

## Identification of 13 DB + dM and 2 DC + dM binaries from the Sloan Digital Sky Survey

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**Abstract.** We present the identification of 13 DB + dM binaries and 2 DC + dM binaries from the Sloan Digital Sky Survey (SDSS). Before the SDSS only 2 DB + dM binaries and 1 DC + dM binary were known. At least three, possibly 8, of the new DB + dM binaries seem to have white dwarf temperatures well above 30 000 K which would place them in the so called DB-gap. Finding these DB white dwarfs in binaries may suggest that they have formed through a different evolutionary channel than the ones in which DA white dwarfs transform into DB white dwarfs due to convection in the upper layers.

**Key words.** binaries: spectroscopic – white dwarfs – stars: late-type – stars: evolution

### 1. Introduction

Our understanding of binary evolution is still severely lacking on a number of points, but most importantly on the physics of common-envelope (CE) evolution (Paczynski 1976). When binaries are close enough that during their evolution Roche lobe overflow can commence from a convective giant to a less massive main-sequence companion star, very quickly the system will evolve into a state where the envelope of the giant encompasses both objects. After the envelope has been expelled a close binary may result that will evolve into a white dwarf – main-sequence binary. Due to its short-lived phase and the intrinsic three-dimensional hydrodynamic nature of the CE phase the physics of this process is not well understood (e.g. Iben & Livio 1993).

One way of improving our knowledge of the CE phase is to determine the space densities and population characteristics of all CE products. Some of these products are white dwarfs (WD) with a low-mass main-sequence (dM) companion. WD + dM binaries (or pre-Cataclysmic Variables), containing a hydrogen-rich white dwarf (DA), are a fairly well known group of objects of which new members are readily found, among others by the efforts of the Sloan Digital Sky Survey (SDSS, York et al. 2000; Raymond et al. 2003). On the contrary, WD + dM binaries containing a helium-rich white dwarf (DB) showing composite spectra are extremely rare, and from literature before the SDSS only two such objects are known, namely GD 325 (Greenstein 1975) and CBS 47 (Wagner et al. 1988). Identification of objects in these classes may not only help in understanding the CE physics and the

evolution of Cataclysmic Variables (CVs), but also in the formation of DBs in the first place.

For single WDs in the SDSS it is found that 9–15% of all systems have helium dominated atmospheres (Kleinman et al. 2004; Harris et al. 2003). In contrast, the fraction of WDs in known binaries that are DBs is  $\ll 1\%$ . DC white dwarfs (with absorption lines less than 5% of the continuum; Wesemael et al. 1993) + dM binaries are an even rarer class with only one member known (EG 388; Moffett et al. 1985). We here report on the discovery of 13 new DB + dM binaries and 2 DC + dM binaries from the SDSS.

### 2. Observations

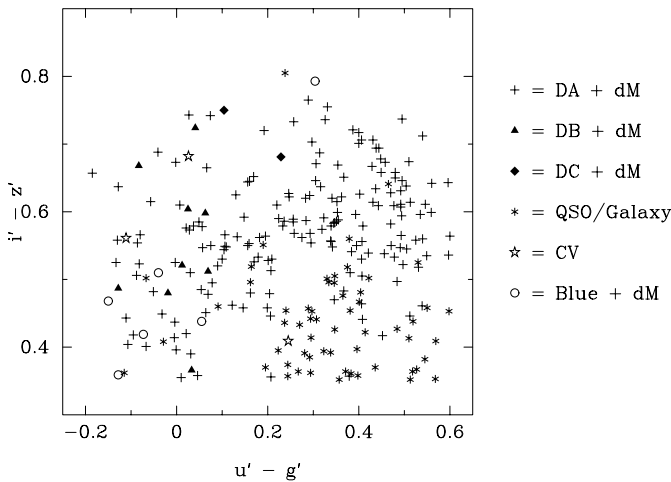
#### *Colour selection of WD + dM binaries*

We have used the spectroscopic data from the Third Data Release of the SDSS (DR3) to select WD + dM candidates. Because of their composite spectra these binaries stand apart from normal main-sequence stars in any colour–colour diagram (see e.g. Fig. 1 of Raymond et al. 2003). We have used the following colour criteria for selecting candidates:  $-0.2 < u' - g' < 0.6$ ,  $-0.2 < g' - r' < 0.3$ ,  $0.35 < r' - i' < 0.85$  and  $0.35 < i' - z' < 0.85$ , where the magnitudes are the psf-magnitudes taken from the spectrophotometric table of DR3. These criteria were derived from colour–colour diagrams of an initial set of WD + dM binaries that were selected from the spectroscopic database.

Using these colour criteria, we selected 260 objects. We classified them on the basis of visual inspection of their spectra.

**Table 1.** The characteristics of our thirteen DB + dM and two DC + dM binaries are given in this table. The uncertainties are about one subtype for the dM star and about 4000 Kelvin in WD temperature for a fixed dM spectral type. The temperatures are shown as given in Kleinman et al. (2004) for the best fit template WD. <sup>a</sup> See Sect. 3. <sup>b</sup> These objects are DC + dM binaries.

Name	$g$	$u - g$	$g - r$	$r - i$	$i - z$	$T_{\text{WD}}$	dM	$D$ (pc)	$\chi^2$
SDSS J075235.79+401339.0	20.01	0.05	0.01	0.58	0.39	30 252	M3V	1544	1.64
SDSS J080636.85+251912.1	19.61	0.07	0.21	0.79	0.60	24 266	M3V	1045	1.68
SDSS J093645.14+420625.6 <sup>a</sup>	20.37	-0.09	-0.14	0.42	0.07	15 919	M5V	860	2.01
SDSS J100636.39+563346.8	19.42	0.10	0.28	0.72	0.49	14 575	M4V	531	3.70
SDSS J102131.55+511622.9	18.27	-0.25	-0.37	0.14	0.35	30 252	M4V	700	1.56
SDSS J113609.59+484318.9 <sup>a</sup>	16.80	-0.38	-0.54	-0.16	0.14	38 211	M6V	354	4.00
SDSS J134135.23+612128.7	19.14	-0.10	0.12	0.50	0.48	30 694	M3V	1054	2.20
SDSS J143222.06+611231.1	18.53	0.02	-0.08	0.49	0.60	36 815	M3V	879	3.56
SDSS J144258.47+001031.5 <sup>a</sup>	18.35	0.04	0.08	0.80	0.72	30 694	M3V	674	11.22
SDSS J150118.40+042232.3 <sup>a</sup>	19.57	0.02	-0.01	0.49	0.48	26 020	M3V	1220	2.42
SDSS J162329.50+355427.2	18.77	0.02	0.22	0.65	0.53	24 266	M3V	695	3.46
SDSS J220313.29+113236.0	19.34	-0.08	-0.10	0.22	0.45	30 694	M4V	1085	2.04
SDSS J232438.31-093106.5	18.64	-0.08	-0.16	0.41	0.66	36 815	M3V	911	3.45
SDSS J074425.42+353040.8 <sup>a,b</sup>	18.91	0.23	0.03	0.70	0.68	15 700	M4V	481	7.14
SDSS J113457.72+655408.7 <sup>a,b</sup>	18.15	0.10	0.02	0.70	0.75	12 500	M4V	278	9.59



**Fig. 1.** A  $u' - g'$  vs.  $i' - z'$  diagram of our 260 objects together with their classification based on visual inspection of all the spectra satisfying our selection criteria.

Of these objects 58 were classified as quasars or galaxies. A further 6 were too noisy to be classified, leaving 196 dM binaries. These are further classified as 176 DA + dM binaries, 9 DB + dM binaries, 2 DC + dM binaries, 3 Cataclysmic Variables and 6 dM binaries with a blue component too noisy to classify. A  $u' - g'$  vs.  $i' - z'$  diagram is shown in Fig. 1.

#### Equivalent width selection of DB + dM binaries

A second, independent, search for DB + dM binaries was performed by looking for He absorption lines in all DR3 spectra. Apart from single DBs this should select all DB + dM binaries in which the DB dominates the blue part of the spectrum. In practice, this means selecting binaries in which the DB has a  $T_{\text{eff}} \geq 20\,000$  K with a companion of spectral type M1 or

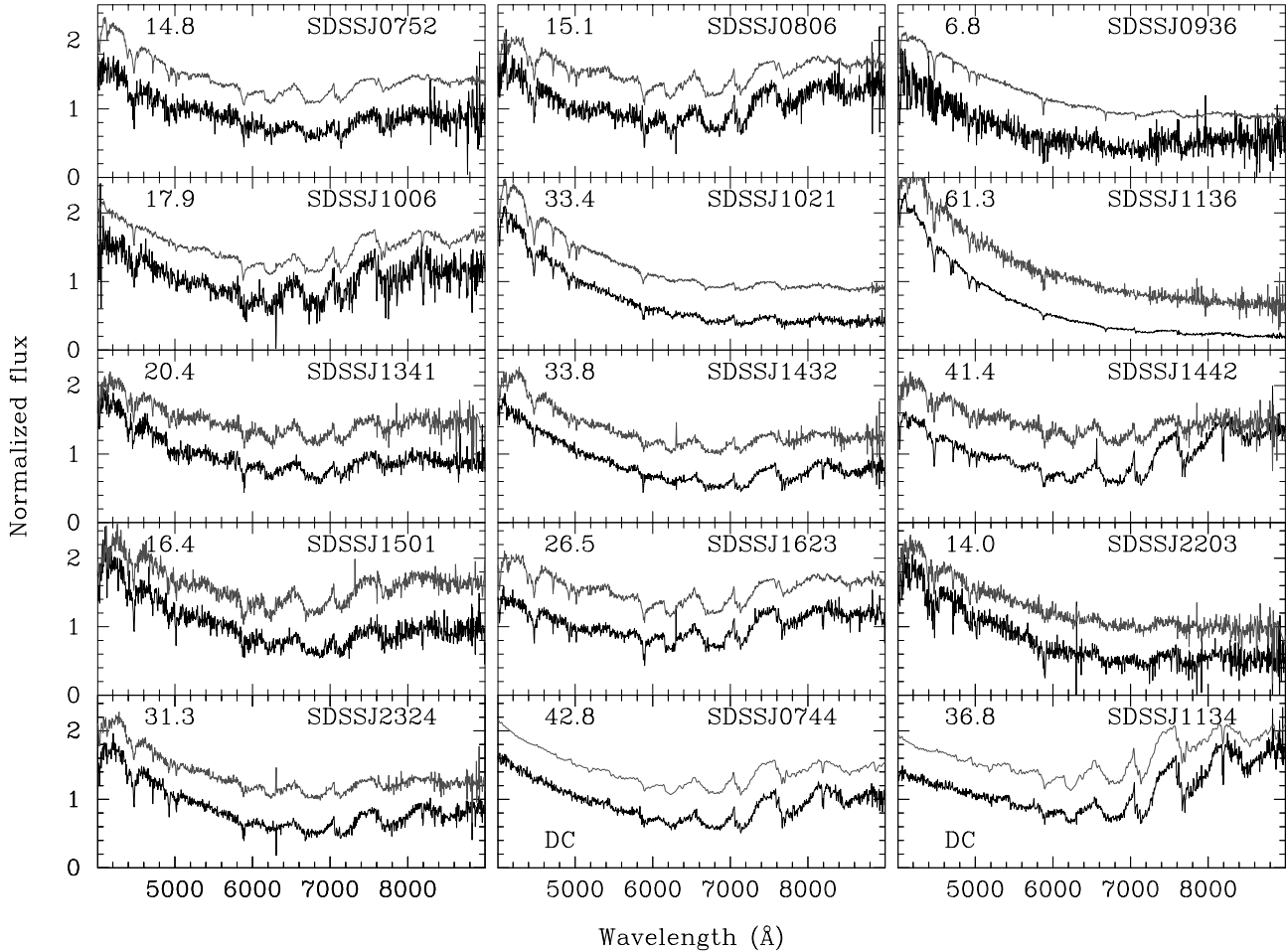
later, and binaries in which the DB has a  $T_{\text{eff}} \geq 14\,000$  K with a companion of spectral type M3 or later. For all spectra we calculated the equivalent width ( $EW$ ) of the He I 4026, 4471, 4921 and 5876 Å lines. On the basis of the distributions of  $EW$ s in a sample of 160 bright DBs and requiring that all four lines are present, DB candidates were selected such that less than an estimated 5% of all DBs fall outside the selection due to weak absorption lines.

All resulting candidates from DR3 were visually inspected for DB + dM signatures. The 9 DB + dM binaries from our colour selection were re-discovered and 4 additional systems (outside our colour selection) were identified, increasing the total number of these rare systems found in the SDSS to 13.

### 3. Results

We fitted the DB + dM spectra with a combined template DB and template dM spectrum using the  $\chi^2$  minimalization method. For the fit we have scaled the flux in the template spectra to a distance of 10 pc before combining them. The 17 template DB spectra and their corresponding temperatures, between 13 390 and 38 211 K, were taken from Kleinman et al. (2004). To derive the temperature of the DC white dwarfs, we have fitted blackbody spectra with a temperature range of 8000–40 000 K. The 7 dM spectra ranging from type M0V to M6V were taken from Pickles (1998).

The best fit Kleinman-temperatures (or blackbody temperatures in case of a DC + dM), spectral types, and  $\chi^2$  for the 15 non-DA + dM binaries are given in Table 1. In most cases, the uncertainty in spectral type of the dM is 1 subtype or less. For a fixed dM the uncertainty on the temperature of the WD is estimated to be about 4000 K. However, there is a correlation between the WD temperature and the dM spectral type. For a fit with a dM one subtype later, the best template WD may have a 8000–10 000 K lower temperature with slightly increased  $\chi^2$ .



**Fig. 2.** The 13 DB + dM and 2 DC + dM (*bottom row*) systems (Table 1). The object spectra are shown as the lower spectra, the best template has been shifted upwards for clarity. The number in the upper left corner of each plot is the  $S/N$  in a 5 Å bin at 4600 Å.

The spectra are shown in Fig. 2 (hereafter we will abbreviate names to the form SDSS Jhhmm). The object spectra are the lower spectra, while the template spectra are the upper ones.

In this paper we give all the parameters as derived assuming a WD with a radius of  $0.0123 R_{\odot}$ , identical to Raymond et al. (2003). The mass-radius relation from Eggleton as quoted by Verbunt & Rappaport (1988) gives a corresponding mass of  $0.6 M_{\odot}$  for this radius. We used several WD radii between  $0.007$  and  $0.02 R_{\odot}$  (a mass between  $1.08$  and  $0.21 M_{\odot}$ , respectively) in all our fits. For the DB + dM binaries the WD temperature, dM spectral type and overall  $\chi^2$  change only very slightly with different radii. However, for the DC + dM binaries the fit improves for a WD with a radius of  $0.008 R_{\odot}$  (a mass of about  $1 M_{\odot}$ ).

#### SDSS J0936

Due to the low signal-to-noise the blue component in SDSS J0936 is tentatively classified as a DB, but a better spectrum is needed to confirm this.

#### SDSS J1136

SDSS J1136 shows He II absorption at  $4686 \text{ \AA}$  and possibly at  $5411 \text{ \AA}$  indicating a high WD temperature. Close inspection shows clear features of a cool companion to the WD. Our best fit to this spectrum is with the combination of a WD with a

temperature of  $38211 \text{ K}$  and an M6 companion which are our hottest template WD and coolest template dM spectra. The  $\chi^2$  is still rather high (see Table 1), suggesting at least a WD with a temperature  $>38000 \text{ K}$  and possibly a companion with a spectral type later than M6V.

#### SDSS J1442

The best fit to this object is still rather poor. If we decrease the radius of the WD in the fit to  $0.009 R_{\odot}$ , the fit result is significantly better. Raymond et al. (2003) have included this object in their paper but they only mention that it has He absorption. In their Table 1 they have given a temperature of  $32000 \text{ K}$ , but this is based on a hydrogen WD model. In Table 1 of Harris et al. (2003) SDSS J1442 is classified as a DB3.5 + M binary but it is not discussed further in their paper either. Furthermore, Raymond et al. (2003) have taken 2 follow-up spectra of this object, because it shows signs of chromospheric activity through strong H $\alpha$  emission, and find a minimum radial velocity variation of  $150 \text{ km s}^{-1}$ . This suggests that SDSS J1442 is a close binary.

#### SDSS J1501

The object SDSS J1501 is mentioned in the table of Raymond et al. (2003) but is not mentioned elsewhere in that paper. They have fitted a hydrogen WD model to this spectrum,

which might (partly) explain the difference in temperature and dM spectral type between our results and theirs. SDSS J1501 clearly shows He absorption and no hydrogen absorption and therefore should be classified as a DB + dM binary.

#### SDSS J0744 and SDSS J1134

The blue parts of the spectra of SDSS J0744 and SDSS J1134 show no absorption lines from the WD stronger than 5% of the continuum and are therefore classified as DC + dM binaries. The object SDSS J1134 is mentioned in the table of Raymond et al. (2003) as well and was also fitted with a hydrogen WD model. If we use a smaller radius which corresponds to a WD mass of about  $1 M_{\odot}$  the fits improve to  $\chi^2 \approx 4$ . This results in later type M dwarf secondaries.

#### 4. Discussion

We have identified 13 DB + dM binaries and 2 DC + dM binaries in the SDSS DR3 and we derived the WD temperature, dM spectral type and distance of these binaries.

Almost no single DBs have been found with temperatures between 30 000 and 45 000 K, the so called DB-gap (Liebert et al. 1986). Kleinman et al. (2004) have found some DBs with temperatures above 30 000 K in the SDSS, but only 11 out of 171 single DBs. Although better spectra and modeling with WD atmospheric models is needed, 3 of our 13 DB + dM binaries appear to have temperatures well above this limit and another 5 have temperatures around 30 000 K. The fraction of DBs in the DB-gap for these binaries is therefore very high compared to the total DB population. From the fact that we do find cool DBs as well, it is clear that this is not due to our selection method. As mentioned before, if the fitted dM spectral type is 1 subtype too early, the temperature may drop with 8000–10 000 K. Even in this worst-case scenario, still at least 3 binaries will have temperatures close to the DB-gap. SDSS J1136 shows He II absorption which suggest a temperature of above 30 000 K, placing it in the DB-gap. Follow-up observations of all 13 DB + dM systems is needed to obtain high S/N spectra. Then we can model these spectra with WD atmospheric models to be certain which part of this sample is in the DB-gap.

It is thought that during the cooling sequence DAs can transform into DBs due to convective mixing in the H layer for temperatures below 30 000 K (e.g. Kalirai et al. 2004). WDs in close binaries might accrete some matter from their companions, making their H layers too thick for the transition to DBs. However, the fact that we do find DBs in (close) binaries may imply that they are formed in a different way so that they have lost their H (almost) completely. This could also explain their existence in the DB-gap and would suggest the DB/DA ratio in binaries might be different from that in single WDs.

The DB/DA fraction for single WDs in the SDSS is 9–15% (Kleinman et al. 2004; Harris et al. 2003). To derive the fraction of DB/DA in binary systems we can not use the EW selection. The He lines in DBs are very useful in an EW selection, but this is not possible for H lines due to the dominance of main-sequence stars. Therefore we use the sample based on the colour selection to derive the DB/DA ratio in binary systems, yielding 5%. Due to the colour selection this could be

biased, but the nine DB + dM binaries that we selected from the colour selection show a similar spread in temperature as the other DB binaries in the sample. This indicates that our colour selection does not specifically bias towards binaries with certain WD temperatures, indicating that the ratio is different in binaries than in single stars, though a more detailed study is necessary.

Raymond et al. (2003) estimate that about 5% of the WD + dM are close binaries with short orbital periods. They have taken 2 follow-up spectra of SDSS J1442 from which a minimum radial velocity variation of  $150 \text{ km s}^{-1}$  can be derived. From this value it can be assumed that SDSS J1442 is a close binary.  $H\alpha$  emission in close binaries can be enhanced due to faster rotation of the secondary or due to strong heating of the secondary by the WD, so  $H\alpha$  emission can be an indication of a close binary (e.g. Raymond et al. 2003). In our sample there are 3 systems (SDSS J1341, SDSS J1432 and SDSS J1442) that show  $H\alpha$  emission. Follow-up observations of all the sources in our sample is needed to determine if they are close binaries, and to compare their periods to those of DA + dM binaries to investigate the formation channel.

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#### References

- Greenstein, J. 1975, *ApJ*, 196, L117
- Harris, H., Liebert, J., Kleinman, S., et al. 2003, *AJ*, 126, 1023
- Iben, I., & Livio, M. 1993, *PASP*, 105, 1373
- Kalirai, J., Richer, H., Hansen, B., Reitzel, D., & Rich, R. 2004, *ApJ*, 618, L129
- Kleinman, S., Harris, H., Eisenstein, D., et al. 2004, *ApJ*, 607, 426
- Liebert, J., Wesemael, F., Hansen, C., et al. 1986, *ApJ*, 309, 241
- Moffett, T., Barnes, T., & Evans, D. 1985, in *Calibration of Fundamental Stellar Quantities*, IAU Symp., 111, 365
- Paczynski, B. 1976, in *Structure and Evolution of Close Binary Systems*, IAU Symp., 73, 75
- Pickles, A. 1998, *PASP*, 110, 863
- Raymond, S., Szkody, P., Hawley, S., et al. 2003, *AJ*, 125, 2621
- Verbunt, F., & Rappaport, S. 1988, *ApJ*, 332, 193
- Wagner, R., Sion, E., Liebert, J., & Starrfield, S. 1988, *ApJ*, 328, 213
- Wesemael, F., Greenstein, J., Liebert, J., et al. 1993, *PASP*, 105, 761
- York, D., Adelman, J., Anderson, J., et al. 2000, *AJ*, 120, 1579