Spectral analysis of 636 WD - M star binaries from the Sloan Digital Sky Survey (Data Release 6)

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Abstract. We present a catalog of 857 WD (WD)-M star binaries from the sixth data release of the Sloan Digital Sky Survey (SDSS), most of them known before. For 636 of them, we give a spectral analysis and derive the basic parameters of the stellar constituents and their distances from Earth. Our purpose is to test the modeled spectra applied in the fitting procedure on the one hand and to confine the respective evolutionary scenarios on the other hand. We use a χ^2 minimization technique in order to decompose each combined spectrum and yield independent parameter estimates for the components. 41 of the stellar duets in our spectroscopic sample are optically resolved on the respective SDSS images. Despite various selection effects, the fraction of 6.4 % of WD-M star binaries with orbital separation around 500 AU and orbital perdiods of $\sim 10^4$ yr is a criterion for evolutionary models of stellar binary systems. We find 20 out of 636 WDs being fitted as DOs, with 16 of them indicating $T_{\rm eff}^{\rm WD}$ around 40 000 K. This excess of cool DOs is most likely due to additional WDs in the DB-DO $T_{\rm eff}$ range, for which no detailed fitting was done. Furthermore, we identify 70 very low-mass objects, meaning secondaries with masses smaller than about 0.1 $M_\odot$, as candidate substellar companions. A trend of WD masses towards higher values in a binary constellation compared to those of field WDs is compatible with our results.

1. Introduction

The Sloan Digital Sky Survey (SDSS) offers a considerable improvement of observational contribution to hat subject. Raymond (2003) threw a first glance at WD-M dwarf (dM) pairs in the SDSS and identified 109 of such objects. 99 of them are in our master sample but we discarded 32 of them for our purpose by reasons given at the end of Sect. 2. Other cataloges and analyses on WDs and WD-main-sequence (MS) binaries have been presented by (Greenstein 1986, Luyten 1997, Luyten 1999, Wachter et al. 2003, Kleinman et al. 2004, Eisenstein et al. 2006, Hügelmeyer 2006, Silvestri 2007, Rebassa-Mansergas et al. 2007). 153 systems from our sample were not included in any of the mentioned studies.

The present work introduces a novel method of analyzing WD-dM binaries by simultaneously fitting model spectra for both the WD and the MS star to the composite spectrum to derive the atmospheric parameters of both stars. Unlike the aforementioned studies, we thus obviate the need to calibrate empirical relations between physical parameters and spectral types. Although current cool star atmosphere models may still have some shortcomings in fitting dM spectra, this approach avoids possible biases due to systematic differences between single dMs and those in close binaries.

2. Observations

A detailed desription of the SDSS' instrumental setup can be found in Adelman-McCarthy et al. (2008). The spectroscopic dataset used for our study consists of 857 objects that were labeled as WD-M dwarf binaries during a search for hot subdwarfs in the SDSS dataset. Our selection procedure resembles that of the SDSS' own in that we investigated a large fraction of the color-color space in the EDR release, and refined our search area in the following releases. Of particular importance for the WD-M sample is the cutoff in $g - r$. For the EDR we imposed no cutoff, but for later releases we imposed $g - r < 0.2$ in addition to the $u - g < 0.8$ criterion used to select stars with UV excess. A more detailed explanation of the color-color loci of WD-M star systems within the SDSS is given in Smolčić et al. (2004).

Our sample is made up of 857 objects: this is our master sample. From that, we discard noisy spectra and those, in which either the WD or the red companion shows rather weak features. Only spectra with either clear DA or DO features are respected. Furthermore, we reject spectra with pollution of nearby light sources, which we verified with the aid of the photometric data. WD-M pairs with cool WDs and dominant red components are preferentially dismissed from our sample by the selection method – those systems with significant light contribution due to mass overflow, too. The buildup of that subsample of 636 systems is consequently subject to severe selection effects.

We assume a mass-radius relation for unevolved main sequence stars by using the evolutionary models of Chabrier & Baraffe (1997) for a fixed M star age of 10^{10} yr to deduce the radius ($R_{\rm M}$) and mass ($M_{\rm M}$) of the M star from its fitted effective temperature ($T_{\rm eff}^{\rm M}$) and metallicity $[{\rm Fe/H}]_{\rm M}$. For the mass range considered here, evolution effects on the main sequence are negligible within a Hubble time, thus only pre-main sequence stars with ages $\lesssim 5 \cdot 10^8$ yr might introduce larger errors in the radius estimate. The errors in surface gravity of the WD ($g_{\rm WD}$) from our fits are in most cases inadequately high for a meaningful deduction of the WD radii. But, as shown by Hu, Wu & Wu (2007), the major part of the SDSS DAs has masses clustering closely around the peak of the field WD mass distribution at $0.58\,M_\odot$. There are observational indications for higher WD masses in close binaries compared to the masses of field WDs (Ramsay 2000, Ritter & Kolb 1998, Cropper, Ramsay & Wu 1998). We therefore use a fixed WD mass ($M_{\rm WD}$) of $0.6\,M_\odot$ together with the WD temperature ($T_{\rm eff}^{\rm WD}$) from the fit to derive the radius of the WD ($R_{\rm WD}$) from the evolutionary tracks calculated by Wood (1994). These models are available for 0.4, 0.5, 0.6, 0.7, 0.8 and 1.0 $M_\odot$.

WD-dM alignment by chance is found to be negligible. The probability $P_{\rm M}$ to find at least one M star within a circle with the $3'$ diameter of the SDSS fiber on the celestial plane by chance is given by the Poisson probability

$$P_{\rm M}(\nu \geq 1) \;=\; 1 - e^{-\mu} \quad , \qquad \mu \;=\; A \cdot \rho_{\rm M} \tag{1}$$

where $A = \pi\,(1.5')^2$ is the probed area and $\rho_{\rm M}$ is the area density of M stars on the celestial plane. To estimate $\rho_{\rm M}$, we refer to private communication with J. Bochanski who measured the field luminosity function of stars in the DR6. We get $\rho_{\rm M} = 9.55 \cdot 10^4\,(`)^{-2}$ and $P_{\rm M} = 6.73 \cdot 10^{-3}$. The expectation value is $P_{\rm M} \cdot 636 \approx 4.3$ for the number of WD-M binaries aligned by chance within our sample.

3. Models

Models for the full parameter range of interest were pre-computed, providing two grids for the spaces of WD parameters $T_{\rm eff}^{\rm WD}$, $g_{\rm WD}$ and M dwarf parameters $T_{\rm eff}^{\rm M}$, $g_{\rm M}$ and $[{\rm Fe/H}]_{\rm M}$, respectively. White dwarf spectra have been calculated for pure hydrogen atmospheres covering surface gravities of $7 \leq \log(g_{\rm WD}) \leq 9$ with a step size of 0.5 dex in a temperature range from 6 to 90 kK. We had 1 kK steps between 6 and 30 kK, 2 kK steps between 30 and 50 kK and 5 kK steps for temperatures above 50 kK. This core model grid was supplemented with existing models for extremely hot ($T_{\rm eff}^{\rm WD} > 90$ kK) or lower-gravity ($\log(g_{\rm WD}) \in \{5, 6\}$) atmospheres and for hot helium-rich atmospheres. The latter were available for $\log(g_{\rm WD}) = 7.5$ in the range of $40\,{\rm kK} \leq T_{\rm eff}^{\rm WD} \leq 80\,{\rm kK}$ every 5 kK. The grid of the MS spectra was almost complete for $2\,600\,{\rm K} \leq T_{\rm eff}^{\rm M}$ every 200 K, $[{\rm Fe/H}]_{\rm M} \in \{-1.5, -1, -0.5, 0, 0.3\}$ and $\log(g_{\rm WD}) \in \{2, 3, 4, 4.5, 5, 5.5\}$.

The WD models have been computed by D. Koester using his codes developed for static, plane-parallel stellar atmospheres in radiative, hydrostatic and local thermodynamic equilibrium (LTE), as described in detail in Finley, Koester & Basri (1997). The main body of this grid covers fully-blanketed pure hydrogen (DA) atmospheres. These models take convective flux into account according to the mixing length approximation (MLT), using a variation of the standard formulation of Mihalas (1978) designated as ML2 in the notation of Finley, Koester & Basri (1997) and references therein, and adopting a mixing length of $\alpha = 0.6$ (in units of pressure scale height). This setup has been demonstrated to be one of the best available configurations for reproducing DA spectra at high resolution and S/N (Homeier et al. 1998, Koester et al. 2001). This grid was extended by an existing set of hydrogen atmosphere models based on the same input physics to cover the more extreme parts of the WD parameter space in high $T_{\rm eff}^{\rm WD}$ and lower gravity (sdB-like atmospheres). In addition for those hot WDs that were not adequately reproduced by DA spectra the sequence of helium-rich (DO) models was used. These models assume a helium-to-hydrogen mixing ratio of 100:1 and the ML1 MLT version with $\alpha = 1.0$ as described in Jordan et al. (1997). These latter models only cover the spectrum up to $\lambda \leq 8\,000$ Å, and thus an important part of the dM flux had to be masked out in the analysis. However among our final results none of the primaries ended up in the low-gravity or ultra-hot domain of the DAs/sdBs; and a quantitative analysis of the helium-rich WDs was beyond the scope of this work, as detailed below.

The secondary spectra were calculated with version 14.2 of the multi-purpose stellar atmosphere code `PHOENIX` (Hauschildt & Baron 1999) for 1D spherically symmetric, static atmospheres in LTE, also considering convective instability in the framework of MLT according to Mihalas (1978) with a mixing length parameter $\alpha = 2.0$. Our models follow the general setup used for the first GAIA grid (Brott & Hauschildt 2005), which includes a number of updates from the NextGen grid (Hauschildt et al. 1999) and the microphysics described by (Allard et al. 2001), but ignores effects of condensate formation. We have therefore restricted the range of validity of these models to $T_{\rm eff} \geq 2800$ K.

4. Mathematical Treatment

With our χ^2 fitting method we move within a 5D parameter space, spanned by $T_{\rm eff}^{\rm WD}$, $T_{\rm eff}^{\rm M}$, $g_{\rm WD}$, $g_{\rm M}$ and $[{\rm Fe/H}]_{\rm M}$. Each observed flux data point $F_i^{\rm obs}$ in a binary spectrum with a total number of m observed data points shall be reproduced by a combination of two single-star models x_i and y_i. These have to be weighted with scaling factors a and b respectively, depending on the stars' distances. χ^2 is defined a

$$\chi^2 \;:=\; \sum_i^m \frac{(F_i^{\rm obs} - F_i^{\rm mod})^2}{\sigma_i^2} \;=\; \sum_i^m \frac{(F_i^{\rm obs} - a\,x_i - b\,y_i)^2}{\sigma_i^2} \;=:\; [(F_i^{\rm obs} - a\,x_i - b\,y_i)^2] \qquad (2)$$

with σ_i as the observational error given in the SDSS .fits file of the object. We use $[w_i]$ as an abbreviation for $\sum_i^m w_i/\sigma_i^2$. With

$$\nabla\chi^2(a,b) \;=\; -2\left([x_i\,(F_i^{\rm obs} - a\,x_i - b\,y_i)]\,,\;[y_i\,(F_i^{\rm obs} - a\,x_i - b\,y_i)]\right) \stackrel{!}{=} 0 \qquad (3)$$

we obtain

$$\begin{pmatrix}[F_i^{\rm obs}\,x_i]\\ [F_i^{\rm obs}\,y_i]\end{pmatrix} \;=\; \underbrace{\begin{pmatrix}[x_i^2]\,[x_i\,y_i]\\ [y_i\,x_i]\,[y_i^2]\end{pmatrix}}_{Z}\begin{pmatrix}a\\ b\end{pmatrix} \quad , \qquad (4)$$

which is equivalent to

$$\begin{pmatrix}a\\ b\end{pmatrix} \;=\; Z^{-1}\begin{pmatrix}[F_i^{\rm obs}\,x_i]\\ [F_i^{\rm obs}\,y_i]\end{pmatrix} \;=\; \begin{pmatrix}[F_i^{\rm obs}\,x_i]\,[y_i^2] - [x_i\,y_i]\,[F_i^{\rm obs}\,y_i]\\ [F_i^{\rm obs}\,y_i]\,[x_i^2] - [y_i\,x_i]\,[F_i^{\rm obs}\,x_i]\end{pmatrix}\frac{1}{[x_i^2]\,[y_i^2] - [x_i\,y_i]^2} \quad . \qquad (5)$$

(5) gives us the scaling factors for both the WD and the M star model, which we then use to compute χ^2 with (2). Using that procedure, we avoid a mutual dependence of a and b since the system of equations is uniquely solvable; we also avoid the possibility of running into a local χ^2 minimum.

4.1. Distances

Once $R_{\rm WD}$ is drawn from the fixed $M_{\rm WD}$, the fitted $T_{\rm eff}^{\rm WD}$ and using models from (Wood 1994), the only thing we still need to obtain the distance $d_{\rm WD}$ of the WD from Earth is the scaling factor $a = (R_{\rm WD}/d_{\rm WD})^2$ from our fitting method which scales the model flux down to the observed flux (and analog for the dM). To make the estimates of the respective distances comparable among all the spectra, we introduce the coefficient

$$C := \frac{\frac{\sqrt{2}}{2}\,(d_{\rm WD} - d_{\rm M})}{\frac{d_{\rm WD}+d_{\rm M}}{2}} = \sqrt{2}\,\frac{d_{\rm WD} - d_{\rm M}}{d_{\rm WD} + d_{\rm M}} \tag{6}$$

which weighs the displacement of a certain binary system from the diagonal in the $(d_{\rm WD} - d_{\rm M})$ plane with the average distance $\overline{d} = (d_{\rm WD} + d_{\rm M})/2$ of the system from Earth.

We use the averaged distance $\overline{d}$ of the system from Earth, the displacement D of the stars on the SDSS images in units of pixels and the given resolution ϱ of the images in $''$/pixel to calculate the angular separation α in units of radian via $\alpha = \varrho\, D/3600 \cdot \pi/180$ and finally, simply using geometry, the projected mutual distance $d_{\rm proj}$

$$d_{\rm proj} = 2\,\overline{d}\,\tan\left(\frac{\alpha}{2}\right) \quad . \tag{7}$$

We may benefit from that visible separation and estimate the period of the system via

$$P \gtrsim 2\pi\,\sqrt{\frac{d_{\rm proj}^3}{G\,(M_{\rm WD} + M_{\rm M})}} \quad . \tag{8}$$

5. Results

The temperature function for our WDs can be seen in Fig. 1. Since most of the WDs in our sample have a surface gravity between 7 and 8 dex, the shape of the WD-distance function in Fig. 2 is quite similar to that of the temperature function.

The standard deviations for the deduced parameters are quite weak in terms of physical significance, which shows that the systematic errors dominate the mathematical ones. For a conservative estimate of the errors resulting from the the incomplete molecular data for the M star models, SDSS flux calibration errors and interstellar reddening, we refer to Hügelmeyer (2006) and assume an uncertainty of 2 000 K for the WDs with temperatures smaller than 50 000 K and a 1-σ interval of 100 K for the MS stars. For $T_{\rm eff}^{\rm WD} > 50\,000$ K the absolute value of our accuracy is given by the half of the model step width of 5 000 K. Our accuracy in the surface gravities is limited by the low resolution of the SDSS spectra and the step size of our model grid and thus we have $\sigma_{\log(g_{\rm WD})} \approx 0.5\,{\rm dex} \approx \sigma_{\log(g_{\rm M})}$. The metallicity determination is merely accurate to about 0.3 dex.

5.1. White Dwarfs Showing He Lines

616 spectra from our original input sample can be fitted well using a DA primary, but among the remaining systems, a small number shows He features in the primary spectrum. These tend to be found at relatively high $T_{\rm eff}^{\rm WD}$, since spectra showing clear DB features have been efficiently removed in the initial selection. Among the remainder, which are mostly dominated by the He II Bracket-equivalent series, we found 20 to be better fitted by spectra from our DO model library. These stars cluster predominantly at the cool end of the DO sequence: 16 of 20 are fitted with the lowest effective temperature in the DO grid

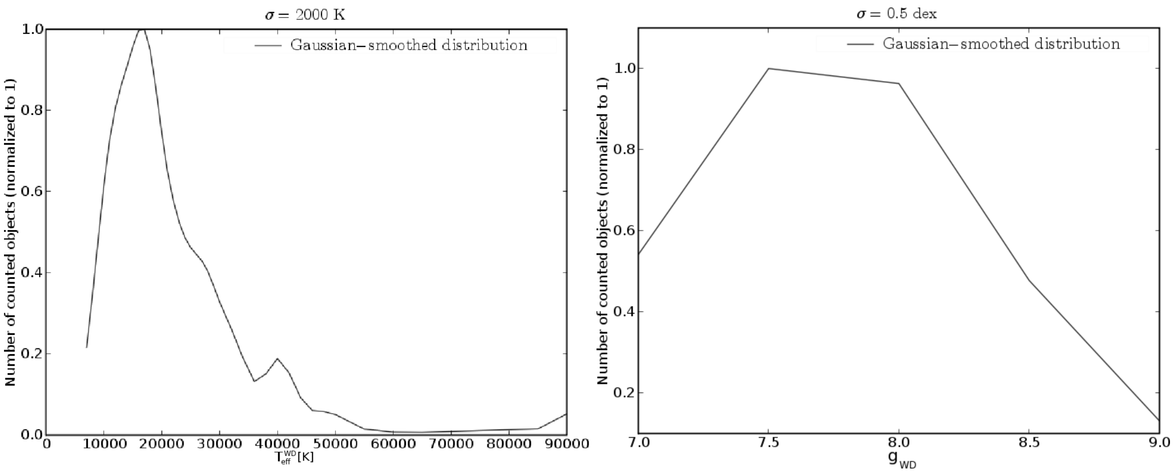

Figure 1. *Left:* Temperature function for the WDs; While the major peak at 17 000 K belongs to the DAs, the bump at 40 000 K is due to the preferential selection of cool DOs for our sample. This plot looks very similar to that shown in Silvestri et al. (2006), except for the DO feature and that it is smoothed. *Right:* Distribution of the WD surface gravities.

of 40 000 K. Many of the latter show stronger He I lines in addition to He II, and would thus probably be better classified as DBO according to the nomenclature of Wesemael et al. (1993). We suspect that this distribution does not reflect the true luminosity function of Helium-rich WDs, but is rather biased by a contribution of WDs below the $T_{\rm eff}$ limit of our DO models.

From the 167 spectra with H emission features, we substract 8 known PCEB candidates and 4 active CVs, which yields 155 WD-M star binaries, corresponding to a fraction of 24.4 %, that probably harbor an active M dwarf. This value is conform with the fraction of 24.4 % for active field M dwarfs in the SDSS as found by West et al. (2004). However, Silvestri et al. (2006) found a significantly larger fraction of active M dwarfs in WD-M binaries. Considering only unresolved binaries, as they did, our fraction of binary systems with H_α emission that probably comes from the M component even decreases to 23.2 % and exacerbates the discord between our results and theirs.

5.2. Optically Resolved Binaries

Of our 636 binaries, 41 are chosen for follow-up studies because, firstly, the red star is found to be located within an area around the WD that was covered by the SDSS fiber and, secondly, these stars have a separation wide enough to distinguish between the two components. For photometric binaries with a separation clearly larger than the SDSS fiber radius of 1.5′ we act on the assumption that the M star on the SDSS image is not the one represented in the spectrum. The respective fitting results are marked and have to be taken with a pinch of salt since we may not state clearly if a significant fraction of the light contribution from the red star was caught by the fiber anyway, despite the separation larger than 1.5′. The results for the resolved binaries can be found in the supplementary data to this acticle. The typical projected distances are large: of the order of some hundred AU with a mean value of roughly 650 AU. The widest separation we find is 1 700 AU for J1006+5633, where the real spatial separation should be even larger. The orbital periods we derive are typically in the order of some 10^4 yr with J1006+5633 indicating a period of $\gtrsim$ 70 000 yr.

6. Discussion

The M star temperatures we fitted are in good accordance with the spectral types derived by Rebassa-Mansergas et al. (2007). In Fig. 3 we compare our fits for $T_{\rm eff}^{\rm M}$ with their spectral types for 41 objects (left panel) and with the spectral classification from (Silvestri et al. 2006) (right panel) for 446 objects,

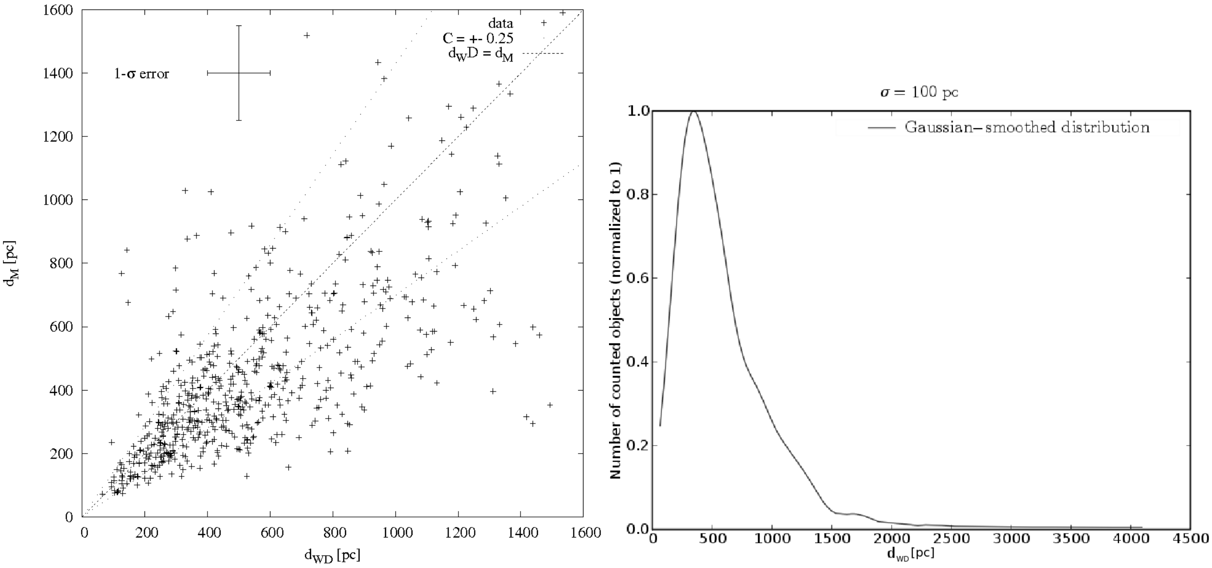

Figure 2. *Left*: Distribution of the derived distances of the stellar components of our systems; The diagonal is the ideal for physical binaries. The dotted curves span a tolerance fan for $C = 0.25$. *Right*: The distribution of the WD distances in our sample is a consequence of the restricted magnitude range of the SDSS. It has its maximum at 354 pc.

which were both in ours and their sample. The authors of the latter publication derived their dM types on the basis of template spectra and color indices as described in Hawley et al. (2002). In both comparisons the maximum is reached at (3 200 K , M4) and the plot shows a monotone decrease of the spectral type with increasing temperature. These counts probably do not mirror the true $T_{\rm eff}^{\rm M}$ or spectral type function due to selection effects like the growing number of M dwarfs towards later types on the one hand and decreasing visibility of the secondary component on the other hand.
In our study, we see a trend towards $d_{\rm M}$ being smaller than $d_{\rm WD}$, and we consider three possible effects:

i. Reiners (2005) has shown the absorption in the TiO ϵ-band to be systematically underestimated by `PHOENIX` M star spectra. Since this band system as a primary temperature indicator deepens with decreasing $T_{\rm eff}^{\rm M}$, model spectra fits to this feature risk to systematically underrate $T_{\rm eff}^{\rm M}$, too. This effect, if present in our models as well, would cause $d_{\rm M}$ to be systematically underestimated.

ii. As mentioned in Sect. 2, there is observational evidence that the masses of WDs in close binaries cluster rather between $0.7\,M_\odot$ and $0.8\,M_\odot$ than around $0.6\,M_\odot$ as for field WDs. Only 12 out of the 636 objects presented here are known to be close systems, i.e. CVs or PCEBs, while 41 are pretty widely separated as inferred from the optical detachment. We cannot give an assessment of the remaining orbits from our data and we may not say precisely if the WD masses are rather close to 0.7 or even $0.8\,M_\odot$ but a potential trend towards higher WD masses would be compatible with the bias towards $d_{\rm WD} > d_{\rm M}$. An increase in mass leads to a decrease in radius for a WD and consequently a smaller distance to Earth is required in order to reproduce the observed flux. Our possible underestimation of $M_{\rm WD}$ could thus contribute to a systematic overestimation of $d_{\rm WD}$.

iii. The M star radii that we deduced from the Chabrier & Baraffe (1997) model tracks, based on the effective temperature and the metallicity from our spectral fits, are systematically underestimated for low-mass objects ($M_{\rm M} \lesssim 0.3\,M_\odot$, see Fig. 2). This general discrepancy between theory and observations is known in the community of low-mass stars science and emerged, hitherto, particularly in observations of eclipsing binary systems with a low-mass component (Ribas et al. 2007). With our – under statistical aspects – large sample we support this claim.

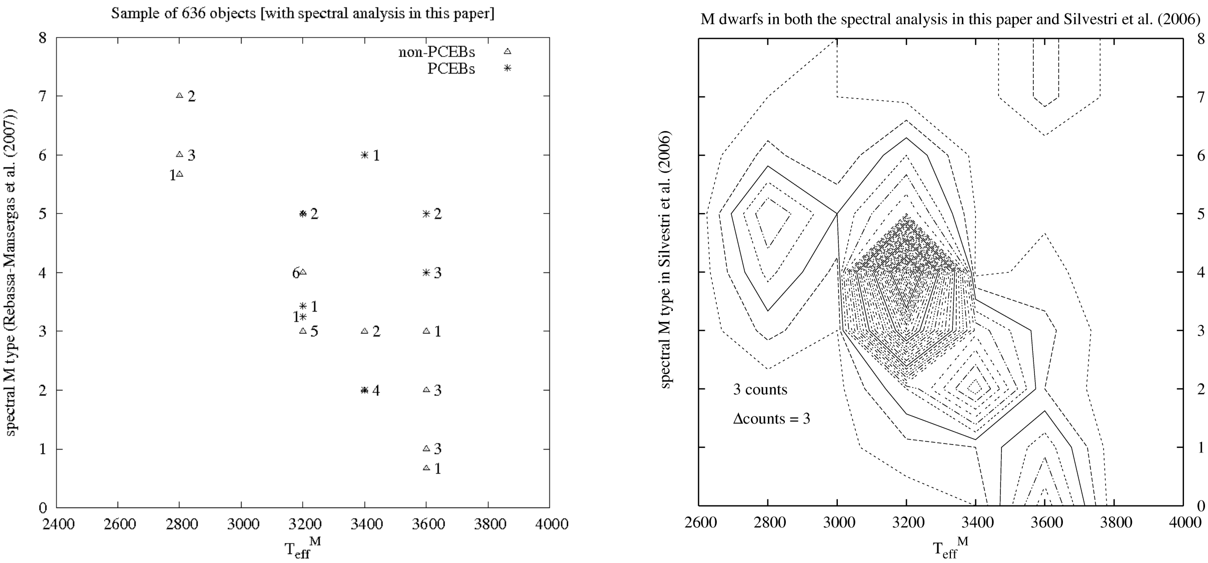

Figure 3. *Left*: Comparison of the spectral types from Rebassa-Mansergas et al. (2007) with our $T_{\rm eff}^{\rm M}$ for 41 M stars, that match both their sample and ours; 11 of them are marked as PCEBs. Labels indicate the counts per grid point. *Right*: Comparison of the spectral types given in Silvestri et al. (2006) with our $T_{\rm eff}^{\rm M}$ for 446 M stars, that match both their sample and ours; The number of dMs per grid point is projected onto the ($T_{\rm M}^{\rm eff}$-SpT) plane. The outer contour marks the path of 3 counts, each subsequent contour symbolizes an increase of 3 counts. The maximum is at (3 200 K , M4) with 115 counts. Their average spectral mismatch was ±1, while our 1-σ accuracy for $T_{\rm eff}^{\rm M}$ is 100 K.

There is a relatively large number of widely-separated binaries with orbital distances $\gtrsim$ 250 AU and up to 1 700 AU: 41/636 = 6.4 %. This is, however, not a stable assessment; we see five effects that may smear the optical-binary fraction to either higher or lower values.

i. If two objects are so close together that they appear as one elongated object with off colors, the SDSS classification procedure may preselect it as a possible galaxy. That would mean that we have underestimated the true optical-binary fraction.
ii. A small number of physical pairs aligned along the line of sight could also drive the true optical-binary fraction to a higher value. We would have missed them just because of their unfavorable geometrical constellation.
iii. Some of the stellar duets on the SDSS images with angular distances > 1.5′ could also be physical pairs (but the secondary on the image would not be the one represented in the respective SDSS spectrum).
iv. A significant contingent of binaries with mass overflow from the MS companion to the WD are supposed to be located out of the color-color region that we studied in order to make up our sample. These stellar duets are close systems with no optical separation on the SDSS images, which pushes the optical-binary fraction to lower values.
v. The statistical considerations presented in Sect. 2 show that about 4 of the binaries in our sample should be aligned by chance – without a common evolutionary background. Probably none, or at most one, of the optical binaries is one of these mavericks.

Asked if stellar duets with such large orbital separations are stable over long timescales, we refer to the paper of Weinberg et al. (1987) and Fig. 2 therein. Their calculations, including both stars passing by and encounters with subclumps within giant molecular clouds, show that binaries with a total mass of

1 $M_\odot$ and initial orbital separations around 650 AU have a typical lifetime of more than the age of the Universe.

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