The SDSS White Dwarf - M Star Library

René Heller\textsuperscript{1}, Axel D. Schwope\textsuperscript{1}, and Roy H. Østensen\textsuperscript{2}

\textsuperscript{1}Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany

\textsuperscript{2}Instituut voor Sterrenkunde, K.U. Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium

Abstract. The Sloan Digital Sky Survey (SDSS), originally targeted at quasi-stellar objects, has provided us with a wealth of astronomical byproducts through the last decade. Since then, the number of white dwarfs (WDs) with physically bound main-sequence star companions (mostly dM stars) has increased radically, allowing for fundamentally new insights into stellar physics. Different methods for the retrieval and follow-up analysis of SDSS WD-dM binaries have been applied in the literature, leading to a rising number of WD-dM catalogs. Here we present a detailed literature search, coupled with our own hunting for SDSS WD-dMs by color selection, the outcome being named the \textit{SDSS White Dwarf - M Star Library}. We also explain improvements of our automated spectral analysis method.

1. Motivation

Among the compact binaries discussed in this conference, those composed of a white dwarf (WD) and a main-sequence (MS) companion, most of them being M dwarfs (dMs), rank among the least massive ones. Masses of free WDs cluster around 0.58 \( M_\odot \) (Hu et al. 2007), with \( M_\odot \) as the mass of the Sun, but there are indications of higher WD masses in magnetic cataclysmic variables (mCVs) (Ramsay 2000) in opposite to lower WD masses in post common envelope binaries (PCEBs) (Rebassa-Mansergas et al. 2011). The MS companions typically have masses between 0.1 and 0.5 \( M_\odot \) (Heller et al. 2009, H09 in the following). With WDs being the common final state of MS star evolution (Fontaine et al. 2001) and dMs as the most abundant stars in the Milky Way, flanked by the fact that about half of WD progenitors exist in stellar binary systems (Fischer & Marcy 1992; Raghavan et al. 2010), WD-dM binaries provide insights into standard paths of stellar evolution. Yet, these systems show a variety of phenomena, ranging from magnetic WD-dM interaction, over PCEBs and CVs to type Ia supernovae, mergers, accretion-induced collapses (Fryer et al. 2002), and the emission of gravitational waves (Yu & Jeffery 2010), especially once both constituents in a close system have become compact objects. Moreover, both the WD and the dM once have formed from the same molecular cloud, thus virtually share same initial but completely different present compositions due to their dissimilar evolutionary stages. And since simulated WD evolutionary tracks offer the possibility to utilize the observed effective temperature and mass of the WD as a clock for the system, the age of widely separated MS companions, which would evolve similar to single stars, can be well constrained.
Since the advent of the Sloan Digital Sky Survey (SDSS, York et al. 2000), the number of known WD-dM pairs has increased dramatically. Since then, several studies have been dedicated to the identification and spectral analysis of these systems (Raymond et al. 2003; Pourbaix et al. 2004; Hügelmeyer et al. 2006; Silvestri et al. 2007; Rebassa-Mansergas et al. 2007; Littlefair et al. 2008; Augusteijn et al. 2008; Heller et al. 2009; Zorotovic et al. 2010; Schreiber et al. 2010; Rebassa-Mansergas et al. 2010). For our ongoing study, we compile these subsamples and use data of the recent SDSS Data Release 8 (DR8) (Aihara et al. 2011). Here we present the outcome of the data acquisition and describe upgrades of the spectral analysis method with respect to H09.

2. Catalog setup

We first perform a query for WD-dM binary candidates in the DR8 using a color-search algorithm (H09). In the next step, we collect WD-dM candidates – including PCEBs, CVs, and wide binaries – from the publications mentioned in Sect. on systems from the SDSS and add the samples of Wachter et al. (2003), Schreiber & Gänsicke (2003), Nilsson et al. (2006), and Brown et al. (2011), whose publications did not originally base on SDSS data. We then check this compilation for duplicates and reference the objects to further historical literature, such as Greenstein (1986), McCook & Sion (1999), Luyten (1999), Eisenstein et al. (2006), Kleinman et al. (2004), Ritter & Kolb (2010), which mostly tabulate WDs. With this method, we accumulate 3540 WD-dM candidates, most of which were observed by the SDSS. This sample constitutes the White Dwarf - M Star Library. We then use the DR8 query to search for sources at the objects’ positions, which yields 2537 WD-dM candidates with SDSS spectra and photometric images (see Fig. 1), this sample being called the SDSS White Dwarf - M Star Library. For 366 of these objects we find multiple spectra, thus more than tripling the repertoire of Rebassa-Mansergas et al. (2007), forming a promising subsample for dynamical follow-up investigations, e.g. in search of PCEBs.
3. Spectral analysis

For our spectral analysis, we use a pre-computed grid of WD spectral models made available by D. Koester (Finley et al. 1997) as well as a grid of PHOENIX models to fit the MS star (Hauschildt & Baron 1999; Hauschildt et al. 1999). Our models are distributed in a five-dimensional parameter space, spanned by the effective temperatures of the two stars ($T_{\text{eff,WD}}$ and $T_{\text{eff,dM}}$), their surface gravities ($\log(g_{\text{WD}})$ and $\log(g_{\text{dM}})$), and the metallicity of the M dwarf ([Fe/H]_{dM}). The mathematics of our $\chi^2$ fitting procedure is described in H09.

The main advancement of our parameter determination with respect to H09 is the derivation of the WD mass from the fitted $T_{\text{eff,WD}}$ and $\log(g_{\text{WD}})$ using evolution models from Renedo et al. (2010), rather than fixing the mass at 0.6 $M_{\odot}$. As a second improvement, we now fit for the radial velocities (RVs) of both objects simultaneously, using a $\chi^2$ minimization method (Fig. 2). As a third enhancement, we measure the equivalent width of the H\alpha emission line in order to assess the activity of the dM.

Analogously to the WD parametrization, we employ the fitted $T_{\text{eff,dM}}$ and [Fe/H]_{dM} to estimate mass and radius of the MS companion from evolutionary models (Chabrier & Baraffe 1997). Hence, we can estimate the distances of both binary constituents to Earth, ideally being equal for physically bound pairs.
Table 1. Comparison of the physical values for SDSS1212−0123 derived by Nebot Gómez-Morán et al. (2009) and in this study. ¹ Conservative error estimates.

| PARAMETER | NEBOT-GÓMEZ-MORÁN ET AL. (2009) | THIS STUDY¹ |
|-----------|---------------------------------|-------------|
| $T_{\text{eff,WD}}$ | 17 700 ± 300 K | 17 000 ± 1000 K |
| $M_{\text{WD}}$ | 0.45 ± 0.01 $M_\odot$ | 0.4 ± 0.1 $M_\odot$ |
| $R_{\text{WD}}$ | 0.017 ± 0.001 $R_\odot$ | 0.02 ± 0.01 $R_\odot$ |
| $\log(g_{\text{WD}}/[\text{cm/s}^2])$ | 7.6 ± 0.1 | 7.5 ± 0.5 |
| $M_{\text{dM}}$ | 0.275 ± 0.015 $M_\odot$ | 0.15 ± 0.05 $M_\odot$ |

4. Results

As a test we apply our python-based Spectral Analyzing and Fitting Tool (SAFT) to the eclipsing benchmark system SDSS J121258.25−012310.1 (SDSS1212−0123), whose parameters have been well constrained by Nebot Gómez-Morán et al. (2009) using detailed photometry and RV observations. A comparison between their parametrization of the system and ours is presented in Table 1, with the results being in good agreement. The error bars from their targeted high-quality observations are much smaller than ours since we only decompose a single SDSS spectrum.

In Fig. 3 we show the DR8 spectrum of SDSS1212−0123 with our fit as an overplot (top), as well as the spectral decomposition (center) and the residuals (bottom). With a reduced $\chi^2$ of 3.341 for 3832 wavelength-flux points in the SDSS file, corresponding to 1595 statistically independent data points (see Eq. (12) in H09), this fit is robust. In the residuals, the shortcomings of the PHOENIX models can clearly be seen for $\lambda \gtrsim 5500$ Å, as well as the Hα emission line around 6564.6 Å (in vacuum), neglected by PHOENIX.

During the library setup we encountered difficulties with the cross-matching of objects, partly caused by the changing SDSS name assignment for one and the same physical object among subsequent DRs. These variations probably stem from (i.) proper motion of the objects, (ii.) changing accuracy of the SDSS pointing [Aihara et al. 2011], and (iii.) occasional optical separation of the binary. As an arbitrary example, the object published by Raymond et al. (2003) as SDSS J020806.39+001834.0, based on the Early DR, is termed SDSS J020806.3+001834.6 in DR1, SDSS J020806.31+001834.6 in DR5 (but published as SDSS J020806.39+001834.0 by Silvestri et al. 2007), SDSS J020806.31+001834.6 in DR7, and both as SDSS J020806.33+001834.5 and SDSS J020806.45+001833.7 in DR8. The latter double identification is probably due to the slight optical separation of the WD and the dM on the SDSS images, resulting in a multiple selection during the automatic SDSS targeting process.

5. Conclusions and outlook

Based on a comprehensive literature search, coupled with an independent search for WD-dM binaries in the color space, our White Dwarf - M Star Library comprises the most complete library of WD-MS binaries up to date. In the following, we will apply an automated spectral analysis to the SDSS White Dwarf - M Star Library, which will not only provide us with a standardized analysis of the catalog but will also enable us to sort out spurious objects, discern DA from DO and possibly other WD sub-types, and
Figure 3. Graphical output of SAFT for the SDSS WD-dM binary SDSS1212−0123 (52367-0332-564). Top: Observed DR8 spectrum and combined WD-dM fit. Center: Best-fit decomposition of the spectrum with physical parameters in the legend. Bottom: Residuals.

...to further explore the RV and Hα emission variability of the sub-sample with multiple spectroscopy. Therefore, it will be necessary to take into account the various selection effects of the publications we used to set up the library, i.e. to label CVs and consider optically resolved pairs. The latter objects serve as interesting targets for follow-up studies. Although their separation might induce a flux loss in the SDSS spectra of one component – each of the 640 SDSS fibers covers a 1.5′′ radius on the celestial plane – those systems which are resolved but with a separation well below 1.5′′ allow for an estimate of their minimum orbital period. Combined with the multi-epoch spectral analysis, triple systems could be identified.

The outcome of the spectral fitting to the whole SDSS White Dwarf - M Star Library, in particular of the intrinsic and observational parameters derived, will be published in a subsequent paper.

In order to place a library as complete as possible at the disposal of the community, we encourage authors and astronomers to inform us about new WD-dM findings as well as about samples we might have been missing so far. Acknowledgements will be published.

Acknowledgments. We thank A. Rebassa-Mansergas and his collaborators for sharing their sample prior to their original publication. R. Heller is supported by the DFG grant SCHW 536/33-1. This research has made use of NASA’s Astrophysics Data...
System Bibliographic Services and of the SIMBAD database, operated at CDS, Strasbourg, France. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is [http://www.sdss.org](http://www.sdss.org).

References

Aihara, H., Allende Prieto, C., An, D., & al. 2011, ApJS, 193, 29.

Augusteijn, T., Greimel, R., van den Besselaar, E. J. M., & al. 2008, A&A, 486, 843

Brown, J. M., Kilic, M., Brown, W. R., & al. 2011, ApJ, 730, 67.

Chabrier, G., & Baraffe, I. 1997, A&A, 327, 1039.

Eisenstein, D. J., Liebert, J., Harris, H. C., & al. 2006, ApJS, 167, 40.

Finley, D. S., Koester, D., & Basri, G. 1997, ApJ, 488, 375

Fischer, D. A., & Marcy, G. W. 1992, ApJ, 396, 178

Fontaine, G., Grassard, P., & Bergeron, P. 2001, PASP, 113, 409

Fryer, C. L., Holz, D. E., & Hughes, S. A. 2002, ApJ, 565, 430.

Greenstein, J. L. 1986, AJ, 92, 867

Hauschildt, P. H., Allard, F., Ferguson, J., & al. 1999, ApJ, 525, 871.

Hauschildt, P. H., & Baron, E. 1999, Journal of Computational & Applied Math., 102, 41

Heller, R., Homeier, D., Dreizler, S., & al. 2009, A&A, 496, 191

Hu, Q., Wu, C., & Wu, X.-B. 2007, A&A, 466, 627.

Hügelmeyer, S. D., Dreizler, S., Homeier, D., & al. 2006, A&A, 454, 617.

Kleinman, S. J., Harris, H. C., Eisenstein, D. J., & al. 2004, ApJ, 607, 426.

Littlefair, S. P., Dhillon, V. S., Marsh, T. R., & al. 2008, MNRAS, 388, 1582.

Luyten, W. J. 1999, VizieR Online Data Catalog, 3070, 0

McCook, G. P., & Sion, E. M. 1999, ApJS, 121, 1

Nebot Gómez-Morán, A., Schwope, A. D., Schreiber, M. R., & al. 2009, A&A, 495, 561.

Nilsson, R., Uthus, H., Ytre-Eide, M., & al. 2006, MNRAS, 370, L56.

Pourbaix, D., Ivezic, Ž., Knapp, G. R., & al. 2004, A&A, 423, 755.

Raghavan, D., McAlister, H. A., Henry, T. J., & al. 2010, ApJS, 190, 1.

Ramsay, G. 2000, MNRAS, 314, 403.

Raymond, S. N., Szkody, P., Hawley, S. L., & al. 2003, AJ, 125, 2621.

Rebassa-Mansergas, A., Gānsicke, B. T., Rodríguez-Gil, P., & al. 2007, MNRAS, 382, 1377.

Rebassa-Mansergas, A., Gānsicke, B. T., Schreiber, M. R., & al. 2010, MNRAS, 402, 620.

Rebassa-Mansergas, A., Gānsicke, B. T., Schreiber, M. R., & al. 2011, MNRAS, 413, 1121.

Renedo, I., Althaus, L. G., Miller Bertolami, M. M., & al. 2010, ApJ, 717, 183.

Ritter, H., & Kolb, U. 2010, VizieR Online Data Catalog, 1, 2018

Schreiber, M. R., & Gānsicke, B. T. 2003, A&A, 406, 305.

Schreiber, M. R., Gānsicke, B. T., Rebassa-Mansergas, A., & al. 2010, A&A, 513, L7+

Silvestri, N. M., Lemagie, M. P., Hawley, S. L., & al. 2007, AJ, 134, 741.

Wachter, S., Hoard, D. W., Hansen, K. H., & al. 2003, ApJ, 586, 1356.

York, D. G., Adelman, J., Anderson, J. E., Jr., & al. 2000, AJ, 120, 1579.

Yu, S., & Jeffery, C. S. 2010, A&A, 521, A85+

Zorotovic, M., Schreiber, M. R., Gānsicke, B. T., & al. 2010, A&A, 520, A86+.