Post-common envelope binaries from SDSS-VII: A catalogue of white dwarf-main sequence binaries

A. Rebassa-Mansergas, B. T. Gansicke, M. R. Schreiber, D. Koester, P. Rodríguez-Gil

ABSTRACT

We present a catalogue of 1602 white dwarf-main sequence binaries (WDMs) from the spectroscopic Sloan Digital Sky Survey Data Release 6 (SDSS DR6). Among these, we identify 440 as new WDMs binaries. We select WDMs binary candidates from template fitting all 1.27 million DR6 spectra, using combined constraints in both 2 and signal-to-noise ratio. In addition, we use Galaxy Evolution Explorer (GALEX) and UKIRT Infrared Sky Survey (UKIDSS) magnitudes to search for objects in which one of the two components dominates the SDSS spectrum. We use a decom position/fitting technique to measure the effective temperatures, surface gravities, masses and distances to the white dwarfs, as well as the spectral types and distances to the companions in our catalogue. Distributions and density maps obtained from these stellar parameters are then used to study the general properties and the selection effects of WDMs binaries in SDSS. A comparison between the distances measured to the white dwarfs and the main sequence companions shows $d_{\text{wd}} > d_{\text{mc}}$ for 1/5 of the systems, a tendency found already in our previous work. The hypothesis that magnetic activity raises the temperature of the inter-spot regions in active stars that are heavily covered by cool spots, leading to a bluer optical colour compared to inactive stars, remains the best explanation for this behaviour. We also make use of SDSS-GALEX-UKIDSS magnitudes to investigate the distribution of WDMs binaries, as well as their white dwarf effective temperatures and companion star spectral types, in ultraviolet to infrared colour space. We show that WDMs binaries can be very efficiently separated from single main sequence stars and white dwarfs when using a combined ultraviolet, optical, and infrared colour selection. Finally, we also provide radial velocities for 1068 systems measured from the Na I 8183.27, 8194.81 absorption doublet and/or the H-β emission line. Among the systems with multiple SDSS spectroscopy, we find new systems exhibiting significant radial velocity variations, identifying them as post-common envelope binary candidates.

Key words: Binaries: spectroscopic | stars:low-mass | stars:white dwarfs | binaries: close | stars:post-AGB | stars:evolution variables

1 INTRODUCTION

Binaries containing a white dwarf primary plus a main sequence companion were initially main sequence binaries in which the more massive star evolved through the giant phase and became a white dwarf. In the majority of cases, the initial separation of the main sequence binary is wide enough to allow the evolution of both stars as if they were single. A small fraction is believed to undergo a phase of dynamical unstable mass transfer once the more massive star is on the giant branch or the asymptotic giant branch (Webbink 1984; de Kool 1993; N. L. Mons & Ko 2004). As a consequence of this mass transfer, the envelope of the giant will engulf its core and the companion star, i.e., the system is entering a common envelope phase (CE, e.g., Livio & Soker 1988; Iben & Livio 1993; Taam & Sandquist).
Population synthesis models have been developed for a variety of binary stars undergoing CE evolution (Dewi & Tauris 2000; Naef & Tout 2003; Pols & Podsiadlo 2004; Davies et al. 2008; Podsiadlo & Pols 2004; Davies et al. 2008). However, the theoretical understanding of both CE evolution and magnetic braking is currently poorly constrained by observations (Schreiber & Ganseke 2003), and progress on this front is most likely to arise from the analysis of a large sample of PCEBs that are well-understood in terms of their stellar companions. W D M S binaries appear most promising in this regard, as their stellar components are relatively simple, and the SD SS (York et al. 2002; Stoughton et al. 2002; A Rebassamanserga et al. 2009) o en the possibility to dramatically increase the number of W D M S binaries available for detailed follow-up studies. Up to date there exist four compilations of SD SS W D M S binaries, namely Eisenstein et al. (2006) (obtained as part of their search of white dwarfs), Silvestri et al. (2003) (which contains also Raymond et al. 2003; Silvestri et al. 2004) as a subset, and was claimed to be complete for the SD SS DR5) A ugustei et al. (2008) (obtained from SD SS DR5 using colour cuts plus proper motions), and H e et al. (2009) (obtained from a search for sdB stars in the SD SS DR6).

Here we initiate a comparative study to compile a master sample of spectroscopic W D M S binaries from SD SS. In this first publication we make use of the SD SS spectroscopic DR6 (A dehan M cC arthy et al. 2003) to create a catalogue of 1300 W D M S binaries and candidates that were serendipitously observed. This list is not only a superset of all previous SD SS W D M S binary compositions, but also includes 440 new W D M S binaries. In addition we provide a coherent analysis of the system parameters of both stellar components, as well as an extension to Ga LEX/U K D SS coobs to study the properties of SD SS W D M S binaries. In a parallel e ort, and as part of SEGUE (the SD SS Extension for Galactic Understanding and Exploration), some of us carried out a dedicated program to identify 300 W D M S binaries containing cold white dwarfs (Schreiber et al. 2007), a population clearly underrepresented in previous samples of W D M S binaries. A detailed analysis of the SEGUE population of W D M S is in preparation (Schreiber et al. 2009). Finally, we plan to summarize our e orts by presenting the W D M S binary content of the na l SD SS data release (DR7, A Rebassamanserga et al. 2009).

This last paper will be accompanied by a public online data base of W D M S binaries.

The na l master sample of all spectroscopic SD SS W D M S binaries will form a superb database for future follow-up studies of W D M S binaries. In particular, analysing the fraction and the characteristics of the PCEBs among the W D M S binaries may provide strong constraints on current theories of compact binary evolution. Rebassamanserga et al. (2003b; Schreiber et al. 2003, Rebassamanserga et al. 2003b; Pyraz et al. 2003; Nebot Gomez-Moran et al. 2003; Schwope et al. 2003b).

The structure of the paper is as follows. In Sect. 2 we present our method of identifying W D M S binaries, and estimate the completeness of the sample in Sect. 3. In Sect. 4 we provide our na l catalogue. Using a spectral decomposition model of an sdD model atmosphere, we derive white dwarf effective temperatures, surface gravities, masses, companion spectral types, and distances in Sect. 5. We compare these stellar parameters to those obtained in other studies in Sect. 9 and Sect. 10, respectively. We finally measure the Na: 8183.27,8194.81 absorption doublet and/or the H emission radial velocities in Sect. 11, and summarise our results in Sect. 12.

2 IDENTIFICATION OF W D M S BINARIES IN SD SS

2.1 Computation of method

We have developed a procedure based on 2 tem plate fitting in order to automatically identify W D M S binary candidates from the SD SS spectroscopic database. A dehan M cC arthy et al. (2003a). Our initial tem plate set consisted of several dozen SD SS spectra of companions of W D M S binaries from Eisenstein et al. (2006) and Silvestri et al. (2007). These spectra were chosen to sample a broad range in white dwarf temperature and subtypes (DA, DB, and DC) as well as companion stellar spectral types, and to be of high signal-to-noise ratio (S/N). A set of representative tem plate plates is shown in Fig. 1. In addition, we compiled a set of 17 single DA white dwarf tem plate spectra from Eisenstein et al. (2006) list, covering the entire observed range of T and log g, as well as the M (O-M 9) Bochanski et al. (2003) M dwarf tem plate plates.

Each of these W D M S binary, white dwarf, and M dwarf tem plate plates were then tied to the full 1.27 m liquid spectrum in DR 6. In this process, the tem plate spectrum was normalised to the SD SS spectrum under scrutiny, and a reduced 2 was calculated using the flux errors of the two spectra added in quadrature. In practice, our tem plate procedure produced for each of the W D M S binary, white dwarf and M dwarf tem plate plates a list of spectrum identi er (MJD-PLT-EB), S/N of the spectrum, and for all SD SS DR5 spectra. For each of the tem plate, we plotted 2 as a function of S/N of the target spectrum (see Fig. 2), and deduced a power law relation 2 2 = a S N . We considered any spectrum with

$$2 \text{spec} << 2 \text{ax}$$
as a candidate W D M S binary, white dwarf, or M-dwarf (depending on the current template). The S/N-dependent form of $\sigma_{\text{max}}$ accounts for the increase of $\sigma$ for higher values of S/N. This constraint had to be defined individually for each of the templates, as the different spectral shapes resulted in a large spread of $\sigma$ distributions. The $(\sigma, S/N)$ planes obtained from fitting the SDSS spectra are shown for two different W D M S binary templates in Fig. 2.

After a first run through the DR6 spectra, we complemented the template set with the spectra of a number of newly identified W D M S binaries, and re-run the fitting for those new templates again. That process was repeated until no new W D M S binary candidates were found (at which point we had used a total of 163 different W D M S binary template spectra.

Even though the above method efficiently identified W D M S binary candidates among the spectra in DR6, the choice of $\sigma_{\text{max}}$ alone does not avoid completely the merging of other astronomical objects, such as quasars, main sequence stars, and galaxies. In addition, for templates that are dominated by the white dwarf (M-dwarf), the list of candidates will unavoidably contain a substantial number of single white dwarfs (M-dwarfs). Hence we visually inspected all W D M S binary candidates, as well as the white dwarf and M-type star subsamples (a total of 70000 spectra), and removed those objects that were not of our interest, i.e., neither W D M S binary, white dwarf, or M-dwarf candidates. The final result of the template fitting was a list of 1491 W D M S binary candidates, 8368 single white dwarf candidates, and 15379 single M-dwarf candidates. It is worth mentioning that we found here 36 W D M S binaries that were observed only first by SEGUE, and consequently decided to include them in the SEGUE list of W D M S binaries (Schreiber et al. 2009, in preparation).

2.2 Red and blue excess in SDSS spectra: help from G A L E X and U K I D S S

While the template fitting proved to be a robust method to nd W D M S binaries in which both stellar components contribute clearly visible amounts of $\nu x$, the procedure is prone to misclassify white dwarf dominated W D M S binaries as single white dwarfs, and M-dwarf dominated W D M S binaries as single M-dwarfs. We therefore decided to probe

Figure 1. Six examples of previously known W D M S binaries used in this work as W D M S binary templates. SDSS names and MJD-PLT-FID identifiers are indicated for each of them. White dwarf effective temperatures and spectral type of the companions (see Sec. 5) are also indicated in each panel.
more specifically for the presence of excess \( \nu \) at the red (blue) end of the SDSS spectra in objects classified initially as single white dwarfs (M-dwarfs).

For the search of red \( \nu \) excess in single white dwarf candidates, we used synthetic white dwarf spectra computed with the code described by Kester et al. (2004) to the SDSS spectra, and then calculated the reduced \( \chi^2 \) over the wavelength ranges 4000 7000 Å (\( \nu_1 \)) and 7000 9000 Å (\( \nu_2 \)). Objects with \( \chi^2 > 1.5 \) were \( \text{promoted} \) from single white dwarf candidates to W D M S binary candidates.

The search for blue \( \nu \) excess proceeded in an analogous fashion for the single M-dwarf candidates, only that we used the set of high S/N M-dwarf templates from Rebassa-Mansergas et al. (2003) instead of M-dwarf spectra, and calculated the reduced \( \chi^2 \) over the wavelength ranges 4000 5000 Å and 7000 9000 Å. Objects with \( \chi^2 > 1.5 \) were \( \text{promoted} \) from single M-dwarf candidates to W D M S binary candidates.

On the left and right top panels of Fig. 3, we show the SDSS spectra (black line) and SDSS magnitudes (red dots) of SDSS J132925.21 + 123025.5 and SDSS J131928.80 + 580634.2, along with the best-\( t \) white dwarf model and M-dwarf template plates (red lines, blue dandles). These two objects were initially classified by our template-fitting procedure as single white dwarf and single M-star candidates, respectively, but \( \text{promoted} \) to W D M S binary candidates by the \( \nu \) excessism measured as described above. The \( \nu \) excess is more obvious when plotting \( F \) (blue left panel) instead of \( F \) (top left panel). However, in several cases, the detection of blue or red \( \nu \) excess is rather marginal.

As a next step in our search for W D M S binaries, we have cross-correlated our entire list of W D M S binary candidates with GALEX (Martin et al. 2007; Morrissey et al. 2007) DR 4, providing near- and far-ultraviolet (\( \nu \)) magnitudes, and with the DR 4 of UK IDSS (Dye et al. 2004; Hewett et al. 2004; Lawrence et al. 2003), providing infrared \( yJH K \) magnitudes. We then inspected the observed ultraviolet-optical spectral energy distribution of all secondary star dominated W D M S binary candidates, and the optical-infrared spectral energy distribution of all white-dwarf dominated W D M S binary candidates. Objects where a clear ultraviolet or infrared excess was detected were then included in our W D M S binary sample.

For SDSS J132925.21 + 123025.5, the UK IDSS magnitudes unambiguously confirm the existence of a low-\( t \) mass companion (bottom left panel of Fig. 3). Similarly, the ultraviolet GALEX magnitudes clearly confirm the presence of a white dwarf primary in SDSS J131928.80 + 580634.2 (bottom right panel of Fig. 3).

2.3 SDSS images

As a final check on the nature of the W D M S binary candidates, we inspected their SDSS DR 6 images for morphological problems and found primarily two types of issues.

Firstly, single white dwarfs (M-dwarfs) may occasionally be located close to very bright M-dwarfs (white dwarfs or A-stars) causing scattered light to enter the spectroscopic box, resulting in an apparent two-componet spectrum. A spectacular example is SDSS J073531.86 + 315015.2 (left panels of Fig. 4); the SDSS spectrum clearly exhibits an M-dwarf at red wavelengths and a blue component with strong Balmer lines in the blue (however, the SDSS image reveals that this is a single M-dwarf at a distance of 12 arcmin in of Castor A/B (two \( V = 188 \) and \( V = 286 \) A-stars). The SDSS magnitudes (red dots) are superimposed on the SDSS spectrum (black) and are consistent with a single red star. Single M-dwarfs are also likely to be found superimposed with single early-type stars in the same figure. An example is SDSS J05827.24 + 05642.6 (see middle top panel of Fig. 4). At first glance one could be tempted to consider it a spatially resolved W D M S binary pair. However, the SDSS spectrum (middle bottom panel of the same figure) shows the typical Balmer lines of an early \( F \) star in the blue, while at redder wavelengths the typical spectral features of a low-\( m \) mass star can be seen. The large difference in absolute magnitudes between the two spectral types implies that these two stars are a chance superposition along the line of sight, and not a physical binary.

Secondly, SDSS images can help identifying W D M S binaries among our sample that are spatially resolved, but close enough that \( \nu \) from both stars will enter into the spectroscopic box. In such cases, the SDSS magnitudes are often discrepant with the \( \nu \)-calibrated SDSS spectrum, and/or have large errors as consequence from the deblending applied by the photometric pipeline. Figure 4 (top right panel) shows the SDSS image of SDSS J025306.37 + 01329.2, which reveals a spatially resolved pair of red and blue stars. The SDSS spectrum of SDSS J025306.37 + 01329.2 contains the typical signatures of a W D M S binary, i.e. broad Balmer lines from the white dwarf and TID absorption bands from the M-dwarf; however, the errors on the SDSS magnitudes are typically large, and do not match well the \( \nu \)-calibrated SDSS spectrum.

2.4 Cross-checks with previous W D M S binary catalogues

A total number of 1491 W D M S binary candidates were identified in Sect. 2.2. From the analysis carried out in Sect. 2.2 and Sect. 2.3 we have identified 94 and 89 W D M S binaries by their blue and red excess respectively, while 115 W D M S binary candidates were removed after inspecting their SDSS images. This increased the number of system to 1559 W D M S candidates in the spectroscopic SDSS DR 6 data base.

In order to evaluate the efficacy of our procedure we compared our results to previous published lists of W D M S binaries from SDSS, namely van den Beesselaar et al. (2004), Eisenstein et al. (2005), Silvestri et al. (2007) (which includes the system from Raymond et al. 2003) and Silvestri et al. (2008) as a subset, Augusteijn et al. (2008), and Heller et al. (2003). This comparison is summarised in Table 1.

The 15 W D M S binaries containing DB (13) and DC (2) white dwarfs presented by van den Beesselaar et al. (2004) have been successfully identified as W D M S binaries with our template-fitting algorithm. The W D M S binary sample presented by Eisenstein et al. (2005) is almost entirely contained in the W D M S binary catalogue provided by Silvestri et al. (2007) (see below for a detailed comparison). Only ten
A catalogue of white dwarf main sequence binaries

Figure 2. S-N plane obtained fitting two of our WDMS binary templates (SDSSJ103121.97+202315.1, left and SDSSJ204431.44-061440.2, right) to the entire SDSS spectra database. Objects falling in the area defined by \( \frac{S}{N} < 0.001 \) were considered WDMS binary candidates. Left panel: \( \frac{S}{N} \approx 0.001 \) \( S=N^0 \). Right panel: \( \frac{S}{N} \approx 0.0001 \) \( S=N^{0.5} \). WDMS binary candidates are shown in magenta, in red the equation \( \frac{S}{N} < a \) \( S=N^0 \) for each template.

Figure 3. Top left: SDSS spectrum of SDSSJ132925.21+123025.5, a WDMS binary candidate initially catalogued as single DA white dwarf. The red dots represent the SDSS magnitudes. Middle left panel: the best white dwarf model is superimposed in red, unambiguously identifying the red excess of the binary. Bottom left panel: SDSS and UKIDSS magnitudes superimposed to the SDSS spectrum. Again, the UKIDSS magnitudes clearly show the presence of a low-mass companion. Top right panel: the same for SDSSJ131928.30+580634.2, an initially catalogured early M-type star. Middle and bottom right panels: the best M-type and the ultraviolet GALAX magnitudes clearly confirm the presence of a white dwarf primary, respectively. The red and blue straight lines represent the white dwarf solutions (red for the hot, blue for the cold) obtained from deconvolving/fitting the spectrum (see Sect5)
objects of [Eisenstein et al. 2004] with available SDSS spectra are not listed in [Silvestri et al. 2007], and our algorithm has successfully identified these ten systems as W D M S binaries.

Silvestri et al. (2007) claim that their catalogue contains 1253 objects but in fact only 1228 spectra (corresponding to 1225 objects) are listed in the electronic edition of their paper, and 996 systems of those appear in our catalogue. One is a SEQUEI object and will be included in Schreiber et al. (in preparation). The vast majority (i.e. 204) of the remaining 229 objects are not classified as W D M S binaries by us, either because of their spectroscopic appearance, or because of morphological problems in the SDSS images. Two example pairs of m-classed W D M S binaries are the z = 0.21 quasar SDSS J032428.78-004613.8 and the z = 0.11 galaxy SDSS J114334.70+455134.2. An updated classification of the 204 objects is given in Table 2, whilst the full table is available in the electronic edition of this paper. The spectra of the 25 genuine W D M S binaries identified by Silvestri et al. (2007) but overlooked by our template fitting algorithm, are dominated by the emission of one of the stellar components. We added these 25 W D M S binaries to our sample.

A ugust e i n et al. (2008) developed a W D M S binary identification algorithm based on SDSS imaging and the proper motion catalogue provided by Cool & Kollmeier (2004). This way they identified 651 W D M S binary candidates with SDSS ugriz photometry, of which 95 are contained in the SDSS DR5 spectroscopic data base. Cross-correlating their full list of 651 objects against the DR6 spectroscopic data base we nd 176 spectra for 130 objects. All but 20 of these objects were in our list. Again, the majority of those systems (16) that have not been identified by our template fitting procedure are not W D M S binaries.

We identify nine quasars, three cataclysmic variables, one F star, one M-dwarf, one DA white dwarf, and one DC white dwarf. The four remaining W D M S binaries have been overlooked by our method because they contain rather cold white dwarfs and the spectra are dominated by the companions. We added the four systems to our sample.

Recently, Heller et al. (2009), discussed the properties of 636 colour selected W D M S binaries from SDSS DR5. Most of their systems had been identified previously. Comparing their sample with our catalogue we nd 82 objects missing in our list. Inspecting the SDSS images and spectra (if available) of these 82 systems we nd 81 of them not being W D M S binaries. Two example pairs are the low-redshift galaxy SDSS J122953.46+473150.3 (U7639, van den Bergh et al. 1998), and again the z = 0.21 quasar SDSS J032428.78-004613.8, also included in Silvestri et al. (2007). An updated classification for these 81 objects is provided in Table 2 whilst the complete table is provided in the electronic edition of this paper. Only one system analysed by Heller et al. (2009) but not in our sample turned out to be a W D M S binary, and we added it to our catalogue.

In summary, comparing the sample of W D M S binaries obtained with our template fitting procedure with previously published catalogues of W D M S binaries shows that our method represents a robust and efficient tool to identify W D M S binaries (Table 1).

### Table 1. Comparison of the W D M S binaries identified here with those provided in previous publications.

| Publication | N_{W D M S} | N_{ident} | N_{rem ov} | N_{lost} |
|-------------|------------|-----------|------------|----------|
| van den Besselaar et al. (2005) | 15 | 15 | - | - (0%) |
| Silvestri et al. (2007) | 1225 | 996 | 204 | 25 (2%) |
| Augusteijn et al. (2008) | 130 | 110 | 16 | 4 (3%) |
| Heller et al. (2009) | 636 | 554 | 81 | 1 (0.1%) |

### Table 2. Updated classification of the 204 objects from Silvestri et al. (2007) which are not considered as W D M S binaries by us. The complete table can be found in the electronic edition of the paper.

| Object | Class ification |
|--------|-----------------|
| SDSS J001324.33-085021.4 | M star + ? |
| SDSS J003839.36+260258.5 | G star |
| SDSS J005714.52-000755.8 | M star |
| SDSS J005827.24+005642.6 | M + M S superposition |
| SDSS J072516.98-010944.2 | M star |

### Table 3. Updated completeness of the sample.

In the previous section we showed that our selection method successfully recovered the vast majority of previously identified SDSS W D M S binaries. In this section, we investigate both the internal completeness of our catalogue, i.e. the fraction of W D M S binaries contained in the DR6 spectroscopic data base that has been identified by our algorithm, and the external completeness, i.e. the fraction of point sources for which SDSS ugriz photometry is available that has been spectroscopically observed by SDSS. A detailed study of the external (spectroscopic) completeness of W D M S binaries within SDSS is currently underway, and we use this paper to provide preliminary results on this issue. To that end, we must definitively regions in SDSS colour-colour planes: the W D M S binary exclusion region that has been defined by Khansari et al. (2002) as part of the quasar selection algorithm, and two small rectangular boxes in the (g r i z) plane that sample a significant portion of W D M S binaries in colour space. Particularly, these two boxes were defined to test how the external completeness varies between inside and outside the W D M S exclusion box. The u g r i z colour-colour diagram shown in Fig 4 illustrate the locations of these regions (W D M S box, 1, box 2). The W D M S binaries in our sample excluding those systems that are classified as cataclysmic variables only (see Sect. 3) are shown in black, stellar sources are in grey, and quasars in light grey. Highlighted in light blue are the white dwarf (W D), A-star (A) and W D M S binary exclusion regions defined by Khansari et al. (2002). Both the A-star and the W D M S binary region in the colour planes are combined with a logical "and". Box 1 and box 2 are defined by (0.5 < g < 0.2, 0 < r < 0.2) and (0.3 < g < 0.3, 0.3 < r < 0.3, respectively).
A catalogue of white dwarf main sequence binaries

Figure 4. SDSS images of three WDMS binary candidates. Top left panel: SDSS image of SDSS J073531.86 + 315015.2 (30° 30'), a single red star initially considered as a WDMS binary candidate. Bottom left panel: SDSS magnitudes (red dots) and spectrum (black line) of the same system. The light from the saturated bright star (Castor A/B) is also dispersed in the spectrum. The magnitudes are consistent with a single red star. Top middle panel: SDSS image of SDSS J005827.24 + 005642.6 (1° 10'), the image suggests a resolved WDMS binary pair. Middle right panel: the detection of the Balmer lines typical of an early F star in the blue, together with the typical spectral features of a low-mass main sequence star in the red (black solid line), indicate that these are two single stars superimposed in the same image rather than a resolved WDMS binary pair. SDSS magnitudes are indicated with red dots, and are consistent with those of a low-mass star. Top right panel: SDSS image of SDSS J025306.37 + 001329.2 (1° 10'), a resolved WDMS binary in our sample. Bottom right panel: SDSS magnitudes (red dots) and spectrum (black line) of the same system. While the SDSS spectrum clearly shows both components, the SDSS magnitude errors are unusually large due to unsuccessful deblending of the close pair.

To determine the completenesses we visually classified all SDSS DR6 spectra of point-sources with g < 20, and used the casjobs interface [Liu and Thakar 2008] to the SDSS data base to determine the number of photometric point sources with clean photometric entries in each of the regions of the red above. The fraction of WDMS binaries identified by the template matching routine among the total number of spectroscopically identified WDMS binaries inside the selected region gives an estimate of the internal completeness. The external completeness is simply given by the fraction of spectroscopically observed point sources inside a given colour-colour region. In order to evaluate the impact of the brightness limit applied in the quasar selection algorithm (R-chairs et al. 2002), i.e. a de-magnified i < 19.1, we additionally performed the external completeness analysis for the ranges 16 < 19.1 and 19.1 < i < 20.1 outside the WDMS exclusion box, i.e. for box 1 and box 2. The results are given in Table 4 and can be summarized as follows.

SDSS DR6 contains 8002 photometric point sources with g < 20 inside the box 1 and 8002 photometric point sources with g < 20 outside the box 1. 8002 photometric point sources with g < 20 inside the box 2. 8002 photometric point sources with g < 20 outside the box 2. The completenesses were determined by visual classification of all SDSS DR6 spectra of point-sources with g < 20, and using the casjobs interface [Liu and Thakar 2008] to the SDSS data base to determine the number of photometric point sources with clean photometric entries in each of the regions of the red above. The fraction of WDMS binaries identified by the template matching routine among the total number of spectroscopically identified WDMS binaries inside the selected region gives an estimate of the internal completeness. The external completeness is simply given by the fraction of spectroscopically observed point sources inside a given colour-colour region. In order to evaluate the impact of the brightness limit applied in the quasar selection algorithm (R-chairs et al. 2002), i.e. a de-magnified i < 19.1, we additionally performed the external completeness analysis for the ranges 16 < 19.1 and 19.1 < i < 20.1 outside the WDMS exclusion box, i.e. for box 1 and box 2. The results are given in Table 4 and can be summarized as follows.

Table 3. Updated classification of the 82 objects from [Heifel et al. 2004] which are not considered as WDMS binaries by us. The complete table can be found in the electronic edition of the paper.

| Object   | Class (c)     |
|----------|---------------|
| SDSS J013007.13+002635.3 | carbon star   |
| SDSS J020538.10+005835.3 | no available spectra, WDMS |
| SDSS J0303906.69+002916.6 | DA star       |
| SDSS J0235622.18+330944.8 | O star       |
| SDSS J032428.78-004613.8 | quasar        |
| ...     | ...           |

1 http://casjobs.sdss.org/CasJobs/
of the point sources) systems, and we visually classify 389 of these as W D M S binaries. The remaining 186 objects are mostly single M stars but we also identify four cataclysmic variables and eight quasars. The small external spectroscopic completeness of SD SS DR 6 (7%) in the W D M S binary box as well as the large number of W D M S binaries (67%) among the spectroscopically observed objects is not surprising, as this region has been explicitly excluded in the quasar selection algorithm (Richards et al. 2002). All but 12 of the 389 W D M S binaries have been successfully identified by our automated template matching algorithm, which gives an internal completeness of 97%. Among the 12 missing objects nine contain cool (probably D C) white dwarfs, one contains a clear D A white dwarf, one a clear D C white dwarf plus any, and one we identify as a low-temperature polar, LARP (SD SS J204837.90 + 005008.9) Schmidt et al. 2002. In all the 12 cases the spectra are dominated by the emission of the companion stars.

Box 1 contains 708 point sources with $g < 20$ in DR 6 and for 247 of these at least one SD SS spectrum is available, corresponding to an external completeness of 35%. As expected, we find the external completeness to sign cantly change at the magnitude $i_{\text{br}}$ incorporated in the quasar selection algorithm. While it increases to 60% for $i_{\text{br}} < 19.1$, it drops to 15% for $i_{\text{br}} < 16.20$.

Among the 247 objects are 67 (27%) W D M S binaries. The remaining 186 systems are mainly quasars, a few single white dwarfs, early-type main sequence stars, and two cataclysmic variables. All the remaining 67 W D M S binaries in this box have been identified by our search algorithm (Se c. 3) equivalent to an internal completeness of 100%.

SD SS DR 6 contains 6689 SD SS point sources in box 2 and for 2280 of them SD SS spectroscopy is available, which gives an external completeness of 34% using $g < 20$.

As for box 1, the quasar list in the reddening corrected $i$ magnitude of 19.1 is very much a reflecting the external completeness. It increases sign cantly to 60% for $i_{\text{br}} < 19.1$, but decreases to 14% for objects fainter than the quasar.

---

**Table 4.** We give here the number of SD SS point sources $N_p$, the number of available SD SS spectra $N_{\text{spec}}$, the number of spectroscopically confirmed W D M S binaries $N_{\text{W D M S}}$, and the number of W D M S binaries we have identified $N_{\text{idem}}$ for each of the W D M S, box 1 and box 2 regions defined in Sect. 4. The external completeness is estimated as $N_{\text{spec}}/N_p$, the internal completeness as $N_{\text{idem}}/N_{\text{W D M S}}$.

| Box | $N_p$ | $N_{\text{spec}}$ | $N_{\text{W D M S}}$ | $N_{\text{idem}}$ | Ext. C. | Int. C. |
|-----|-------|-----------------|----------------|----------------|--------|--------|
| box 1 | 708 | 247 | 67 | 67 | 35% | 100% |
| box 2 | 6689 | 2280 | 135 | 131 | 34% | 97% |
| box 1 | 313 | 188 | 7 | 7 | 60% | 100% |
| box 2 | 2822 | 1672 | 135 | 131 | 34% | 97% |
| box 1 | 389 | 59 | 15% | 15% |
| box 2 | 13110 | 1770 | 14% | 14% |

---

At first glance, one might consider the spectroscopic completeness of 60% for $i_{\text{br}} < 19.1$ to be surprisingly low compared to the 95% obtained for the quasar selection algorithm (Vanden Berk et al. 2009). However, one should keep in mind that outside the exclusion boxes is not equivalent to inside the (rather complex) quasar selection. In addition, DR 6 of the area of the footprint followed spectroscopically was only 82% of the imaging area, in playing a systematically lower spectroscopic completeness than expected for DR 7. As mentioned earlier, a more comprehensive analysis of the completeness of SD SS W D M S binaries is underway and will be presented in a subsequent publication.

From the 2280 spectra that are available in box 2 only 135 (6%) are W D M S binaries. The vast majority of the remaining objects are quasars but we also identify some single main sequence stars and one cataclysmic variable. All but four of the 135 W D M S binaries have been found by our template fitting method, corresponding to the internal completeness of 97%.
Identified by our algorithm are SDSSJ110539.77+250628.6, which is in fact the same detached magnetic cataclysmic variable STLM1 observed during a deep low state; SDSSJ124959.76+035726.6, a typical W D M S binary previously listed as a cataclysmic variable candidate by Szkody et al. (2004); SDSSJ150954.40+243449.3, which has a broken SDSS spectrum; and SDSSJ204218.52-065638.4, a spatially resolved main sequence star in the W D M S binary.

Three main conclusions can be drawn from the analysis carried out in Fig. 5. Firstly, the spectroscopic completeness in SDSS is much larger in quasar domain in the colour-colour space, i.e. 34% in box 2, compared to only 7% in the W D M S binary exclusion box of Richards et al. (2002). The low completeness in the W D M S binary exclusion box, combined with the high fraction of W D M S binaries among all objects in this region (67%) implies that the number of SDSS W D M S binaries could be dramatically increased by additional follow-up spectroscopy of point sources located in this box. Since the spectroscopic completeness in the W D M S binary exclusion box is 7%, only 389 W D M S binaries benefit from spectra, this implies then that SDSS did not target 5500 W D M S binaries for follow-up spectroscopy within this region. As partners of SEGUE some of us perform such a program and identify 300 new W D M S binaries (Schreiber et al. 2007). Secondly, outside the exclusion boxes the external completeness drops significantly from 60% to 15% at the imagnitude in the 19 mag limit entered in the quasar search algorithm. Finally, in the outer part, only 16 W D M S binaries (four in box 2 and 12 in the W D M S binary exclusion box), have not been identified by our template fitting routine. A summing that the three analysed colour boxes are representative for the entire W D M S binary bridge, we derive an internal completeness of our catalogue of 98%. Virtually all systems in our search algorithm failed to identify are dominated by the emission of the secondary star. Such systems are therefore expected to form the missing 2% of W D M S binaries contained in the SDSS DR6 data base.

The 16 W D M S binaries that we previously overlooked have been added to our sample that now forms our nal SDSS DR6 W D M S catalogue, as described in the following section.

4 THE FINAL CATALOGUE

From the analysis described in Sect. 3 and Sect. 4 a total number of 1602 W D M S binaries have been identified. These systems from our nal catalogue of SDSS DR6 W D M S binaries and W D M S binary candidates. We describe in this section the main tables characterising our sample. An excerpt of each table is given here, while the complete tables can be found in the electronic edition of the paper.

In Table 6 we list the coordinates, GALEX DR4, SDSS DR6 and UKIDSS DR4 magnitudes. Occasionally multiple SDSS and GALEX magnitudes are available for one system. In these cases we give averaged magnitudes. We used PSF (point spread function) SDSS magnitudes when available, otherwise GALEX magnitudes are available for 1327 W D M S binaries, UKIDSS magnitudes for 466.

Table 6 provides relative number of the stellar component in our W D M S binary catalogue. For the white dwarfs we use the agsDA, DB, DC, WD (if the white dwarf type is unknown), DH (if the white dwarf is magnetic), and PG 1159 (hot hydrogen-de cient pre-white dwarf). We use the acronym LARP to indicate a low-accretion-rate polar. The secondary stars are aged as M or K according to their spectral type. If the ag is followed by a colon, the classification of the stellar component is uncertain. Finally, we list in brackets the W D M S binary candidates. We consider basically two types of candidates: (1) system with very low S/N ratio spectroscopy that does not allow a clear classification of the stellar component in their spectra, and (2) system with marginal blue (red) excess in their SDSS spectra, without morphological problems in their SDSS ages (Sec. 2.4), and with the values (Sec. 2.2) favouring a binary classification, but no GALEX (UK ID SS) magnitudes available to confirm the existence of the secondary component.
The entire table (including also the photometric errors) is provided in the electronic edition of the paper. We use \( \cdots \) to indicate that no magnitude is available.

\[
\begin{array}{cccccccccccc}
\text{SDSS J} & m(\text{J}) & \text{dec}(\text{J}) & \text{n} & \text{f} & \text{u} & \text{g} & \text{r} & \text{i} & \text{z} & \text{y} & \text{J} & \text{H} & \text{K} \\
00152.09+000644.7 & 0.46704 & -0.11242 & 18.45 & 17.90 & 19.03 & 18.61 & 17.94 & 17.50 & 17.25 & 16.51 & 16.05 & 15.40 & 15.28 \\
00442.00+002011.6 & 1.37500 & -0.33566 & - - & - & 23.72 & 20.38 & 19.13 & 18.65 & 18.28 & - - - & - - - \\
00611.94+003466.5 & 1.54975 & 0.57958 & 21.78 & - & 21.38 & 20.92 & 20.12 & 19.00 & 18.38 & 17.53 & 17.05 & 16.58 & 16.20 \\
01029.87+03126.2 & 2.62466 & 0.52394 & 20.17 & 21.96 & 21.92 & 20.85 & 19.97 & 19.00 & 18.42 & 17.65 & 17.14 & 16.52 & 16.36 \\
01247.18+01048.7 & 3.19658 & 0.18019 & 20.50 & 20.71 & 20.73 & 20.21 & 19.66 & 18.63 & 17.96 & 17.09 & 16.60 & 16.13 & - \\
01339.20+01924.3 & 3.41333 & 0.32342 & 16.41 & 19.73 & 15.94 & 15.56 & 15.55 & 15.63 & 15.89 & - - - & - - - \\
01359.39+11038.6 & 3.49749 & -11.14405 & 17.77 & 17.42 & 18.30 & 18.43 & 18.31 & 20.75 & 22.82 & - - - & - - - \\
01549.02+010937.3 & 3.95425 & 1.16036 & 20.97 & 20.68 & 21.23 & 20.86 & 20.60 & 19.85 & 19.27 & 18.46 & 17.86 & 17.45 & 17.12 \\
01726.63+002451.1 & 4.36096 & -0.41419 & 19.71 & 20.30 & 19.67 & 19.28 & 19.02 & 18.18 & 17.54 & 16.60 & 16.07 & 15.56 & - \\
01733.59+004030.4 & 4.38996 & 0.67511 & 20.83 & 22.43 & 22.09 & 20.79 & 19.58 & 18.17 & 17.38 & 16.37 & 15.84 & 15.27 & 14.97 \\
01749.24+000955.3 & 4.45517 & -0.16536 & 15.87 & 15.40 & 16.56 & 16.86 & 17.03 & 16.78 & 16.47 & 15.75 & 15.33 & 14.76 & 14.56 \\
01853.79+005021.5 & 4.72412 & 0.83931 & 20.46 & 20.27 & 21.00 & 20.38 & 19.64 & 18.80 & 18.35 & 17.52 & 17.09 & 16.51 & 16.27 \\
01855.19+002134.5 & 4.72996 & 0.39598 & 22.42 & 22.12 & 21.60 & 20.60 & 19.87 & 18.97 & 18.38 & 17.54 & 17.09 & - - - & - \\
02134.78+001507.9 & 5.42242 & -0.25219 & 22.20 & - & 22.58 & 19.63 & 18.39 & 17.02 & 16.30 & 15.40 & 14.87 & 14.31 & 14.05 \\
... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... \\
\end{array}
\]

### 5 STELLAR PARAMETERS

In Rebassa-Mansergas et al. (2003), Schreiber et al. (2008); Rebassa-Mansergas et al. (2003) we presented a spectral-convolution position/fitting technique and a M-dwarf spectral type (radius relation to determine the stellar parameters of W D M S binaries spectroscopically identified by the SDSS. Our method allows to estimate the effective temperature, surface gravity, mass and radius of the white dwarf, as well as the spectral type and radius of the main sequence companion. In addition, two independent distance estimates can be obtained by estimating the best-\( \chi^2 \) scaling factors of the two components (see Rebassa-Mansergas et al. (2003) for details). We here basically use the same procedure but incorporate two modifications.

Firstly, we compiled an additional library of 222 high S/N spectra of DB white dwarfs from SDSS DR 4 (Eisenstein et al. 2004) covering the entire range of observed Te. Decomposing the binary spectrum and fitting the stellar components in the same way as in Rebassa-Mansergas et al. (2007), but using the joint mentioned DB template instead of DA template allows to estimate the DB and DB+ective temperature in our catalogue.

As a second modification we take into account the ultraviolet GALEX magnitudes if the spectral fitting does not provide a unique solution for the white dwarf temperature. An example is given in Fig. 8. Performing the spectral decomposition of SDSS J082609.72+194126.3 into the white dwarf and main sequence component (Fig. 9) and modelling the Balmer lines of the white dwarf model provides two solutions for the white dwarf temperature, the so-called cold and hot solutions (black dots in the top right panel of Fig. 9).

In most cases an additional t to the entire spectrum breaks this ambiguity and clearly indicates which of the two solutions has to be preferred. However, in the case of SDSS J082609.72+194126.3 the ambiguity remains as the t to the entire spectrum results in values that fall exactly on the line of maximum H equivalent width. As shown in the bottom panel of Fig. 9, the ultraviolet magnitudes measured by GALEX clearly exclude the hot solution.

The stellar parameters and distances obtained for the 1602 W D M S binaries in our catalogue are given in Table 5. Both the cold and the hot solutions are provided for each spectrum, while the solution preferred by us is given in the first line. The complete table is available in the electronic version of the paper.

### 6 DISTRIBUTION OF STELLAR PARAMETERS

We present in this section distributions of surface gravity and effective temperature of the white dwarfs, as well as the spectral type distribution of the companion stars in our catalogue. To facilitate the comparison with previous works we also provide the distribution of white dwarf masses. Our template fitting algorithm covers secondary star spectral types M 0-M 9 and the spectral type distribution shown here includes only clear class detections in this range. For the distribution of the white dwarf stellar parameters we only considered systems with relative errors smaller than 25%. This resulted in 1433, 1198, 1127, and 558 W D M S binaries for the spectral type, surface gravity, effective temperature, and white dwarf mass distributions, respectively (see Fig. 9).

In general terms the distributions are similar to those presented in Rebassa-Mansergas et al. (2003); the most frequent white dwarf temperature range between 10000(\( \cdots \)20000) K, while dwarf mass clusters around M, = 0.5 M, log g = 7.8 for the vast majority of the white dwarfs, and the spectral type of the companion stars are typically M 3. In Fig. 10 we show the Te, , M d, log g, and spectral type cumulative distributions obtained from the W D M S binaries studied in this work (blue lines), the system s analysed in Rebassa-Mansergas et al. (2007) (red lines) and of a volume e-inlined sample of single white dwarfs (black lines, Hulsbergen et al. 2008). Kilmogorov-Smirnov (K S) tests were applied to compare the sets of effective temperature, white dwarf masses, and log g. As the secondary spectral type distribution consists of discrete values we perform a \( \chi^2 \) test in this case. We briefly describe each parameter distribution in the following sub-sections.
A catalogue of white dwarf main sequence binaries

Table 7. White dwarf mass, effective temperatures, surface gravities, spectral types and distances of the 1602 W D M S binaries in our catalogue, as determined from spectral modelling. W e list both the hot and the cold solutions, with preferred solution given in the r st line for each spectrum. The other solution is given for completeness. The complete table, including also notes for individual systems, can be found in the electronic version of this paper. We use the age, e, s, and h and `e for those systems which have been studied previously by Eisestein et al. (2006), Silvestri et al. (2007), Augustijn et al. (2008) and Helke et al. (2009), and which are resolved W D M S binary pairs, respectively. Again, we indicate that no stellar parameters are measured with `-e."

| SDSS J | type | MJD | PLT | FIB | T_e (k) | err | log g | err | M_vd [M_J] | err | d_m (pc) | err | Sp | d_s (pc) | err | ag |
|--------|------|-----|-----|-----|--------|-----|-------|-----|-------------|-----|----------|-----|-----|----------|-----|----|
| 013356.07-091535.1 | DA/M | 53612 | 1915 | 431 | 12392 | 1324 | 7.47 | 0.36 | 0.36 | 0.16 | 531 | 112 | 8 | 247 | 100 |
| 013356.07-091535.1 | DA/M | 53612 | 1915 | 431 | 12250 | 1328 | 7.49 | 0.36 | 0.36 | 0.16 | 523 | 110 | 8 | 247 | 100 |
| 013418.52+010100.0 | DA/M | 53741 | 1502 | 517 | 22811 | 2601 | 7.75 | 0.41 | 0.50 | 0.22 | 912 | 224 | 1 | 1146 | 225 |
| 013418.52+010100.0 | DA/M | 53741 | 1502 | 517 | 9844 | 473 | 8.66 | 0.46 | 1.01 | 0.25 | 201 | 73 | 1 | 1146 | 225 |
| 013441.30-092212.7 | DA/M | 52147 | 662 | 477 | 12110 | 2657 | 7.06 | 1.13 | 0.24 | 0.48 | 2464 | 1314 | 2 | 1914 | 456 |
| 013441.30-092212.7 | DA/M | 52147 | 662 | 477 | 11699 | 2808 | 7.14 | 1.19 | 0.26 | 0.56 | 2315 | 1285 | 2 | 1914 | 456 |

6.1 W hite dwarf tem perature

We obtain a 40% probability (called KS probability in what follows) for the maximum vertical distance between the white dwarf temperature distribution obtained here and the distribution in Rebassa-Mansergas et al. (2007) being equal to or larger than the maximum vertical distance between the two cumulative white dwarf temperature distributions. Hence, there are no indications that the two distributions are not drawn from the same parent population. In contrast, comparing the W D M S binary white dwarf temperature distribution with the temperature distribution of the volume limited sample of single white dwarfs ( Rebassa-Mansergas et al. 2007), we obtained a KS probability of 10^{-12}. This is straightforward to understand as the presence of the secondary star makes the identication of cold white dwarf primaries rather difficult.

6.2 W hite dwarf mass and surface gravity

Comparing the obtained distribution with those derived from a volume-limited sample of single white dwarfs ( Rebassa-Mansergas et al. 2007, black lines in Fig.10), we obtained KS probabilities of 10^{-12} for the white dwarf masses and 10^{-15} for the surface gravities. The white dwarf mass distribution of W D M S binaries and single white dwarfs is indeed expected to be different. The white dwarf mass distribution of W D M S binaries is composed of two different types of system, i.e., W D M S binaries with an initial main sequence binary separation large enough to avoid main mass transfer during the evolution of the more massive star, and systems that suffer from CE evolution (PCEBs). The white dwarf mass distribution of the non-interacting W D M S population is expected to be identical to the mass distributions of single white dwarfs, i.e., clustering at M_vd ~ 0.6 M, while PCEBs are expected to contain a large number of low-mass He-core white dwarfs (M_vd ~ 0.04 M). For example, de Kool & Ritter (1993) estimate the fraction of such systems amongst PCEBs to be about 50%. As 30% of the presented sample of W D M S binaries from the SDSS have evolved through a CE phase (Schreiber et al. 2008), the rather large fraction of white dwarfs with and PCEBs in our sample and to measure their orbital parameters. A detailed analysis of the white dwarf mass distribution of PCEB and white dwarfs is underway ( Rebassa-Mansergas et al. 2009a, in preparation).
6.3 Secondary star spectral type

The distribution of spectral types is shown in the bottom panel of Fig. 9. The cut-off at early spectral types is very likely a consequence of selection effects as discussed in more detail in Sect. 3. The strongly decreasing number of W D M S binaries with late type (M 7-M 9) companions might also be related to selection effects, as late-type stars are faint and harder to detect against a moderately hot white dwarf. Nevertheless, SD SS covers a much broader colour space than previous surveys and, in principle, should be able to identify more W D M S binaries containing cool white dwarfs plus very late-type companions. It is worth mentioning also that Farh et al. (2003) have constructed the relative distribution of spectral types in the local M/L dwarf distribution, which peaks around M 3(4), and steeply declines towards later spectral types, suggesting that late-type companions to white dwarfs are intrinsically rare (see Sect. 3 for more details). The 2 comparison of the W D M S binary spectral type distribution presented here with the one described in Rebassaa-Mansergas et al. (2003) gives a probability of 82% that both distributions are drawn from the same parent distribution (see also Fig. 10).

6.4 D istances

In Sect. 5, we derived two independent distance estimates for the W D M S binaries in our catalogue. We compare these val-
A catalogue of white dwarf–main sequence binaries

In which the two distances agree within 1.5 of 603 WDM S binaries.

Use average distances. This procedure resulted in a sample of 603 WDM S binaries.

In the top panel of Fig. 11, black dots represent systems with relative errors in the white dwarf distance less than 25%. The relative error in is dominated by the scatter in the mass-radius relation provided in Rebassa-Mansergas et al. (2003). Hence, it represents an intrinsic uncertainty rather than a statistical error related to the and we therefore do not apply any cut in . Moreover, we excluded from the analysis any WDM S binary containing a white dwarf of less than 12000 K, as spectral to tends to overestimate the surface gravity, and hence the mass. Hence, we adopt a cut in the white dwarf radii, and hence the distance. If more than one SDSS spectrum is available, we use averaged distances. This procedure resulted in a sample of 603 WDM S binaries.

In the top panel of Fig. 11, black dots represent systems in which the two distances agree within 1.5 (3/4 of the total sample), while the differences in the two distances obtained for the objects in red exceed this limit. Most of the outliers are above (1/5 of our WDM S binaries), while we nd (for only 5% of the total sample). Hence, these systems are at公司将 this leads to overestimating the secondary star distances. As in Rebassa-Mansergas et al. (2003), we assume that magnetic activity raises the temperature of the inter-spot regions in active stars that are heavily covered by cool spots, leading to a blue-shift of the optical colours compared to inactive stars. However, to nally evaluate this interpretation one needs to perform a detailed analysis of the sample based on H emission. This would further require to distinguish between the different sub-samples forming the WDM S binary population, i.e., PCEBs and wile systems, as the fraction of active stars is expected to depend on the rotation rate. This is beyond the scope of this paper but will be presented in a forthcoming publication (Rebassa-Mansergas et al. 2009).

As a simple test, we adjust the spectral type of the secondaries to bring into agreement the two distances. It turns out that a change of ±2 spectral subclasses is enough for the majority of cases. Only ten systems in the right panel of Fig. 11 need a change of one or two spectral subclasses to reach . We have inspected these objects in more detail and the large discrepancy might be explained as follows:

Six objects contain hot white dwarfs, i.e., SDSSJ003221.86+073934.4, SDSSJ032510.84-011114.1, SDSSJ080229.99+072858.1, SDSSJ095719.25+234240.8, SDSSJ101323.90+043956.1, SDSSJ141536.40+011718.2. If these are short orbital period systems, irradiation of the secondary by the hot primary may lead to overestimating the distance to the secondary star. These WDM S binaries might therefore be considered as candidates to probe for radial velocity variations. SDSSJ032510.84-011114.1 bene ts from two SDSS radial velocity measurements in Table but no variation is detected. This may re ect the speculative nature of the just given argument or be caused by the SDSS spectroscopy sampling the same orbital phase twice.

Three systems (SDSSJ025306.37+001329.2, SDSSJ204729.04-064536.7, SDSSJ210624.12+004030.2) are resolved in their SDSS images. Depending on the exact placement of the core, the u contribution of one or both stars is likely to be underestimated. This translates to underestimated u scaling factors and overestimated distances.

For one object, SDSSJ232624.72-011327.2, the S/N of the corresponding SDSS spectrum is very low (S/N ≈ 4.2). This is probably the reason for the discrepancy found in the distances.

7 COMPARISON WITH PREVIOUS STUDIES

Since Smolcik et al. (2004) discovered the WDM S binary bridge several SDSS WDM S binary catalogues have been presented, and several tting routines to determine the stellar parameters have been applied. In this section we compare in more detail the results of our spectral decomposition method with those obtained by earlier studies.

7.1 Comparison with Rebassa-Mansergas et al. (2007).

Given that the SDSS spectra reduction pipeline was improved with DR6 (Adebahr & McCarthy 2008), we decided to compare the stellar parameters obtained here with those we obtained in Rebassa-Mansergas et al. (2007). The stellar parameters for those objects with multiple SDSS spectra were averaged. Fig. 12 compares white dwarf–main sequence parameters, surface gravities, and secondary spectral types. Both studies agree within the errors in the majority of cases, with average relative di erences of 13.5 and 2.5% in and respectively, and an average di erence of 0.3 spectral subtypes. We obtain signi cantly di erent values especially for systems containing white dwarfs with temperatures in the range 10,000-20,000 K (see top panels of Fig. 12). In 50% of the cases this is due to the fact that we are making use of ultraviolet GALEX magnitudes to constrain the white dwarf line solutions in

Figure 10. Effective tem perature (top left), white dwarf mass (top right), surface gravity (bottom left) and spectral type (bottom right) cumulative distributions obtained from the stellar parameter of the WDM S binaries presented here (blue lines),analyzed in Rebassa-Mansergas et al. (2003) (red lines), and from a volume-limited sample of single white dwarfs (black lines, Holberg et al. 2002).

Figure 11. 603 WDM S binaries.

Table 9 but no variation is detected. This may re ect the speculative nature of the just given argument or be caused by the SDSS spectroscopy sampling the same orbital phase twice.

Three systems (SDSSJ025306.37+001329.2, SDSSJ204729.04-064536.7, SDSSJ210624.12+004030.2) are resolved in their SDSS images. Depending on the exact placement of the core, the u contribution of one or both stars is likely to be underestimated. This translates to underestimated u scaling factors and overestimated distances.

For one object, SDSSJ232624.72-011327.2, the S/N of the corresponding SDSS spectrum is very low (S/N ≈ 4.2). This is probably the reason for the discrepancy found in the distances.

7 COMPARISON WITH PREVIOUS STUDIES

Since Smolcik et al. (2004) discovered the WDM S binary bridge several SDSS WDM S binary catalogues have been presented, and several tting routines to determine the stellar parameters have been applied. In this section we compare in more detail the results of our spectral decomposition method with those obtained by earlier studies.

7.1 Comparison with Rebassa-Mansergas et al. (2007).

Given that the SDSS spectra reduction pipeline was improved with DR6 (Adebahr & McCarthy 2008), we decided to compare the stellar parameters obtained here with those we obtained in Rebassa-Mansergas et al. (2007). The stellar parameters for those objects with multiple SDSS spectra were averaged. Fig. 12 compares white dwarf–main sequence parameters, surface gravities, and secondary spectral types. Both studies agree within the errors in the majority of cases, with average relative di erences of 13.5% and 2.5% in and respectively, and an average di erence of 0.3 spectral subtypes. We obtain signi cantly di erent values especially for systems containing white dwarfs with temperatures in the range 10,000-20,000 K (see top panels of Fig. 12). In 50% of the cases this is due to the fact that we are making use of ultraviolet GALEX magnitudes to constrain the white dwarf line solutions in

Figure 10. Effective tem perature (top left), white dwarf mass (top right), surface gravity (bottom left) and spectral type (bottom right) cumulative distributions obtained from the stellar parameter of the WDM S binaries presented here (blue lines),analyzed in Rebassa-Mansergas et al. (2003) (red lines), and from a volume-limited sample of single white dwarfs (black lines, Holberg et al. 2002).

Figure 11. 603 WDM S binaries.

Table 9 but no variation is detected. This may re ect the speculative nature of the just given argument or be caused by the SDSS spectroscopy sampling the same orbital phase twice.

Three systems (SDSSJ025306.37+001329.2, SDSSJ204729.04-064536.7, SDSSJ210624.12+004030.2) are resolved in their SDSS images. Depending on the exact placement of the core, the u contribution of one or both stars is likely to be underestimated. This translates to underestimated u scaling factors and overestimated distances.

For one object, SDSSJ232624.72-011327.2, the S/N of the corresponding SDSS spectrum is very low (S/N ≈ 4.2). This is probably the reason for the discrepancy found in the distances.
In the present paper (see Sect. 5), in the remaining 50% this is most likely a consequence of the systematic changes in the u/v calibration pipeline. The most dramatic case is SDSS J151045.70+040827, a clear outlier in the bottom left panel of Fig. 12, with a difference in $T_\text{eff}$ and log $g$ of 21,000 K and 1.7 dex, respectively. This was one of the cases in which the solution was modified by the use of GALEX magnitudes. The obtained differences in spectral type are consistent with the general uncertainty of our decom position/fitting procedure of 0.5 spectral subclasses (see Sect. 5). Only for SDSS J173548.36+541424.4, this difference exceeds one spectral subtype. This system is very faint ($i > 20$), and the low S/N ratio is causing the spectral type determination to be rather uncertain.

7.2 Comparison with van den Besselaar et al. (2005)

We have identified in this work 53 DB/M-dwarf binaries, 13 of them in common with van den Besselaar et al. (2005). The stellar parameters of these systems are given in Table 3. Apparently, the white dwarf temperatures differ significantly. As van den Besselaar et al. (2005) used DR3 SDSS spectra and measured all parameters by assuming a white dwarf mass of 0.6 $M_\odot$, these discrepancies are not too surprising. In addition, as stated by van den Besselaar et al. (2005), their derived effective temperatures are related to the u/v fitting of the secondary star, i.e., changing the spectral type by one subclass can lead to differences in the white dwarf effective temperature of $8000^\circ$K to $10000^\circ$K.

The distance measurements by van den Besselaar et al. (2005) are based on the white dwarf fitting, while we use the secondary star spectral type in case the primary is not a DA white dwarf. Taking into account the uncertainties involved in both distance measurement, we obtain reasonable agreement between both values.

Concerning the spectral type of the companion stars our values are in good agreement with those obtained by van den Besselaar et al. (2005). In all but two (SDSS J093645.14+420625.6 and SDSS J113609.59+484318.9) cases the difference does not exceed one subclass. SDSS J093645.14+420625.6 is a $i = 20$th magnitude object with a low S/N spectrum leading to large uncertainties in the obtained parameters. SDSS J113609.59+484318.9 contains a hot white dwarf ($>30000^\circ$K) that significantly contaminates the spectrum of the M-dwarf.

7.3 Comparison with Silvestri et al. (2006)

We compare in Fig. 13 the white dwarf effective temperatures and surface gravities, and secondary spectral types obtained in Sect. 5 with those obtained by Silvestri et al. (2006). We considered a sample of 421 spectra for which both studies present values for the stellar parameters.

The average relative difference in effective temperatures and surface gravities is reasonably low, i.e., 14.7% and 2% respectively. For systems with white dwarf temperatures below $20000^\circ$K, however, the obtained values can differ by up to $22000^\circ$K and 1.6 dex. As discussed in Rebassa-Mansergas et al. (2007), we interpret this strong disagreement to be caused by the ambiguity between the hot and the cold solutions. At higher temperature ($>50000^\circ$K) our method tends to provide lower values of $T_\text{eff}$ than those given by Silvestri et al. (2008). This is probably caused by the use of DR4 spectra that were reduced with a different pipeline. In the majority of cases the secondary star spectral types are in reasonably good agreement (i.e., the difference is not exceeding one subclass). However, for 17% of the W D M S binaries the difference is of two or more subclasses, with a maximum difference of four.

We have also inspected the systems that Silvestri et al. (2006) failed to fit and noted that in 70% of these we are able to find a solution. As previously discussed in Rebassa-Mansergas et al. (2007) this indicates that our method is more robust if the S/N ratio is low or if one of the stellar components contributes little to the total flux.
Figure 12. Bottom panels from left to right: comparison of the white dwarf effective temperatures, surface gravities, and the spectral types of the secondary stars determined in this work and those of Rebbas-Hanser et al. (2007). Top panels, from left to right: the white dwarf effective temperature ratio, and the difference in surface gravity and the secondary’s spectral types from the two studies as a function of the white dwarf temperature.

Figure 13. Bottom panels from left to right: comparison of the white dwarf effective temperatures and surface gravities and the spectral types of the secondary stars determined from our ts and those of Silvestri et al. (2006). Top panels, from left to right: the white dwarf effective temperature ratio, and the difference in surface gravity and the secondary’s spectral types from the two studies as a function of the white dwarf temperature.
Figure 14. Bottom panels from left to right: comparison of the white dwarf effective temperatures, distances and surface gravities determined from our ts and those of Heiler et al. (2009). Top panels, from left to right: the white dwarf effective temperature and distance ratios, and the difference in surface gravity from the two studies as a function of the white dwarf temperature.

Figure 15. Bottom panels from left to right: comparison of the secondary star effective temperatures, distances and masses determined from our ts and those of Heiler et al. (2009). The colors red, blue, green, yellow, magenta, black, and cyan refer to spectral types M1-M7 respectively. Top panels, from left to right: the secondary star effective temperature and distance ratios, and the mass difference from the two studies as a function of the white dwarf temperature.
Table 8. Effective temperatures, spectral types and distances obtained from [van den Besselaar et al. 2003] and this work. The
first line on each system corresponds to the results obtained by
[van den Besselaar et al. 2003]. The second line provides our re-
sults.

| SDSS J  | T_e (K) | err | Sp  | d(pc) | err |
|---------|---------|-----|-----|-------|-----|
| 075235.79+ 401339.0 | 30252 | 4000 | 3   | 1544  |
| 080636.85+ 251912.1 | 16811 | 56   | 3   | 1295  | 255 |
| 17439  | 78   | 3   | 852  | 168  |
| 093464.14+ 420625.6 | 15919 | 4000 | 5   | 860   |
| 101509.59+ 563346.8 | 14575 | 4000 | 4   | 531   |
| 116571.46+ 31324.22 | 16071 | 46   | 3   | 817   | 161 |
| 134135.23+ 612128.7 | 30252 | 4000 | 4   | 700   |
| 143222.06+ 611231.1 | 17622 | 25   | 5   | 479   | 245 |
| 113609.59+ 484318.9 | 38221 | 4000 | 6   | 354   |
| 134135.23+ 612128.7 | 31324 | 234  | 3   | 896   | 176 |
| 143222.06+ 611231.1 | 30694 | 4000 | 3   | 1054  |
| 144258.47+ 001031.5 | 16051 | 10   | 3   | 886   | 175 |
| 150118.40+ 042232.3 | 16180 | 47   | 4   | 527   | 155 |
| 162329.50+ 355427.2 | 30694 | 4000 | 3   | 674   |
| 17622  | 25   | 5   | 479  | 245  |
| 18394  | 40   | 3   | 1111 | 219  |
| 19992  | 127  | 4   | 1036 | 305  |
| 21394  | 96   | 4   | 530  | 156  |

7.4 Comparison with [Heller et al. 2009]

[Heller et al. 2009] studied a sample of 857 W D M S bi-
nary candidates. For 636 of these systems they provide the results of an independent spectrophotometric parame-
ting method. Figure 15 compares the white dwarf effective
temperatures, distances and surface gravities obtained by
[Heller et al. 2009] with the values obtained here. The aver-
age relative differences between the two analyses are 12.1% (white dwarf temperature), 23.3% (distance) and 3.8% (sur-
face gravity). The agreement between both studies is diffi-
cult to assess as [Heller et al. 2009] do not provide error
estimates. If one assumes uncertainties of 2000 K and 0.3
dex for their T_e and log g values, and a typical error of 1% for their obtained distances, we nd that only 18%, 7% and
16% of the given values (for T_e , distance, and log g)
do not overlap at the 1.5 level. Hence we conclude that the
results obtained in both studies are in agreement. Fi-
nally, we note that the horizontal patterns in the bottom
right panel of Figure 15 illustrate that [Heller et al. 2009]
estimate the surface gravities by using a grid with a rather
poor resolution of 0.5 dex.

Figure 16. Selection effects in SDSS W D M S binaries can be un-

derstood by analysing the density m aps obtained from the tis-
nar parameter sets. From top to bottom the (log T_e , M_d , d), (log T_e , Sp),
and (log T_e , Sp) density m aps.

The colours refer to objects containing secondaries of
the same spectral type, i.e. red, blue, green, yellow, magenta,
and cyan for spectral types M 1-M 7. Values of effective tem-
peratures and masses for the systems in our catalogue were
estimated using the spectral type-radius mass-effective
temperature relations given in [Rebassa-Mansergas et al.
2003]. Therefore W D M S binaries containing secondaries
of the same spectral type are associated to the same effective
temperature and mass, while the estimate provided by
[Heller et al. 2009] cover a considerably larger range in both
mass and effective temperature (lower left and lower
right panels of Fig 15). According to the lower right panel,
[Heller et al. 2009] measure systematic lower masses. A com-
parison of the obtained distances to the secondary stars is
shown in the middle panels of Fig 15. Since the observed
ux is the same for a given SDSS spectrum, the only dif-
cence between both methods comes from the radius and
the ux at the stellar surface. As the grid of model spectra
is not as large as our grid of Kepler spectral amplitudes, we
did not perform a constant for a given spectral subtype/secondary mass correction. This can clearly be seen in the bottom middle panel of Fig 15. Each pair of
Kepler/SDSS spectrum we obtain one or two straight lines in the distance-radius diagram. It seems that we overestimate the distances. However, we presented
[Rebassa-Mansergas et al. 2003] (see also Sect. 6.7) a rea-
sonable explanation for the 1/5 of the W D M S binaries
with $d_{\text{los}} > d_{\text{wd}}$, while there is no obvious physical mechanism that in my account for the estimated white dwarf distances being systematically smaller than the companion distances as the values of [Rebassa-Mansera et al. 2005] seem to suggest. We have to keep in mind though the uncertainties related to both methods are quite large and the activity interpretation of the system at large secondary distances still needs to be confirmed. We therefore conclude that the question of whether our ten plates or the model spectra provide more reliable distances remains open.

8 SELECTION EFFECTS

In [Rebassa-Mansera et al. 2003], we briefly discussed possible selection effects that may affect the observed SDSS W D M S binary population. The much larger sample presented here allows to investigate these selection effects in more detail. To avoid contamination from unreliable stellar parameters we base our analysis on system whit m errors of less than 25% in their white dwarf parameter error. As discussed in detail in [Rebassa-Mansera et al. 2003] the distance derived from the white dwarf parameter error is probably more reliable than those derived from the secondary stars. We therefore use the white dwarf distances here and quote them simply as distances in the following.

Fig. 16 shows three density maps that illustrate the selection effects acting the SDSS W D M S sample. Due to the restrictions in the white dwarf parameter errors 597, 692, and 1052 system from top to bottom were considered. The $T_{\text{eff}}$, $d_{\text{wd}}$ density map in the top panel shows that binaries with white dwarf primaries cooler than 10,000 K are only detectable at relatively short distances (< 400 pc), while systems containing hotter white dwarfs have been detected at much wider range of distances (> 20000 pc). In addition there is obviously a general trend of increasing distance with white dwarf temperature. This is straightforward to understand as cool white dwarfs become too faint to be detected at larger distances. In contrast hot white dwarfs are intrinsically brighter, but also rarer than cool white dwarfs, and hence dominate at larger distances where the volume surveyed by SDSS is sufficiently large. Most objects are hence concentrated at 400-500 pc, with white dwarfs effective temperatures between 15000-25000 K, as also shown in the effective temperature distribution (Fig. 9). The middle panel of Fig. 16 shows a similar effect but for the secondary star spectral types, Sp. Early M dwarfs are relatively hot and consequently exceed the lower SDSS brightness limit at distances of < 300 pc. In contrast, late secondary spectral types are cool enough to be detected at short distances (100-200 pc) but too dim to be observed at distances larger than 500 pc. Finally, the bottom panel of Fig. 16 shows the $T_{\text{eff}}$ Sp density m ap. A clear trend of later spectral type companions to cooler white dwarf primaries can be seen. This is again easy to understand: while late-type companions to hot white dwarfs are too faint to be detected, cool white dwarf primaries are out-shined by early spectral type secondaries. The selection effects just described can explain the cut-off at early spectral types in the bottom panels of Fig. 9, as the white dwarf primaries are not detectable. The scarcity of system with later-type ($>$ M 6) secondaries, however, is probably not only related to selection effects, as the spectral type distribution of low-mass field stars also peaks at Sp’ M 4/5, and decline towards later spectral types (e.g. [Farhi et al. 2003, Reb L et al. 2003, 2008]). The lack of W D M S binaries with late-type companions is therefore probably an intrinsic property of the W D M S binary population that appears more pronounced due to selection effects. We will address this systematically in a forthcoming publication.

From the analysis of Fig. 16 we conclude that a typical SDSS W D M S binary contains a M 3/4 companion, a 10000-20000 K primary, and is observed at a distance 400-500 pc. However, we have to keep in mind that a typical SDSS W D M S binary is not necessarily a typical W D M S binary. Overcoming the selection effects just described requires to combine the SDSS with companion entry magnitude limited surveys. Detecting binaries consisting of a hot white dwarf and a late-type companion is most likely to arise from the use of infrared surveys such as UKIDSS or 2MASS, while the identification of cool white dwarfs with early-type dominated M dwarfs requires to incorporate ultraviolet surveys such as GALEX [Mathis et al. 2003].

9 COLOUR-COLOUR DIAGRAMS

We have provided in the previous sections of this paper a detailed spectroscopic analysis of W D M S binaries in SDSS. In this section, we make use of the photometric magnitudes given in [Table 4] and combine them with the stellar parameters measured from the SDSS spectra to investigate the appearance of W D M S binaries in colour-colour space. Figure 17 and 18 show four relevant colour-colour diagrams. Stellar sources are shown in grey, DA/M W D M S binaries in yellow, the few DB/M are in blue and the DC/M binaries in green. Finally, DA-DB-DC/K systems are shown in red, while the black dots represent the W D M -K binaries (see Sect. 2.2).

A general feature evident in all diagrams is that a certain number of systems appear to be outliers from the general stellar locus of W D M S binaries, i.e. the W D M S binary bridge described in [Smolcic et al. 2004]. We have inspected these outliers and nd the majority of them being resolved in the SDSS images (see Sect. 2.3).

To further evaluate the information provided by photometric studies we show the white dwarf eective tem parature and secondary star spectral type distributions in six different regions for each colour-colour diagram, as indicated by the horizontal (dotted) and vertical (dashed) lines. The resulting distributions are shown above and below the colour-colour diagram s. As previously, we considered only those white dwarf eective tem paratures with relative error less than 15%. In the following sub-sections we brie y describe the main conclusions that can be drawn from the four colour-colour diagrams.

9.1 $u-g$ vs $g-r$

The most commonly used SDSS colour-colour diagram for stellar sources in SDSS is $u-g$ vs $g-r$ [Fan 1999, Richards et al. 2003, Schreiber et al. 2003]. Inspecting the left-hand side of Fig. 17 it can clearly be seen that the white dwarf eective tem parature distribution is shifted towards...
A catalogue of white dwarf main sequence binaries

Figure 17. Middle left: $u - g$ vs $g - r$ colour-colour diagram. WDMS binaries are represented according to their binary components as follows: DA/M in yellow, DB/M in blue, DC/M in green, DA-DB-DC/K in red, and WD/M in black. Stellar sources are represented with grey dots. Two vertical (dashed) lines divide the diagram in three rectangular regions (column left, centre, right). In the same way, two horizontal (dotted) lines divide the diagram in three different regions (rows top, middle, bottom). Top and bottom left: distributions of white dwarf effective temperature and spectral type of the companions obtained for the six different regions outlined above (three rows and three columns). The right panels follow the same structure, but for the $nuv - u$ vs $u - r$ colour-colour diagram.

lower temperatures if $u - g$ or $g - r$ increases, i.e., for redder colors (compare the left, centre, and right as well as the top and the middle distributions). Only two WDMS binaries with reliable effective temperatures are found in the bottom region close to the main sequence. As expected, the distributions of secondary spectral types contain more early-type secondaries if one moves to redder colors (left to right or top to bottom).

9.2 $nuv - u$ vs $u - r$

The $nuv - u$ vs $u - r$ colour-colour diagram is provided in the middle right panel of Fig. 17. The white dwarf effective temperature and spectral type distributions in the six regions of the diagram (see top and bottom right panels in Fig. 17) are similar to those discussed in the above subsection, the main difference being the decrease in the number of systems. This is due to the smaller percentage of SDSS WDMS binaries that have been detected with GALEX.

9.3 $nuv - i$ vs $nuv - H$

Figure 18 (left panels) shows the $nuv - i$ vs $nuv - H$ colour-colour diagram and the corresponding distributions of white dwarf effective temperatures and secondary spectral types. Clearly, requesting SDSS-GALEX-UKIDSS magnitudes reduces the number of WDMS binaries and the shown distributions are statistically less robust. However, the general trend observed in the previous colour-colour diagram remains: systems composed of white dwarfs hotter than
20000 K are generally detected in the top and left regions of the diagram and there is a clear trend of decreasing white dwarf effective temperature towards redder colours (top to bottom and left to right). The previously observed shift towards earlier spectral types for redder colours seems still to be present but is much less pronounced. The most striking feature of the colour-colour diagram is the nice separation of W D M S binaries and single stars.

9.4 i-J vs J-H

Finally, we provide in Fig. 18 (right panels) the i-J vs J-H red colour-colour diagram and the corresponding distributions. Again, due to the reduced number of systems the overall trend of having less hot white dwarfs and more early spectral type secondaries for redder colours seems to be present but less significant. Nearly all systems containing hot white dwarfs are located in the upper region. This colour-colour diagram represents an additional example of nicely separating W D M S binaries and single stars. We provide several colour-cuts that can be used to select W D M S binaries in the next section.

10 COLOUR CUTS

Having studied in the previous section the relation between colours and stellar parameters (i.e., white dwarf effective temperature and spectral type) in four colour-colour space diagrams, we define here four colour-cuts of W D M S binaries. The fact that we are considering a total of 11 photometric band passes (two from GALEX, five from SDSS and four from UKIDSS) increases considerably the number of possible colour-cut selections. We hence provide four examples (two of them already introduced in Sect. 8) in which W D M S binaries are clearly separated from the locus of single main sequence stars (see Fig. 8). To quantify how complete these colour-cuts are would imply an analysis on the different SDSS-L, SEGUE, Stripe 82 areas, where different
target strategies were tested. Such an endeavour is beyond the scope of this paper and will be pursued elsewhere.

The top left panel of Fig. 19 shows the \( \text{nuv} \) vs \( \text{nuv} \)  \( \text{H} \) colour-colour diagram introduced above, which offers an excellent opportunity to unambiguously isolate \( \text{W D M S} \) binaries from single main sequence stars and white dwarfs with a simple colour-cut. We represent in light gray main sequence stars and white dwarfs, in dark gray \( \text{W D M S} \) binaries. With a straight black line, i.e.,

\[
\text{nuv} \text{ i} < 0.85 + 0.83 \ (\text{nuv} \text{ H}) \quad (2)
\]

both populations can be distinguished.

As we have seen in Sect. 9, \( \text{W D M S} \) binaries and single stars also separate nicely in the \( \text{i J} \) vs \( \text{J H} \) colour plane. However, the location of \( \text{W D M S} \) binaries containing hot white dwarfs overlaps with those of single stars. The colour-cuts shown in the right top panel of Fig. 19, i.e.,

\[
0.3 < (\text{J H}) < 0.7 \\
(\text{i J}) > 1.2 \\
(\text{z J}) > 0.36 + 1.25 \ (\text{J H}) 
\]

will therefore mainly select \( \text{W D M S} \) binaries composed of cold white dwarfs.

Recently Banchi et al. (2007) studied the properties of the GALEX-SDSS matched source catalogues and classified sources by studying their colours. Inspired by their Fig. 5, we show in the left bottom panel of Fig. 19 the \( \text{fuv} \) \( \text{nuv} \) vs \( \text{r} \) \( \text{z} \) colour diagram, and provide colour-cuts that should select the main population of \( \text{W D M S} \) binaries:

\[
(\text{r z}) > 0.3 \\
(\text{fuv nuv}) < 0.85 + 3.9 \ (\text{r z}) \quad (7)
\]

Finally, we provide in the bottom right panel of Fig. 19 the colour-colour diagram and colour-cuts for \( \text{W D M S} \) binaries in \( \text{y K} \) vs \( \text{u z} \). Again stars are represented in light gray, \( \text{W D M S} \) binaries in dark gray, and colour cuts by straight black lines. This colour diagram has been already used by Chiu et al. (2007) for quasar selection. We here only slightly modified their colour-cuts and obtain

\[
(\text{u z}) > 5 \\
(\text{y K}) > 0.7 \\
(y K) > 0.36 + 0.14 \ (u z) \quad (10)
\]

which should successfully select \( \text{W D M S} \) binaries.

11 RADIAL VELOCITIES AND NEW PCEB CANDIDATES

In this final section of the paper we follow Rebassa-Mansergas et al. (2003) and use the NaI: 8183,27,8194,41 absorption doublet and/or the \( \text{H} \) emission to measure radial velocities. As in Rebassa-Mansergas et al. (2003), Schreiber et al. (2008) we use a single width parameter for both line components in the NaI doublet. The radial velocities of 1068 systems with
Table 9. Radial velocities measured from the Na: 8183.27,8194.81 doublet and the H emission for 1068 system in our catalogue. The complete table can be found in the electronic edition of the paper. In the last column we quote with ‘\(^\circ\)’ and ‘\(^\circ\)’ those radial velocity values obtained from spectra that are, and are not combined from individual exposures taken on different nights, respectively. We use ‘\(^\circ\)’ to indicate that no RV is available.

| SD SS J | HJD | RV (Na) err | RV (H) err | Com.7 |
|---------|-----|-------------|------------|-------|
| 000152.09+ 000644.7 | 1791.8092 | 0.7 | 21.1 | 24.2 | 16.7 n |
| 001247.18+ 001048.7 | 2519.8962 | - | - | 12.3 | 18.6 n |
| 001247.18+ 001048.7 | 2518.9219 | -14.3 | 30.1 | 30.6 | 14.4 n |
| 01359.39+110838.6 | 2138.3933 | 28.9 | 16.9 | - | y |
| 017926.64+022451.2 | 2559.7852 | -33.7 | 15.5 | -30.1 | 11.4 n |
| 017266.04+010451.2 | 2518.9219 | -19.8 | 17.4 | -26.5 | 11.8 n |
| 017335.92+004030.4 | 1794.7373 | -3.7 | 15.8 | - | n |
| 017493.25+000955.4 | 2518.9218 | -18.3 | 17.4 | -3.2 | 11.6 n |
| 017493.25+000955.4 | 2518.7373 | -36.5 | 15.5 | -22.8 | 10.1 n |
| 018853.20+021341.5 | 1816.8000 | 41.4 | 27.4 | - | n |
| 018853.20+021341.5 | 1893.0883 | 15.0 | 22.2 | - | y |
| 021437.88+015079.7 | 2581.7411 | 1.5 | 14.7 | - | n |
| 021579.91+110331.6 | 3318.6951 | 148.4 | 15.8 | -9.1 | 13.3 y |

Table 10. Upper limits to the orbital periods of the ve PCEB candidates identified in Sect. 11. White dwarf mass are taken from Table 7, except for SD SS J2346+4340, where we assume e of mass of 0.5 M\(_\odot\). The secondary stars are estimated from Table 5 in Rebassa-Mansergas et al. (2003). K\(_{sec}\) values are obtained from Table 9, where we use the Na: doublet radial velocities for SD SS J2346+4340.

| SD SS J | K\(_{sec}\) (\(\mu\) cm s\(^{-1}\)) |
|---------|-------------------------------|
| 0054 | +0054 |
| 01315 | +01315 |
| 01627 | +01627 |
| 02134 | +02134 |
| 02143 | +02143 |
| 02157 | +02157 |

P\(_{orb}\) (d) | 575 | 121 | 8 | 5 | 2

(*) The effective temperature is below 12000 K, and consequently the white dwarf mass is likely overestimated.

The incomplete function then gives the probability for the measured radial velocities being consistent with a constant value. If this probability is below 0.0027 the measured radial velocity variations are significant and we consider the corresponding W D M S binary a strong PCEB candidate.

We find here nine and 16 PCEB candidates using the Na: doublet and H emission respectively. A comparison with the results obtained in Rebassa-Mansergas et al. (2007) shows that four system s, i.e. SD SS J030904.82-010100.9, SD SS J113800.35-001144.5, SD SS J173727.27+540352.2, and SD SS J234534.50-001453.7 are not among our considered PCEBs, while we find new PCEB candidates, namely SD SS J033301.51+005418.5, SD SS J074329.62+283528.0, SD SS J145300.99+005557.1, SD SS J231874.73+03403.3, and SD SS J231874.76+43401.7. Apparently, the differences in the method of determining radial velocities and/or the re-reduction of the SDSS data can cause a given system to move either way across our criterion.

A comparison with the radial velocities obtained in Rebassa-Mansergas et al. (2003) gives an average relative difference of 19.5%, and the mean errors generally overlap within the errors. The reasons for the small changes have been already discussed in detail in the work of Rebassa-Mansergas et al. (2003) and can be summarised as follows: (1) we modified the procedure to the Na: absorption doublet by using a single width parameter for both line components; and (2) we used DR6 spectra here (instead of DR5).

Table 10. Upper limits to the orbital periods of the ve PCEB candidates identified in Sect. 11. W hite dwarf masses are taken from Table 7, except for SD SS J2346+4340, where we assume e of mass of 0.5 M\(_\odot\). Secondary stars are estimated from Table 5 in Rebassa-Mansergas et al. (2003). K\(_{sec}\) values are obtained from Table 9, where we use the Na: doublet radial velocities for SD SS J2346+4340.

2 Note that the HJDs in the work of Rebassa-Mansergas et al. (2003) were wrong by -0.5 days because of an erroneous conversion of the FITS headers of the SDSS spectra.

12 SUMMARY

We have presented a catalogue of 1602 W D M S binaries from the spectroscopic SDSS DR6. We have used a deconvolution technique to measure the effective temperatures, surface gravities, masses and distances to the white dwarfs, as well as the spectral types and distances to the companions in our catalogue. Distributions and density maps obtained from these stellar parameters have been used to study both the general properties and the selection effects of W D M S binaries in SDSS. A comparison between the distances measured to the white dwarfs and the main sequence companion shows d\(_{\text{meas}}\) > d\(_{\text{cal}}\) for 1/5 of the system. We have made use of GALEX, SDSS and UK IDSS magnitudes to study the distribution of W D M S binaries in colour-colour space and present simple colour-cuts that allow to clearly separate W D M S binaries from other stellar objects. Finally, we have measured radial velocities for 1068 W D M S binaries.
ACKNOWLEDGEMENTS.

ARM acknowledges financial support from ESO, and Genini/Conity in the form of grant number 32080023. MRS thanks for support from Fonddecyt (1061199). We thank the anonymous referee for his suggestions that helped improving the quality of the paper. We also thank Pierre Maxted for useful discussions.

REFERENCES

Abażajian, K. N., et al., 2009, ApJ, 182, 543
A delman-MCarthy, J. K., et al., 2008, ApJS, 175, 297
Augusteijn, T., G. rein, R., van den Besselaar, E. J. M.,
Groot, P. J., N. rueda-Rueda, L., 2008, A & A, 486, 843
Bingham, L., et al., 2007, ApJ, 173, 659
Bochanski, J. J., West, A. A., Hawley, S. L., Covey, K. R.,
2007, AJ, 133, 531
Chir, K., R. iradj, G. T., Hewett, P. C., M. addox, N., 2007,
M. N. ras, 375, 1180
Davis, P. J., Kolb, U., W. ilmen, B., G. ansicke, B. T.,
2008, M. N. ras, 1028
Davis, P. J., Kolb, U., W. ilmen, B., 2009, A & A.
eprints de Kool, M., 1992, A & A, 261, 188
de Kool, M., Ritter, H., 1993, A & A, 267, 397
Dew, J. D. M., Taursis, T. M., 2000, A & A, 360, 1043
Dye, S., et al., 2006, M. Nras, 372, 1227
Eisenstein, D. J., et al., 2006, ApJS, 167, 40
Fan, X., 1999, ApJ, 117, 2528
Farhi, J., Beckin, E. E., Zuckeram, B., 2005, ApJS, 161, 394
Gouli, A., Kolm eier, J. A., 2004, ApJ, 152, 103
Hauschildt, P. H., Baron, E., 1999, Journal of Computational
and Applied Mathematics, 109, 41
Heller, R., H. on er, D., D. reizler, S., stenssen, R.,
2009, A & A, 496, 191
Hewett, P. C., W arren, S. J., Leggett, S. K., Hodgkin, S. T.,
2006, M. Nras, 367, 454
Hoben, J. B., Simon, E. M., O walt, T., McCook, G. P.,
Foran, S., Subasavage, J. P., 2008, ApJ, 135, 1225
Iben, I. J., Livio, M., 1993, PASP, 105, 1373
Koeiter, D., Napiwotzki, R., Voss, B., H. omen, D.,
Reimers, D., 2005, A & A, 439, 317
Koeiter, D., K eppler, S. O., K leihm an, S. J., Nit ta, A., 2009,
Journal of Physics Conference Series, 172, 012006
Lawrence, A., et al., 2007, M. Nras, 375, 1599
Li, N., Thakar, A. R., 2008, Com puting in Science
and Engineering, 10, 18
Livio, M., Soker, N., 1988, ApJ, 329, 764

Makarova, L., Karachentsev, I., Takabo, L. O., Heinemeier, A., Valtonen, M., 1998, A & A, 128, 459
Martin, D. C., et al., 2005, ApJ Lett., 619, L1
Maxted, P. F. L., Gansicke, B. T., Burleigh, M. R., Southworth, J., Naish, T. R., Napiwotzki, R., Nelemans, G.,
Wood, P. L., 2009, ArXiv e-prints
Morrison, P., et al., 2005, ApJ, 619, L7
Nagel, T., Schuh, S., Kusterer, D. J., Stahn, T.,
Hugelmeier, S. D., D. reizler, S., G. ansicke, B. T., Schreiber, M. R., 2006, A & A, 448, L25
Neboz gm ez-Moran, A., et al., 2009, A & A, 495, 561
Nelemans, G., Tout, C. A., 2005, M. Nras, 356, 753
Pollino, M., W. eller, K. P., 2006, ApJ Lett., 641, L137
Pollino, M., W. eller, K. P., 2007, ApJ, 665, 663
Pyrazs, S., et al., 2009, M. Nras, 394, 978
Raymond, S. N., et al., 2003, AJ, 125, 2621
Rebassa-Mansergas, A., G. ansicke, B. T., R. odrz, G. L.,
Schreiber, M. R., K. oester, D., 2007, M. Nras, 382, 1377
Rebassa-Mansergas, A., et al., 2008, M. Nras, 390, 1635
Reid, I. N., Cruz, K. L., Almen, P. R., 2007, ApJ, 133, 2825
Reid, I. N., Cruz, K. L., K. ipatrick, J. D., Almen, P. R.,
M. ungall, F., Liebhart, J., Lowrance, P., Sweet, A.,
2008, ApJ, 136, 1290
Richards, G. T., et al., 2002, ApJ, 123, 2945
Schmitt, G. D., et al., 2005, ApJ, 630, 1037
Schreiber, M., Neboz gm ez-Moran, A., Schwope, A.,
2007, in Napiwotzki, R., Burleigh, R., eds., 15th European
Workshop on W hite Dwarfs, ASP Conf. Ser. 372, p. 459
Schreiber, M. R., G. ansicke, B. T., 2003, A & A, 406, 305
Schreiber, M. R., G. ansicke, B. T., Southworth, J., Schwope, A. D.,
K. oester, D., 2008, A & A, 484, 441
Schwope, A. D., Neboz gm ez-Moran, A., Schreiber, M. R.,
G. ansicke, B. T., 2009, A & A, 500, 867
Silberstjern, N. M., et al., 2006, AJ, 131, 1674
Silberstjern, N. M., et al., 2007, AJ, 134, 741
Smolec, V., et al., 2004, ApJ, 615, L141
Stoughton, C., et al., 2002, AJ, 123, 485
Szkody, P., et al., 2004, AJ, 128, 1882
Szkody, P., et al., 2009, ApJ, 137, 4011
Taam, R. E., Sands, E. L., 2000, ARA & A, 38, 113
van den Besselaar, E. J. M., Roick, G. H. A., Nelemans, G. A.,
Augusteijn, T., G. root, P. J., 2005, A & A, 443, L13
Vanden Berk, D. E., et al., 2005, ApJ, 129, 2047
Webbink, R. F., 1984, ApJ, 277, 355
Webbink, R. F., 2008, in Nilson, E. F., Leahy, D. A., Ho-bill, D. W., eds., A star physics and Space Science Library,
vol. 352 ofA star physics and Space Science Library, p. 233
W. ilmen, B., Kolb, U., 2004, A & A, 419, 1057
York, D. G., et al., 2000, AJ, 120, 1579

A catalogue of white dwarf-main sequence binaries