted et al. 2002b) and a wide M4 companion (Farhi et al. 2005), and PG 1241–010, a close double-degenerate with a period of 3.3 d (Marsh et al. 1993) and a wide M9 companion (Farhi et al. 2005). Therefore, a radial velocity survey of the low-mass white dwarfs among the wide binary candidates in our sample will be an interesting exercise. In the same way, as the double degenerate scenario may account for low-mass white dwarfs in wide WDMS binaries, the formation channel proposed by Nelemans & Tauris (1998) (stellar envelope ejection due to nearby giant planets) should work in wide binary systems. Nearby planets exist around the stellar components of binary systems (see Desidera & Barbieri 2007, and references therein) and the presence of a wide companion does not affect the interaction between the planet and its host star. Another possibility is given by the single star formation scenario for low-mass white dwarfs proposed by Kilic et al. (2007a). If severe mass loss of the white dwarf progenitors on the first giant branch accounts for single low-mass white dwarfs, it should be present in wide binaries too as the stellar components of wide binaries evolve just like single stars.

In contrast, the supernova Ia channel proposed by Justham et al. (2000) appears to be unlikely to produce low-mass white dwarf primaries in wide binary systems. The explosion supposed to strip off the envelope should accelerate the core of the former secondary star far beyond the velocity required to escape from a wide M-dwarf companion.

9.3 A note on spectroscopic white dwarf masses

Since large scale surveys such as the SDSS or the SPY (the ESO SN Ia Progenitor survey, see Napierwotzki et al. 2001) provide spectra of thousands of white dwarf stars, fitting atmosphere models to observed spectra has become the most frequently used method to determine white dwarf masses (e.g. Finley et al. 1997; Liebert et al. 2003; Kepler et al. 2007). The white dwarf masses used in this work have been obtained with such an algorithm combined with spectral decomposition methods (Rebassa-Mansergas et al. 2010). Atmosphere model fits to optical spectroscopy are generally thought to provide reliable estimates of white dwarf masses, with the exception of the well known problems concerning cool white dwarfs mentioned above. For this reason, we have excluded white dwarfs with effective temperatures below 12000 K, and by common standards, our white dwarf masses should be robust and reliable.

However, recent work suggest that there may be a systematic problem with mass determination from model atmosphere fits. Silvestri et al. (2001) presented gravitational redshift mass estimates for a sample of 41 white dwarfs in common proper motions pairs and noticed that their mean mass was slightly higher than in previous studies. More recently Falcon et al. (2010) reported an average white dwarf mass of 0.647 M⊙ for 449 non-binary DA white dwarfs from SPY determined also from gravitational redshift measurements. This value is again significantly exceeding (by ~ 0.03 – 0.05 M⊙) the mean white dwarf masses that have been obtained from model atmosphere fits to large samples. A similar trend has been found by Tremblay & Bergeron (2009) who incorporated improved physics of the Stark broadening of the Balmer lines in their white dwarf atmosphere models and obtained a mean white dwarf mass higher by 0.034 M⊙. It seems hence that the previous work based on atmosphere models may have systematically underestimated the white dwarf masses.

Our white dwarf masses were determined based on the models of Koeper et al. (2003), which did not incorporate the new Balmer line profiles of Tremblay & Bergeron (2009), and hence there is the possibility that our masses are systematically lower than the true white dwarf masses by 0.03 – 0.05 M⊙. This would imply a slight decrease in the relative numbers of low-mass white dwarfs in wide binaries as the close binary fraction is increasing towards smaller masses below the mass limit of 0.5 M⊙ (see Fig. 3). However, this effect can clearly not explain the existence of all alleged low-mass white dwarfs that appear not to be within close binaries.

9.4 The missing very low-mass white dwarf primaries

Recently, a number of extremely low-mass white dwarfs (< 0.2 M⊙) have been found in double degenerates (Liebert et al. 2003; Kawka et al. 2006; Kilic et al. 2007a; Marsh et al. 2010; Kulkarni & van Kerkwijk 2010), including the first eclipsing double-degenerate binary (Steinfadt et al. 2010). In contrast, we do not find any good candidate for such an ultra-low-mass white dwarf within the entire WDMS binary sample.

For PCEBs this difference might be related to the fact that the formation of very low-mass white dwarfs requires the progenitor of the white dwarf to fill its Roche-lobe early on the first giant branch. While systems with relatively massive companions apparently can survive the resulting common envelope evolution, systems containing M-dwarf companions may instead merge (as they must have smaller initial binary separations and consequently less orbital energy is available to expel the envelope of the primary).
In wide WDMS binaries, the lack of extremely low-mass white dwarfs seems to indicate that a triple system consisting of a double degenerate primary (of which at least one of the components is an extremely low-mass white dwarf) with an M-dwarf secondary in a wide orbit (Sect.10), might not be a common configuration. One may finally speculate that the majority of all double degenerate primaries containing extremely low-mass white dwarfs have merged to form wide WDMS binaries in which the resulting white dwarf mass is at least \( \gtrsim 0.35M_\odot \).

10 CONCLUSION

The white dwarf mass distributions of PCEB and wide WDMS binary candidates are significantly different. While the mass distribution of wide WDMS binary candidates resembles those of single white dwarfs, the PCEB white dwarf mass distribution contains a large number of low-mass white dwarfs. Taking into account both the PCEB detection probabilities of the measurements and selection effects in SDSS we find that the large majority of low-mass white dwarfs resides in close binary stars. This result confirms a crucial prediction of current theories of close binary evolution and provides the so far strongest observational evidence for common envelope evolution forming most close compact binary stars.

In agreement with the fraction of \( \sim 4 \) per cent apparently single low-mass white dwarfs identified in single white dwarf samples, \( \sim 0.5 - 10 \) per cent of the wide binaries in our sample seem to contain low-mass white dwarfs. These low-mass white dwarfs in wide binaries must have either formed due to exceptionally strong mass-loss of the primary progenitor on the first giant branch or are the descendants of triple systems, and some are expected to contain a close double degenerate primary component.

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