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A Population Synthesis Study of White Dwarf–Main Sequence Binaries in the Galactic Disk

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Abstract. The companion mass ratio distribution (CMRD) of main sequence binaries is a crucial physical quantity for understanding the evolution of stars in binary systems and for constraining models of binary star formation. However, although much work has been done during the last years, the shape of the CMRD remains rather uncertain. We present a population synthesis study of white dwarf-main sequence (WDMS) binaries in the Galactic disk aimed at constraining the properties of the CMRD. To this end, we computed a set of Monte Carlo simulations aimed at reproducing the WDMS binary population observed by the SDSS. We used different prescriptions for the CMRD and we took into account all the known observational biases. We show that our simulations reproduce reasonably well the observed distributions of masses and luminosities of the white dwarf star and of spectral type of the main sequence star. Moreover, our simulations place constraints, albeit weak, on the shape of the CMRD.

1. Introduction

White dwarf-main sequence (WDMS) binaries are the evolutionary products of main sequence (MS) binaries, and can be formed through two channels. When the initial separation of the binary is large enough, the two components of the pair evolve as if they were single stars (Willems & Kolb 2004). However, if the two components are close enough, the system experiences a phase of dynamically unstable mass transfer that results in a common envelope (Webbink 2008). The WDMS binary population thus contains close binary systems that evolved through a common envelope and wide systems that did not interact during their evolution.

During the last few years modern large scale surveys, such as the Sloan Digital Sky Survey (SDSS) have allowed us to have large catalogs of WDMS binaries and other objects (York et al. 2000). The recently released WDMS binary catalog of Rebassa-Mansergas et al. (2016) is the largest and most homogeneous available to date, containing 3,291 systems identified within the data release 12 of the SDSS. WDMS of the SDSS have been used to improve our understanding of several different astrophysical problems (Schreiber et al. 2010; Rebassa-Mansergas et al. 2011; Ferrario 2012; Rebassa-Mansergas et al. 2013b). In this work, we use the WDMS binary catalog of the SDSS to constrain the properties of the companion mass ratio distribution (CMRD)

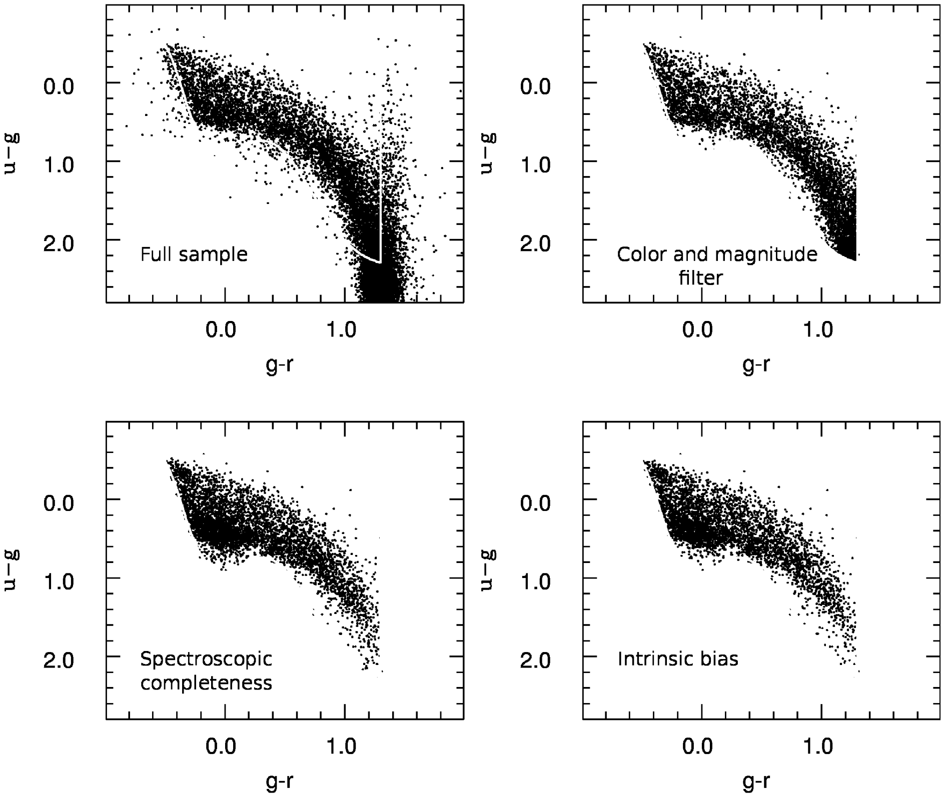

Figure 1. Color-color diagram of the synthetic WDMS binary sample obtained using our population synthesis code, after applying the different observational biases (blue dots). The red dots represent the observed WDMS binary population in the SDSS.

of MS binaries – that is, $n(q)$, where $q = m_2/m_1$, being m_1 the mass of the primary star and m_2 that of the secondary star. To do this we computed a grid of Monte Carlo simulations of the full WDMS binary population in the Galactic disk, which we calibrate using the WDMS binary sample of the SDSS (Rebassa-Mansergas et al. 2016). It is important to keep in mind that the observed sample is composed of data obtained from the four different sub-surveys of SDSS. These are the Legacy, BOSS, SEGUE and SEGUE2. The work presented here improves that of Camacho et al. (2014), that only focused on the close WDMS binary population observed by the Legacy survey. We also take into account observational selection effects for each subsurvey, as explained in the following section.

2. The Population Synthesis Code and the Observational Biases

We adapt and update an existing population synthesis code (García-Berro et al. 2004; Torres et al. 2005; Camacho et al. 2014), which amongst other features includes a Galactic model that accounts for stellar densities and kinematics, separate modules for single and binary stellar evolution and a detailed treatment of the observational biases. For binary evolution we employ the BSE package of Hurley et al. (2002). However, we recompute luminosities, temperatures, surface gravities and photometric magnitudes using modern white dwarf cooling tracks (Renedo et al. 2010; Althaus et al. 2005; Al-

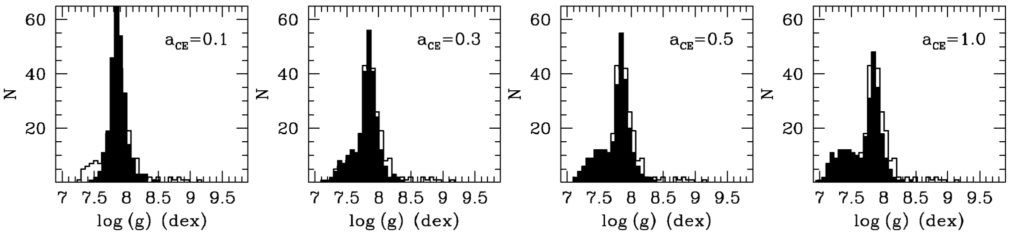

Figure 2. Distribution of surface gravities of the white dwarf star for different values of $\alpha_{\rm CE}$. We adopt $\alpha_{\rm int} = 0.0$.

thaus et al. 2007; Serenelli et al. 2001) and evolutionary sequences for low-mass MS stars (Baraffe et al. 2015).

The observational biases are incorporated in our simulations as follows. Firstly, we filter the synthetic WDMS binary population according to both magnitude and color cuts specific to the Legacy, BOSS, SEGUE-2 (Rebassa-Mansergas et al. 2013a) and SEGUE (Rebassa-Mansergas et al. 2012) sub-surveys. Secondly, we follow the procedure of Camacho et al. (2014) to apply a spectroscopic completeness filter, which takes into account the probability for each of our synthetic WDMS binaries to be observed by the SDSS. Thirdly, we use a multi-dimensional grid of WDMS binary parameters (effective temperatures and surface gravities, secondary star spectral types and distances) that allows us to evaluate whether a specific synthetic binary would have been detected as a genuine binary in the SDSS. This intrinsic WDMS binary bias excludes systems in which one of the components overshines the companion, as well as systems that would be associated to very low signal-to-noise ratio spectra simply because they are located too far away. Fig. 1 shows the number of WDMS synthetic binaries surviving each of these filters. The final filtered sample comprises $\sim 1\%$ of the synthetic WDMS binaries that are initially generated.

Finally, before performing any comparison with the observational data sets, we also incorporate uncertainties in the parameters of our synthetic WDMS binary samples. That is, we take into account the photometric errors, as well as errors in the observed stellar parameters – namely, effective temperature and surface gravity of the white dwarf, and spectral type of the secondary star.

3. Results

Our standard model uses a flat CMRD. For the age of the disk we adopt a value of 10 Gyr. The star formation rate is assumed to be constant. Regarding the parameters controlling the common envelope phase we adopt $\alpha_{\rm CE} = 0.3$, and a internal energy contribution $\alpha_{\rm int} = 0.0$. To explore the effect of $\alpha_{\rm CE} = 0.3$ on the synthetic samples, we analyze its impact on the distribution of surface gravities. The results are displayed in Fig. 2. It becomes evident that the best fit to the observed data is obtained assuming $\alpha_{\rm CE} = 0.3$. This is in full agreement with the results of Camacho et al. (2014), where only the close WDMS binary population was simulated.

In order to study the CMRD, a set of twelve different models is adopted. They have been selected from Camacho et al. (2014) and Ducati et al. (2011) – see Table 1. In seven of the models we also consider the influence of the so-called minimal mass ratio parameter, q_0, which we vary between 0.08 and 0.10. Using each of these models we

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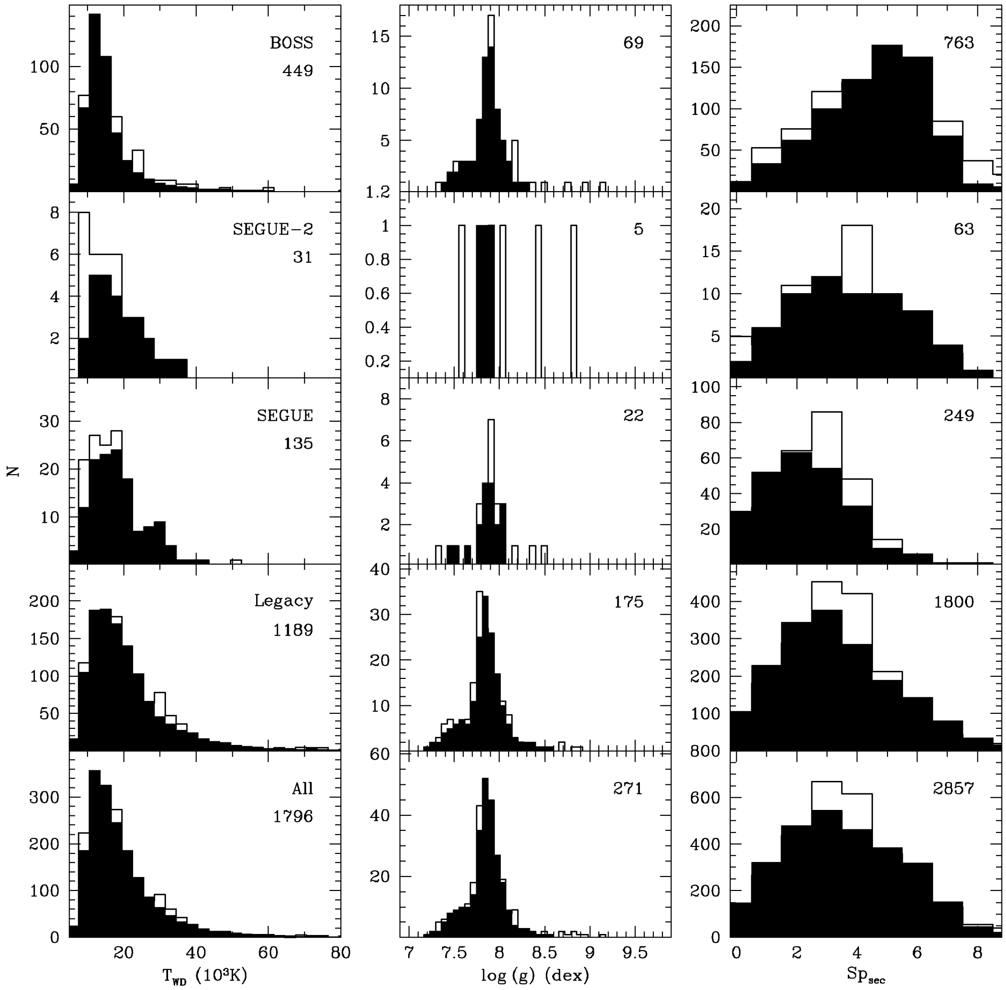

Figure 3. Distributions of white dwarf ffective temperatures and surface gravities and spectral types of the M dwarf. The observational data has been taken from Rebassa-Mansergas et al. (2016). The synthetic stars were obtained assuming $n(q) \sim q^{-1}$. This an example of a good fit.

compute the distributions of effective temperatures and surface gravities of the white dwarf and the distribution of spectral types of the secondary stars. Additionally, to compare the simulated distributions to the observed ones, we use three distance metrics. This allows us not only to decide which simulated distribution compares more favorably with the observed one, but also to order our models from best to worst. We do this not only for each synthetic/observed sub-samples corresponding to the Legacy, BOSS, SEGUE and SEGUE-2 surveys, but also for the total synthetic/observed WDMS binary samples. Specifically, we use the three following different distance metrics, where P is the observed distribution and Q the simulated one. First we use the standard least squares technique:

$$D_{\rm LS} = \sum_i (P(i) - Q(i))^2 \qquad (1)$$

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Table 1. Different models for $n(q)$, ordered from best to worst according to the fit to observational data. In the last three columns we list the average value of the three distance metrics used in our analysis. Models 7 to 12 increase with q, and can all be safely discarded.

Order	$n(q)$	Type	$\langle D_{\mathrm{KL}} \rangle$	$\langle D_{\mathrm{LS}} \rangle$	$\langle\beta\rangle(^\circ)$
1	q^{-1}	Decreasing	7.89×10^{-2}	6.28×10^{-3}	9.1
2	$\left(q - \frac{1+q_0}{2}\right)^2$, $q_0 = 0.08$	Bimodal	7.97×10^{-2}	6.65×10^{-3}	8.9
3	$1 - aq$, $a = 0.5$	Decreasing	8.46×10^{-2}	9.07×10^{-3}	10.4
4	q^{-2}	Decreasing	8.90×10^{-2}	9.02×10^{-3}	10.5
5	1	Flat	9.49×10^{-2}	9.96×10^{-3}	10.8
6	$\left(q - \frac{1+q_0}{2}\right)^2$, $q_0 = 0.1$	Bimodal	1.07×10^{-1}	1.33×10^{-2}	12.1
7	q	Increasing	1.79×10^{-1}	2.25×10^{-2}	14.7
8	$(q - q_0)^{1/3}$, $q_0 = 0.08$	Increasing	2.09×10^{-1}	2.39×10^{-2}	15.5
9	$q - q_0$, $q_0 = 0.08$	Increasing	3.42×10^{-1}	4.14×10^{-2}	18.7
10	$q - q_0$, $q_0 = 0.1$	Increasing	4.66×10^{-1}	4.49×10^{-2}	20.2
11	$(q - q_0)^2$, $q_0 = 0.08$	Increasing	5.15×10^{-1}	5.97×10^{-2}	23.5
12	$(q - q_0)^2$, $q_0 = 0.1$	Increasing	5.10×10^{-1}	6.56×10^{-2}	23.0

We also use the Kullback-Leibler divergence:

$$D_{\mathrm{KL}} = \sum_i P(i) \ln\left(\frac{P(i)}{Q(i)}\right) \tag{2}$$

Finally, we also employ the Bhattacharyya coefficient:

$$\cos(\beta) = \sum_i \sqrt{P(i)Q(i)} \tag{3}$$

We apply these three methods over the normalized synthetic/observed distributions and order our models from lowest to largest distance (or angle in case of the Bhattacharyya coefficient). We obtain roughly the same order from best to worse model for all three metrics (see an example of a good fit in Fig. 3). By setting a limit of $\beta > 13^\circ$ above which we consider a model incompatible with observations, we obtain that all the models that increase with q can be discarded (see Table 1).

4. Conclusions

We have performed a population synthesis study of the WDMS population of the Galactic disk and have compared the outcome of the simulations to the observed distributions (Rebassa-Mansergas et al. 2016). Namely, we compared the distributions of effective temperatures and surface gravities of the white dwarf members and the distribution of secondary star spectral types. We have tested twelve different models for the CMRD and have found that all increasing CMRDs can be excluded due to their poor fit to the observational data. This agrees with the results of other studies, that favor either flat or decreasing CMRD (Ducati et al. 2011; Duchêne & Kraus 2013). We also find that a CE efficiency parameter ~ 0.3 is compatible with the observed data. This is also consistent with previous observational (Nebot Gómez-Morán et al. 2011) and theoretical (Camacho et al. 2014) findings.

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